Solar panel performance analysis under Indonesian tropic climate using Sandia PV array performance model and five parameter performance model

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Abstract. Evaluation and monitoring of solar panel are need to be done, primarily related to how much energy is produced. Energy production by a solar panel is affected by the characteristics of climate or weather of a particular location such as solar radiation and ambient temperature. This study aimed to compare two models of solar panel performance calculation, i.e., Sandia PV Array Model and Five Parameter Model by considering the tropical climate of Indonesia and see the effect of temperature and solar radiation changes on the results of the calculations of both methods through the I-V curve. The types of solar panels on monitored are a monocrystalline, polycrystalline, and thin film. The results show that the energy produced by Sandia PV Array Performance Model for the three types of solar panels are 54.36 Wdc, 51.57 Wdc, and 39.62 Wdc, respectively. Five Parameter Performance Model results are 56.58 Wdc, 52.7 Wdc, and 43.29, respectively. These results show that with a small amount of data, the Five Parameter Model is more optimal and efficient for the tropics compared to Sandia PV Array Model.

1. Introduction

Investments worth USD809 reported by Bloomberg for the construction of the power plant of the year 2010-2015 photovoltaic [1]. Most of this investment was allocated for the purchase of solar panels that power the output values based on Standard Condition Test (STC) as radiation 1000 W/m², solar panel temperature 25°C, wind speed 1 m/s and Air Mass (AM) 1.5 [2]. However, the advantage of this investment is not determined based on conditions of STC but rather determined by the energy produced by solar panels that are affected by environmental conditions [3]. The performance of a solar panel is rated based on the energy produced, reliability, and efficiency of its conversion [4], [5].

The production of energy by solar panels through the process of converting solar energy into electricity depends heavily on climate or environmental parameters of a particular region [2], [6], those parameters are solar radiation intensity, solar panel temperature, wind speed and humidity [7]–[9]. Solar panel performance testing studies are mostly conducted in sub-tropical regions, so the results do not necessarily represent the general tropical conditions, including Indonesia. Tropical environments have distinctive characteristics [7]–[10]:

1. Have a high-temperature range 18-40°C that can cause a rise in temperature of the solar panel reach 90°C so it can degrade the performance of the solar panel.
2. The high level of humidity, i.e., 35-85% with low wind speeds ranged from 0.2 m/s.
3. The trend of clouds and has high annual precipitation. This condition causes the low index of brightness that has an impact on the performance of solar panels.

With these characteristics, the solar panels operating in tropical regions need to be evaluated to determine how much energy is produced for the benefit of the investment due to the tropical climate leads to a significant deviation from STC conditions [2].

Some research on evaluation and testing the performance of solar panels associated with a tropical climate have been carried out by several researchers. In Nigeria which is a tropical country, conducted a study to investigate the influence of environmental temperature on the solar panel [11]. The result shows the presence of correlation between the temperature of the environment with the power generated by the solar panels. At low temperatures, the power generated is high but on the contrary with the high temperatures the generated power is low. Furthermore, research that evaluates the efficiency of the solar panel power conversion related dust, humidity and air speed [12] report, the power conversion efficiency decline in some tropical countries. In the U.S. that reaches 1-4.7% for two months, in Saudi Arabia in the amount of 32-40% in a month, the 17-65% 6-8 in Kuwait for 38 days, and a decrease of 33.5-65.8% for six months in Egypt, and in Thailand reached 11%.

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In Sinegal, Ababacar Ndiaye, et al [13] evaluates the degradation of short circuit current ($I_{sc}$) and open-circuit voltage ($V_{oc}$) associated with power. The results shown in the period of 10 years there is a decrease in $I_{sc}$ and $V_{oc}$ respectively by 13% and 11%. Furthermore, research was done in Singapore by Timothy M. Walsh et al [14] against commercial solar panels of various types, the results showed that some solar panels have a less good performance in Singapore's tropical climate.

The primary focus of the research is to compare two models calculation of the solar panels performance, i.e., Sandia PV Array Performance Model (SPAPM) and Five Parameters Performance Model (FPPM). These methods are chosen because in its calculation SPAPM method uses the results of climatology data processing directly to determine the value of solar panel output at its operating conditions, whereas in the FPPM method, the working principle of solar panels is modeled into a single diode equivalent circuit. The analysis of this circuit will yield five parameter values i.e $a$, $I_L$, $I_o$, $R_s$, $R_{sh}$. These five parameters are components of a single diode equivalent circuit used to determine the value of solar panel output.

2. Solar Radiation

The distance between the center of the earth and the sun is estimated as far as $1.495 \times 10^{11}$ m, and solar radiation reaches the Earth's surface through a process called radiation. Solar radiation outside the Earth's atmosphere is called the solar constant ($G_{sc}$) of $1.367 \text{ W/m}^2$ [15].

2.1 The Geometric Solar Radiation to Earth's Surfaces

The geometric relationship between the beam radiation and the earth's surface is shown in Fig.1[15]. $\beta$ is Slope Angle i.e. the angle between the surface plane and the horizontal plane ($0^o \leq \beta \leq 180^o$). $\gamma$ is Surface Azimuth Angle i.e. the projection deviation on a horizontal plane from normal to the surface of the local meridian. While $\gamma_s$ is solar azimuth angle that is the angular displacement from the southern beam radiation projection on the horizontal plane. Zenith angle ($\theta_z$) is the angle between the vertical surface and the line to the sun, i.e. the angle of incident beam radiation on a horizontal surface. $\alpha_s$ or solar altitude angle is the angle between the horizontal surface and the line to the sun, or the complement angle of zenith.

2.2 Solar Time

Solar Time is the time of movement of the sun's angle visible in the sky with solar noon as the sun passes the observer's longitude or is the relative position of the sun to the observation point [15]. Solar time depends on the time of observation and the day of observation in a year [16].

$$EoT = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B$$ (1)

$$B(deg) = \frac{360^o}{365} \times (d - 81)$$ (2)

Substitution of equation (2) into (1) then the obtained value of the EoT. Thus the solar time can be calculated using the equation:

$$T_{Solar} = T_{local} + \frac{EoT}{60} + \frac{Long_{sm} - Long_{local}}{15}$$ (3)

$$\theta_{hr} = 15^o \times (T_{Solar} - 12)$$ (4)

Equation 4 is the hour angle that is a representation of the solar time in the form of the value of the degrees from the movement of the sun at all times.

2.3 Sun Declination

Sun declination angle ($\delta$) is the angle between the line of the equator the Earth with a straight line that connects the center of Earth to the center of the Sun. This angle determines the position of the Sun towards the Earth at a given day within a year. The angle of declination varies every season because of the tilt of the Earth on the axis of its rotation and the rotation of the earth around the Sun.
The magnitude of the angle of declination is calculated with the equation:

\[
\delta = \sin^{-1}(\sin 23.45 \sin(\frac{360}{365}(d - 81)))
\]  

(5)

2.4 Sun Elevation

Sun elevation angle (h) is the height of the Sun in the sky angle measured from the horizontal line (ground level) or in other words the angle formed between the direction of the oncoming sunlight with the soil surface. The elevation angle is 0° at the time of sunrise and sunset, and 90° valued when the Sun is exactly above head [18]. The elevation angle is calculated using the equation:

\[
h = \sin^{-1}(\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \theta_{hr})
\]  

(6)

Zenith angle (\(\theta_z\)) is the complement of the angle of elevation or angle formed between the direction of the oncoming sunlight with a vertical line. The magnitude of the zenith angle:

\[
\theta_z = 90^\circ - h
\]  

or

\[
\theta_z = \cos^{-1}(\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \theta_{hr})
\]  

(8)

2.5 Sun Azimuth Angle

Sun azimuth angle denoted by \(\mu_s\) is the direction of the compass from which sunlight comes. As in the compass direction the azimuth angle will be 0° when the sun is to the north of the observation point and will be 180° when the sun is on the south [19]. The azimuth angle is calculated by the equation:

\[
\mu_s = \sin^{-1}\left(-\frac{\sin \theta_{hr} \cos \delta}{\cos \theta_z}\right)
\]  

(9)

2.6 Angle of Incidence

Angle of Incidence (AOI) is the angle between the direction of the coming of the light from the Sun to the surface of the solar panel and the line normal to the surface of the solar panel. The value is determined by the angle of the AOI formation especially solar panel tilt angle (tilt angle) the effect on solar radiation absorbed by the solar panels. The greater the value of the AOI then solar radiation absorbed progressively reduced so that the output of solar panels to decrease. This happens when AOI worth 65° or more [20]. The value of AOI is determined by the equation:

\[
AOI = \cos^{-1}(\cos \theta_z \cos \beta + \sin \theta_z \sin \beta \cos(\mu_s - \mu))
\]  

(10)

2.7 Beam Radiation

Beam Radiation (\(E_b\)) Beam Radiation (Eb) is the solar radiation received directly without the occurrence of scattered by the earth's atmosphere [15]. Beam Radiation is the multiplication of Direct Normal Irradiance (DNI) with Angle of Incidence (AOI) written as [21]:

\[
E_b = DNI \cos \theta
\]  

(11)

2.8 Diffuse and Ground Reflected Radiation

\(E_d\) or diffuse radiation is solar radiation received after scattering occurs which is caused by the Earth's atmosphere so that the direction of the radiation is turned or deflected [15]. \(E_d\) is calculated using equation [22]:

\[
E_d = DHI x \frac{1+\cos \beta}{2}
\]  

(12)

While the ground reflected radiation (\(E_g\)) that is leaning on the surface radiation reflected from the ground, and formulated as [23]

\[
E_g = DHI \times Albedo \times \frac{1-\cos \beta}{2}
\]  

(13)

\[GH1 = DHI + DNI \cos \theta_z \]  

(14)

2.9 Total Radiation (Plane of Array Irradiance)

Total Radiation or Plane of Array Irradiance (\(E_{poa}\)) is the summation of the beam radiation, diffuse radiation and ground reflected radiation [24]. Written mathematically as :

\[
E_{poa} = E_b + E_d + E_g
\]  

(15)

2.10 Air Mass

Air Mass is the length of the path traversed by the light rays through the atmosphere normalized to the along the path with the shortest possible. Air mass quantifies the reduction in strength of the light when passing through the atmosphere and is absorbed by air and dust [25]. The air mass is calculated based on the equation:

\[
AM = \frac{1}{\cos \theta_z}
\]  

(16)

The air mass is calculated based on the equation [26]:

\[
AM_a = AM e^{-0.0001184h}
\]  

(17)

Furthermore, to calculate the air mass in the form of a function of a polynomial of the air mass absolute or referred to as the air mass modifier (\(MAM\)) used equation [27]:

\[
M_{AM} = a_0 + a_1AM_a + a_2AM_a^2 + a_3AM_a^3 + a_4AM_a^4
\]  

(18)

Value of \(a_0, a_1, a_2, a_3, a_4\) are the coefficient vektor whose value is determined while testing the solar panel.

3. Methodology

In this study, the selected location is Halim Perdanakusuma area in East Jakarta (-6.264451 N and 106.895859 E). Data required such as solar radiation climatology, environment temperature, air mass, albedo,
and wind speed. The data obtained by use of the software of Meteonorm. As for the data is as follows:

Table 1. Climatology Data

| Parameter | Value |
|-----------|-------|
| DNI (W/m²) | 95 |
| DHI (W/m²) | 422 |
| GHI (W/m²) | 516 |
| Tₑₑ (Dry Bulb) °C | 30.6 |
| Wₑₑ (m/s) | 7.4 |
| Longitude Standar Meridian (deg) | 105 |
| Local Longitude (deg) | 106.9 |
| Local Latitude (deg) | -6.25 |
| Eₑₑ (W/m²) | 1000 |
| Tₑₑ (°C) | 25 |
| Albedo | 0.2 |
| Day of Measurement | 296 |
| Tilt (deg) | 45 |
| Elevation (m) | 30 |
| Azimuth (deg) | 0 |

On the research of this type of solar panel that evaluated i.e. polycrystalline, monocrystalline and thin film with specifications and data in a condition of STC as indicated in table 2.

Table 2. Specification of Solar Panel (Sandia National Laboratory)

| Type of Panel | Astropower Apex Bin | Siemens Bin1/SP75 | Solaris Mega Cell/MSX |
|---------------|---------------------|-------------------|----------------------|
| G/IPX-90 | | |
| ISc0 (A) | 5.11 | 4.37 | 4.25 |
| Imp0 (A) | 4.49 | 3.96 | 3.82 |
| Voc0 (V) | 29.61 | 42.93 | 41.50 |
| Vmp0 (V) | 23.17 | 33.68 | 32.94 |
| a | 0.938110 | 0.935823 | 0.918093 |
| b | 0.062191 | 0.054269 | 0.086257 |
| α | -0.015021 | 0.000867 | -0.02445 |
| β | 0.001271 | 0.000527 | 0.002816 |
| αSc (%/°C) | 0.000916 | 0.000401 | 0.000560 |
| αmp (%/°C) | 0.003538 | 0.0000011 | 0.000013 |
| βVoc (V/°C) | -0.12995 | -0.15237 | -0.15280 |
| βVmp (V/°C) | -0.13039 | -0.15358 | -0.15912 |
| bSc | 0.999890 | 1.000341 | 0.998515 |
| bmp | -0.006098 | -0.005557 | -0.001212 |
| bSc | 0.0008117 | 0.0006553 | 0.0001440 |
| bmp | -0.0003376 | -0.0000273 | -0.000005 |
| bs | 5.647E-07 | 6.416E-07 | 8.78E-07 |
| bs | -3.371E-09 | -2.806E-09 | -4.9E-09 |
| e0 | 0.9615 | 0.9995 | 1.0144 |
| e1 | 0.0368 | 0.0026 | -0.0055 |
| e2 | 0.2322 | -0.5385 | -0.3211 |
| e3 | -9.4295 | -21.4078 | -30.2010 |
| n | 1.357 | 1.026 | 1.025 |
| e (eV) | 1.12 | 1.12 | 1.14 |
| PV type | Poly | Mono | Thinfilm |

The temperature of the solar panel is one of the parameters is calculated in this study based on equation [27]:

\[ T_m = E_{POA} e^{(\alpha + \beta W_0)} + T_a \]  

(19)

The value of a dan b on the equations (19) and (20) are parameters that depend on the material of construction, as well as the configuration of the installation of the solar panels specified [28] as shown in the table below:

Table 3. Parameters values various of module types and configurations

| Solar Panel Type | Mount | a | B | ΔT (°C) |
|------------------|-------|---|---|--------|
| Glass/cell/glass | Open Rack | -3.47 | -0.0594 | 3 |
| Glass/cell/glass | Close roof | -2.98 | -0.0471 | 1 |
| Glass/cell/polymers | Open Rack | -3.56 | -0.0750 | 3 |
| Glass/cell/polymers | Insulated Back | -2.81 | -0.0455 | 0 |
| Polymer/thinfilm/steel | Open Rack | -3.58 | -0.113 | 3 |

3.1 Performance Model for Solar Panel Modul

3.1.1 Sandia Photovoltaic Array Performance Model

Sandia Photovoltaic Array Performance Model (SPAPM) is one of the solar panel performance calculation models developed by David L. King et al. [27] at Sandia National Laboratories. The basic equations used to describe the electrical performance of individual solar panels, but can also be used in array configurations. The equations used in this model are:

\[ I_{SC} = I_{SC0} x f_1 \left( \frac{f_2 + f_3}{f_4} \right) x (1 + \alpha_{SC}(T_c - T_0)) \]  

(21)

\[ I_{MP} = I_{MP0} (C_1 E_c + C_2) \left( 1 + \alpha_{MP}(T_c - T_0) \right) \]  

(22)

\[ V_{OC} = V_{OC0} + N_\delta \ln(E_c) + \beta_{VOC}(T_c - T_0) \]  

(23)

\[ V_{MP} = V_{MP0} + C_1 N_\delta \ln(E_c) + C_2 N_\delta (\ln(E_c))^2 + \beta_{VMP}(T_c - T_0) \]  

(24)

\[ P_{MP} = I_{MP} V_{MP} \]  

(25)

\[ FF = \frac{P_{MP}}{I_{SC} V_{OC}} \]  

(26)

Where,

\[ E_c = \frac{I_{SC0} (1 + \alpha_{SC}(T_c - T_0))}{I_{SC0} (1 + \alpha_{SC}(T_c - T_0))} \]  

(27)

\[ \delta = \frac{n k (T_c - 273.15)}{q} \]  

(28)

To form a more precise I-V curve with this model two more equations are added when Ix is V = 0.5 VOC and Ixx when V = 0.5 (VOC + Vmp), the equation is:

\[ I_x = I_{x0} (C_4 E_c + C_5 E_2^2) \left( 1 + \alpha_{x0}(T_c - T_0) \right) \]  

(29)

\[ I_{xx} = I_{xx0} (C_6 E_c + C_7 E_2^2) \left( 1 + \alpha_{x0}(T_c - T_0) \right) \]  

(30)
Five point on I-V Curve in SPAPM

Equation 21-30 are used to calculate the amount of power and energy generated by solar panels under the assumption that the performance coefficients of solar panels are predetermined and solar data sources are available. The calculation process using the SPAPM model is shown in the flowchart below:

![Flowchart](image_url)

Fig. 3. PAPM calculation procedure

3.1.2 Five Parameter Performance Model

Five Parameter Performance Model (FPPM) is a method that is also used to calculate the performance of solar panels. This model was developed by W. De Soto et al. [20]. Unlike the SPAPM model, FPPM requires fewer data in its calculations. The required data are the initial parameter values found in nameplate solar panels Isc0, Imp0, Voc0, Vmp0, a Isc, a Imp, b Voc, b Vmp, E0, E ref, E P OA, E0, Tc, T0, n, N sk, q, a0-a4, b0-b5, C0-C7, fd.

![Equivalent circuit](image_url)

Fig. 4. Equivalent circuit representing the FPPM [20]

Based on Kirchoff’s current law the following equations are obtained:

$$I = I_L - I_D - I_{sh}$$

(31)

$$I = I_L - I_0 \left[ e^{\frac{V+I R}{a}} - 1 \right] - \frac{V+IR}{R_{sh}}$$

(32)

where

$$a = \frac{N_s n B_{Tc}}{q}$$

(33)

The equivalent circuit in Fig. 2 shows the relation of voltage and current at the temperature of the cell and the constant solar radiation expressed in equation (32). In that equation five parameters must be known to determine current and voltage and also the power to the load, the five parameters are I_L (Light Current), Diode Reverse Saturation Current, R_s (Series Resistance), and R_sh (Shunt Resistance) and a (Diode Ideality Factor) are shown in equation (33). To obtain the value of the five parameters in equation 32, five parameters of the solar panel are required in the STC condition, i.e. short-circuit current (Isc), open circuit voltage (Voc), Imp and Vmp, i.e. current and voltage at maximum power (Pmp) as it appears on the nameplate solar panel [20].

The five parameters found in equation (32) correspond to the operating conditions of the STC: I_{sc, ref}, I_{imp, ref}, a_{ref}, R_s, and R_{sh, ref}. To determine these five reference parameters, three known conditions on the I-V characteristic curve of the STC substituted into equation (32) are:

1. For short circuit current: I = I_{sc, ref} ; V = 0

$$I_{sc0} = I_{L, ref} - I_{0, ref} \left[ e^{\frac{V_{sc0}+R_{ref}}{a_{ref}}} - 1 \right] - \frac{V_{sc0}+R_{ref}}{R_{sh, ref}}$$

(34)

2. For open circuit voltage: I = 0 ; V = V_{oc, ref}

$$0 = I_{L, ref} - I_{0, ref} \left[ e^{\frac{V_{oc0}+R_{ref}}{a_{ref}}} - 1 \right] - \frac{V_{oc0}+R_{ref}}{R_{sh, ref}}$$

(35)

3. For maximum power point I = I_{mp, ref} ; V = V_{mp, ref}

$$I_{mp0} = I_{L, ref} - I_{0, ref} \left[ e^{\frac{V_{mp0}+R_{mp0}+R_{ref}}{a_{ref}}} - 1 \right] - \frac{V_{mp0}+R_{mp0}+R_{ref}}{R_{sh, ref}}$$

(36)
at the maximum condition the power derivative of the voltage is zero, then:

\[
\frac{d(V)}{dV}_{mp} = 0
\]

(37)

\[
\frac{dI}{dv} = -\frac{1}{R_{sh,ref}}
\]

(38)

and for \(a_{ref}\) values can be determined by the equation:

\[
a_{ref} = \frac{n N_s k T_0}{q}
\]

(39)

Thus, to determine the value of five parameters under operating conditions can be seen in the following flowchart:

![Flowchart](image)

**Fig. 5.** Five parameters calculation procedure

### 4. Results and Discussion

#### 4.1 Climatology data process

Climatological data in table 1 is used to obtain the values of B, EoT, T_{Solar}, \(\delta\) and \(\theta_{hr}\) with measurement day (d) is the 296th substituted to equation (2) then the value of B is 212.05\(^{\circ}\). This value is then fed to equation (1) so that Equation of Time (EoT) is 16.05. Solar Time (T_{Solar}) is calculated using the equation (3) with the selected local time i.e. 12 noon then the value of the T_{Solar} is 12.14 and the hour angle (\(\theta_{hr}\)) is 2.114\(^{\circ}\) calculated using equation (4). The amount of declination angle on the 296th day of -12.19\(^{\circ}\) is calculated using equation (5).

Next is to determine the magnitude of zenith angle (\(\theta_z\)) with local latitude equal to -6.25 (table 1), based on equation (8) then \(\theta_z\) is 6.298\(^{\circ}\). This zenith angle value is used to determine \(\mu_s\) or sun azimuth angle, based on equation (9) the value of \(\mu_s\) is -2.079\(^{\circ}\).

Based on the zenith and azimuth angle, Angle of Incidence (AOI), Air Mass (AM) dan Air Mass Absolut (AM_{abs}) values can be calculated using equations respectively (10), (16) and (17). With the equation we get the value of AOI (38.71\(^{\circ}\), AM (1.006) and AM_{abs} (1.0025). The next step is to determine the total value of solar radiation absorbed by the surface of the solar panel or Plane of Array Irradiance (E_{POA}). However, to determine E_{POA}, we first determine the value of Beam Radiation (E_b), Diffuse Radiation (E_d) and Ground Reflected Radiation (E_g) using equations (11), (12) and (13). From the three equations E_b (74.13 W/m\(^2\)), E_d (360.2 W/m\(^2\)), dan E_g (15.11 W/m\(^2\)). Based on these values, the magnitude of Plane of Array Irradiance (E_{POA}) shown in equation (15) are:

\[
E_{POA} = 74.13 + 360.2 + 15.11 = 449.45 \text{ W/m}^2
\]

The final part of this calculation is to determine the temperature of the module (T_m) and cell temperature (T_c). T_m and T_c are determined based on the material configuration and the type of mounting of the associated solar panels values of coefficients a, b and \(\Delta T\). In this study using three types of solar panels are polycrystalline, monocrystalline, and thin film. The related information specifications of the three types of solar panels as well as the coefficients a, b and \(\Delta T\) are presented in table 2 and table 3. The calculations of T_m and T_c are done using equations (19) and (20), as for the values are as follows:

\[
T_m = 449.45 e^{(-3.56+(0.075 \times 7.4))} + 30.6 = 37.94^{\circ}
\]

\[
T_c = 37.94^{\circ} + \frac{449.45}{1000 \times 3} = 39.28^{\circ}
\]

T_m and T_c in this study are considered the same for all three types of solar panels because they have the same material configuration and mounting type.

#### 4.2 Calculation process of SPAPM

The SPAPM calculation process is done based on the flowchart shown in Figure 3. The data used are solar electrical specification data and the results of data processing climatology.

Calculations will be made on solar panels with the type of monocrystalline, but the results of the three types of solar panels will be displayed.

The first step of this process is to do the calculation of f_1 that is the value of Air Mass Modifier (M_{AM}) using equation (18) and produce f_1 (AM_{a}) is 0.982. While f_2 is the value of the Angle of Incidence Modifier (M_{AOI}) and the calculation uses the equation:

\[
M_{AOI} = b_0 + b_1 AOI + b_2 AOI^2 + b_3 AOI^3 + b_4 AOI^4 + b_5 AOI^5
\]

(40)

Based on equation (40) then the value of f_2(AOI) is 0.9818. Next, determine the value of thermal voltage (\(\delta\))using equation (28) which yields 0.028 V.
Equation (21) is used to determine the value of $I_{sc}$ under its operating conditions. This $I_{sc}$ value is influenced by the level of solar radiation absorbed by the solar panel. Through the equation (21) the resulting $I_{sc}$ value is 1.87 A. The next is to determine the effective radiation value ($E_e$), this value is determined by the ratio of the short circuit current value at the operating condition and at the STC condition. Based on equation (27) the value of $E_e$ produced is 0.425 (unitless).

$P_{mp} = 1.67 \times 32.44 = 54.36 \text{ Wdc}$

The results of the calculations for the three types of solar panels using SPAPM are shown in the table below:

| Type of PV            | $I_{sc}$ (A) | $V_{oc}$ (V) | $I_{mp}$ (A) | $V_{mp}$ (V) | $P_{mp}$ (Wdc) |
|----------------------|--------------|--------------|--------------|--------------|----------------|
| Monocrystalline      | 1.87         | 39.05        | 1.67         | 32.44        | 54.36          |
| Polycrystalline      | 1.83         | 37.62        | 1.65         | 31.25        | 51.57          |
| Thinfilm             | 2.22         | 26.02        | 1.89         | 20.98        | 39.62          |

### 4.3 Calculation process of FPPM

Calculation of the performance of solar panels using FPPM is done following the flowchart is shown in Figure 5. The data used are solar panel specification data on STC condition, total radiation absorbed by a solar panel, and cell temperature.

The first step of the calculation is to determine the value of reference or $a_{ref}$ ideality factor with equation (39). With the resulted equation $a_{ref}$ is 1.898 eV. Next is to determine $R_{s,ref}$ using equation (41):

$$R_{s,ref} = -m \frac{V_{oc}}{I_{mp}} + \frac{V_{mp}}{I_{mp}} \left(1 - \frac{I_{sc}}{I_{mp}}\right)$$

The value of $M$ is the slope of the $V_{oc}$ on the characteristic curve calculated using equation (42):

$$M = \frac{V_{oc}}{I_{sc}} \left( \frac{V_{mp}}{V_{oc}} + k_2 \frac{V_{mp}}{V_{oc}} + k_3 \frac{V_{mp}}{V_{oc}} + k_4 \right)$$

while the $k_1, k_2, k_3$, and $k_4$ are:

$$k = \begin{pmatrix} -5.411 \\ 6.450 \\ 3.41 \\ -4.422 \end{pmatrix}$$

In some cases the value of $R_{s,ref}$ produced by equation (41) is sometimes negative. This problem is solved by removing $R_s$ and $R_{sh}$ components in equivalent circuits and replacing them with photovoltaic resistance or $R_{pv}$.

Thus the single diode equivalent circuit in figure. 4 becomes:

$$I = I_{ph} - I_0 \left( e^{\frac{V+I R_{mp}}{V_T}} \right)$$

$$V = V_T \ln \frac{I_{mp}+I_0}{I_0} - I R_{mp}$$

The equation model generated according to the equivalent circuit in Fig. 6 is:

$$I = I_{ph} - I_0 \left( e^{\frac{V+I R_{mp}}{V_T}} \right)$$

$$V = V_T \ln \frac{I_{mp}+I_0}{I_0} - I R_{mp}$$

The values of $V_1$ and $V_2$ are given by equation (45), while $V_1$ and $V_2$ are:

$$V_1 = V(I_{sc1} - \Delta I, R_{pv1}, V_T, I_0, I_{ph1})$$

$$V_2 = V(I_{sc2} - \Delta I, R_{pv2}, V_T, I_0, I_{ph2})$$

Index 2 represents a parameter with a characteristic value with a lower short-current. The value of $I$ is determined by the equation:

$$I_n = I_{scn} - \Delta I$$

with

$$\Delta I = 0.5 \times I_{sc2}$$

Determination of $R_{s,ref}$ value on solar panel with monocrystalline type (table 2) using equation (41), because it does not produce a negative value. The value of $R_{s,ref}$ is determined by first determining the value of $M$ in equation (42):
\[ M = 42.93 \left( -5.411 + 6.45 \right) = 42.93 \]

\[ M = -1.102 \]

So the value of \( R_{s,ref} \):

\[ R_{s,ref} = \frac{-1.102}{4.37} \]

The next step after the known value of \( R_{s,ref} \) is to determine the value of \( I_{L,ref} \) and \( I_{0,ref} \). To determine \( I_{L,ref} \) the equation (35) can be written as:

\[ I_{L,ref} = I_{0,ref} \left( \frac{V_{oc,ref}}{R_{sh,ref}} - 1 \right) \]

Equation (34) is substituted into equations (34) and (36), resulting in the equation:

\[ I_{sto} = I_{0,ref} \left( \frac{V_{oc,sto}}{R_{sh,ref}} - 1 \right) + \frac{V_{oc,sto} - V_{mpo,sto} R_{sh,ref}}{R_{sh,ref}} \]

\[ I_{mpo} = I_{0,ref} \left( \frac{V_{mpo,sto}}{R_{sh,ref}} - 1 \right) + \frac{V_{mpo,sto} - V_{mpo,sto} R_{sh,ref}}{R_{sh,ref}} \]

From equation (55) and (56) two unknowns are \( I_{0,ref} \) and \( I_{L,ref} \). By using an algebra elimination operation, one of the unknown variables can be eliminated so that other variables can be determined. In this case the eliminated variables are \( I_{L,ref} \). So it can be determined by \( I_{0,ref} \):

\[ I_{0,ref} = \frac{I_{mpo} V_{mpo,sto} R_{sh,ref} - I_{sto} V_{mpo,sto} - I_{sto} V_{mpo,sto} R_{sh,ref}}{V_{mpo,sto} - V_{mpo,sto} R_{sh,ref}} \]

\[ I_{L,ref} = I_{0,ref} \left( \frac{V_{oc,sto}}{R_{sh,ref}} - 1 \right) \]

By equation (57) the value of \( I_{0,ref} \):

\[ I_{0,ref} = 5.92 \times 10^{-10} A \]

As for \( R_{sh,ref} \) is determined by using equation (56) and its value is

\[ R_{sh,ref} = 96.01 \Omega \]

and

\[ I_{L,ref} = 4.38 A \]

I \( I_{L,ref} \) is determined by using equation (54).

After all parameters in the reference condition (STC) is known then the next step is to determine the value of the five parameters of the solar panel under its operating conditions.

The five parameters are ideality factor \( a \), this value depends on the cell temperature of the module. The value of \( a \) is determined by using equation (33):

\[ a = 1.989 \text{ } e^V \]

Subsequently determined \( I_{L}, I_{0}, \) and \( R_{sh} \), \( I_{L} \) values are only affected by cell temperature alone whereas \( R_{sh} \) is affected by solar radiation. Using the equation:

\[ I_{L} = \frac{E_{PA}}{E_{0}} \left[ I_{L,ref} + a (T_c - T_0) \right] \]

\[ I_{0} = I_{0,ref} \left( \frac{V_{oc,sto}}{R_{sh,ref}} \right) e^{a (T_c - T_0)} \]

\[ R_{sh} = \frac{E_{PA}}{E_{0}} \]

From equation (57),(58) and (59) we obtained:

\[ I_{L} = 1.97 A \]

\[ I_{0} = 4.75 \times 10^{-9} A \]

\[ R_{sh} = 213.62 \Omega \]

The five parameters are then substituted into equation (32) so that in obtaining the current equation is:

\[ I = 1.97 - 4.75 \times 10^{-9} \left[ \frac{V + 0.341}{213.62} - 1 \right] \]

Equation (60) is used to plot the characteristic curve (I-V) of the solar panel under its operating conditions.

### 4.4 Characteristic Curve on Operating Conditions

Equation (60) is used to plot the characteristic curve (I-V). But it cannot be directly used to plot characteristic curves. It is known that the current can be indicated as a function of the voltage \( I = I (V) \) by the Lambert's W transcendental function [30]. Lambert's W function is a W(x) solution of the equation \( x = W(x) e^{W(x)} \). Using this function equation (32) to form \( I = I (V) \). The initial step of equation (32) is changed to:

\[ I = I_{0} + \frac{V}{R_{sh}} \]

\[ I = ax + b \]

Then we get

\[ t = ax + \frac{ad}{c} \]

Substituting equation (61) into (63) so that it is produced:

\[ p^{-t} a \frac{ad}{c} b = c \left( -t - \frac{ad}{c} \right) + d \]

\[ p^{-t} a \frac{ad}{c} b = \frac{-tc}{a} \]

\[ p = \frac{-a}{tc} \]

\[ p = \frac{-a}{tc} \]

\[ t = \frac{-a}{p} \]

Then \( p \) in equation (64) is changed by exponential form:

\[ \frac{-a}{p} \ln p = -\frac{a}{tc} \ln p \]

Using the definition of Lambert's W function, then the equation 65 can be converted to \( x = W(y) \) then in the equation:

\[ 8 \]

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The values of the five parameters under operating conditions are substituted into equations (68) and (69) resulting in the value of the current of each voltage of the solar panel. Equation (69) cannot be directly substituted into (68), but it must be entered into Lambert’s W function calculator to determine the value of the function W(θ). This value is inputted into the current calculation in equation 68.

Based on the calculation in Table 5, the curve of I-V under operating conditions is shown in the following figure:

Fig. 7. I-V Curve of Solar Panel under Operating Condition

In the calculation of solar panel performance with five parameters method, the value of solar panel output parameters can be known from the calculation of the current for each voltage value and characteristic curve. The calculation results for the three types of solar panels using five parameters are shown in the table below:

Table 6. Parameters output of each type of PV using FPPM

| Type of PV                  | Ioc (A) | Voc (V) | Imp (A) | Vmp (V) | Pmp (Wdc) |
|----------------------------|---------|---------|---------|---------|-----------|
| Monocrystalline (Siemens SP-75) | 1,97    | 39,27   | 1,72    | 32,9    | 56,58     |
| Polycrystalline (Solarex MSX-64) | 1,91    | 37,71   | 1,65    | 31,91   | 52,57     |
| Thinfilm (AstropowerAPX-90)   | 2,29    | 26,08   | 2,17    | 19,98   | 43,29     |

5. Conclusion

In this research, performance assessment with SPAPM method, in monocrystalline type solar panels yielded a larger Pmp value of 54.36 Wdc, and in second and third order of Polycrystalline 51.57 Wdc, Thinfilm was 39.62 Wdc. The same thing is produced by FPPM method where Monocrystalline type solar panel produces larger Pmp which is 56.58 Wdc and followed by Polycrystalline 52.7 Wdc and Thinfilm 43.29 Wdc. The results of the calculations of both methods show that for the three types of solar panels used, the FPPM method yields a larger Pmp value than the SPAPM method. This is because the calculation using SPAPM method is much influenced by the climatological conditions, while the FPPM method is only influenced by the total radiation and cell temperature. Nevertheless the Pmp value generated by
FPPM method for the three types of solar panels is close to the \( P_{mp} \) value generated by the SPAPM method.

The results of this study show that FPPM method is more efficient and optimal in assessing the performance of solar panel compared with SPAPM method. This occurs because the FPPM method requires only a small amount of data but can provide the results of solar panel output parameters that approximate the results obtained by the PAPM method. In addition to these two methods, solar panels with thin film types have smaller \( P_{mp} \) values because theoretically thin film has a smaller efficiency than the other two types.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| Eot | Equation of Time |
| B | Slope Angle in degree |
| d | the number of days since the start of the year |
| Tsolar | Solar Time |
| Tlocal | Local Time |
| Longsm | Longitude Standard Meridian |
| Longlocal | Longitude Local |
| θh | Hour Angle |
| δ | Sun Declination Angle |
| h | Sun Elevation |
| ϕ | Local Latitude |
| θr | Zenith Angle |
| μ | Sun Azimuth Angle |
| AOI | Angle of Incidence (θ1) |
| MAOI | Incidence Angle Modifier |
| n1 | Air refreksi index |
| n2 | Surface of Solar Panel Refraksi Index |
| θc | Refraksi Angle |
| τ1 | Fresnel equation for non-reflected Unpolarized radiation |
| τr | absorbed radiation |
| K | Constant Proportionality (4m-1) |
| τ | Transmittance |
| Tm | Module Temperature (°C) |
| Tk | Cell Temperature (°C) |
| Ta | Ambient Temperature (°C) |
| EPoA | Plane of Array Irradiance (W/m²) |
| Eo | Solar Radiation at STC (1000 W/m²) |
| Wa | Wind Speed (m/s) |

| Symbol | Description |
|--------|-------------|
| a,b | constant |
| ΔT | temperature difference between module surface and back modul |
| Iac | Short Circuit Current (A) |
| Isc | Short Circuit Current at STC (A) |
| Imp | Maximum Current (A) |
| Imp0 | Maximum Current at STC (A) |
| Vmp | Open Circuit Voltage (V) |
| Vmp0 | Maximum Voltage at STC |
| Voc | Open Circuit Voltage at STC (V) |
| Voc0 | Maximum Voltage at STC |
| αic | Normalized Temperature Coefficient (%/°C) |
| αisc | Coefficient Temperature of open circuit voltage (°C) |
| βVmp | Coefficient Temperature of MaximumVoltage (V/°C) |
| Pmp | Maximum Power (W) |
| FF | Fill Factor |
| k | Boltzman Constanta (1,38066 x 10⁻²³) |
| To | Cell Temperature at STC |