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OPTIMIZATION OF A PHOTOVOLTAIC POWER PLANT IN INDONESIA WITH PROPER TILT ANGLE AND PHOTOVOLTAIC TYPE USING A SYSTEM ADVISOR MODEL

Aiman Setiawan[1,2*], Eko Adhi Setiawan[1,2]

[1]*Tropical Renewable Energy Center (TREC), Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*
[2]*Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*

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ABSTRACT

As a tropical country, Indonesia has great solar energy potential, with an average solar radiation intensity of 4.8 kWh/m^2/d. Consequently, the optimization of solar power plants in Indonesia is necessary. The objective of this paper is to investigate solar panel optimization in Indonesia using system advisor model (SAM) software. Optimization focuses on two main concerns, choice of photovoltaic (PV) type and optimum PV tilt angle. Research is conducted in three different cities in Indonesia. The annual energy production simulation is conducted on 5 kW$_{DC}$ PV on-grid systems with different PV types and slope angles. According to simulation results, Indonesia has a relatively low proper PV tilt angle, with a value of 11^o, 11^o and 6^o for Jakarta, Makassar and Jayapura, respectively. It can also be derived that when compared to crystalline PV modules, thin film PV modules have better performance, with the highest annual energy production due to its temperature coefficient characteristics.

Keywords: Cost of energy; Photovoltaic; PV tilt angle; System advisor model; Temperature

1. INTRODUCTION

Indonesia is located near the equator, from 6° North latitude to 11° South latitude and from 95° East longitude to 141° East longitude. Therefore, its geographic location means Indonesia receives stable sunshine throughout the year, with an average intensity of 4.8 kWh/m^2/d (Wibisono & Setiawan, 2015). However, solar energy has not been maximized in Indonesia, which has a total capacity of only 8 MW from photovoltaic (PV) power plants (Indonesia Ministry of Energy and Mineral Resources, 2010). With such tremendous solar energy potential, deep knowledge of PV system characteristics and performance is necessary in order to optimize solar energy empowerment in Indonesia.

A PV device directly converts solar energy to electricity. With their use, there are at least two ways to optimize an entire solar panel system's performance. Solar panels can produce optimum electricity if they are installed at an optimum PV module tilt angle. Most of the research about optimum tilt angles for solar panels indicate that the magnitude of the optimum solar tilt angle is influenced by the solar panels' latitude (Wenxian, 1989; Manes & Lanetz, 1983; Hottel, 1954; Yakup & Malik, 2015; Garg, 1982). Table 1 shows the recommended optimum solar panel tilt angles from the research of Garg (1982), Lunde (1980), Löf and

*Corresponding author's email: aimansetiawan@gmail.com, Tel. +62-87-841-939000, Fax. +62-21-7270077
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Tybout (1973), and Chinnery (1971).

Table 1 Recommended optimum PV module tilt angle

Research	Tilt Angle
Garg (1982)	(ϕ±15°)
Lunde (1980)	(ϕ±15°)
Löf & Tybout (1973)	(ϕ + 10° → 30°)
Chinnery (1971)	(ϕ + 10°)

These studies were mostly conducted in subtropical regions, and therefore, these results are not necessarily relevant to the tropics in general or Indonesia in particular (Wibisono & Setiawan, 2015).

Recently, some researchers around the world have endeavored to investigate proper PV module orientations and slope angles in their areas. In Tabbas, Iran, a new model for predicting the diffuse component of solar radiation was proposed. The model was processed using MATLAB to determine the yearly optimum tilt angle, with the results showing the optimum tilt to be around 32° (Khorasanizadeh et al., 2014). Similar research related to the proper tilt angle for solar collectors was conducted in South Africa (Le Roux, 2016). By analyzing solar insulation data from the Southern African Universities Radiometric Network (SAURAN), the proper tilt angle could be investigated, with the result that the optimum tilt angles are within 2.6° of the latitude, with the exception of Graaff-Reinet (within 3.5°), Vanrhynsdorp (within 4.6°) and Stellenbosch (within 6.9°) (Le Roux, 2016).

Other than utilizing the appropriate PV module tilt angle, choosing the proper solar module is also important for optimizing solar power plants in Indonesia. Due to its location in the tropics, Indonesia has characteristically high temperatures, and solar panel performance is strongly affected by temperature. Therefore, the proper PV type can be determined by considering its installation location. Figure 1 shows PV characteristics at various temperatures (Pukhrem, 2013). It can be seen that an increase of PV temperature can make PV open-circuit voltage decrease. Additionally, it makes the short circuit current of PV slightly increase. As a result, PV produces less electricity in higher temperature conditions (Pukhrem, 2013).

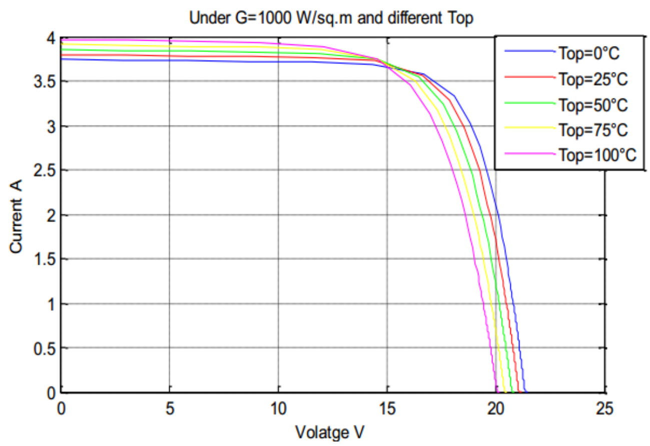

Figure 1 PV I-V characteristics at various temperatures

The main purpose of this study is to investigate solar panel optimization using a system advisor model (SAM). Optimization focuses on two main steps, evaluation of solar panel tilt angle and a choice of silicon monocrystalline, silicon polycrystalline or thin film PV. Results are given for optimizing PV power plants utilizing optimum tilt angles and the proper PV type for different cities in Indonesia.

2. SOLAR RADIATION AND BASIC PV POWER OUTPUT

The distance between the center of the earth and the sun is approximately 1.495×10^{11} m, and solar radiation reaches the earth's surface through a process of radiation. The solar radiation outside the earth's atmosphere is called the solar constant (G_{sc}), which is 1,367 W/m^2 (Duffie & Beckman, 1980).

2.1. The Geometric Relationship of Solar Radiation to the Earth's Surface

The geometric relationship between beam radiation and the earth's surface is shown in Figure 2 (Duffie & Beckman, 1980). The slope angle (*β)* is the angle between the plane of the surface and the horizontal. The deviation of the projection on a horizontal plane from the normal angle of the surface from the local meridian is called the surface azimuth angle (γ), whereas the angular displacement from south of the projection of beam radiation on the horizontal plane is called the solar azimuth angle (γ_s). The zenith angle (θ_z) is the angle between the vertical surface and the line to the sun; that is, the angle of incidence of beam radiation on a horizontal surface. The solar altitude angle (α_s) is the angle between the horizontal surface and the line to the sun, or the complement of the zenith angle.

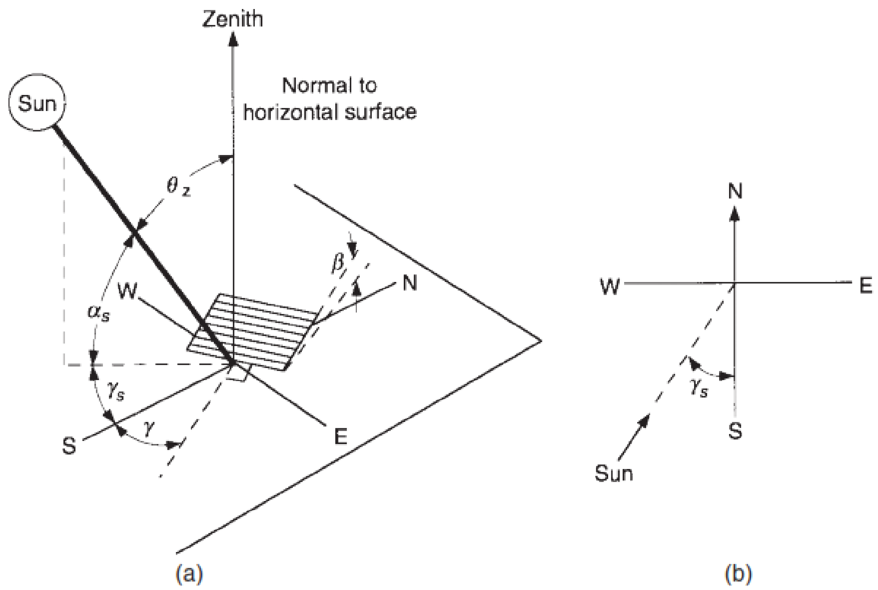

Figure 2 (a) Zenith angle, slope, surface azimuth angle and solar azimuth angle for a tilted surface; (b) Plan view showing solar azimuth angle

2.2. Incidence of Solar Radiation on a PV Surface

The total solar radiation received by a PV surface consists of three main parts. Aside from solar beam radiation (H_B), which is directly absorbed by a PV surface, there is also reflected radiation (H_R) and diffuse radiation (H_D). Diffuse radiation is the result of the intermingling of solar radiation as it passes through the earth's atmosphere, and reflected radiation comes from the earth's surface reflecting solar radiation. The effect of the inclination of solar radiation received by solar panels is expressed in the form of R_B (surface inclination to beam radiation ratio), R_D (surface inclination to diffuse radiation ratio) and R_R (surface inclination to reflected radiation ratio) (Duffie & Beckman, 1980).

The formulation of R_B is unique and depends upon the PV module installation location. For applications in the Northern Hemisphere, where the PV surface faces the equator and $\Upsilon = 0°$, R_B is expressed in Equation 1.

$$R_B = \frac{\cos(\emptyset - \beta)\, cos\delta\ sin\omega_s' + \left(\frac{\pi}{180}\right)\omega_s' \sin(\emptyset - \beta) \sin\delta}{cos\emptyset\ cos\delta\ sin\omega_s' + \left(\frac{\pi}{180}\right)\omega_s' \sin\emptyset\ \sin\delta} \tag{1}$$

For PV module installations in the Southern Hemisphere, where the PV surface faces the equator and $\Upsilon = 180^o$, R_B is formulated in Equation 2.

$$R_B = \frac{\cos(\emptyset + \beta)\, cos\delta\ sin\omega_s' + \left(\frac{\pi}{180}\right)\omega_s' \sin(\emptyset + \beta) \sin\delta}{cos\emptyset\ cos\delta\ sin\omega_s' + \left(\frac{\pi}{180}\right)\omega_s' \sin\emptyset\ \sin\delta} \tag{2}$$

For both Equations 1 and 2, ω_s' is expressed as:

$$\omega_s' = \begin{bmatrix} cos^{-1}(-tan\emptyset\ tan\delta) \\ cos^{-1}(-\tan(\emptyset - \beta)\ tan\ \delta) \end{bmatrix} \tag{3}$$

It can be seen that R_B is affected by several parameters, which represent the PV module site characteristics and the PV module surface slope angle. Therefore, it can be concluded that the amount of solar radiation absorbed by a PV surface depend on the installation location and tilt angle. On the other hand, R_B, R_D and R_R do not depend on the installation location of a PV surface. The values of R_D and R_R are defined by Equations 4 and 5, respectively.

$$R_D = \frac{1 + cos\beta}{2} \tag{4}$$

$$R_R = \frac{\rho 1(1 - cos\beta)}{2} \tag{5}$$

As a result, the total solar radiation received by a PV surface can be determined by Equation 6 (Duffie & Beckman, 1980).

$$H_T = H_B R_B + H_D R_{D+} H_R R_R \tag{6}$$

2.3. PV Module Output Power and Annual Energy Production

Equation 7 shows that, as a device that converts solar energy directly into electricity, a PV panel's output is strongly affected by the amount of solar radiation it receives. As the total solar radiation received by a PV module nears $H_{T,STC}$ (1,000 W/m^2), the PV module output power will reach to nearly its rated power. Furthermore, the PV dating factor and the cell temperature also affect power output such that as the temperature increases, the power output decreases due to the characteristics of PV cells, which is represented as a PV temperature coefficient of power (HOMER, 2016).

$$P_{PV} = P_{RPV} \frac{H_T}{H_{T,STC}} [1 + \alpha_P(T_C - T_{C,STC}) \tag{7}$$

$$E_P = P_{RPV} Hr_{day} \tag{8}$$

The electricity generated by a PV panel can be approximated by using Equation 8 (Morcillo-Herrera et al., 2015), where the amount of energy is equal to the rated power of a PV panel multiplied by daylight hours. Daylight hours can be defined as hours during which the solar radiation is at a maximum, or equal to $H_{T,STC}$. As mentioned previously, the solar radiation that is received by a PV panel at any particular coordinate is affected by the PV panel installation slope. The proper tilt angle can maximize the solar radiation absorbed by a PV panel, allowing the PV panel to operate at close to its rated power. As a result, the daylight hours can be longer and the energy produced by the PV panel greater.

3. METHODOLOGY

In this study, the optimum tilt angles for PV panels in three different cities in Indonesia were determined. The cities chosen were Jakarta (6.1745° S, 106.8227° E), Makassar (5.1477° S, 119.4327° E) and Jayapura (2.5916° S, 140.6690° E), representing the west of Indonesia, middle of Indonesia and east of Indonesia, respectively. With an optimum tilt angle, a PV surface can absorb much more solar radiation, and as a result, it can produce more electricity. SAM software was used to simulate PV module energy production in these areas. The simulation employed various data describing the solar resources and temperatures at a particular location for a period of one year. While both technical and economic simulations of a PV power plant can be conducted for up to 25 years of the project's lifetime, in this research, the simulations were limited to only the technical aspects and only the first year of a project's lifetime.

The optimum PV panel tilt angle can be obtained by varying the PV panel slope from 0° to 90° in steps of 1°. For the first simulation, the polycrystalline PV module was utilized. The PV module specifications used in this research are presented in Table 2.

Table 2 Electrical information of the PV modules

PV Module	Mono PV	Poly PV	Thin Film PV
Maximum Power (P_{MP})	125 W	124.915 W	125.08 W
Max Power Voltage (V_{MP})	29.1 V	41.5 V	17.0 V
Max Power Current (I_{MP})	4.3 A	3.0 A	7.4 A
Open-Circuit Voltage (V_{OC})	36.6 V	55.2 V	21.0 V
Short Circuit Current (I_{SC})	4.74 A	3.4 A	8.2 A
V_{OC} Temperature Coefficient	-0.369%/^{o}C	-0.358%/^{o}C	-0.33%/^{o}C
P_{MP} Temperature Coefficient	-0.5%/^{o}C	-0.47%/^{o}C	-0.35%/^{o}C

After the proper PV surface angle has been investigated, simulations were also conducted to verify PV module types, such as monocrystalline or thin film, to determine the best PV module by also searching the value of a PV module's maximum annual electricity production. Indonesia is located in a tropical region and has relatively high temperatures. Hence, the PV module that has the best performance in high-temperature conditions is proper for Indonesia.

The PV module with the best performance would be determined using 5 kW_{DC} power plant systems in each of the cities. SAM was used to simulate the annual energy production of three different PV modules with the same capacity of 5 kW_{DC} and optimum tilt angles that were determined in the first step. The types of PV modules were monocrystalline, polycrystalline and thin film, each with a power capacity of 125 W_P.

The PV module with the largest annual energy production was chosen as the best PV module for Indonesia. The best PV module can properly adapt to the thermal conditions of Indonesia, and therefore, it can yield the optimum energy. The electrical information of the monocrystalline, polycrystalline and thin film PV modules is shown in Table 2.

4. RESULTS AND DISCUSSION

4.1. Optimum PV Panel Tilt Angle

This simulation was done using SAM on three different areas of Indonesia with 125 W_P polycrystalline PV modules having a total capacity of 5 $kW_{DC.}$ The simulation results with different PV panel tilt angles are shown in Table 4. Generally, Jayapura has the largest annual PV module energy production. According to the SAM simulation, the available solar radiation in Jayapura is the highest, with a value of 4,706 kWh/m^2/d, followed by Makassar and Jakarta, with values of 4,351 kWh^2/m/d and 4,189 kWh/m^2/d, respectively.

Figures 3, 4 and 5 show that the effects of variation in a PV panel's tilt angle on the PV module's annual energy production has the same data pattern in all three areas. As the tilt angle increases, a PV module's annual energy production also increases until it reaches its peak. The curve's peak represents the maximum energy production and the optimum PV panel tilt angle (β_{Opt}). Jakarta and Makassar have a maximum PV module annual energy production of 6,281 kWh and 6,437 kWh, respectively with a β_{Opt} of 11^o, and Jayapura has a maximum PV module annual energy production of 6,577 kWh with a β_{Opt} of 6^o.

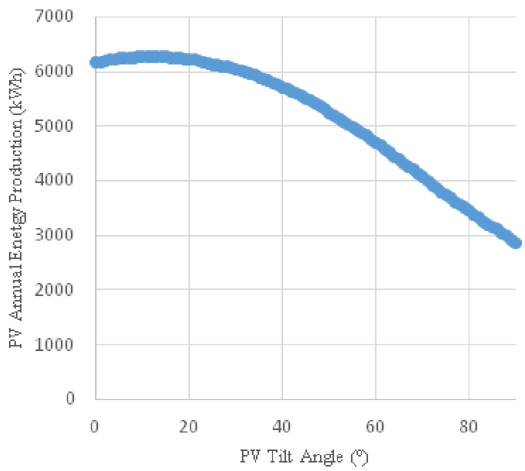

Figure 3 PV module tilt angle variation vs. PV module annual energy production in Jakarta

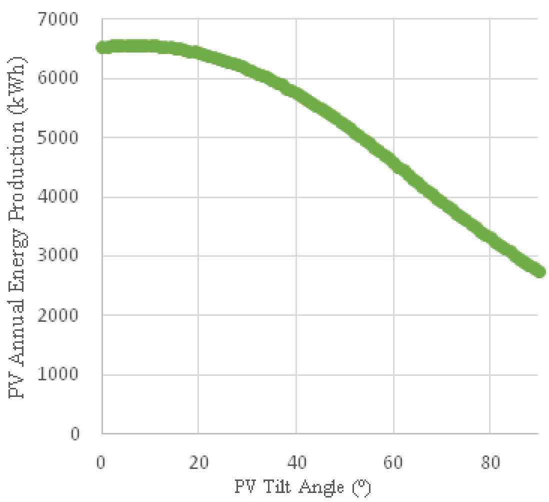

Figure 4 PV module tilt angle variation vs. PV module annual energy production in Jayapura

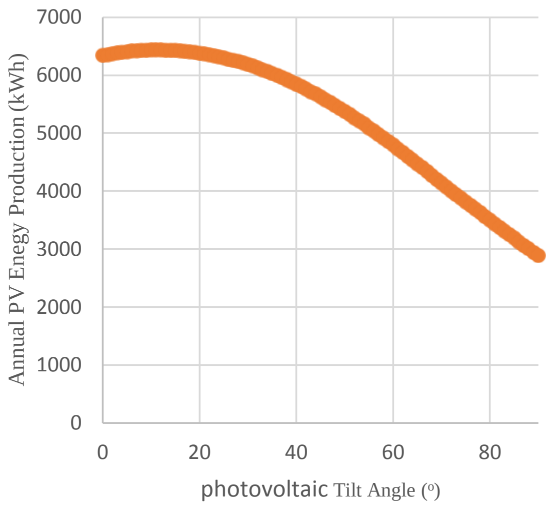

Figure 5 PV module tilt angle variation vs. PV module annual energy production in Makassar

The simulations show that the optimum tilt angle is relatively close to the latitude coordinate of the research areas, and Makassar and Jakarta have similar optimum slope angles because they have slightly similar latitude coordinates. On the other hand, Jayapura has a lower optimum tilt angle than the other research areas because its latitudinal angle is also lower than Makassar and Jayapura.

The longitude coordinate does not affect the optimum tilt angle according to our simulation. The optimum tilt angle of Makassar and Jakarta is the same although their longitude coordinates are different. Soulayman and Hammoud (2016), and Darhmaoui and Lahjouji (2013) also have stated that the optimum tilt angle is a function of the latitude coordinate. Soulayman and Hammoud (2016) suggested that the annual $\beta_{Opt}= 0.916\emptyset + 1.171°$, whereas Darhmaoui and Lahjouji (2013) suggested the annual $\beta_{Opt}= 1.253510\emptyset - 0.00728944\emptyset^2$. Both studies reported that the latitude coordinate strongly affected the optimum tilt angle and that the optimum tilt angle is relatively close to the latitude coordinate.

The optimum PV module tilt angle recommendations shown in Table 1 were also used for the research areas. Using the latitude coordinates of the study areas, the optimum PV module tilt angles and annual PV module energy production based on the recommendation in Table 1 were also obtained through SAM simulation, and the results are shown in Table 3.

Table 3 PV module annual energy production in Jakarta, Jayapura and Makassar

City	Optimum Tilt Angle Recommendations	Optimum Tilt Angle (°)	PV Annual Energy (kWh)
Jakarta	Garg (1982)	21	6,222
	Lunde (1980)	21	6,222
	Löf & Tybout (1973)	16	6,269
	Chinnery (1971)	16	6,269
Makassar	Garg (1982)	20	6,427
	Lunde (1980)	20	6,427
	Löf & Tybout (1973)	15	6,382
	Chinnery (1971)	15	6,382
Jayapura	Garg (1982)	17	6,493
	Lunde (1980)	17	6,493
	Löf & Tybout (1973)	12	6,553
	Chinnery (1971)	12	6,553

According to Table 3, there are some energy losses if the recommendations are used. For example, in Jakarta, with a PV module tilt angle of 11°, a 5 kW_{DC} PV power plant produces 0.19% and 0.9% more electricity when compared to Garg's (1982) and Chinnery's (1971) recommendations, respectively. Similar results were achieved for Makassar and Jayapura.

Therefore, based on the previous research in addition to this study, it can be concluded that because Indonesia is located at a low latitude, in order to produce the optimum annual energy production, a PV module should be installed at a relatively low slope angle (β).

4.2. PV Module Annual Energy Production Comparison

Simulations of annual energy production by the three different types of PV modules were done using SAM with a total PV module capacity of 5 kW_{DC} and the optimum tilt angles obtained in the previous section. Table 4 presents the annual energy production of polycrystalline, monocrystalline and thin film PV modules in the research cities.

Table 4 PV module annual energy production on Jakarta, Jayapura and Makassar

City	Annual Energy Production of Polycrystalline PV	Annual Energy Production of Monocrystalline PV	Annual Energy Production of Thin Film PV
Jakarta	6,281 kWh	6,265 kWh	6,836 kWh
Jayapura	6,577 kWh	6,561 kWh	7,232 kWh
Makassar	6,437 kWh	6,402 kWh	7,004 kWh

In each of the different PV modules, Jayapura showed the greatest annual PV module energy production because Jayapura has more solar radiation potential than Jakarta and Makassar. It is noteworthy that thin film is the best PV module, showing the greatest annual energy production of 6,836 kWh, 7,232 kWh and 7,004 kWh in Jakarta, Jayapura and Makassar, respectively. Due to its power temperature coefficient, thin film PV modules have better performance in our simulation than crystalline PV modules. Thin film PV modules have the smallest power temperature coefficient with a value of -0.35%/^{o}C. On the other hand, monocrystalline and polycrystalline PV modules have temperature coefficients of -0.5%/^{o}C and -0.47%/^{o}C, respectively. Therefore, the thin film PV module could operate close to its standard test conditions (STC) even though a PV cell's temperature in Indonesia is significantly different than the STC temperature. Furthermore, with a smaller power temperature coefficient, thin film PV modules produced more energy than the monocrystalline PV module in all cities.

5. CONCLUSION

The results of this research can be used as a reference for optimizing PV power plants in Indonesia. According to the simulation results, Jakarta, Makassar and Jayapura have optimum PV panel tilt angles of 11^o, 11^o and 6^o, respectively, and we recommend the tilt angle that should be implemented at the research areas. In general, it can be concluded that Indonesia has relatively low PV panel tilt angles necessary for producing the optimum annual energy production. The simulation results also showed that a thin film PV module has the best performance when compared to crystalline PV modules due to thin film PV's temperature coefficient, which is relatively small compared to other PV modules. Therefore, thin film PV modules can operate close to their STC despite the fact that a PV cell's temperature in Indonesia is significantly different than its STC temperature. As a result, thin film is the best PV module to use for power plant applications in Indonesia.

6. NOMENCLATURE

H_B : Beam Radiation (W/m^2)
HD : Diffuse Radiation (W/m2)
HR : Reflected Radiation (W/m2)
RB : Surface inclination ratio toward beam radiation
RD : Surface inclination ratio toward diffuse radiation
RR : Surface inclination ratio toward reflected radiation
$\emptyset$: Latitude (o)
θz : Zenith angle (θz)
αs : Solar altitude angle (αs)
β : PV slope angle (o)
β_{Opt} : PV optimum slope angle (o)
δ : Declination angle (o)
ρ : Albedo of ground coefficient

ω_s' : Hour angle of sunset (rad)
P_{PV} : Rated capacity of the PV array (W)
f_{PV} : PV derating factor (%)
H_T : Solar radiation on the PV array in the current time step (W/m2)
$H_{T,STC}$: Solar radiation on the PV array in STC (1,000 W/m2)
α_P : Temperature coefficient of power (%/°C)
$T_{C,STC}$: PV cell temperature in STC (°C)
T_C : PV cell temperature in the current time step (°C)

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