Development of A Model to Predict Annual Global Solar Radiation for Photovoltaic System's Sizing in UUM Area, Malaysia

Sanusi Y. K1*, Ojeniyi Y, A. Mohamad Ghozalih1 and Lateef T. A3

Corresponding author: Sanusi Y.K

ABSTRACT: In order to develop many solar energy devices and estimate their performances, an accurate knowledge of solar radiation distribution at a particular geographical location is required. Here, estimation of global solar radiation at University Utara Malaysia (UUM) area, Malaysia, (Latitude 6°N and longitude 100°E) was carried out in this study. In this study, a developed model based on the available simple atmospheric parameters of ambient temperature was used to predict the global solar radiation. The statistical analyses were employed to validate the results obtained from the model. The results obtained indicate that the values of the measured global solar radiation and the estimated values from the proposed model have a very close agreement and the correlation coefficients of 0.93 given by the model performance for the studied area is reasonably high. Therefore, the model can be utilized accurately and efficiently in predicting global solar radiation for photovoltaic system application in UUM area and its environs. The values of mean bias error, root mean square error and mean percentage error are 0.0062, 0.0812 and -0.813 respectively. All these confirmed the strong capacity of using the model to estimate global solar radiation in designing photovoltaic system utilization in the studied area.

Keywords: Global Solar Radiation, Photovoltaic, Temperature, Clearness Index, UUM, Malaysia

INTRODUCTION

The energy transferred from the sun in the form of radiant to the earth's surface is normally called solar radiation. Solar energy is a source of energy that free, clean and inexhaustible source of energy. Its effective harnessing and utilization are of importance to the world especially at this time of instability in the production of fossil fuel, rising fuel costs and environmental effects such as depletion of the ozone layer and greenhouse effect (J. H. Van Boxel, 2002). In any solar energy applications system, the knowledge of global solar radiation is very important for the optimal design and prediction of the system performance. The best way the amount of global solar radiation at a location can be determined is through recorded data. Daily solar radiation data are required in agro-metrical calculations particularly in computing a water budget for irrigation or to run a crop growth simulation model but these are measured only at a few stations (K. Bristow and G. Campbell, 1984). The immediate short term to the long term solutions to address the problems of inadequate infrastructure in the area of solar energy data acquisitions have been the application of empirical models that rely on the correlation between the weather parameters obtained from measured meteorological data (K. Bristow and G. Campbell, 1984). Therefore, several empirical formulae have been developed to predict the global solar radiation using various atmospheric parameters such as sunshine hours, cloud cover, relative humidity, maximum temperature, and water vapour pressure (Journal of Geophysics 16; 139 – 145; YK Sanusi and Abisoye SG, 2011; Kumar R and Umanand H, 2005; Fletcher AL, 2007; Sanusi YK, Abisoye SG, 2013). The knowledge of these solar radiation measurements on the earth’s surface is required for engineers, agriculturists and hydrologists in many applications. Since, the measurements of solar radiation are done only at a few locations, then for places where no measuring equipment are not available, modelling becomes an essential and economical tool for the estimation of solar radiation. Using various atmospheric parameters, several models have been developed in different locations (Y K Sanusi and Abisoye SG, 2011; Fletcher AL, 2007; Sanusi YK, Abisoye SG, 2013; Okundamiya MS, Nzeako AN, 2010; Poudyal KN, 2012). However, the objective of this study is to propose a model using clearness index, a simple weather parameter and ambient temperature for estimating global solar radiation for photovoltaics’ system sizing in UUM area Kedah, Malaysia.
Climatic Zone Under Study

The characteristic features of the climate of Malaysia are uniform temperature, high humidity and copious rainfall. Winds are generally light. Situated in the equatorial doldrum area, it is extremely rare to have a full day with completely clear sky even during periods of severe drought. At the same time, it is also rare to have a stretch of a few days with completely no sunshine except during the northeast monsoon seasons. In view of these, there exist four different seasons i.e, the southwest monsoon, northeast monsoon and two shorter periods of inter-monsoon seasons (World Meteorological Organisation, 2014). The seasonal wind flow patterns coupled with the local topographic features determine the rainfall distribution patterns over the country. During the northeast monsoon season, the exposed areas like the east coast of Peninsular Malaysia, Western Sarawak and the northeast coast of Sabah experience heavy rain spells. On the other hand, inland areas or areas which are sheltered by mountain ranges are relatively free from its influence. It is best to describe the rainfall distribution of the country according to seasons (World Meteorological Organisation, 2014).

However, the area of this study, northern part of Malaysia features a tropical rainforest climate under the Köppen climate classification. The area has a very lengthy wet season. As is common in several regions with this climate, precipitation is seen even during the short dry season. Temperatures are relatively consistent throughout the course of the year, with average high temperatures around 32 degrees Celsius and average low temperatures around 23 degrees Celsius.

![Figure 1. The Map of Area of Study](image)

MATERIAL AND METHODS

The data used for this study was obtained from the Malaysian Meteorological Department. The data obtained cover a period of eleven years (1999 – 2009) in the area of study (latitude 6°N, longitude 100°E). The monthly average data obtained were converted to annual average data in preparation for the estimation of annual global solar radiation of the study area as shown in Table I. The methodology used in this research work was based on (A. Angstrom, 1924). Thus, the equation postulated by (A. Angstrom, 1924) and modified by (YK Sanusi and Abisoye SG, 2011) was used to formalize the proposed models;

\[
\frac{H}{H_0} = a + b \frac{S}{L_d}
\]

Where:
- \(H\) is the incoming daily global solar radiation given as (MJ m\(^{-2}\) d\(^{-1}\)),
- \(H_0\) is the daily extra-terrestrial radiation (MJ m\(^{-2}\) d\(^{-1}\)),
- \(a\) and \(b\) are empirical constant s,
- \(S\) is bright sunshine hours per day (hr),
- \(L_d\) is the Astronomical day length (hr) and calculated with

\[
L_d = \frac{2}{15} \cos^{-1}[-\tan(\phi)\tan(\delta)]
\]

Where:
- \(\phi\) = latitude in degree
- \(\delta\) = Solar declination angle in degree

Also, \(H_0\) is given as;

\[
H_0 = \left(\frac{24}{\pi}\right) I_{sc} E_0 \cos \phi \cos \delta \left(\frac{\lambda}{180}\right) W_s \tan W_s
\]

\(I_{sc}\) = solar constant, 1367 W m\(^{-2}\),
\(\phi\) is the latitude of the station.
\( \tau_0 \) is the eccentricity factor and is given by the relation

\[
E_0 = \frac{\tau_0^2}{\Gamma_2} = 1.00011 + 0.034221 \cos\Gamma + 0.00128 \sin\Gamma + 0.000719 \cos^2\Gamma + 0.000077 \sin\Gamma\quad(4)
\]

The declination \( \delta \) for each day of the year is expressed as

\[
\delta = (0.006918 - 0.399912 \cos\Gamma + 0.070257 \sin\Gamma + 0.006758 \cos^2\Gamma + 0.000907 \sin^2\Gamma + 0.000719 \cos^2\Gamma + 0.000077 \sin\Gamma)
\]

Sunrise hour angle, \( W_s \) is expressed as

\[
W_s = \cos^{-1}(-\tan\Phi \tan\delta)
\]

However, from equation 3 and 4, \( \Gamma \) is in radians and is the day angle which is expressed as

\[
\Gamma = 2\pi(dn/J) / 365
\]

Where \( dn \) is the Julian day number of the year ranging from the first day of January to 365 on December 31. February is assumed to have 28 days. \( H_0 \) is obtained through a Visual Basic computer program.

From the figure 1, trend line equations of polynomial, was obtained as shown below:

Polynomial/Quadratic: \( K_T = -0.003T^2 + 0.057T + 0.382 \)

(8)

The models was analysed sequentially to obtain their regression co-efficient. The performance of the prepared models were evaluated using the following statistical: mean percentage error (MPE), root mean square error (RMSE) mean bias error (MBE), Chi-square (\( \gamma^2 \)), coefficient of correlation (R) and coefficient of determination (R^2).

\[
\text{MPE} = \frac{\sum_{i=1}^{n} (K_{Tp} - K_{Tm})}{n} \times 100
\]

(9)

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (K_{Tp} - K_{Tm})^2}{n}}
\]

(10)

\[
\text{MPE} = \frac{\sum_{i=1}^{n} (K_{Tp} - K_{Tm})}{n} \times 100
\]

(11)

\[
\gamma^2 = \frac{\sum_{i=1}^{n} (K_{Tp} - K_{Tm})^2}{n}
\]

(12)

Where \( K_{TP} \) and \( K_{TM} \) are respectively predicted and measured clearness index.

RESULTS AND DISCUSSION

Table 1 shows the measured ambient temperature, measured global solar radiation (Hm), and the predicted or estimated global solar radiation (Hp) from the proposed model. From the table, it is seen clearly that the highest magnitude of solar radiation was received on the earth surface in the year 2001 and the lowest magnitude of solar radiation was received in the year 2000 at the study area. Also, it is observed from the table that year 2002, 2003, 2005 and 2008 have a close range of magnitude of solar radiation, this implies that in these years, at the area of study, approximately, the same values of solar radiation were received on the earth surface from the sun. Hence, the effect of solar radiation characteristic will also be in close range in these years, thus, this could also be attributed to stable climate characteristics in the study area. From this mean annual global solar radiation provided for each of the year in the table 1, it is an evidence and ascertained that the area of study and its environs actually have high potential for the solar energy applications, especially for the photovoltaic solar system to sustain both long term and less expensive power supply compared to conventional power system currently using in the area.

Figure 2 display the variation of the measured values of global solar radiation obtained in the study area and predicted results of global solar radiation by the proposed model with number of years. Comparison of the results predicted by the proposed model and measured values of annual global solar radiation is presented graphically in figure 2. It could be deduced from this graphical analysis that result obtained from the model has a closer agreement with the measured values of annual global solar radiation in the study area. Also, it is deduced from the figure 2, that the results of the differences between the measured values and the proposed model values of global solar radiation for the year 2001, 2002, 2008 and 2009 are approximately equal to zero. While in the other years, the model gives global solar radiation values very close range with the measured values of global solar radiation. This confirms that predictive value by the proposed model and measured values are of the same values. Hence, the model can serve as a baseline tool that will use in designing and sizing photovoltaic system application UUM area and its environs for both PV installers and users.
Global solar radiation depends upon the location and has many effects on the type and rate of chemical reaction in the atmosphere. It affects the air convection and mixing and thus, the ambient temperature of the day. However, it is observed from figure 3, that the maximum temperature always recorded in the months of February to April is around 29°C, while the minimum temperature recorded is round 27°C in the months of May to December and January. Generally, the trend of temperature variation expected to be similar to all the studied years in the area, since the ambient temperature is the function of the global solar radiation reaching the earth’s surface.

Validation of the results estimated by the model using error analysis gives the values of mean bias error (MBE) as 0.0062, root mean square error (RMSE) as 0.0812 and mean percentage error (MPE) as -0.813. It can be concluded from the errors analysis results that low values of both MBE and RMSE attributes to the good performance of the proposed model. It is also important to note from the results that the value of MPE from the model is less than 1%. From table 3, even when the model was subjected to further statistical analyses; TSTAT and Chi², the model stood out uniquely, correlation coefficient (0.93) is high for the studied area. This implies that, there are statistical significant relationships between the clearness index (K_T) and ambient temperature (T) in the location considered.

CONCLUSION

The development and implementation of many solar energy devices and for estimates of their performances require an accurate knowledge of global solar radiation distribution at a particular geographical location. The best way the amount of global solar radiation can be determined is through recorded atmospheric data at the actual location. In this study, using the northern part of Malaysia particularly UUM area as a case study, a developed model was used for estimation of global solar radiation using annual ambient temperature covers a period of eleven years (1999-2009). The results obtained from the model were validated using three different error analysis. Based on the validation results, it therefore, becomes clear that the proposed model has better agreement in performance with measured values of global solar radiation in the study. The model is simple and could estimate the global solar radiation with relatively high accuracy. Therefore, it is recommended that the model should be used, even when only temperature data are available, for estimation of global solar radiation in the UUM area, Malaysia and other locations with similar solar characteristics. Finally, the model provides a simple and low cost system for estimating global solar radiation in the study area. It does not require information from neighboring stations for spatial interpolation and it does not require expensive hardware for data processing.

<table>
<thead>
<tr>
<th>Year</th>
<th>Min Ambient temperature( °C)</th>
<th>Max Ambient temperature( °C)</th>
<th>Average Ambient temperature( °C)</th>
<th>Mean Annual Measured Global solar Radiation, Hm ( Kwh/m²)</th>
<th>Mean Annual Predicted Global solar Radiation, Hp ( Kwh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>23.0</td>
<td>32.0</td>
<td>27.5</td>
<td>5.45</td>
<td>5.69</td>
</tr>
<tr>
<td>2000</td>
<td>23.0</td>
<td>31.0</td>
<td>27.0</td>
<td>5.40</td>
<td>5.75</td>
</tr>
<tr>
<td>2001</td>
<td>23.0</td>
<td>31.0</td>
<td>27.0</td>
<td>5.66</td>
<td>5.80</td>
</tr>
<tr>
<td>2002</td>
<td>24.0</td>
<td>31.0</td>
<td>27.5</td>
<td>4.84</td>
<td>4.90</td>
</tr>
<tr>
<td>2003</td>
<td>23.0</td>
<td>32.0</td>
<td>27.5</td>
<td>4.84</td>
<td>5.00</td>
</tr>
<tr>
<td>2004</td>
<td>23.0</td>
<td>32.0</td>
<td>27.5</td>
<td>5.20</td>
<td>5.60</td>
</tr>
<tr>
<td>2005</td>
<td>24.0</td>
<td>32.0</td>
<td>28.0</td>
<td>4.80</td>
<td>5.10</td>
</tr>
<tr>
<td>2006</td>
<td>23.0</td>
<td>31.0</td>
<td>27.0</td>
<td>5.54</td>
<td>5.90</td>
</tr>
<tr>
<td>2007</td>
<td>24.0</td>
<td>32.0</td>
<td>28.0</td>
<td>5.30</td>
<td>6.00</td>
</tr>
<tr>
<td>2008</td>
<td>23.0</td>
<td>31.0</td>
<td>27.0</td>
<td>4.82</td>
<td>4.90</td>
</tr>
<tr>
<td>2009</td>
<td>23.0</td>
<td>31.0</td>
<td>27.0</td>
<td>5.44</td>
<td>5.60</td>
</tr>
</tbody>
</table>

| Model | Co-efficients | K_T = 0.32+0.063T-0.003T² | 0.532 | 0.063 | -0.003 |

<table>
<thead>
<tr>
<th>Model</th>
<th>r</th>
<th>R²</th>
<th>MBE</th>
<th>RMSE</th>
<th>MPE</th>
<th>CHI²</th>
<th>TSTAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_T = 0.32+0.063T-0.003T²</td>
<td>0.93</td>
<td>93.0%</td>
<td>0.0062</td>
<td>0.0812</td>
<td>-0.813</td>
<td>0.012</td>
<td>0.168</td>
</tr>
</tbody>
</table>
Figure 1. Graph of mean monthly yearly $K_T$ against ambient temperature.

Figure 2. Variation of Measured and Predicted Mean Annual Global Solar Radiation With Number of Years

ACKNOWLEDGEMENT

The authors wish to thank the Malaysian Meteorological Department for providing the data for this study.

REFERENCES


J. H. Van Boxel, "Modelling Global Radiation for the Portofino Area in Italy", Institute for Biodiversity and Ecosystem Dynamics IBED, University of Amsterdam, Netherlands (2002).


Politoreanu CR, Mihailescu I, F, Torica: v (2002); Correlation between Sunshine and Air Temperature.


