Evaluation of Incident Solar Radiation on Inclined Plane by Empirical Models at Kuching, Sarawak, Malaysia

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Abstract. In this paper six different empirical models (three isotropic and three anisotropic sky models) were used for the estimation of available solar radiation on inclined surface at Kuching, Sarawak, Malaysia. Five year with monthly average solar radiation and meteorological data was used to compute the available radiation falling on the inclined plane. The tilt angle was fixed at 11ºS towards the equator to obtain more energy from the sun in the worst months of the year. From the results of selected models, it is revealed that the Reindl et al. model displayed the highest estimated values among all models; while the Badescu model demonstrated the lowest results as compared to isotropic as well as anisotropic models. It is recommended that Lieu & Jordan model is better model for cloudy weather conditions at Kuching. It can also be used for the estimation of solar radiation on tilted surfaces in overcast skies conditions.

Keywords. Empirical models, global solar radiation, tilted surface radiation, isotropic sky model, anisotropic sky model

1. Introduction

Solar energy is one of the most viable renewable energy resources in the world, and promising alternative and sustainable energy, omnipresent, safe, abundant, freely available, and environment friendly [1, 2]. A drawback, common to the solar energy systems (photovoltaic applications, active and passive heating and cooling), is their unpredictable nature and their output cannot be accurately predicted, because, these systems are dependent on weather and climatic conditions [3, 4]. Research and development efforts are required to improve the performance of solar energy systems, and to establish new techniques for accurate prediction of their output from available environmental and climatic conditions [5]. Solar radiation data are the best source of information for estimating average incident radiation necessary for proper design and the assessment of solar energy conversion systems [6]. The availability of more comprehensive solar radiation data is invaluable for the design and evaluation of solar-based conversion systems. Particularly, the basic solar radiation data for the surfaces of interests are not readily available in most developing countries [7, 8]. Generally, the meteorological stations measure global and diffuse solar radiation intensities mostly on horizontal surfaces only [9]. Whereas, the stationary solar conversion systems (both for the production of electrical and thermal energy i.e., photovoltaic cells and flat plate collectors) are tilted towards the sun in order to maximize the amount of solar radiation incident on the collector or cell surface. But, the availability of these data on tilted surfaces is very rare [10]. Therefore, the tilted surface irradiation in most cases is calculated from measured global horizontal irradiation [11]. This can be done by empirical correlations through models [12].

Solar radiation data could be used in several forms and for a variety of purposes. Daily data is often available and hourly radiation can be estimated from available daily data. Monthly total solar radiation on a horizontal surface can be used in some process design methods. However, the process performance is generally not linear with solar radiation. The use of averages may lead to serious errors if non-linearties are not taken into account [13]. So that, the measurements of solar radiation on tilted planes are important in determining the proper input to solar photovoltaic (PV) systems or collectors [14]. Basically, two types of irradiance models are required to estimate tilted surface irradiation from global horizontal irradiation. One type of model estimates beam and diffuse components from global horizontal irradiation and the other predicts tilted surface irradiation [11]. The total radiation on a tilted surface consists of three components: beam, reflected radiation from the ground and diffuse from the all part of the sky. The direct and reflected components can be computed with good accuracy by using simple algorithms but the nature of diffuse part is more complicated. Calculation of diffuse radiation requires information of both global and direct radiation incident on a horizontal surface at the same time period [15, 16]. Empirical models which were proposed for the estimation of diffuse radiation is mostly based on the data collected from the stations of United States, Canada, Australia, and Northern European countries [17]. However, a large number of empirical models exist, and attempts were made to correlate the diffuse radiation on a tilted surface to that measured on horizontal surface according to local climatic conditions for a particular area. The abundant of such models indicated the complexity of the task for converting diffuse solar radiation measured on a horizontal to that on a tilted surface [12]. Thus, six different empirical models are chosen for this study to compare and assess the performance of these models according to the meteorological conditions of Kuching, Sarawak.

2. Methodology

The data was obtained from Malaysian Meteorological Services, Regional Office Kuching. The global solar radiation data was taken for the year 2005-2009, by Kipp & Zonen Solarimeter. Total six empirical models were selected and employed for the determination of solar radiation on inclined surface at Kuching (01°33’N and 110°25’E). First, the determination of extraterrestrial radiation of the area has been carried out by empirical relationships; then, beam and diffuse components on the horizontal surface is computed from monthly mean global radiation data by a well known model put forwarded by Erbs et al. (1982). Finally, the amount of incident solar radiation on tilted surface has been calculated with the help of three isotropic and three anisotropic sky models.

A. *Determination of Extraterrestrial Solar Radiation of the Area*

The monthly average daily extraterrestrial solar irradiance $\bar{H}_o$ on the horizontal surface is computed by taking the values of a single day (close to monthly mean values) for every month of the year by using days suggested by Klein (1977), which are representing the individual month. The proposed days were; 17th of January and July, 16th of February, March and August, 15th of April, May, September and October, 14th of November, 11th of June, and 10th of December [18]. The monthly average daily extraterrestrial solar irradiance $\bar{H}_o$ on the horizontal surface is determined by the following empirical relationship.

$$\bar{H}_o = \frac{24 \times 3600}{\pi} G_{sc}\left(1 + 0.033\cos\frac{360\,n}{365}\right) \times \left(\cos\varphi\cos\delta\cos\omega_s + \frac{\pi\omega_s}{180}\sin\varphi\sin\delta\right) \quad (1)$$

where, $\bar{H}_o$ is monthly average daily extraterrestrial solar irradiance $\left(\frac{\mathrm{J}}{\mathrm{m}^2}\right)$, G_{sc} *is* **solar constant** $\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right)$, n is the day of year (n =1 for 1st January and n= 365 for 31st of December), φ is the latitude (degrees) of the area, δ is declination (degrees), and ω_s is the sunset hour angle for the mean day of the month (degrees).

The declination(δ) is the angular position of the solar noon with respect to the plane of the equator, and was calculated by the formula proposed by Cooper (1669) as follows:

$$\delta = 23.45\sin\left(360\frac{284 + n}{365}\right) \quad (2)$$

ω_s is actually the solar hour angle (ω) corresponding to the time when the sun sets. Since, the solar hour angle (ω) is the angular displacement of the sun east or the west of the local meridian; morning negative afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from the solar noon. The sunset hour angle (ω_s) was computed by the following equation:

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta) \quad (3)$$

B. *Calculation of Diffuse Component of Radiation on Horizontal Surface*

The solar radiation coming from the sun is attenuated by the atmosphere and the clouds, before reaching the surface of the earth. The ratio of solar radiation at the surface of the earth to the extraterrestrial radiation is termed as clearness index $(\bar{K}_T)$, which is defined as:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_o} \quad (4)$$

where, $\bar{H}$ is the monthly mean daily solar radiation on a horizontal surface $\left(\frac{\mathrm{J}}{\mathrm{m}^2}\right)$. The monthly mean daily diffuse radiation ($^{-}H_1(d$)) can be computed from monthly mean daily global radiation $(\bar{H})$ based on the value of clearness index $(\bar{K}_T)$. For determination of $\bar{H}_d$, the most widely established correlation is used which was given by Erbs et al. (1982) [13, 19].

When the sunset hour angle (ω_s) for average day of the month is $\leq 81.4°$ **and** $0.3 \leq \bar{K}_T \leq 0.8$, then $\bar{H}_d$ is calculated from the following equation:

$$\frac{\bar{H}_d}{\bar{H}} = \{1.391 - 3.560\,\bar{K}_T + 4.189\,\bar{K}_T^2 - 2.137\,\bar{K}_T^3 \quad (5)$$

If the sunset hour angle (ω_s) is $> 81.4°$ **and** $0.3 \leq \bar{K}_T \leq 0.8;$ then $\bar{H}_d$ is computed from the following correlation:

$$\frac{\bar{H}_d}{\bar{H}} = \{1.311 - 3.022\,\bar{K}_T + 3.427\,\bar{K}_T^2 - 1.821\,\bar{K}_T^3 \quad (6)$$

C. *Estimation of Monthly Mean Daily Incident Solar Radiation on a Tilted Surface*

The incident radiation on a tilted plane is the sum of a set of radiation streams including beam radiation, the three components of diffuse radiation from the sky, and the radiation reflected from the various surfaces seen by the tilted surface. The total incident radiation ($\bar{H}_T$) on tilted plane can be written as in the following form:

$$\bar{H}_T = \bar{H}_{T,b} + \bar{H}_{T,r} + \bar{H}_{T,d} \quad (7)$$

where, ($\overline{H}_T$) is the monthly total incident radiation on a tilted surface, $(\overline{H}_{T,b})$ is beam radiation, $(\overline{H}_{T,r})$ is ground reflected, and $(\overline{H}_{T,d})$ is diffuse component on an inclined plane.

The beam radiation on tilted plane $(\overline{H}_{T,b})$ is given by:

$$\overline{H}_{T,b} = \overline{H}_b \overline{R}_b \tag{8}$$

where, $\overline{H}_b$ is monthly average daily beam radiation on horizontal surface, and $(\overline{R}_b)$ is the ratio of average daily beam radiation on the tilted surface to that on a horizontal surface. Basically, $\overline{R}_b$ is a function of transmittance of atmosphere, which is equal to $\left(\frac{\overline{H}_{T,b}}{\overline{H}_b}\right)$ and be determined by the following expression for the surfaces that are sloped towards the equator ($\textbf{surface azimuth angle } (\gamma) = 0$) in the northern hemisphere:

$$\overline{R}_b = \frac{\cos(\varphi - \beta)\cos\delta \sin\omega_s' + \left(\frac{\pi}{180}\right)\omega_s' \sin(\varphi - \beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s \sin\varphi\sin\delta} \tag{9}$$

The numerator of the above equation is the extraterrestrial radiation on tilted surface and the denominator is that on horizontal surface. Each of these is obtained by integration of angle of incident of beam radiation over the appropriate time period, from the true sunrise to sunset for the horizontal surface and from apparent sunrise to apparent sunset on the tilted surface. **Where,** ω_s' is the sun set hour angle for tilted surfaces of the month under consideration, which can be computed as:

$$\omega_s' = \min\left\{\begin{matrix} \cos^{-1}(-\tan\varphi\tan\delta) \\ \cos^{-1}(-\tan(\varphi - \beta)\tan\delta) \end{matrix} \quad \text{or} \right\} \tag{10}$$

The minimum value of either relationship can be taken and employed for the calculation of $\overline{R}_b$.

The ground reflected radiation on incline surface $(\overline{H}_{T,r})$ is composed of diffuse reflectance (ρ_g) from the ground (also called ground albedo) and a view factor (F_{c-g}) . The $\overline{H}_{T,r}$ is defined as:

$$\overline{H}_{T,r} = \overline{H}\rho_g F_{c-g} \tag{11}$$

$$\overline{H}_{T,r} = \overline{H}\rho_g \left(\frac{1 - \cos\beta}{2}\right) \tag{12}$$

where, β represents the slope of the PV array. The ground Albedo (ρ_g) is taken as 0.2, if the average monthly temperature is greater than 0ºC and the measuring station is located on a roof top with a low reflectance. Its value could be taken as 0.7 if the temperature is less than -5ºC [13, 20].

The methods used to estimate the diffuse radiation on a tilted surface to that of a horizontal are broadly classified as isotropic and anisotropic models. The isotropic models assume that the intensity of diffuse sky radiation is uniform over the sky dome. Hence, the diffuse radiation incident on a tilted surface depends on a fraction of the sky dome seen by it. The anisotropic models on the other hand, presume that the anisotropy of the diffuse sky radiation in the circumsolar region (sky near the solar disk) plus the isotropically distributed diffuse component from the rest of the sky dome (horizon brightening fraction) [15]. For this study, total six models were chosen, and their results were compared for selection of suitable and appropriate model for this area. Out of six, three isotropic models (Liu and Jordan, Koronakis, and Badescu model), and three anisotropic models (Hay and Davies, Reindl et al., and HDKR model) were examined. In general, the diffuse fraction of radiation on inclined surface is considered as follows:

$$\overline{H}_{T,d} = \overline{H}_{d,iso} F_{c-s} + \overline{H}_{d,cs} \overline{R}_b + \overline{H}_{d,hz} F_{c-hz} \tag{13}$$

$$F_{c-s} = \left(\frac{1 + \cos\beta}{2}\right) \tag{14}$$

Equation (6) for calculating $\overline{H}_T$ can be rewritten as follows:

$$\overline{H}_T = \overline{H}_b \overline{R}_b + \overline{H}\rho_g \left(\frac{1 - \cos\beta}{2}\right) + \left[\overline{H}_{d,iso}\left(\frac{1 + \cos\beta}{2}\right) + \overline{H}_{d,cs}\overline{R}_b + \overline{H} \right. \tag{15}$$

There is agreement among authors in terms of beam and reflected radiation (15). However, the differences are largely in the defining and treating of diffuse radiation on tilted surface. Due to the complicated nature of diffuse fraction many researchers use a simple isotropic model to estimate the amount of diffuse radiation incident on tilted surfaces [13].

1) Liu and Jordan model (1963)

The radiation on tilted surface was considered to be composed of three parts such as; beam, reflected from ground and diffuse fraction. It was assumed that the diffuse radiation is isotropic only; whereas, circumsolar and horizon brightening were taken as zero [13, 17].

Hence, $\overline{H}_{T,d} = \overline{H}_d \left(\frac{1 + \cos\beta}{2}\right)$, and the overall formula for computing the total radiation on tilted surface is proposed as sum of beam, earth reflected and isotropic diffuse radiation. Then, the $\overline{H}_T$ was given as follows.

$$\overline{H}_T = \overline{H}_b \overline{R}_b + \overline{H}\rho_g \left(\frac{1 - \cos\beta}{2}\right) + \overline{H}_d \left(\frac{1 + \cos\beta}{2}\right) \tag{16}$$

2) Koronakis model (1986)

Koronakis modified the assumption of isotropic sky diffuse radiation and proposed that the slope $(\beta = 90°)$ provides 66.7% of diffuse solar radiation of the total sky dome, for example, $F_{c-s} = \frac{1}{3(2+\cos\beta)}$. Thus, following correlation was suggested to measure radiation on tilted surface [21].

$$\overline{H}_T = \overline{H}_b\overline{R}_b + \overline{H}\rho_g\left(\frac{1-\cos\beta}{2}\right) + \overline{H}_d\left[\frac{2+\cos\beta}{3}\right] \quad (17)$$

3) Badescu Model (2002)

Badescu demonstrated model for the solar diffuse radiation on a tilted surface, and considered the view factor as $\frac{3+\cos 2\beta}{4}$. Therefore, the total radiation on a tilted surface was expressed as [22]:

$$\overline{H}_T = \overline{H}_b\overline{R}_b + \overline{H}\rho_g\left(\frac{1-\cos\beta}{2}\right) + \overline{H}_d\left(3 + \frac{\cos[(2\beta))}{4}\right] \quad (18)$$

Isotropic models are easy to understand and make calculation of radiation on tilted surfaces simple. However, the anisotropic models have been developed which takes into account the circumsolar diffuse and horizon brightening components on a tilted surface. A brief description of the selected anisotropic models is given below.

4) Hay and Davies Model (1981)

Hay and Davies assumed that the diffuse radiation from the sky is composed of an isotropic and circumsolar component only, whereas, the horizon brightening part was not taken into account [23]. They presumed that the diffuse parts coming directly from the sun's direction is circumsolar and the diffuse component reaching through the rest of the sky dome isotropically. These components were weighted according to an anisotropy index (A). The anisotropy index was used to quantify a portion of diffuse radiation treated as circumsolar with remaining part of the diffuse radiation assumed to be isotropic. The reflected part is dealt with same as suggested by Liu and Jordan. The total radiation on a tilted surface is proposed as follows [24]:

$$\overline{H}_T = (\overline{H}_b + \overline{H}_d A)\overline{R}_b + \overline{H}\rho_g\left(\frac{1-\cos\beta}{2}\right) + \overline{H}_d\left[\left(\frac{1+\cos\beta}{2}\right)(1-A) + A\,\overline{R}_b\right] \quad (19)$$

where, A is anisotropy index, which is the function of transmittance of the atmosphere for beam radiation and defined as:

$$A = \frac{\overline{H}_{b,n}}{\overline{H}_{o,n}} = \frac{\overline{H}_b}{\overline{H}_o} \quad (20)$$

5) Reindl et al. Model (1990)

Horizon brightening factor was added to isotropic diffuse and circumsolar radiation component, and considered beam and reflected fraction same as recommended by Liu and Jordan and other authors, and employed same definition of anisotropy index (A), as proposed by Hay and Davies. The modulating factor $f = \sqrt{\frac{\overline{H}_b}{\overline{H}}}$ was also added to multiply the term of $\sin^3\left(\frac{\beta}{2}\right)$ for horizon brightening factor. They considered all three components of diffuse fraction, such as $\overline{H}_{T,d,iso}$, $\overline{H}_{T,d,hz}$ and $\overline{H}_{T,d,cs}$, and their proposed model is given below [25].

$$\overline{H}_T = (\overline{H}_b + \overline{H}_d A)\overline{R}_b + \overline{H}\rho_g\left(\frac{1-\cos\beta}{2}\right) + \overline{H}_d\left\{(1-A)\left(\frac{1+\cos\beta}{2}\right)\right. \quad (21)$$

6) HDKR Model

When the beam, reflected and all terms of diffuse radiation such as isotropic, circumsolar and horizon brightening are added to the radiation equation, a new correlation develops called HDKR (the Hay, Davies, Klucher, Reindl) model [13, 26]. The total radiation on tilted plane is then determined as:

$$\overline{H}_T = (\overline{H}_b + \overline{H}_d A)\overline{R}_b + \overline{H}\rho_g\left(\frac{1-\cos\beta}{2}\right) + \overline{H}_d\left\{(1-A)\left(\frac{1+\cos\beta}{2}\right)\right. \quad (22)$$

3. Results and Discussions

The tilt angle was fixed at 11°S towards the equator to capture maximum solar radiation in the worst months of the year from October to March. Low solar radiation confronts the plane of array particularly in the month of January due to cloudy weather conditions. It is revealed from the results, that all models predicted more incident solar radiation on tilted surface than on horizontal surface due to low incidence angle of solar radiation in these months. The models predicted less amount of radiation in good weather conditions due to high angle of incidence of solar radiation. It is found that all isotropic models estimated lower solar radiation availability in the worst months due to conservative results of these models in overcast skies, and executed higher results in the good weather conditions from April to September as shown in Fig. 1. Overall, both the Hay & Davies and HDKR models demonstrated same results and established slightly more values than Lieu & Jordan model. This may be due to addition of the circumsolar component in diffuse radiation fraction in these models as compared to isotropic models. The Reindl et al. model displayed highest estimated values among all models. This is because of the individual consideration of all diffuse components and incorporation of modulating factor, which was multiplied by the term used for horizon brightening. The Badescu model demonstrated lowest results as compared to isotropic as well as anisotropic models. It is due to the factor used in the cosine of tilt angle which results the lower values of diffused radiation. Statistically, it is discovered that isotropic models executed the higher values than anisotropic models. Although, on the whole, all selected models established nearly 1% mean difference predicted values among each other.

4. Conclusions

It is concluded that the Reindl et al. model established the highest estimated values among all models. The Badescu model demonstrated the lowest results when compared with isotropic as well as anisotropic models. It is discovered that all isotropic models estimated lower solar radiation availability in worst months and demonstrated higher results in the good weather conditions from April to September. For cloudy weather condition Hay & Davies and HDKR models displayed almost the same results and executed slightly more values as compared to Lieu & Jordan model. However, it is recommended that Lieu & Jordan model is better model for cloudy weather condition at Kuching, Sarawak. It can also be used for the estimation of solar radiation on tilted surfaces in overcast skies conditions.

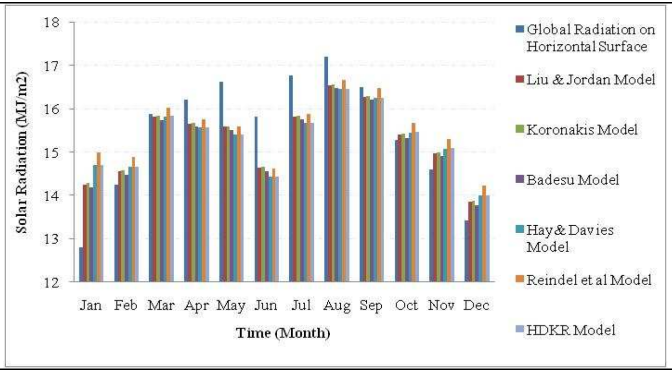

Figure1. Amount of monthly mean daily incident solar radiation (MJ/m^2) on tilted surface by different models at Kuching, Sarawak

Table I. Amount of Monthly Mean Daily Incident Solar Radiation (MJ/m^2) on Tilted Surface by different Models at Kuching, Sarawak

MONTH	EXTRA-TERREST-RIAL SOLAR RADIATION	GLOBAL SOLAR RADIATION ON HORIZONTAL SURFACE	INCIDENT SOLAR RADIATION ON TILTED SURFACE					
			Liu & Jordan Model	Koronakis Model	Badescu Model	Hay & Davies Model	Reindel et al. Model	HDKR Model
Jan	35.60	12.80	14.25	14.28	14.19	14.71	14.99	14.71
Feb	36.98	14.24	14.55	14.57	14.48	14.66	14.89	14.66
Mar	37.70	15.87	15.81	15.83	15.73	15.82	16.03	15.83
Apr	36.90	16.21	15.65	15.67	15.58	15.56	15.76	15.56
May	35.24	16.63	15.58	15.60	15.51	15.41	15.60	15.41
Jun	34.03	15.82	14.63	14.65	14.56	14.43	14.62	14.43
Jul	34.47	16.77	15.81	15.84	15.75	15.68	15.87	15.68
Aug	35.99	17.21	16.55	16.57	16.48	16.46	16.66	16.46
Sep	37.20	16.51	16.28	16.30	16.21	16.26	16.47	16.26
Oct	37.00	15.28	15.40	15.42	15.32	15.45	15.68	15.46
Nov	35.76	14.59	14.97	14.99	14.9	15.08	15.31	15.09
Dec	35.04	13.42	13.85	13.87	13.78	14.00	14.23	14.00
Mean	35.99	15.44	15.28	15.30	15.21	15.29	15.51	15.29

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