

Comparison of Solar Photovoltaic Module Temperature Models

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Abstract: This paper presents the comparative study of the different models that used to predict the solar photovoltaic module temperature, which is one of the most important factors responsible for lowering the performance of photovoltaic modules. The approach of the different models was examined in order to evaluate the estimated behavior of module temperature increase with respect to ambient temperature and solar radiation. A total of 16 models have been reviewed by employing monthly mean daily meteorological data of Kuching, Sarawak. The most models showed similar trend of increase or decrease of solar photovoltaic module temperature due variation of solar radiation intensity. However, the results of reviewed models were quite different under constant solar radiation and ambient temperature conditions. It was found that the variation in the results was due to the use of different variables, climatic conditions, configuration of photovoltaic modules and the approach used by various researchers in their models.

Key words: Photovoltaic modules • Cell temperature models • Solar photovoltaic systems • Solar radiation • Sunshine hours

INTRODUCTION

Photovoltaic module operating temperature is one of the most important parameters for the evaluation of long term performance of PV systems, as it modifies the power output and system efficiency. Its affect varies with characteristics of module encapsulating material, thermal absorption and dissipation properties, types of PV cells, configuration, installation and operating point of module and climatic conditions of locality such as solar irradiation level, ambient temperature and wind speed [1-3].

Photovoltaic module performance or efficiency is usually inversely proportional to the operating temperature of cell. Two challenging factors are playing the conflicting role in the power output of PV modules. Firstly, as temperature increases, the band gap of the intrinsic semiconductor shrinks, the open circuit voltage (V_{oc}) decreases following the p-n junction voltage temperature, which contains diode factor. It is equivalent to the charge (q) divided by the product of cell temperature (T) and a constant (k), in which the q is electronic charge (1.602×10^{-19} Coulomb), k is Boltzmann's constant (1.381×10^{-23} J/K) and T is cell temperature ($^{\circ}C$). Hence, the PV cells have a negative

temperature coefficient of open circuit voltage (βV_{oc}). Likewise, that caused a lower power output at a given photocurrent, because the charge carriers are liberated at a lower potential. Thus, the reduction in V_{oc} results lower theoretical maximum power ($P_{max} = I_{sc} \times V_{oc}$) at a particular short-circuit current I_{sc} . Secondly, as temperature increases again the band gap of the inherent semiconductor shrinks, which results more absorption of incident energy. The greater percentage of the incident light has sufficient energy to raise charge carriers from the valence band to the conduction band. A larger photocurrent result the increase of I_{sc} at a definite solar insolation. The PV cells have a positive temperature coefficient of short circuit current (αI_{sc}). This effect alone would raise the theoretical maximum power by the relationship above [4-7]. Consequently, at a fixed solar radiation level increasing temperature leads to decreased open circuit voltage and slightly increased short circuit current, eventually it reduces the power output [6]. Thus it requires lowering the operating temperature of modules but with high irradiance. Since, the temperature of cells is very difficult to measure, because the cells are firmly enclosed for moisture protection. Therefore, in most cases, the back side temperature of a PV module is

commonly measured and assumed that the junction temperatures (T_j) of cells are the same as that of its back surface temperature [2]. Besides back side of temperature, some researchers are using the average value of the surface temperatures of the both the front side and the back side of PV module as the junction temperatures (T_j) of cells [4]. Many studies demonstrated that the models give satisfactory results, but they are not suitable for all conditions where the ventilation system is poor. Since, the accuracy of most models is questionable because the environmental and geographical conditions are totally different from the specified conditions where the models were justified. Unfortunately, a small number of studies have been conducted in equatorial regions where the environmental factors are extensively different from the climate conditions of high latitude areas [2]. The reliable quantified data from the tropical climates such as the Southeast Asian region is very difficult to obtain, although the data is available for various parts of the world [8]. The aim of this study was to compare the projected results of different models and to select a suitable model for the estimation of module temperature for the design of solar photovoltaic systems in tropical conditions.

PV Module Temperature Prediction Models: The models for the prediction of photovoltaic module operating temperature are mathematically explicit or implicit in form. Explicit models predict the value of cell temperature (T_c) directly, whereas, the implicit correlations involve variables which themselves depend on T_c . Thus, an iteration procedure is necessary for the relevant calculation of implicit models [5]. Most models usually include a reference state and the corresponding values of the relevant variables. PV module temperature prediction models could also be classified basically into two approaches, steady state approach and transient or non-steady state approach. A basic difference between these two approaches is that all parameters in the former approach are assumed to be independent of time, while in the latter one, some parameters are considered to be varying with respect to time.

The Steady State Approach: In this approach, it is simply assumed that, within a short time period (normally less than 1 h), the intensity of the incoming solar radiation and other parameters affecting the PV modules performance are constant. If the variation rates of overall heat losses to the environment of the PV module is small, then it can be assumed that the rate of heat transfer from the PV module

to the environment is steady and the temperatures at each point of the PV module is constant over the short time period. Nominal operating cell temperature (NOCT) is considered as an indicative of module temperature, which is provided by the manufacturers, which is defined as the mean solar cell junction temperature within an open-rack mounted module in Standard Reference Environment (SRE). SRE conditions includes the tilt angle at normal incidence to the direct solar beam at local solar noon; total irradiance of 800 W/m^2 ; ambient temperature of 20°C ; wind speed of 1 m/s and zero electrical loads. The estimation of PV system performance is generally based on the determination of module temperature from ambient temperature and NOCT conditions. The models are based on the fact that difference between module temperatures minus ambient temperature is largely independent of air temperature and is essentially linearly proportional to irradiance level [1, 2]. It can be assumed that the difference between the cells junction temperature (T_j) and ambient temperature (T_a) is linearly proportional to the solar irradiance (G_p) if the conditions of the surroundings are fixed. If heat conduction and convection losses are constant under a given wind speed, then the value of NOCT can be directly determined from the correlation between the cells temperature, the ambient temperature and the solar irradiance [2]. The values of the NOCT are generally provided by the manufacturers. If NOCT values are not available, then it is very difficult to estimate the cell operating temperature. Another limitation in NOCT models is that significant errors could occur when the conditions of installation are dissimilar from the standard conditions as regards mounting configuration, loading and environmental conditions. Additionally, if the protecting cover of the PV module is thin and has a low thermal resistance, then the temperature of the cells inside the PV module (T_j) is approximately equal to the temperature at the back surface of the PV module (T_c) or $T_j \approx T_c$.

The Non-Steady State Approach: In this approach, parameters affecting the changing of the module temperatures are considered to be time dependent. Therefore, this approach is more realistic, considering the nature of a PV system and could give a more precise prediction of the changing of the operating PV module temperatures over a time period, especially if there is a rapid fluctuation of solar irradiance within a short period of time intervals. This technique is based on the concept that the operating temperature of a PV module is determined by an energy balance [2]. The solar energy

that is absorbed by a module is converted partly in to thermal energy and partly into electrical energy, which is removed from the cell through the external circuit. An energy balance on a unit area of a module which is cooled by losses to the surroundings can be expressed as:

$$(\tau\alpha) G_T = \eta_m G_T + U_L (T_c - T_a) \quad (1)$$

Where, $(\tau\alpha)$ is effective transmittance-absorbance product, η_m is efficiency of module converting incident solar radiation (G_T) into electrical energy, U_L is the loss coefficient includes losses by convection, radiation and conduction [29]. Measurements of the solar radiation, ambient temperature and cell temperature can be used in Eq. (1) at NOCT conditions given as:

$$(\tau\alpha) G_{T,NOCT} = U_{L,NOCT} (T_{NOCT} - T_{a,NOCT}) \quad (2)$$

At any ambient temperature, the cell temperature can be found from the following equation.

$$T_c = T_a + \left(\frac{G_T}{G_{T,NOCT}} \right) \left(\frac{U_{L,NOCT}}{U_L} \right) (T_{NOCT} - T_{a,NOCT}) \left(1 - \frac{\eta_{m,ref}}{\tau\alpha} \right) \quad (3)$$

The value of $(\tau\alpha)$ is generally not known, but an estimate of 0.9 can be used without serious error. Since, the term $\eta_{m,ref}/\tau\alpha$ is a small compared to unity. The Eq. (3) does not account the variation in cell temperature with wind speed unless the ratio of two loss coefficients is known. One approximation for the replacement of the ratio of loss coefficients in Eq. (3) with a relationship, which is applicable for heat transfer coefficients at NOCT in real operating conditions is.

$$T_c = T_a + \left(\frac{G_T}{G_{T,NOCT}} \right) \left(\frac{9.5}{5.7 + 3.8V_w} \right) (T_{NOCT} - T_{a,NOCT}) (1 - \eta_{m,ref}) \quad (4)$$

Where, V_w is wind speed, m/s.

MATERIALS AND METHODS

The data was acquired from Malaysian Meteorological Services, Regional Office Kuching. Analysis was carried out for all meteorological parameters for 10 years from 2000 to 2009 except the data of global solar radiation, which was utilized from 2005 to 2009. A total of 16 models are selected and investigated for the estimation of module operating temperature from the climatic data of Kuching (01°33'N and 110°25'E) Sarawak.

First, the calculation of extraterrestrial radiation of the area was carried out by empirical relationships. Then the module operating temperature was determined by different cell operating temperature models and finally the results and outputs were compared among each other.

The monthly average daily extraterrestrial solar irradiance \bar{H}_o on the horizontal surface was computed by taking the values of a single day suggested by Klein (1977), such as the 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 [7]. The selected days gave results close to the monthly mean values for every month, representing that individual month. The \bar{H}_o on the horizontal surface is determined by the following empirical relationship.

$$\bar{H}_o = \frac{24 \times 3600}{\pi} \times G_{sc} \times \left(1 + 0.033 \cos \frac{360n}{365} \right) \times \left(\cos \phi \cos \delta \cos \omega_s + \frac{\pi \omega_s}{180} \sin \phi \sin \delta \right) \quad (8)$$

Where, \bar{H}_o is monthly average daily extraterrestrial solar irradiance (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, which was calculated by the formula:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \quad (9)$$

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 with morning (- ve) and afternoon (+ ve). The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour as deviated from it. The sunset hour angle (ω_s) was computed by the following equation:

$$\omega_s = \cos^{-1} (-\tan \phi \tan \delta) \quad (10)$$

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. The selected models are summarized in Table 1 and 2 and their predicted results are graphically displayed in Figures 1-6.

Table 1: Empirical Models for Estimation of Photovoltaic Module Temperature

Sr. #	Author (s)	Empirical Models	Comments
01	Ross (1976)	$T_c = T_a + k G_T$ where, $k = \frac{\Delta(T_c - T_a)}{\Delta G_T}$	$k = 0.02 - 0.04^\circ\text{C m}^2/\text{W}$
02	Rauschenbach (1980)	$T_c = T_a + \frac{G_T}{G_{T,NOCT}} (T_{c,NOCT} - T_{a,NOCT}) \left(1 - \frac{\eta_m}{\tau\alpha}\right)$	With constant Heat loss coefficient (U_L) and $V_w > 1\text{m/s}$
03	Risser and Fuentes (1983)	$T_c = 3.81 + 0.0282 \times G_T + 1.31 \times T_a - 165 \times V_w$	Verified for 104 kW array with MPPT.
04	Schott (1985)	$T_c = T_a + 0.028 \times G_T - 1$	Verified for V_w from 1-1.5 m/s and T_a from 0-35°C
05	Servant (1985) (Implicit and Explicit Equations)	$T_c = T_a + \alpha G_T (1 + \beta T_a) (1 - \gamma V_w) (1 - 1.053 \eta_m)$ $T_c = T_a + \alpha G_T (1 + \beta T_a) (1 - \gamma V_w)$	$\alpha = 0.0138$, $\beta = 0.031$, $\gamma = 0.042$, Temperature taken as °C with constant V_w of 1m/s. The efficiency of module was not considered in Explicit Equation.
06	Ross and Smokler (1986) (Implicit and Explicit Eq.)	$T_c = T_a + \frac{G_T}{800} (T_{c,NOCT} - 20)$ and $T_c = T_a + 0.035 \times G_T$	The equation is valid only for free standing modules and V_w taken as 1m/s with constant U_L
07	Lasnier and Ang (1990)	$T_c = 30.006 + 0.0175 (G_T - 300) + 1.14 (T_a - 25)$	For p-Si modules only, T in °C, V_w and U_L were not taken into account

Table 2: Models for the Determination of Photovoltaic Module Temperature

Sr. #	Author (s)	Empirical Models	Comments
01	Didier (2001)	$T_c = T_a + \frac{(T_{c,NOCT} - 20)}{800} (219 + 832 \bar{K}_t)$ $C_f = 1 - 1.17 \times 10^{-4} (S_M - S)^2$	For non-optimal values, use a multiplier with \bar{K}_t , S_M denotes optimal tilt angle and S actual tilt angle (Degrees)
02	Krauter (2004)	$T_c = T_a + k G_T$ and $k = 0.0058, 0.012$ and 0.03	The value of k for lower, upper and usual modules
03	Mondol et al., (2005 and 2007)	$T_c = T_a + 0.031 G_T$ and $T_c = T_a + 0.031 G_T - 0.058$	T_c is taken as mean of front and back temp. of module °C, $V_w > 1\text{m/s}$ with constant U_L
04	Duffie and Beckman (2006)	$T_c = T_a + \frac{G_T}{G_{T,NOCT}} \left(\frac{9.5}{5.7 + 3.8 V_w} \right) \times (T_{c,NOCT} - T_{a,NOCT}) (1 - \eta_m)$	The value of transmittance and absorbance product ($\tau\alpha$) was taken as 0.9 Coefficient of heat losses (U_L) was associated with wind speed.
05	Chenni et al., (2007)	$T_c = 0.943 T_a + 0.028 G_T - 1.528 V_w + 4.3$	Coefficient of heat losses (U_L) was not taken into account

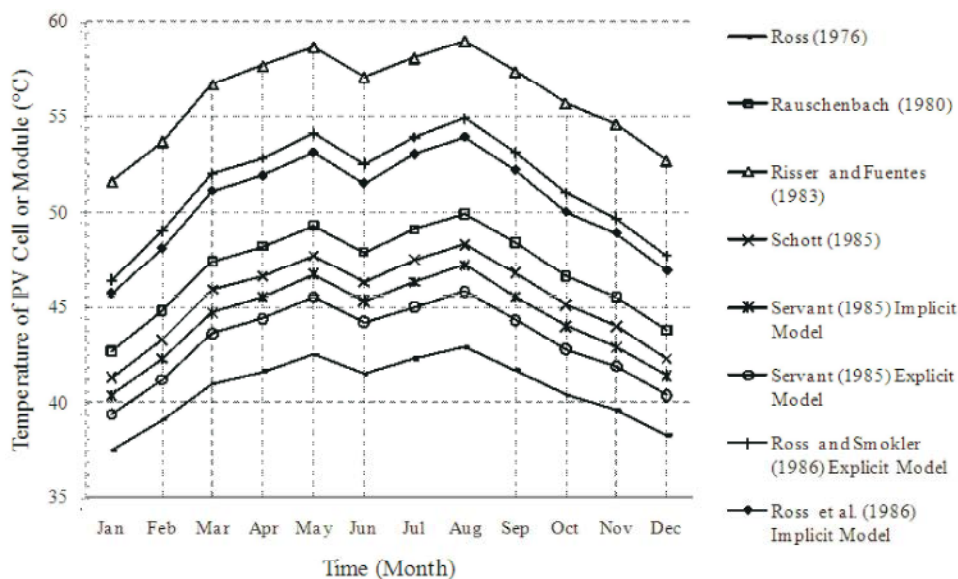


Fig. 1: Estimated values of Module Temperature verses Time at Kuching from various Models

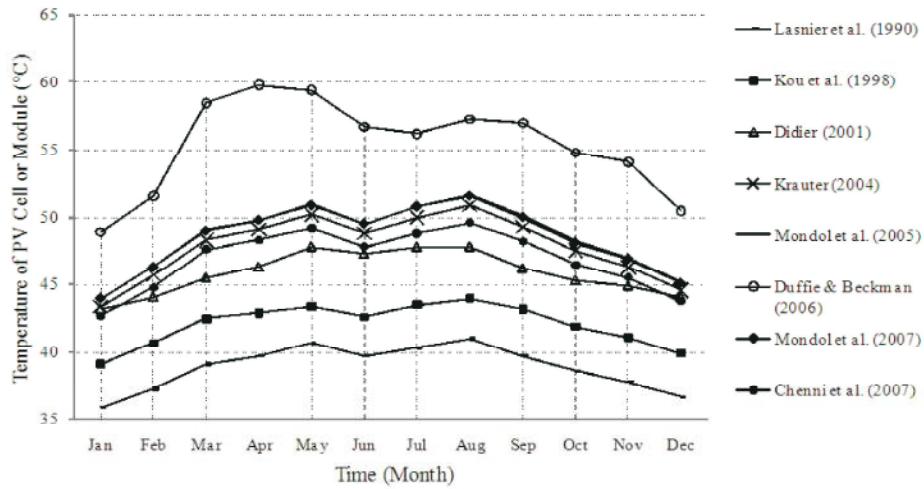


Fig. 2: Estimated values of Module Temperature verses Time at Kuching from various Models

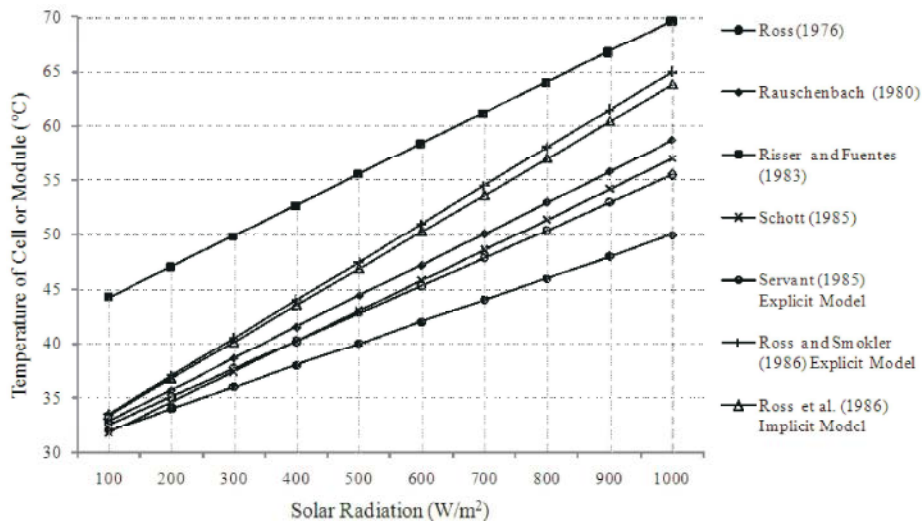


Fig. 3: Estimated Module Temperature verses Solar Radiation at Constant Temperature

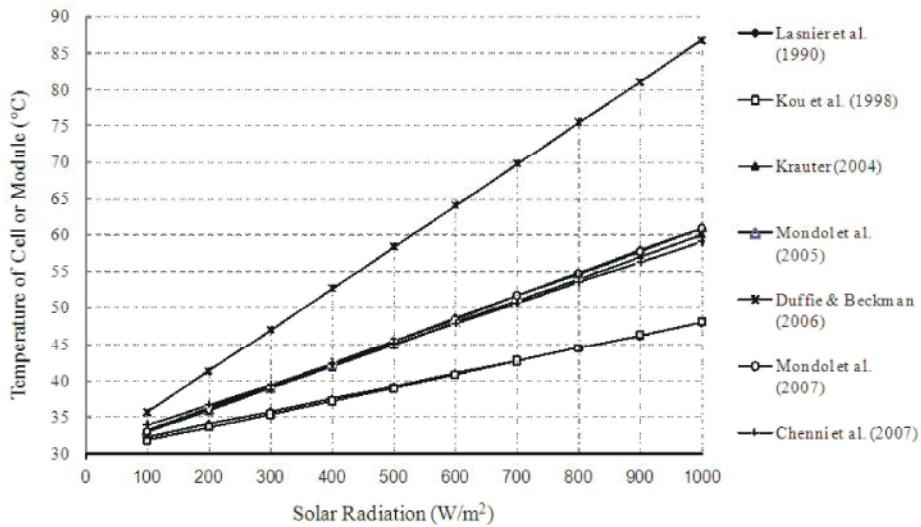


Fig. 4: Estimated Module Temperature verses Solar Radiation at Constant Temperature

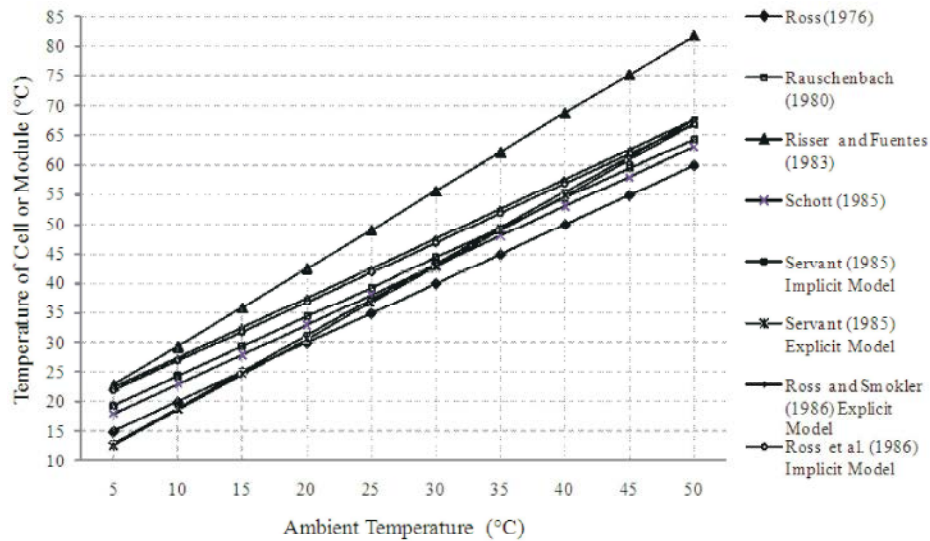


Fig. 5: Estimated Module Temperature versus Ambient Temperature at Constant Solar Radiation

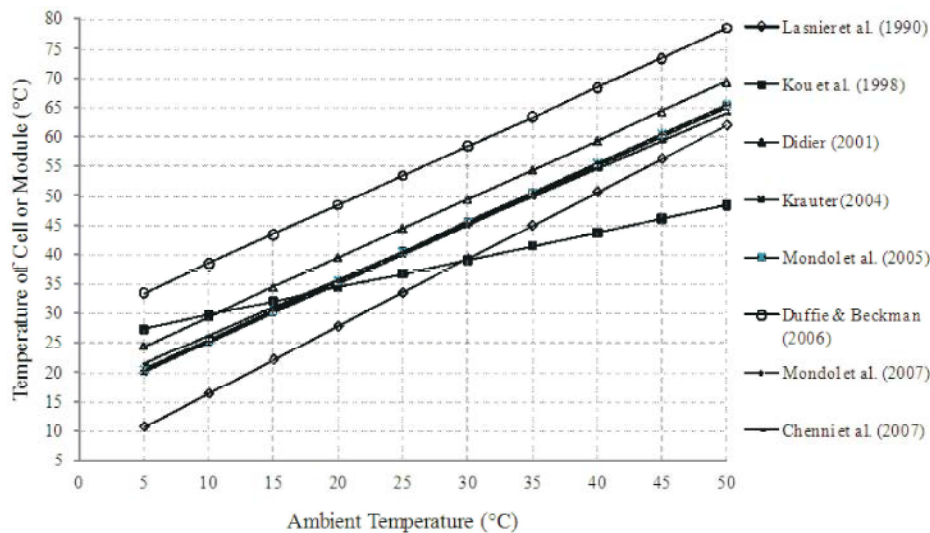


Fig. 6: Estimated Module Temperature versus Ambient Temperature at Constant Solar Radiation

RESULTS AND DISCUSSIONS

It was exposed from the results, that Risser and Fuentes (1983) model displayed highest values of module operating temperature with more than 50°C in the month of January and approximately 60°C in the month of August with an yearly average of 56.1°C in Kuching as illustrated in Figures 1 and 2. This may due to the incorporation of ambient temperature, solar radiation and wind speed coefficients in their model. The second yearly mean highest value of 55.4°C was found in the model proposed by Duffie and Beckman (2006) among 16 examined models. The values in the month of January were slightly less than Risser and Fuentes model but

approaches 60°C in the month of April. This is due to the integration of heat loss coefficients and wind speed for balancing the equation. The lowest estimated module temperature values were observed in the Lasnier and Ang (1990) and Ross (1976) models with annual average values of 38.9°C and 40.7°C respectively. The former model considered only the ambient temperature and solar radiation parameters and did not account the wind speed and other losses in their model, whereas the latter model proposed a wide range of coefficient values from 0.02 per °C to 0.04 per °C. The coefficient used for this analysis was 0.02 per °C. It was hard to choose these values because no criteria was suggested and provided by the investigators as shown in Table 1 and 2. It is inferred that

Risser and Fuentes (1983) and Duffie and Beckman (2006) models displayed the highest estimated values for module operating temperature at Kuching, as these both models are incorporated the effect of all three influential parameters such as solar radiation, atmospheric temperature and wind speed in their models. Wind speed is quite low in the equatorial latitudes, which results less heat loss from the modules by convection and therefore models predicted higher values of module operating temperatures. The models proposed by Servant (1985), Ross (1976 and 1986) exhibited lowest values, as they considered wind speed as constant in their models.

The influence of solar radiation from 100 W/m² to 1000 W/m² on module operating temperature has been investigated by keeping other parameters constant, such as ambient temperature at 30°C and wind speed at 1 m/s as shown in Figures 3 and 4. It is revealed that the maximum value was estimated by Duffie and Beckman (2006) model with 86.8°C of module operating temperature and 35.7°C at the solar radiation of 100W/m² and the second highest values were estimated by Risser and Fuentes (1983) models with 69.7°C and 44.3°C at 1000 W/m² and 100 W/m² respectively. The Duffie and Beckman (2006) model shows sharp gradient because the wind speed and atmospheric temperature were kept constant. Hence, it is confirmed that the model estimated the sharpness and rise of module temperature with the increase of solar radiation at constant wind speed is applicable. The lowest module temperature of 48°C, 48.1°C at 1000 W/m² and 32.2°C and 31.8°C at the solar radiation of 100 W/m² was demonstrated by Lasnier and Ang (1990) and Kou *et al.*, (1998) models respectively. They did not consider the effect of wind speed and heat loss factor and other ambient temperature and solar radiation coefficients were make constants, hence there results shows lower values of module temperature with respect to increase of solar radiation.

CONCLUSIONS

It was discovered from the results that most models shown similar trend regarding module temperature variation. However their values were quite distinct when compared among each other. It was revealed that Risser and Fuentes (1983), Duffie and Beckman (2006) models displayed highest values and the models proposed by Lasnier and Ang (1990), Ross (1976) Kou *et al.*, (1998) and Servant (1985) established lowest results of module operating temperature for Kuching meteorological data. Moreover, the models demonstrated similar trend but

different results under constant solar radiation and ambient temperature conditions respectively. The variation in results may be due to the use of different variables, climatic conditions, configuration of PV modules and approach used by various researchers.

Based on the model results and observations Duffie and Beckman (2006) model was preferred for size optimization, simulation and design of solar photovoltaic systems. The selected model was formulated on the basis of energy balance approach and was more realistic than steady state approach models. It will give more precise predictions during fluctuated operating conditions when the intensity of solar radiation and temperature will change within a short period of time.

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