Modelling of photovoltaic array temperature in a tropical site using generalized extreme value distribution

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Abstract

The standard approach of assessing the efficiency of a solar cell is strongly depending on the cell temperature (T_c). The value T_c is calculated based on solar radiation and ambient temperature values as well as the nominal operating cell temperature (NOCT). NOCT is defined as the temperature element in a solar cell exposed at 800 w/m^2 of solar radiation, 20°C of ambient temperature and a wind speed of 1 m/s. However, these conditions may vary depending on the climate zone nature. In this research a new condition called tropical field operation cell temperature (tFOCT) is introduced based on the maximum daily standard climatic parameters under tropical field conditions. These parameters are calculated and justified using generalized extreme value distribution based on the transient conditions of the tropical weather as a unique approach of field value adaptation. The results show that the suitable weather conditions for measuring the tFOCT are 886 W/m^2 of solar radiation, 34 ^{0}C of ambient temperature and a wind speed of 3.2 m/s. In addition to that, it is concluded that the recommended tFOCT value is 52.5 °C. Based on these conditions, an enhanced T_c model is proposed and it is found that this model has higher accuracy than the standard model.

Keywords: PV systems; solar cell temperature; NOCT; tropical condition; generalized extreme value distribution.

1. Introduction

Global energy consumption is expected to rise by 1.6% annually, or 45% in total for the next 20 years. In Malaysia, the demand for electricity is forecasted at around 19,000 megawatts (MW) in 2020 and it is escalating to 23,000 megawatts (MW) in 2030[1]. In recent years, there has been evidence of growing interest by the Malaysian government towards renewable energy sources, and subsequently, this national concern is highlighted during the recent official launching of the green technology policy**.** This policy contains five strategic thrusts which place focus on strengthening the institutional framework, providing a conducive environment for the green technology development, intensifying human capital development by introducing green collar jobs, supporting green technology research and innovations and upgrading promotion and public awareness. This policy also includes long term goals, and it extends up to the 12th Malaysia Plan (2021–2025) [1].

According to Khatib et al. in [2], the Malaysian weather characteristics feature a climate of uniform temperature, with high humidity and rainfall and generally light wind. The land is situated in the equatorial doldrums, where on normal days it is almost impossible to have a full day with completely clear sky, even during the drought season. Most of the areas in peninsular Malaysia receive a strong solar radiation with average values from 14 to 18 MJ/m^2 for approximately 6 hours daily. Based on this, the photovoltaic (PV) technology is adopted by the renewable energy policy approved by the Malaysian government based on the fact that PV systems are clean, environment friendly and secure energy sources. However, PV system size and performance strongly depend on meteorological variables such as solar energy and ambient temperature and therefore, to optimize these systems, extensive studies related to solar energy as well as ambient temperature at the site where the system is installed have to be done [3].

According to [4] increasing solar radiation increases the output power of a solar cell. However, solar cell temperature affects the solar cell output voltage inversely. According to [4], increasing PV cell's temperature by 1 degree decreases PV module's power by (0.5-0.6) %. In the meanwhile, solar cell temperature is reduced by wind according to [5]. This statement is further supported by [6] who explains that solar cell temperature rise is mainly due to waste heat creation from low efficient conversion process. Thus, a mechanism is suggested in [6] to fully utilize the natural wind flow arrangements which will reduce the high temperature generation.

Therefore, the cell temperature is mainly correlated to the ambient temperature, solar radiation and wind speed. Consequently, the main objective of this paper is to develop a correlation model between these meteorological variables and the cell temperature for a PV system installed in a specific location in Malaysia. The correlation model is derived based on new weather conditions for measuring the NOCT. Data for a ten months yield experience of a PV system installed at Universiti Putra Malaysia, Serdang, Malaysia is used in this research. The objective of this research is to bring forward a new reference condition of cell temperature for PV manufacturers who intend to install their PV products in tropical-based countries.

2. Standard testing and operation conditions for a PV module

Temperature effect on solar cells and photovoltaic modules efficiency has been studied for the past few decades involving elements of photocurrent, absorption of energy and solar radiation. The standard testing conditions (STC) as described in MS/IEC 61836 standards for the photovoltaic technology refers to the reference values of the in-plane solar radiance (G) of 1000 W/m^2, PV cell junction temperature of 25 ^{0}C and air mass (AM) of 1.5. These values are to be used during the quality testing of any PV module. A high quality, safe and durable PV module delivers the expected rated power (Wp) withstanding extremely wide range of environmental conditions. Moreover, it is reputedly capable of delivering high energy yield over a period of time. However, for standard operating conditions (SOC), the MS/IEC standard defines it as the operating values of in-plane solar radiance (1000 W/m^2), PV devise junction temperature equals to the nominal operating PV cell junction temperature (NOCT) with Air Mass of 1.5. The nominal operating cell temperature (NOCT) based on [7] is defined as the temperature element in a PV module exposed at 800 W/m^2 of solar radiation, 20^{0}C of ambient temperature and a wind speed of 1 m/s. Therefore, most PV manufacturers provide the temperature elements for PV modules based on the NOCT to calculate the cell temperature using the following equation [8],

$$T_c = T_a + \frac{G}{800W/m^2}\left(NOCT - 20^oC\right) \quad (1)$$

where T_c is the cell temperature, T_a is the ambient temperature, G is the instant solar radiation, NOCT is the nominal operation cell temperature and it is usually obtained from the PV module's datasheet.
However, in [9] Osterwald et al. explain that the temperature measurements of a solar cell are mostly difficult to conduct, because the temperature measurement of the surface of the PV module usually leads to an error due to the temperature difference between the surface and cells laminated inside. In other words, ambient temperature values do not always suit the standard test condition (STC) which is usually applied and referred by PV makers. Koelh et al. in [10] highlight that the NOCT value should characterize the temperature dependence of the PV module which allows the estimation of the performance and the energy yield for a specific time duration and proposed realistic nominal operating cell temperature (ROMT) as illustrated in equation (2).

$$ROMT = 20°C + \frac{800\ W/m^2}{U_0 + U_1 \times v} \quad (2)$$

where, v is wind speed and U_0, U_1 are model parameters to consider the seasonal variation.

In addition to that, the location of the measuring temperature element in the PV module is still being debated by researchers with the issue of how much the cell temperature (T_c) is being affected by the surface temperature (FF_s), bottom temperature (FF_b), and surrounding temperature (T_a) [11]. Mattei et al. in [8] have proven that the temperature is uniform in the PV panel via the field test arrangement. In [8] a mathematical equation (equation 3) with additional surface temperature elements as a crucial factor is proposed for the calculation of solar cell temperature as given below,

$$T_C = \frac{U_{PV}T_a + G[(\tau\alpha) - \eta_r - \delta T]}{U_{PV} - G\delta} \quad (3)$$

where T_c is the cell temperature, δ is the temperature coefficient, U_{pv} is the heat exchange coefficient corresponding to the total surface area of the module, η_r is the reference module efficiency (cell temperature of 25 °C, Radiation (G) of 1000 W/m^2) and τα is the PV module transmittance-absorbance factor.

In the meanwhile, some studies that conducted in various tropical locations show that the ambient temperature values also do not always suit the standard test condition (STC) [12,13]. Moreover, Ye et al. in [14] emphasizes that for tropical regions, it is important to understand the impact of module's temperature and the best approach to control it. While, Katsumata et al. in [15] studied the gap of the common method of estimating the PV module efficiency in STC despite the fact that it varies from actual outdoor conditions. In addition, Tsai and Tsai in [16] conducted a verification approach using STC and nominal operating cell temperature (NOCT) condition for a PV system.

Based on that, it is claimed in this study that the value of the STC in IEC standards deflects the fluctuating phenomena of transient weather conditions especially in tropical regions. Therefore, alternative nominal operation conditions for T_c would be presented considering the field data and PV module behaviour under conditions that deviate from the standard. Moreover, the relation between the surface temperature and bottom temperature and T_c is studied for more accurate model.

3. Experiment setup and procedure

A 1.14 kWp grid-tied PV Pilot Plant was successfully installed in September 2011 at University Putra Malaysia, Serdang, Malaysia. This system is equipped with a GPRS- monitoring system as well as a weather station as shown in Figure 1.

Figure 1: System setup for FF PV array with environmental sensors

The graphical LabVIEW software and cRIO housing are used as data acquisition and real-time monitoring systems. This enables the process of capturing environmental measurement from multiple sources and analysing the data visually in both real-time and synchronize mode which is the crucial aspect for rapid fluctuating data flow. The installed PV system is also equipped with pre-calibrated three temperature sensors, one solar radiation sensor and one wind speed sensor. The three temperature sensors are for measuring the ambient temperature, PV cell face temperature and the PV cell bottom temperature. The PV array is slanted at 7.6 degree tilt angle facing 160^0 South based on previous researches done for Malaysia [17]. The generators implies fixed mounting structure of free air-flow on the bottom side of the PV array which has the following characteristics (see Table 1)

Table 1 Installed PV array characteristics

PV array capacity	1.14 kWp
PV array configuration	12x95 kWp Monocrystalline PV modules connected in series
PV array Area	3.6m × 2.4m
PV array output voltage	270 V_{dc} (22.5 V x 12)
PV array output current	5.56 A_{dc}

In this research data for ten months (September, 2011 to June, 2012) were recorded comprising 12,000 actual measurements by 15 minutes intervals. Based on the stochastic nature of tropical weather condition, the ten months duration from September till June are considered to be sufficient whereby the data shows all weather trends covering the whole year. These records have been taken for each fifteen minutes in order to consider the uncertainty nature of the recorded data. The annual averages calculated at site throughout the monitoring period are 339.7 W/m^2 of solar radiation, 29.4 ^{0}C of ambient temperature and 1.27 m/s of wind speed. These values are comparable to the findings reported by [10].

Extreme value theory and analysis for rapid fluctuating data are used extensively in engineering application by adapting unique method of generalized extreme value distribution (GEV). GEV is the enhance version of the Weibull distribution and Frechet distribution [18]. A major benefit of GEV is the stabilized inference of block maxima to show dependence on covariate effects (short-term) and long-term trends due to gradual climatic change or non-stationary trends [19]. The theoretical analysis is essential to appropriately choose parametric distribution function, data calibration and extrapolating or manipulating the described distribution function. GEV can be described as follows,

$$\mathbf{F}(\boldsymbol{x};\ \mu, \boldsymbol{\sigma}, \boldsymbol{\xi}) = \mathbf{exp}\left\{-\left[\mathbf{1} + \boldsymbol{\xi}\left(\frac{\mathbf{x}-\mu}{\boldsymbol{\sigma}}\right)\right]^{-\frac{1}{\xi}}\right\} \tag{4}$$

where σ is scale parameter ζ is shape parameter. μ is a location parameter that determines where the origin will be located when the function is plotted and it has to be measured based on a specific location. In this research, The GEV is applied due to its cumulative extreme value behaviour either as parent distribution or asymptotic approximation to describe the data trend for solar radiation (G) and ambient temperature (T_a) via maxima location parameter (μ) characteristic.

Note that in this study the wind effect is assumed to be negligible and only is considered as the nominal field condition in the tropics. This is due the fact that the solar radiation has a low correlation with wind speed as claimed by [20]. Moreover, Koelh et al. in [10] supports this statement and suggested that natural wind convection can be neglected for wind speeds above 2 m/s. The value of wind speed based on GEV is 3.2 m/s ± 0.07, assuming that the wind direction is constant and the maximum daily wind speed occurrences at 10.00 am till 8.00 pm. However, in this research a multiple linear regression (MLR) with the analysis of variance test (ANOVA) is conducted in order show that wind speed has a very weak correlation with solar radiation. On the other hand, the same analysis is done for the ambient temperature data which show a high correlation with the solar radiation data. The results of the statistical test conducted show that the correlation between the solar radiation and the wind speed is lower than the correlation between the solar radiation and the ambient temperature.

4. Results and Discussion

For comprehensibility, we introduce a new term called tFOCT. tFOCT is defined as the equilibrium maximum daily cell temperature at standard climatic parameter in tropical field conditions. tFOCT value is assumed to be more accurate that NOCT value and we claim in this study that the best weather conditions for measuring the tFOCT can be found using the generalized extreme value distribution via maxima location parameter (μ). As mentioned before, NOCT is usually measured at solar radiation of 800 W/m^2, ambient temperature of 20 ^{o}C and wind speed of 1m/s. However, it is claimed in this research that there are better conditions to measure this value. These conditions are represented by the most frequent maximum value of the aforementioned meteorological variables. In the other words, the most frequent values occurred of solar radiation, ambient temperature and wind speed are considered to be better conditions for measuring the NOCT which called after this new assumption as tFOCT. This methodology led to the conclusion that the mean daily maximum solar radiation and the mean daily maximum ambient temperature are the best weather condition to measure tFOCT at. Figures 2 show normal distributions for solar radiation and ambient temperature for the adopted site.

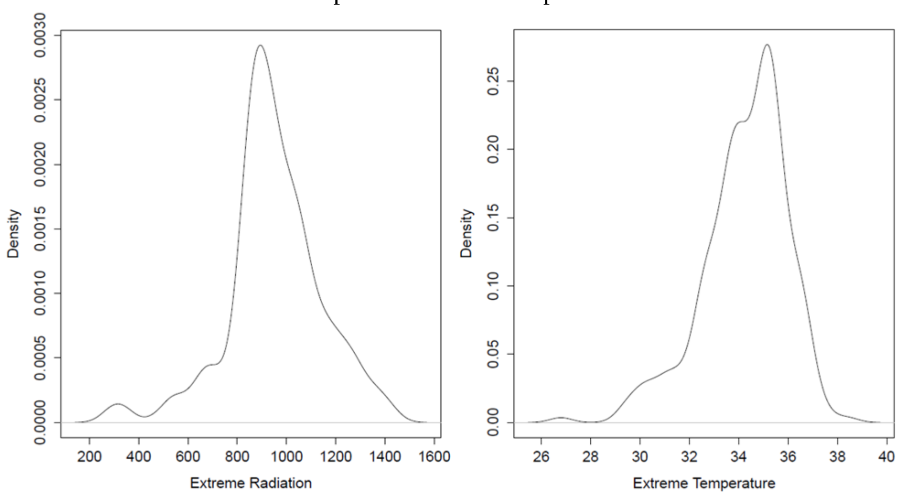

Figure 2 Data analysis based on GEV distribution for solar radiation and ambient temperature

For the figure, the location parameter (μ) is calculated at 886 W/m^2 ± 13.7 solar radiation and 34 ^{0}C ± 0.12 of ambient temperature. Based on this analysis, the solar cell temperature in equation (1) must be calculated considering new weather conditions which are solar radiation of 886 W/m^2 and 34 ^{0}C of ambient temperature as follows,

$$T_c(t) = T_a(t) + \frac{G(t)}{886}\left(tFOCT - 34^o C\right) \qquad (5)$$

Based on equation 5, the tFOCT appears under 886 W/m^2 of solar radiation, and 34 ^{0}C of ambient temperature. However, in this research two cell temperature sensors were used which are cell surface temperature (FF_s) and cell bottom temperature (FF_b) sensors. According to this, there are two possible ways to estimate the tFOCT of the solar cell based on FF_s and FF_b. Therefore, in this research the tFOCT is calculated based on both values. Sixty daily samples of the FF_s and FF_b values that occurred at the recommended weather condition for calculating the tFOCT are taken with tolerance of ± 5% (see figure 3).

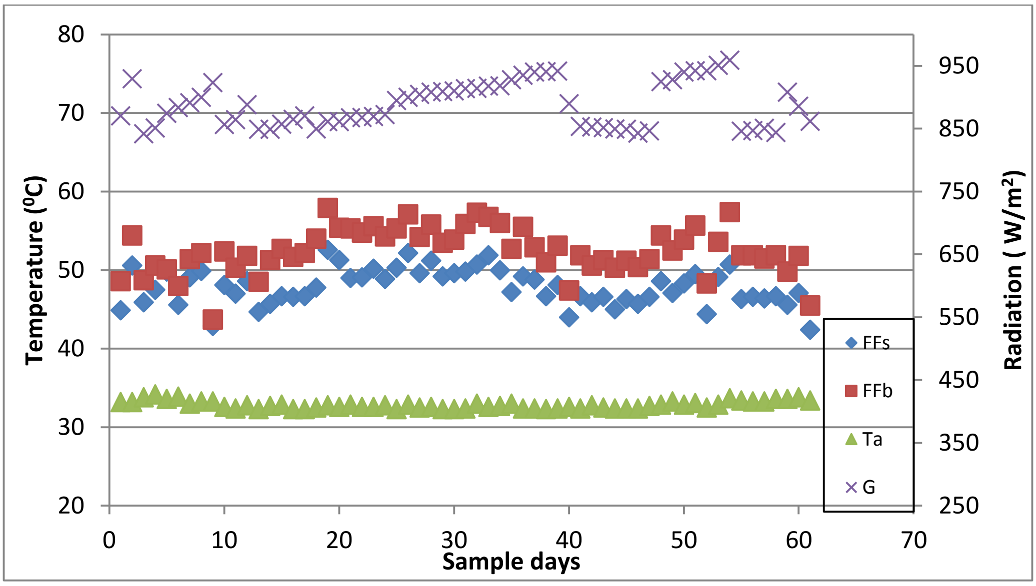

Figure 3 FF_s and FF_b at the daily maximum weather condition for calculating the tFOCT

From Figure 3, two values of tFOCT can be concluded; one based on the surface temperature of the solar cell (FF_s) and another based on the bottom temperature of a solar cell (FF_b). The tFOCT based on daily average FF_s values is 47.9 ^{0}C while the tFOCT based on FF_b is 52.5 ^{0}C. The FF_s fluctuates between the ranges of 42.4 ^{0}C to 52.6 ^{0}C while FF_b ranges from 43.7 ^{0}C up to 57.9^{0}C. Based on this, two correlation equations can be given for the cell temperature as follows,

$$\begin{Bmatrix} T_c(t) = T_a(t) + 0.016G(t) \rightarrow FFs \\ T_c(t) = T_a(t) + 0.02G(t) \rightarrow FF_b \end{Bmatrix} \qquad (6)$$

The first part of equation 6 shows the relation between the cell temperature and the solar radiation and the ambient temperature using the surface temperature to calculate the tFOCT. Meanwhile the second part shows the same relation but using the bottom temperature of the solar cell for calculating the tFOCT. To validate the proposed cell temperature models, the cell temperature values for 60 samples in the month of June 2012 are calculated. These values are calculated using the models proposed in equation 6 and using the standard equation presented in equation 1. As for the NOCT value used in equation 1, it is assumed to be equal to 47 ^{0}C based on the used PV modules datasheet. Figure 4 shows the results of equation 6 compared to equation 1.

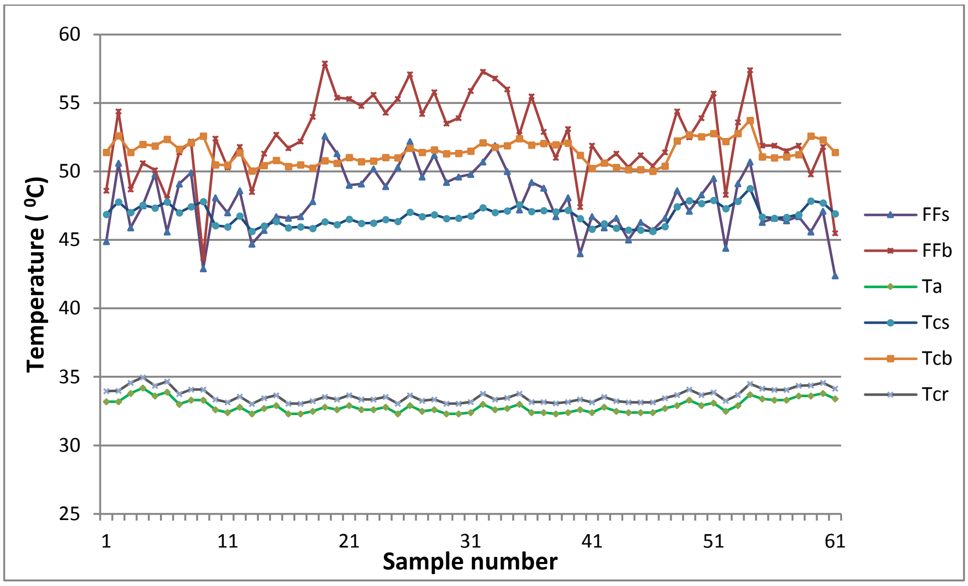

Figure 4 Testing results of the proposed models for calculating the solar cell temperature

From Figure 4, the solar cell temperature values calculated based on the proposed model which is presented in equation 6 are more accurate than the results of the standard model shown in equation 1. The values of solar cell temperature calculated based on the FF_s values (T_{cs}) and the values of the solar cell temperature calculated based on FF_b (T_{cb}) are closer to the actual values of FF_s and FF_b than the values of the solar cell temperature calculated based on the standard equation (T_{cr}). The average absolute error (AE) between the actual FF_s values and the predicted values of FF_s (T_{cs}) is 1.99%. In addition to that the AE between the FF_b (actual values) and T_{cb} (predicted values) is 1.72%. On the other hand the AE values between the T_{cr} values and FF_s and FF_b are 29.6% and 35.7% respectively.

5. Conclusion

We introduced a new term, tFOCT, as the equilibrium cell temperature mean value of the maximum average monthly standard climatic parameter in tropical field conditions. Based on a ten-month yield of a PV pilot ülant with statistical justifications, the value of 886 W/m^2 of solar radiation, 34 ^{0}C of ambient temperature are suggested for measuring the best nominal operating cell temperature represents by tFOCT value . The proposed model for calculating the solar cell temperature is more accurate than the standard model. This work is intended as a helpful reference for those who are interested in PV system installation in Malaysia and nearby regions.

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References

[1] Shafie, S. M., Mahlia, T. M. I., Masjuki, H. H., & Andriyana, A. (2011). Current energy usage and sustainable energy in malaysia: A review. *Renewable and Sustainable Energy Reviews, 15*(9), 4370-4377.

[2] Khatib, T., Mohamed, A., Mahmoud, M., Sopian, K.. Modeling of daily solar energy on a horizontal surface for five main sites in Malaysia. J. of Green Energy. 2011. 8(8): 795-819.

[3] Khatib, T., Mohamed, A., Sopian, K.. A Review of photovoltaic systems size optimization techniques. Renewable and Sustainable Energy Reviews.2013.22():454–465.

[4] Khatib, T., Sopian, K., & Kazem, H. A. (2013). Actual performance and characteristic of a grid connected photovoltaic power system in the tropics: A short term evaluation. *Energy Conversion and Management, 71*(0), 115-119.

[5] Brinkworth, B. J., & Sandberg, M. (2006). Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays. *Solar Energy, 80*(1), 89-103.

[6] Tonui, J. K., & Tripanagnostopoulos, Y. (2007). Improved PV/T solar collectors with heat extraction by forced or natural air circulation. *Renewable Energy, 32*(4), 623-637.

[7] Osterwald, C. R. (2012). Chapter III-2 - standards, calibration, and testing of PV modules and solar cells. *Practical handbook of photovoltaics (second edition)* (pp. 1045-1069). Boston: Academic Press.

[8] Mattei, M., Notton, G., Cristofari, C., Muselli, M., & Poggi, P. (2006). Calculation of the polycrystalline PV module temperature using a simple method of energy balance. *Renewable Energy, 31*(4), 553-567.

[9] Osterwald, C., Hammond, R., Zerlaut, G., & D'Aiello, R. (1994). Photovoltaic module certification and laboratory accreditation criteria development. *Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference-1994, 1994 IEEE First World Conference on, , 1.* pp. 885-888.

[10] Koehl, M., Heck, M., & Wiesmeier, S. (2012). Modelling of conditions for accelerated lifetime testing of humidity impact on PV-modules based on monitoring of climatic data. *Solar Energy Materials and Solar Cells, 99*(0), 282-291.

[11] Skoplaki, E., & Palyvos, J. A. (2009a). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy, 83*(5), 614-624.

[12] Ahmad, S., Kadir, M. Z. A. A., & Shafie, S. (2011). Current perspective of the renewable energy development in malaysia. *Renewable and Sustainable Energy Reviews, 15*(2), 897-904.

[13] Amin, N., Lung, C. W., & Sopian, K. (2009). A practical field study of various solar cells on their performance in malaysia. *Renewable Energy, 34*(8), 1939-1946.

[14] Ye, J., Ding, K., Reindl, T., & Aberle, A. G. (2013). Outdoor PV module performance under fluctuating irradiance conditions in tropical climates. *Energy Procedia, 33*(0), 238-247.

[15] Katsumata, N., Nakada, Y., Minemoto, T., Takakura, H. 2011. Estimation of Radiation and bOutdoor Performance of Photovoltaic Modules by meteorological data. Solar Energy Materials and Solar Cells. 95:199-202.

[16] Tsai, H., Tsai, H. 2012. Implementation and verification of integrated thermal and electrical models for commercial PV modules. Solar Energy. 86: 654-665

[17] Effendy Ya'acob, M., Hizam, H., Htay, M. T., Radzi, M. A. M., Khatib, T., & Bakri A, M. (2013). Calculating electrical and thermal characteristics of multiple PV array configurations installed in the tropics. *Energy Conversion and Management, 75*(0), 418-424.

[18] Kaplani, E., & Kaplanis, S. (2012). A stochastic simulation model for reliable PV system sizing providing for solar radiation fluctuations. *Applied Energy, 97*(0), 970-981.

[19] Trinuruk, P., Sorapipatana, C., & Chenvidhya, D. (2009). Estimating operating cell temperature of BIPV modules in thailand. *Renewable Energy, 34*(11), 2515-2523.

[20] Khatib, T., Mohamed, A., Sopian, K.. A review of solar energy modeling techniques. J. of Renewable & Sustainable Energy Reviews. 2012.16(5): 2864-2869.