ISSN 2250-3153

Estimation of Incident Solar Radiation on Tilted Surface by Different Empirical Models

Abdul Qayoom Jakhrani*,†, Al-Khalid Othman*, Andrew R.H. Rigit*, Saleem Raza Samo, Shakeel Ahmed Kamboh*****

* Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia
**, † Faculty of Engineering, Quaid-e-Awam University of Engineering, Science and Technology Nawabshah, Sindh, Pakistan
*** Faculty of Computer Science and Information Technology, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia

Abstract- This paper evaluates the different empirical models used for the estimation of solar energy irradiation on tilted surfaces. For this purpose, three isotropic and the same number of anisotropic sky models were employed by using monthly mean solar radiation and weather data of Kuching, Sarawak, Malaysia. The tilt angle was fixed at 11ºS towards the equator for optimization of incoming solar radiation from the sun during the worst months of the year from October to March due to overcast skies. It was discovered that the Reindl et al. model estimated the highest amount of incident solar energy in the whole year and Badescu model established the lowest among all isotropic as well as anisotropic models, whereas, Liu and Jordan model performs well at the time of bad weather conditions. It is concluded that the selection of Liu and Jordan model could be useful for the prediction of solar energy irradiation on tilted surfaces in the study area, where the weather is mostly cloudy.

Index Terms- Anisotropic sky models, Empirical models, Incident solar radiation, Isotropic sky models, Tilted surface

I. Introduction

Out of all renewable energy resources, solar energy is one of the most feasible alternative and sustainable energy resources in the world. It is omnipresent, safe, abundant, freely available, and environment friendly [1-4]. A drawback, common to the solar energy systems is their unpredictable nature and their output cannot be accurately predicted, because, these systems are dependent on weather and climatic conditions [5-7]. 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 [8]. 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 [9]. 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 [10, 11]. Generally, the meteorological stations measure global and diffuse solar radiation intensities mostly on horizontal surfaces only [12]. Whereas, the stationary solar conversion systems are tilted towards the sun in order to maximize the amount of solar radiation incident on the collector or module surface. But, the availability of required data on tilted surfaces is very rare [13-15]. Therefore, the tilted surface irradiation in most cases is calculated from measured global horizontal irradiation by means of empirical models.

There are several forms of solar radiation data, which could be used for a variety of purposes in the design and development of solar energy systems. 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-linearities are not taken into account [16]. So that, the measurements of solar radiation on tilted surfaces are important for determination of accurate input to solar photovoltaic (PV) systems or collectors [17]. Basically, two types of solar radiation models are required to predict the tilted surface irradiation from global horizontal irradiation. One type of model predicts beam and diffuse components from global horizontal irradiation and the other estimates the incident radiation on tilted surfaces [14, 30]. 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. Calculations of diffuse radiation require information of both global and direct radiation incident on a horizontal surface at the same time period [18, 19]. Empirical models which were found in literature for the estimation of diffuse radiation is mostly based on the data collected from the meteorological stations of United States, Canada, Australia, and Northern European countries [20]. Although, 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 surface to that on a tilted surface [15]. Thus, six different empirical models are selected for this study to evaluate their output for the prediction of incident solar radiation on tilted surfaces.

II. Materials and Methods

Solar radiation and climatic data was acquired from Malaysian Meteorological Services, Regional Office Kuching. The global solar radiation data was taken for the year 2005-2009, by Kipp & Zonen Solarimeter in the station. Total six empirical models were evaluated and used for the determination of solar energy irradiation on tilted surface at Kuching (01°33'N and 110°25'E). The determination of extraterrestrial radiation of the area was carried out by empirical relationships. The amount of beam and diffuse components of solar radiation on the horizontal surface was computed from monthly mean global radiation data by a well known model put forwarded by Erbs et al. (1982). The amount of incident solar energy on tilted surface was calculated by means of three isotropic and three anisotropic sky models.

A. Determination of Extraterrestrial Solar Radiation on Horizontal Surfaces

The monthly mean daily extraterrestrial solar radiation $(\overline{H}_o)$ 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 [21]. The monthly average daily extraterrestrial solar radiation $(\overline{H}_o)$ on the horizontal surface is determined by the following empirical relationship.

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

where $\overline{H}_o$ is monthly mean daily extraterrestrial solar radiation (J/m^2), G_{sc} is solar constant (W/m^2) 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:

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

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° per hour from the solar noon. The sunset hour angle (ω_s) was computed by the following equation:

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

B. Determination of Diffuse Radiation on Horizontal Surfaces

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 $(\overline{K}_T)$ which is expressed as:

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

where $\overline{H}$ is the monthly mean daily solar radiation on a horizontal surface (J/m^2).

Monthly mean daily diffuse radiation $(\overline{H}_d)$ was computed from monthly mean daily global radiation $(\overline{H})$ based on the value of clearness index $(\overline{K}_T)$. The most widely cited model given by Erbs et al. (1982) was used for the determination of $\overline{H}_d$ [16, 22]. When the sunset hour angle (ω_s) for mean day of the month is $\le 81.4^o$ and $0.3 \le \overline{K}_T \le 0.8$, and then $\overline{H}_d$ can be calculated from the following equation:

$$\frac{\overline{H}d}{\overline{H}} = 1.391 - 3.56\overline{K}T + 4.189\overline{K}T^2 - 2.137\overline{K}T^3 \quad (5)$$

If the sunset hour angle (ω_s) is $> 81.4^o$ and $0.3 \le \overline{K}_T \le 0.8$ then $\overline{H}_d$ could be obtained from the following correlation:

$$\frac{\overline{H}d}{\overline{H}} = 1.311 - 3.022\overline{K}T + 3.427\overline{K}T^2 - 1.821\overline{K}T^3 \quad (6)$$

C. Determination of Incident Solar Radiation on Tilted Surfaces

The incident solar irradiation on a tilted surface 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 $(\overline{H}_T)$ on tilted surface can be written as in the following form:

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

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

$$\overline{H}_{T,b} = \overline{H}_b \overline{R}_b \quad (8)$$

where $\overline{H}_b$ is monthly mean daily beam radiation on horizontal surface, and $(\overline{R}_b)$ is the ratio of mean 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 $(\overline{H}_{T,b}/\overline{H}_b)$ and be determined by the following expression for the surfaces that are sloped towards the equator $(\gamma = 0)$ in the northern hemisphere.

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

The numerator of Eq. (9) denotes amount of the extraterrestrial radiation on tilted surface and the denominator is that on horizontal surface. Each of these expressions are obtained by integration of incident angle of beam radiation over the appropriate time period, from the true sunrise to sunset on horizontal surface and from apparent sunrise to apparent sunset on the tilted surface. Whereas, $\omega_s^{'}$ is the sunset hour angle for tilted surfaces of the month under consideration, which is expressed as:

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

The minimum value of either relationship from Eq. (10) can be used for the calculation of $\overline{R}_b$. The ground reflected radiation on tilted 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}), which is expressed as:

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

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

where β represents the slope of the PV array. The ground reflectance (ρ_g) is taken as 0.2 in a condition that the mean 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 [16, 23].

D. Determination of Diffuse Radiation on Tilted Surfaces

The models used to predict the diffuse radiation on a tilted surface are broadly classified as isotropic and anisotropic sky 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) [18]. For this study, total six empirical models were chosen, and their results were compared for selection of suitable and appropriate model for this area. Out of six, three isotropic models namely Liu and Jordan, Koronakis, and Badescu model, and three anisotropic models namely Hay and Davies, Reindl et al., and HDKR model were investigated. In general, the diffuse fraction of radiation on inclined surface is composed of isotropic, circumsolar and horizon brightening factors as given in Eq. (13).

$$\overline{H}_{T,d} = \overline{H}_{d,iso}F_{c-s} + \overline{H}_{d,ics}\overline{R}_b + \overline{H}_{d,hz}F_{c-hz} \quad (13)$$

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

Thus, Eq. (7) for calculating $(\overline{H}_T)$ can be rewritten as follows:

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

It is found from the literature, that there is an agreement among authors in terms of beam and reflected radiation [18]. 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 mostly use isotropic models to estimate the amount of diffuse radiation incident on tilted surfaces [16]. Because, the isotropic sky 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 isotropic and anisotropic sky models selected for comparison of estimated results is given below:

Liu and Jordan model (1963)

In this model, the solar radiation on tilted surface is 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 [16, 20]. Hence, $\overline{H}_{T,d} = \overline{H}_d[(1+\cos\beta)/2]$, and the overall formula for computing the total radiation on tilted surface is proposed as sum of beam, earth reflected and isotropic diffuse radiation. Thus, $\overline{H}_T$ is given as follows.

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

Koronakis model (1986)

Koronakis modified the assumption of isotropic sky diffuse radiation and proposed that the slope $\beta = 90^o$ provides 66.7% of diffuse solar radiation of the total sky dome, for example $F_{c-s} = (2+\cos\beta)/3$. Thus, following correlation was suggested to measure incident radiation on tilted surface [24].

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

Badescu Model (2002)

Badescu demonstrated model for the solar diffuse radiation on a tilted surface, and considered the view factor (F_{c-s}), which is equal to $[(3+\cos 2\beta)/4]$. Therefore, the total radiation on a tilted surface was expressed as [25]:

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

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 [26]. It was assumed 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 [27]:

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

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

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

Reindl et al. Model (1990)

In this model, horizon brightening factor was added to isotropic diffuse and circumsolar radiation component. Beam and reflected fraction of solar radiation was taken as same, which were proposed by Liu and Jordan and other authors. A definition of anisotropy index (A) was introduced as proposed by Hay and Davies. The modulating factor $f = \sqrt{\overline{H}_b / \overline{H}}$ was also added to multiply the term of $\sin^3(\beta/2)$ 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 [28].

$$\overline{H}_T = \left(\overline{H}_b + \overline{H}_d A\right)\overline{R}_b + \overline{H}_{\rho_g}\left(\frac{1-\cos\beta}{2}\right) + \overline{H}_d\left\{(1-A)\left(\frac{1+\cos\beta}{2}\right)\left[1+\sqrt{\frac{\overline{H}_b}{\overline{H}}}\sin^3\left(\frac{\beta}{2}\right)\right] + A\overline{R}_b\right\} \tag{21}$$

HDKR Model (2006)

If the beam, reflected and all terms of diffuse radiation such as isotropic, circumsolar and horizon brightening are added to the solar radiation equation, a new correlation develops called HDKR model [16, 29]. It is basically the combination of Hay and Davies, Klucher and Reindl models. The solar energy irradiation on tilted surface is then determined as:

$$\overline{H}_T = \left(\overline{H}_b + \overline{H}_d A\right)\overline{R}_b + \overline{H}_{\rho_g}\left(\frac{1-\cos\beta}{2}\right) + \overline{H}_d\left\{(1-A)\left(\frac{1+\cos\beta}{2}\right)\left[1+\sin^3\left(\frac{\beta}{2}\right)\right]\right\} \tag{22}$$

III. 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 as shown in Table 1. It is revealed from the results, that all models predicted more incident solar energy irradiation 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 Figure 1.

Overall, both the Hay & Davies and HDKR models demonstrated same results and established slightly more values than Liu & 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 in their model 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 in good weather conditions and clear skies days. However, all examined models executed nearly 1% of mean difference in estimated results among each other.

IV. CONCLUSIONS

It was found from the analysis that Reindl et al. model predicted the highest and Badescu model demonstrated the lowest values of solar energy irradiation on tilted surfaces among all isotropic as well as anisotropic sky models. Most isotropic models predicted lower solar radiation availability in worst months and established higher results in the good weather conditions from April to September. Hay & Davies and HDKR models displayed almost the same results for cloudy weather conditions, and executed slightly more values as compared to Liu & Jordan model. It is concluded that Liu & Jordan model is better for prediction of solar energy irradiation in cloudy weather conditions. It could be used for the estimation of available solar radiation incident on tilted surfaces in overcast skies.

.

REFERENCES

[1] H. Li, W. Ma, Y. Lian and X.Wang, "Estimating daily global solar radiation by day of year in China". Applied Energy, 2010, 87: pp. 3011-3017.

[2] A.Q. Jakhrani, A.K. Othman, A.R.H. Rigit and S.R. Samo, "Model for Estimation of Global Solar Radiation in Sarawak, Malaysia". World Applied Sciences Journal, Special Issue of Food & Environment, 2011, 14: pp. 83-90.

[3] A.Q. Jakhrani, A.K. Othman, A.R.H. Rigit and S.R. Samo, "Comparison of Solar Photovoltaic Module Temperature Models". World Applied Sciences Journal, Special Issue of Food & Environment, 2011, 14: pp. 1-8.

[4] A.Q. Jakhrani, A.K. Othman, A.R.H. Rigit and S.R. Samo, "A simple method for the estimation of global solar radiation from sunshine hours and other meteorological parameters". IEEE ICSET 2010, 6-9 Dec 2010, Kandy, Sri Lanka.

[5] P. Nema, R.K. Nema and S. Rangnekar, "A current and future state of art development of hybrid energy system using wind and PV-solar: A review". Renewable and Sustainable Energy Reviews, 2009, 13(8): pp. 2096-2103.

[6] E.M. Nfah, J.M. Ngundam and R. Tchinda, "Modeling of solar/diesel/battery hybrid power systems for far-north Cameroon". Renewable Energy, 2007, 32: 832–844.

[7] M.T.Y. Tadros, Uses of sunshine duration to estimate the global solar radiation over eight meteorological stations in Egypt". Renewable Energy, 2000, 21(2): pp. 231-246.

[8] M.K. Deshmukh, S.S. Deshmukh, "Modeling of hybrid renewable energy systems". Renewable and Sustainable Energy Reviews, 2008, 12(1): pp. 235-249.

[9] A.A. Sabziparvar, " A simple formula for estimating global solar radiation in central arid deserts of Iran". Renewable Energy, 2008, 33: pp. 1002–1010.

[10] D.H.W. Li, T.N.T. Lam and V.W.C. Chu, "Relationship between the total solar radiation on tilted surfaces and the sunshine hours in Hong Kong". Solar Energy, 2008, 82(12): pp. 1220-1228.

[11] A. El-Sebaii, F.S. Al-Hazmi, A.A. Al-Ghamdi and S. J. Yaghmour, "Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia". Applied Energy, 2010, 87: pp. 568–576.

[12] E.G. Evseev and A.I. Kudish, "The assessment of different models to predict the global solar radiation on a surface tilted to the south". Solar Energy, 2009, 83: pp. 377–388.

[13] C.K. Pandey and A.K. Katiyar, "A note on diffuse solar radiation on a tilted surface". Energy, 2009, 34: pp. 1764–1769.

[14] K. Soga, H. Akasaka and H. Nimiya, A comparison of methods to estimate hourly total irradiation on tilted surfaces from hourly global irradiation on a horizontal surface, Kagoshima University, 1-4-7, Korimoto, Kagoshima, 890-0065, Japan, 1999.

[15] D. Miguel, J. Bilbao, R. Aguiar, H. Kambezidis nad E. Negro, "Diffuse solar irradiation model evaluation in the north mediterranean belt area". Solar Energy, 2001, 70(2): pp. 143–153.

[16] J. Duffie and W.A. Beckman, 2006. Solar Engineering of Thermal Processes, 3rd Ed. John Wiley & Sons, Inc. USA.

[17] P.G. Loutzenhiser, H. Maz, C. Felsmann, P.A. Strachan, T. Frank and G.M. Maxwell, "Emprical validation of models to compute solar irradiance on inclined surfaces for building energy simulation". Solar Energy, 2007, 81: pp. 254-267.

[18] M. Noorian, I. Moradi and G. A. Kamali, "Evaluation of 12 models to estimate hourly diffuse irradiation on inclined surfaces". Renewable Energy, 2008, 33: pp. 1406–1412.

[19] G. Notton, C. Cristofari, M. Muselli, P. Poggi and N. Heraud, "Hourly solar irradiations estimation from horizontal measurements to inclined data". First International Symposium on Environment Identities and Mediterranean Area, ISEIMA, IEEE Transactions, 2006, pp: 234-239.

[20] B.Y.H. Liu and R. C. Jordan, "The interrelationship and characteristic distribution of direct, diffuse and total solar radiation". Solar Energy, 1960, 4 (3): pp. 1-9.

[21] J.K. Page, "The estimation of monthly mean values of daily total short wave radiation on vertical and inclined surface from sunshine records for latitudes 40N–40S". Proceedings of UN Conference on New Sources of Energy, 1961, pp: 378–390.

[22] D. Erbs, S.A Klein and J.A. Duffie, "Estimation of diffuse radiation fraction for hourly daily and monthly average global radiation". Solar Energy, 1982, 28: pp. 293.

[23] RETScreen International, "Photovoltaic project analysis" ISBN 0-662-35672-1, Canada, 2004, pp:1-46.

[24] P.S. Koronakis, "On the choice of angle of tilt for south facing solar collectors in Athens Basin Area". Solar Energy, 1986, 36: pp. 217-225.

[25] V. Badescu, "3-D isotropic approximation for solar diffuse irradiance on tilted surfaces". Renewable Energy, 2002, 26: pp. 221-223.

[26] J.E. Hay, "Solar energy system design: The impact of mesoscale variations in solar radiation". Atmosphere-Ocean, 1983, 21(2): pp. 138-157.

[27] J.E. Hay, "Calculation of solar irradiances for inclined surfaces: Validation of selected hourly and daily models". Atmosphere-Ocean, 1986, 24(1): pp. 16-41.

[28] D.T. Reindl, W.A. Beckman and J.A. Duffie, "Diffuse fraction correlations". Solar Energy, 1990, 45(1): 1-7.

[29] T.M. Klucher, "Evaluation of models to predict insolation on tilted surfaces". Solar Energy, 1979, 23(2): pp. 11-114.

[30] A.Q. Jakhrani, A.K. Othman, A.R.H. Rigit, S.R. Samo and S.A. Kamboh, "A novel analytical model for optimal sizing of standalone photovoltaic systems". Energy, 2012, 46, pp. 675-682.

AUTHORS

First / Corresponding Author – Abdul Qayoom Jakhrani, M.E, Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia.
E-mail: aqunimas@hotmail.com, aqsindh@gmail.com, H/Phone # +60109741450.

Second Author – Al-Khalid Othman, PhD, Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia.
E-mail: okhalid@feng.unimas.my

Third Author – Andrew R.H. Rigit, PhD, Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia.
E-mail: arigit@feng.unimas.my

Fourth Author – Saleem Raza Samo, PhD, Faculty of Engineering, Quaid-e-Awam University of Engineering, Science and Technology Nawabshah, Sindh, Pakistan.
E-mail: sfaizsamo@yahoo.com

Fifth Author – Shakeel Ahmed Kamboh, Faculty of Computer Science and Information Technology, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia.
E-mail: shakeel.maths@yahoo.com

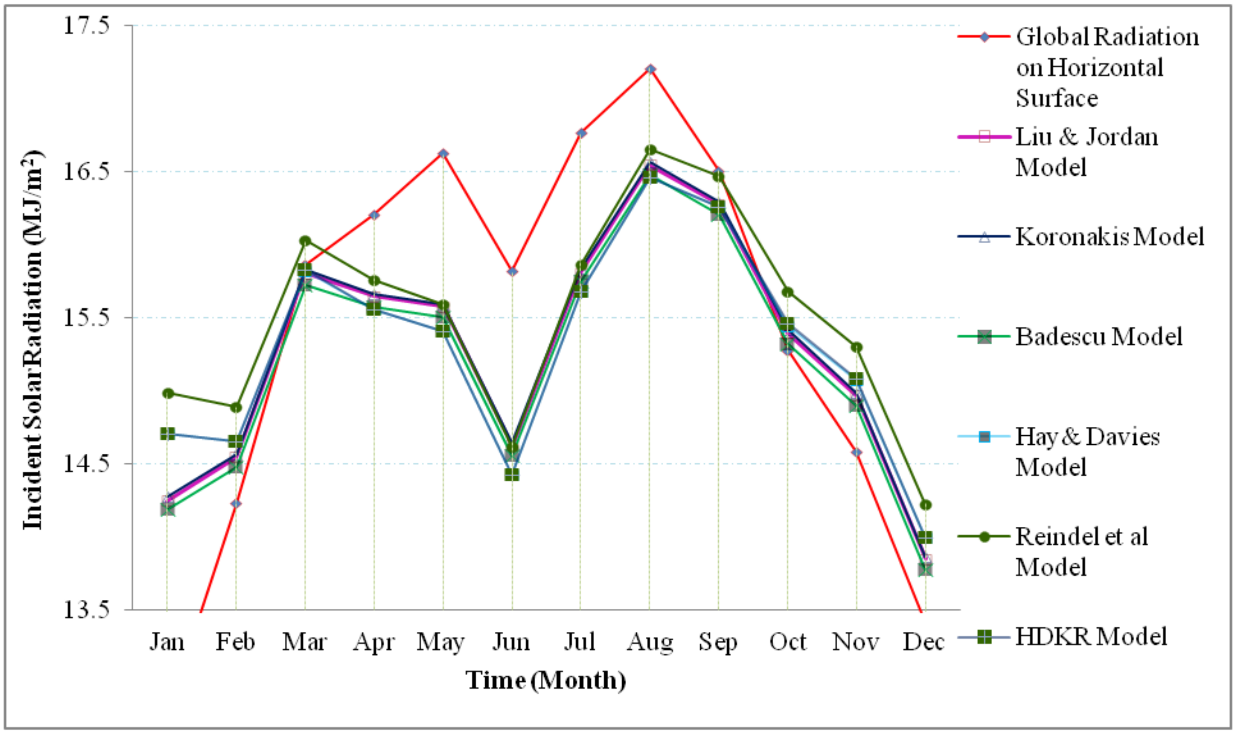

Figure 1: Comparison of model estimations for incident solar radiation on tilted surface versus time

Table I: Estimated monthly mean daily incident solar radiation (MJ/m^2) on tilted surface by different models at Kuching, Sarawak

Month	**Extra-terrestrial Solar Radiation** $(\overline{H}_o)$	**Global Solar Radiation on Horizontal Surface** (H)	**Estimated Incident Solar Radiation on Tilted Surface** $(\overline{H}_T)$					
			Liu & Jordan Model	***Koronakis Model***	***Badescu Model***	***Hay & Davies Model***	***Reindl 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