Research Article

Field Measurement of PV Array Temperature for Tracking and Concentrating 1 kW_p Generators Installed in Malaysia

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The effect of temperature elements for PV array with tracking and concentrating features installed in the tropical ground condition is presented. The temperature segment covers ambient temperature and surface and bottom temperature for three types of PV generator systems, namely, Fixed Flat (FF), Tracking Flat (TF), and Concentrating PV (CPV) generators. The location of measuring the cell temperature, T_c for 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 (T_s), bottom temperature (T_b), and surrounding temperature (T_a) furthermore when it is located in fluctuating weather conditions. In this study, ΔT is calculated based on the difference between surface temperature and bottom-side temperature whichever the highest recorded at site for different kinds of PV generator systems but using the same CEEG 95 W monocrystalline PV module. The study embraces the direct correlation of various temperature elements in tropical-based condition with ΔT values of 2.19°C for FF module, 2.22°C for TF module, and 2.72°C for CPV module. These values which reflect the different unique configurations are further analyzed using multiple linear regression (MLR) and analysis of variance (ANOVA) test for T_{array} models. This study supports the continuous research in adapting PV technology for Malaysia.

1. Introduction

Energy generation via photovoltaic technology and application has been the most economical viable green resources, especially in tropical-based countries [1–7]. Based on ground condition of the tropics with fluctuating environmental weather condition, temperature element is a crucial factor to be determined based on standard testing condition (STC) and nominal operating cell temperature (NOCT) equations.

Electricity generation is one of the biggest energy sectors utilizing a lot of fossil fuels as the main supply, and this contributes significantly to the emission of greenhouse gas (GHG) that pollutes the environment. Because of this adverse effect on the environment, the government of Malaysia under the Ministry of Energy, Green Technology and Water has introduced Green Technology initiatives to promote this technology application in the country. Malaysia which is located near the equator naturally has an abundance of sunshine which produces solar radiation. Although Malaysia

enjoys a uniform temperature throughout the year, it is, however, extremely rare to have a full day with completely clear sky in various seasons even in periods of severe drought. On the average, Malaysia receives about 6 hours of direct sunshine per day where it is seasonal, and spatial variations are thus very much the same as in the case of sunshine [8–12].

Maximum radiation received during a sunny day produces peak power (W_p), where 90% of the extraterrestrial radiation becomes direct radiation, while the rest is being deflected as diffuse radiation [5].

This research intends to explore the effect of various temperature factors which correlates directly to the ground radiation level and crystalline PV energy generation. Two segments of temperature have been classified which are surface and bottom temperatures for three types of PV generator systems, namely, Fixed Flat (FF), Tracking Flat (TF), and Concentrating (CPV). The solar PV pilot plant with rated capacity of 10 kW is monitored, recorded, and analysed in real

time via solar PV monitoring system (SPMS) using LabVIEW programming embedded in Compact Reconfigurable Input Output (cRIO) platform for system integration. The data have been collected for the duration of thirty consecutive days in June 2012.

1.1. Harvesting Energy from the Sun. Harvesting energy from the sun is a zero-carbon energy production activity where the sun reflects a solar fusion reactor emitting huge power of 63.11 MW. For every square metre surface the earth receives approximately 3.9×10^{24} J which is equivalent to 1.08×10^{18} kWh of solar energy annually [13]. This figure is about ten thousand times more than the annual global primary energy demand and much more than all available energy reserves on earth. Solar energy can be subdivided in two forms which are the direct and the indirect solar energy sources. Technical systems using direct solar energy convert incoming solar radiation directly into useful energy application for instance heat and electricity. Natural process systems using indirect solar energy convert solar energy into other types of energy before coming to the user application for instance, wind, river, and plant growth.

Baños et al. [14] define solar energy as radiant energy that is produced by the sun where in many parts of the world, direct solar radiation is considered to be one of the best prospective sources of energy. Direct solar energy applications are usually based on the building design and concept where an active design converts solar energy into electricity or heat by means of solar energy conversion system and contrarily a passive design utilizes the light energy from the sun for artificial lighting and heating. Based on MS IEC 61836:2010 [15], the photovoltaic panels are defined as PV modules which are mechanically integrated, preassembled, and electrically interconnected whereas photovoltaic system is assembly of components that produce and supply electricity by the conversion of solar energy.

Generally, a photovoltaic solar cell consists of two-layer semiconductor material which, in nonradiated condition, behaves like a diode whose I-V curve is traditionally described by the equation $I_D = I_0(\exp(qV_D/nkT) - 1) - I_L$ where I_0 is the reverse saturation current or leakage current of the diode, I_L is the light generated current or the photocurrent, V_D is the voltage across diode is the reverse saturation current of the diode, q the electron charge (1.602×10^{-19} C), k the Boltzmann constant (1.381×10^{-23} J/K), and T the junction temperature which depends on the kind of the semiconductor used [16].

Around the globe, research on photovoltaic cell and processing technologies are focusing on new approach to reduce cost via reducing the number of processing steps with high consideration of overall performance and efficiency [17]. Photovoltaic conversion can be defined as the direct conversion of pure energy sunlight into electricity without any heat engine to interfere as described by Parida et al. in [18]. Photovoltaic devices are rugged and simple in design requiring very little maintenance, and their biggest advantage is their construction as portable standalone systems to give outputs from microwatts to megawatts. MS IEC 61836:2010

defines PV conversion efficiency as ratio of maximum PV output to the product of PV device area and incident irradiance measured under specified test conditions usually at standard testing condition (STC).

1.2. Temperature Factor in PV Cell Equation. Skoplaki and Palyvos [19] explain the effect of temperature rise in the PV cell as the thermally excited electron begins to dominate the electrical properties of the semiconductor bands. Wu et al. [20] further supported the temperature rise effect towards PV energy performance due to losses created when lattice vibrations interfere with the free passing of charge carriers and the junction begins to lose its power to separate charges and proposes temperature-dependent charge controller devise for effective solution.

The importance and effect of radiation toward the energy generation in Oman have been studied by Gastli and Charabi [21] with the application of GIS-based solar radiation map. Power conversion efficiency and overall output power of the solar cells change with temperature and solar irradiance level, and this statement is further supported via conducting field study for four different types of solar panels in real performance under tropical weather condition.

A significant positive correlation between PV module temperature and spectral irradiance distribution parameter by means of energy production has been proven by Minemoto et al. [22] in which both parameters were characterized using contour plots. The influence of module temperature variations towards the energy efficiency which can be described using contour graph created from statistical analysis method based on average photon energy (APE) and field output factor (FOF) of the silicon PV Module has been analysed by Nagae et al. [23]. This technique also proves that temperature rise really affects the PV module performance ratio (PR) by producing contour graph for the temperature impact towards single-crystalline and amorphous silicon modules [24].

Skoplaki and Palyvos [25] found that there are other forms of heat energy transfer besides internal processes taking place within the semiconductor material during its bombardment by photons where convection mechanism in front and back sides of PV module panels plus heat conduction through mounting frames should be included in defining the energy balance. Park et al. [26] conducted a study to prove that there are such significant effects of the PV module's thermal characteristics on its electrical generation performance building-integrated photovoltaic (BIPV) where approximately 0.5% reduction of energy generated based on 1°C increase of the module temperature. This statement is supported by Kim et al. [27] where they emphasize that through a proper method of cooling PV module by means of heat dissipation process using fins, interestingly, the energy efficiency from a common PV module usually falls at a rate of 0.5%/°C and it can be increased due to the drop in surface temperature especially on the highest heated portions of PV cell and ribbon where all means of cooling approach comes into the picture.

The effect of temperature in PV system can be practically calculated based on cell temperature (T_c) of each PV module. Nevertheless, the location of measuring T_c in the PV module is still being debated by researchers [16, 28, 29] with the issue of how much the cell temperature (T_c) is being affected by the surface temperature (T_s), bottom temperature (T_b), and surrounding temperature (T_a). An in-depth review on the PV module temperature by Iyengar et al. [17] highlighted a constant value of k known as Ross coefficient as described in (1) based on simple expression of (2):

$$T_c = T_a + kG_T, \quad (1)$$

$$T_c = T_b + \frac{G_T}{G_{ref}} \Delta T. \quad (2)$$

Ross coefficient, k , is derived by the ratio $\Delta T/\Delta G$ where ΔT is the difference between cell temperature (T_c) and ambient temperature (T_a), and in this case it represents seven types of PV arrays commonly applied. The values of T_c have also been investigated by several studies [30–33] as follows:

$$\begin{aligned} T_c &= T_a + 0.035G_T, \\ T_c &= T_a + 0.028G_T - 1, \\ T_c &= T_a + 0.031G_T, \\ T_c &= T_a + 0.031G_T - 0.058. \end{aligned} \quad (3)$$

In this study, the value of ΔT are calculated based on the difference between surface temperature and bottom-side temperature whichever the highest recorded at site and the value is suggested to be 3°C [17]. Highest temperature value is chosen to be the benchmark of ΔT mainly because of the PV performance degradation due to increase in temperature as described earlier. The value is derived based on average daily data in the month of June 2012 for different kinds of PV generator system but using the same CEEG 95 W monocrystalline PV module. This study embraces the justification of direct correlation of various temperature elements in tropical-based ground condition with a specified ΔT value for Fixed Flat, Tracking Flat, and Concentrating PV modules purposely to support the continuous research in adapting green resources of Solar PV in Malaysia. Statistical analysis of multiple linear regression (MLR) and the analysis of variance (ANOVA) are further applied to develop mathematical modelling for T_{array} equations.

2. Experimental Procedures

Three types of PV generator systems with a rated (at STC) capacity of 1kW each with the total sum energy of 10 kW_p have been successfully configured in the Universiti Putra Malaysia (UPM), Serdang, Malaysia, at GPS coordinate of $2^\circ 59' 20''\text{N}; 101^\circ 43' 30''\text{E}$ as illustrated in Figure 1. The PV system is equipped with precalibrated temperature sensors, one solar-radiation sensor and one wind-speed sensor. The temperature sensors are for measuring the ambient temperature (sensor located close to the PV arrays), the PV cell face temperature, and the PV cell bottom temperature.

FIGURE 1: PV generator system configuration at site comprising CPV, Tracking Flat, and Fixed Flat arrays.

FIGURE 2: Arrangement of distribution box for DC and AC breakers connecting to the data logger and UPM Electricity Grid (Feeder Pillar).

The system is directly connected to UPM electrical distribution line via Feeder Pillar (FP) which links to the main switch board (MSB) as shown in Figure 2. Grid-connected system ensures full capacity generation with assumption of the highest generator efficiency during the operation period compared to a standalone system which has some limitations. The ten units of PV generator are connected to three units of Aurora inverter system with the capacity of $2 \times 3.6\text{ kW}$ and 6.0 kW for the purpose of Grid-tied operation.

The build-up areas for all PV generators are the same including the type of crystalline PV module used which is 3.6 m (L) $\times$ 2.4 m (W) $\times$ 2.8 m (H) with surface area of 8.64 m². The differences between the 3 systems are quantity of PV module either 6 units or 12 units, tracking mechanism for 360° rotation (dual-axis), and concentrating mirror. The open-circuit voltage (V_{oc}) for TF and FF is 270V_{dc}, while CPV generates 135V_{dc}. The short-circuit current (I_{sc}) for all PV arrays is the same which is 5.56A_{dc}.

Field evaluation and comparison of the temperature effect are verified via installation of 10 units of type-K thermocouple sensor at the surface and bottom side of each PV generator system. The other temperature elements of internal inverter temperature and surrounding temperature are taken directly from the weather station and Aurora inverter internal temperature sensor link to solar PV monitoring system (SPMS) as illustrated in Figure 3.

FIGURE 3: Data flow in Solar PV Monitoring Station (SPMS).

FIGURE 4: Correlation between sun radiation (W/m^2) and ambient temperature ($^{\circ}\text{C}$) in time-series dependence for tropical condition at site.

To achieve the research objective of investigating correlations of real-time and synchronize mode between temperature elements in PV system application, the data logging and monitoring process are done using NI compact RIO device (cRIO) platform with preembedded combination of LabVIEW programming to represent the overall system flow. The monitoring process is done continuously throughout the duration of 30 days in the month of June 2012 and the data for radiation (G) and ambient temperature (T_a) are described in Figure 4. The sample data is taken for the whole 30 days by 15-minute interval so as to show fluctuating pattern at a specific time of the day.

The fluctuation pattern of radiation, G , ranges from 3 W/m^2 at 4.30 AM up to 1023 W/m^2 at 2 PM which is the highest value in the month. On the other hand, ambient temperature fluctuates at the value of 22.8°C up to 36.7°C . The

TABLE 1: Sample of average daily data for surface and bottom temperature for different PV generator systems.

$\text{FF}_s (^{\circ}\text{C})$	$\text{FF}_b (^{\circ}\text{C})$	$\text{TF}_s (^{\circ}\text{C})$	$\text{TF}_b (^{\circ}\text{C})$	$\text{CPV}_s (^{\circ}\text{C})$	$\text{CPV}_b (^{\circ}\text{C})$
38.68	40.67	40.82	44.43	52.01	49.76
38.29	40.8	40.96	43.8	51.67	49.21
36.99	38.83	39.37	41.47	46.84	44.91
40.09	41.69	43.53	46.79	56.2	53.54
35.49	37.52	37.49	39.27	42.96	41.4
33.95	35.25	34.79	36.07	38.83	37.56
37.42	39.58	41.07	43.19	50.8	48.45
36.65	38.75	39.44	41.65	47.73	45.78
30.65	31.08	31.76	32.28	33.26	33.3
37.49	39.69	40.65	42.61	49.15	46.99
36.22	38.81	38.89	41.15	48.54	46.1
36.33	38.37	39.27	41.89	49.74	46.89
31.94	33.61	33.89	36	40.8	38.86
36.22	38.46	38.35	42.23	50.26	42.7
37.13	39.57	40.98	43.1	51.87	49.07
34.53	36.25	35.77	37	39.98	38.49

sun hours calculated for the whole month are 240 hours with 200 W/m^2 as the minimum sun radiation reference.

3. Results and Discussion

Sample data showing correlations between surface, bottom and ambient temperature is illustrated in Figure 5 with 700 samples of one-minute intervals.

The measured data for all temperature elements in this study is plotted with respect to radiation level at site as shown in Figure 6.

Based on Figure 6, the maximum value recorded for each temperature elements is 54°C for surface temperature, 48°C for bottom temperature, and 33.3°C for ambient temperature at the same time interval. The overall comparison of temperature elements for all 3 types of PV generator systems is described in Table 1 for average daily data with the highest temperature value comes from surface temperature of CPV generator.

For all the three types of PV generators, the surface and bottom temperatures fluctuate in the range from 30°C to 60°C which is an important value to determine cell or module temperature. For CPV generator, the surface temperature is much higher than the bottom value due to the mirror concentrating effect of heat convection. The surrounding or ambient temperature fluctuates in the range from 25°C to 33°C which reflects the nominal operating cell temperature (NOCT) in MS/IEC Standards with an average daily value of 29.56°C .

Based on the average daily data analysis, the relationship between surface temperature (T_s) and the bottom temperature (T_b) are described in Table 2.

TABLE 2: Relationship between temperature effects towards 3 types of PV generator systems.

	Temperature effect	Comments
Fixed Flat PV generator	$\Delta T = 2.19^\circ\text{C}$ Surface temperature (T_s) is <i>lower</i> by the AE value of 5.63% compared to the bottom temperature (T_b)	Most researchers adapt the bottom-side values as the cell/module temperature for crystalline PV due to the higher temperature value
Tracking Flat PV generator	$\Delta T = 2.22^\circ\text{C}$ Surface temperature (T_s) is <i>lower</i> by the AE value of 5.4% compared to the bottom temperature (T_b)	The same concept as above. The tracking mechanism which receives peak radiation level most of the time results in higher bottom temperature values compared to FF generator
CPV generator	$\Delta T = 2.72^\circ\text{C}$ Surface temperature (T_s) is <i>higher</i> by the AE value of 5.8% compared to the bottom-side temperature (T_b)	The uniqueness of adapting two elements of tracking mechanism and mirror concentrator creates much higher value on the surface side of the PV module which <i>contradicts</i> the normal concept of T_c

FIGURE 5: Correlation between ambient, surface, and bottom temperatures recorded on June 6, 2012.

Furthermore, based on MLR and ANOVA test, PV array temperature model with respect to the radiation and ambient temperature is described as follows:

For FF array,

$$T_{\text{array}}(\text{FF}) = -0.117 \cdot T_a + 0.002 \cdot G + 1.189 \cdot \text{FF}_s \quad (R^2 = 0.975, \text{SE} = 0.444). \quad (4)$$

For TF array,

$$T_{\text{array}}(\text{TF}) = 0.356 \cdot T_a - 0.007 \cdot G + 1.08 \cdot \text{TF}_s \quad (R^2 = 0.946, \text{SE} = 0.885). \quad (5)$$

For CPV array,

$$T_{\text{array}}(\text{CPV}) = 0.233 \cdot T_a - 0.006 \cdot G + 1.053 \cdot \text{CPV}_b \quad (R^2 = 0.956, \text{SE} = 1.417). \quad (6)$$

FIGURE 6: Plotted data for measured temperature elements with radiation levels in June 2012.

From the plotted data in Figure 6, an interesting temperature correlation can be obtained for internal inverter temperature (T_{inv}) as follow

$$T_{\text{inv}} = 0.867 \cdot T_a - 0.005 \cdot G \quad (R^2 = 0.875, \text{SE} = 0.65). \quad (7)$$

The linear regression model in (4) to (7) shows fairly strong correlation of the temperature elements with the tropical conditions of radiation and ambient temperature.

4. Conclusion

Review and field analysis on correlation between four temperature elements are presented. It was concluded that all temperature elements discussed have significant contribution either direct or indirect influences which affect the performance of photovoltaic generator system in providing sufficient energy supply. It is a known fact that PV conversion process does produce heat as energy wastage and PV module

TABLE 3: CEEG PV module specification.

Electrical typical data	CEEG CSUN 95W-36M
P_{mpp} [W]	95
V_{oc} [V]	22.5
I_{sc} [A]	5.56
V_{mpp} [V]	18.3
I_{mpp} [A]	5.21
Practical module efficiency	17.05%
Voltage temperature coefficients	−0.307%/K
Current temperature coefficients	+0.039%/K
Power temperature coefficients	−0.423%/K
Series fuse rating [A]	10
Cells 4×9 @ 36 pieces monocrystalline solar cells series strings	125 mm $\times$ 125 mm
Junction box	with 2 bypass diodes
Cable	length 600 mm, $1 \times 4 \text{ mm}^2$
Front glass	White toughened safety glass, 3.2 mm
Cell encapsulation	EVA (Ethylene-Vinyl-Acetate)
Back sheet	composite film
Frame	Anodised aluminium profile
Dimensions	1211 $\times$ 546 $\times$ 35 mm ($L \times W \times H$)
Maximum surface load capacity	2,400 Pa
Hail	Maximum diameter of 25 mm with impact speed of $23 \text{ m}\cdot\text{s}^{-1}$
Temperature range	−40°C to +85°C

TABLE 4: (a) Summary output (FF). (b) and (c) ANOVA.

(a)					
Regression statistics					
Multiple R	0.987429459				
R Square	0.975016936				
Adjusted R Square	0.972134275				
Standard error	0.444029697				
Observations	30				

(b)					
	<i>df</i>	SS	MS	<i>F</i>	Significance <i>F</i>
Regression	3	200.0616483	66.68722	338.235	6.10857E − 21
Residual	26	5.126221676	0.197162		
Total	29	205.18787			

(c)		
	Coefficients	Standard error
Intercept	−1.678085319	2.015645509
T_a	−0.117136967	0.071238145
Radiation (G)	0.001492943	0.001202588
FF _s	1.188748497	0.04219168

TABLE 5: (a) Summary output (TF). (b) and (c) ANOVA.

(a)

Regression statistics	
Multiple R	0.97275466
R Square	0.946251629
Adjusted R Square	0.940049894
Standard error	0.885232775
Observations	30

(b)

	<i>df</i>	SS	MS	<i>F</i>	Significance <i>F</i>
Regression	3	358.698573	119.5662	152.5785	1.2743E − 16
Residual	26	20.37456371	0.783637		
Total	29	379.0731367			

(c)

	Coefficients	Standard error
Intercept	−9.503340876	4.063070816
T_a	0.356280226	0.135307719
Radiation (G)	−0.006620823	0.002569022
TF _s	1.080144819	0.056718604

TABLE 6: (a) Summary output (CPV). (b) and (c) ANOVA.

(a)

Regression statistics					
Multiple R	0.977883672				
R Square	0.956256475				
Adjusted R Square	0.951209145				
Standard error	1.417568074				
Observations	30				

(b)

	<i>df</i>	SS	MS	<i>F</i>	Significance <i>F</i>
Regression	3	1142.14649	380.7155	189.4579	8.80068E − 18
Residual	26	52.24698035	2.009499		
Total	29	1194.39347			

(c)

	Coefficients	Standard error
Intercept	−4.542469701	6.027512011
T_a	0.232758421	0.216798907
Radiation (G)	−0.006474561	0.004029298
CPV _b	1.053363488	0.048316856

efficiency degrades with the increase in temperature which usually falls at a rate of $0.5\%/^{\circ}\text{C}$. The highest ΔT value comes from the CPV array with the surface side producing higher heat energy. This study shares some findings of linearly correlated T_{array} model with respect to radiation and ambient temperature for three types of uniquely configured PV arrays installed in the tropics.

Appendix

See Table 3.

MLR and ANOVA Test. See Tables 4, 5, 6, and 7.

TABLE 7: (a) Summary output (T_{inv}). (b) and (c) ANOVA.

(a)					
Regression statistics					
Multiple R					0.934929786
R Square					0.874093704
Adjusted R Square					0.864767312
Standard error					0.650565694
Observations					30

(b)					
	df	SS	MS	F	Significance F
Regression	2	79.33350216	39.66675	93.72259708	7.08991E-13
Residual	27	11.4273645	0.423236		
Total	29	90.76086667			

(c)		
	Coefficients	Standard error
Intercept	14.03251613	2.691542602
T_a	0.867171815	0.099396709
Radiation (G)	0.004692967	0.00174276

Nomenclature

DART:	Data acquisition and real-time
cRIO:	Compact reconfigurable input output
SPMS:	Solar PV monitoring station
G_{ref} :	Reference radiation value of 1000 W/m ²
G_T :	Measured radiation value in W/m ²
T_a :	Ambient temperature
T_c :	Cell temperature
T_m :	Module temperature
T_{array} :	Array temperature
FF _s :	Surface temperature for fixed flat PV generator
FF _b :	Bottom-side temperature for fixed flat PV generator
TF _s :	Surface temperature for tracking flat PV generator
TF _b :	Bottom-side temperature for tracking flat PV generator
CPV _s :	Surface temperature for concentrating PV generator
CPV _b :	Bottom-side temperature for concentrating PV generator
SE:	Standard error
NI:	National instrument
ANOVA:	Analysis of variance
MLR:	Multiple linear regression
R^2 :	Significant correlation factor
DAQ:	Data acquisition
RT:	Real time
HMI:	Human machine interface.

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