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Estimation of clear sky global solar irradiance as potential of electrical power generation of photovoltaic module based on latitude angle in semarang, Indonesia

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Abstract
The data of solar irradiance is very important to give information that one area is suitable or not to develop a photovoltaic (PV) power generation. Normally, the data of solar irradiance is recorded by government weather station. But some time, it is due to the limitation of equipment installation, financial support or error reading, thus the data of solar irradiance is missing. This paper presents an estimation of clear sky solar irradiance as potential of electrical power generation in Semarang, Indonesia. A mathematical modeling is applied to obtain the beam, diffuse, reflected and clear sky global solar irradiance using Matlab software. The electrical power generation of PV module is simulated based on the reported annual temperature in Semarang and the estimated beam solar irradiance. The results show that minimum, maximum and average clear sky global solar irradiance are 991.8 W/m^2, 1120 W/m^2 and 1061 W/m^2, respectively. It indicates that the sky in Semarang is very clear and suitable to be developed a PV power generation. Based on the reported annual temperature of 26.9^{0}C and the beam solar irradiance of 968.3 W/m^2 in Semarang, if 250 W YGE PV module is simulated using PSpice, thus it will generate the electrical power of 243.2 W. It has dimension of 1.65 m x 0.99 m or 1.64 m^2. An area of 1 km^2 in Semarang can be installed around 610,000 units of 250 W YGE PV modules. The total of 250 W YGE PV modules will generate the electrical power of 148.352 MW.

Keywords: solar irradiance; electric power; photovoltaic module

1. Introduction
The performance of a photovoltaic (PV) depends on the amount of solar irradiance reaching the surface of the PV module, if the solar irradiance decreases or increases then the performance of PV module will decrease or increase, respectively [1]. The maximum performance of PV module can be reached when the solar irradiance of 1000 W/m^2 and the surface temperature of PV module is 25 ^{0}C. But this real condition is difficult to be achieved by PV module. In the real condition will be obtained that the increasing of solar irradiance causes the increasing of temperature. The increasing of temperature above 25 ^{0}C will affect the decreasing of PV module performance (it is below the nominal performance of PV module following the data sheet). For this reason, an evaluation of PV module performance should be carefully for different area and time period to reach the optimum output of PV electrical energy.
There are two type of solar related to solar power and energy, the firs is solar irradiance means solar power per area unit in W/m^2, the second is solar irradiation means solar energy per area unit in Wh/m^2. Solar irradiance is fusion process of atom in the sun. Inner layer of the sun is higher than outer layer, the radiation of outer layer spreads and penetrate the chromospheres, atmosphere and arrive the earth surface. The total solar irradiance arriving the earth surface can be called as clear sky global solar irradiance. It can be divided by three parts when arriving the photovoltaic module surface; the first is beam solar irradiance, it is defined as solar irradiance that comes from the sun and directly arrive the photovoltaic module surface, the second is diffuse solar irradiance, it is defined as solar irradiance that comes from the sun and goes to the chromospheres and atmosphere and touch the water grain or cloud in the atmosphere layer and it is reflected by them and arrive the photovoltaic module surface, the last is reflected solar irradiance, it is defined as solar irradiance that comes from the sun and arrive the earth surface and reflected to the photovoltaic module surface. A mathematical modeling of solar irradiance and tilt angle of PV module in one area has been implemented by [2] and [3]. It is applied to calculate the daily, monthly of beam, diffuse and reflected solar irradiance in the area. Also, the optimum tilt angle can be obtained by applying the mathematical modeling. The empirical correlation is applied by [4] to estimate the solar irradiance incident on horizontal surface of PV module in Saudi Arabia (Jeddah), Makkah, Sanaa (Yaman) and Hong Kong. The result shows that the PV module has been installed facing south to obtain the maximum overall electrical power of PV module for the optimum tilt angle and maximum solar irradiance throughout the year.
This paper presents a calculation of the daily, monthly solar irradiance in Semarang, Indonesia. The beam, diffuse and reflected solar irradiance are implemented by using Matlab software that they are shown in line and bar graph. The annual solar irradiance throughout the year is applied to calculate the electrical power potential of PV module using PSpice software.

2 Methodology
2.1 Latitude of Semarang
Semarang is capitol of central Java, Indonesia. It is

metropolitan city and the fifth biggest city in Indonesia after Jakarta, Surabaya, Bandung and Medan. As one of the most developing city in Java, Semarang has number of people is almost 2 millions. It has latitude of 6.58^0 N and land area of 373.67 km² as shown in Figure 1 [5, 6]. The annual temperature in Semarang is 26.9^0C [7].

Fig 1: Map of Semarang, Indonesia has latitude of 6.58^0 N and land area of 373.67 km² [5, 6]

2.2 Solar Irradiance

The power generated by PV module as in Figure 2 depends on the clear sky global solar irradiance arriving the PV module surface [8]. The position of PV module with optimum tilt angle, β should be considered to obtain the maximum clear sky global solar irradiance and the maximum overall power of PV module. When some PV modules are arranged in one area, thus the module row distance, *d* should be considered well. The consideration based on the some factor, they are shadow and also air flow as natural cooling system to reduce the surface temperature of PV modules. The total clear sky global solar irradiance, I_{tt} is summation of beam solar irradiance, I_{bt} diffuses solar irradiance, I_{bt} and reflected solar irradiance, I_{rt}. The total clear sky global solar irradiance on tilt angle of PV module is given by [9].

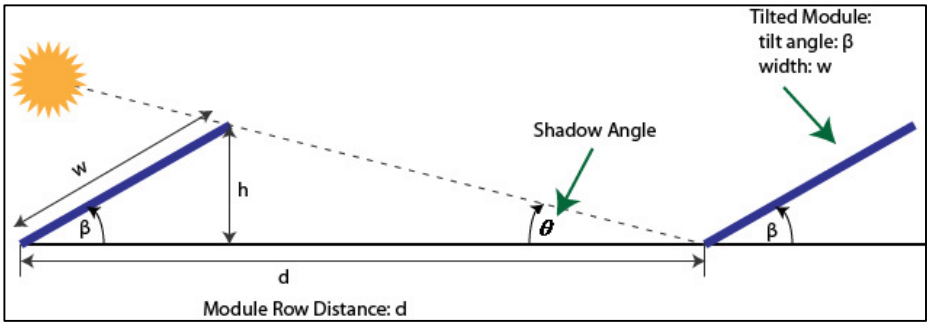

Fig 2: Total clear sky global solar irradiance of optimum tilt angle of PV module [8]

$$I_{tt} = I_{bt} + I_{dt} + I_{rt} \quad (1)$$

$$I_{bt} = I_b \cos\theta \quad (2)$$

where I_b is the beam portion of the irradiance arriving the earth surface, it is given by

$$I_b = Ae^{-km} \quad (3)$$

where A is an "apparent" extraterrestrial flux, and k is a called the optical depth and dimensionless factor. They are given by

$$A = 1160 + 75 \sin\left[\frac{360}{365}(n - 275)\right] \quad (4)$$

$$k = 0.174 + 0.035 \sin\left[\frac{360}{365}(n - 100)\right] \quad (5)$$

The air mass ratio m is given by

$$m = \frac{1}{\sin\beta} \quad (6)$$

$$I_{dt} = CI_b\left(\frac{1 + \cos\Sigma}{2}\right) \quad (7)$$

where C is a sky diffuse factor and a approximation value is stated below :

$$C = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right] \quad (8)$$

$$I_{rt} = \rho I_b(\sin\beta + C)\left(\frac{1 - \cos\Sigma}{2}\right) \quad (9)$$

Where ρ is a reflectance and depends on the earth surface.

2.3 Mathematical Modeling of PV Module

The most popular photovoltaic module is a particular case of a series string of solar cells. In terrestrial application the PV standard modules are composed of a number solar cells connected series. The number is usually 33 to 36 but different associations are also available. The PV module characteristic is the result of the voltage scaling of the $I(V)$ characteristic of a single solar cell. Consider the $I(V)$ characteristic of a single solar [10, 11].

$$I = I_L - I_0\left(e^{\frac{V+IR_s}{nV_T}} - 1\right) - I_{02}\left(e^{\frac{V+IR_s}{2V_T}} - 1\right) - \frac{V+IR_s}{R_{sh}} \quad (10)$$

250 W YGE PV module performance in Semarang is simulated using PSpice software based on the calculated annual clear sky global solar irradiance, It has dimension 1.65 m x 0.99 m and its electrical parameters as shown in Table 1 [12].

Table 1: Electrical parameters at Standard Test Conditions (STC)

Parameters	
Power output, P_{max} (watt)	250
Efficiency, η_{pv} (%)	15.3
Voltage at P_{max} (volt)	30.4
Current at P_{max} (ampere)	8.24
Open circuit voltage, V_{out} (volt)	38.4
Short circuit current, I_{sc} (ampere)	8.79

3 Results and Discussion

3.1 Solar Irradiance

Figure 3 and Figure 4 show the daily and monthly beam, diffuse, reflected and clear sky global solar irradiance throughout the year in Semarang. The minimum, maximum and average clear sky global solar irradiance are 991.8 W/m^2, 1120 W/m^2 and 1061 W/m^2, respectively. It is summation of beam, diffuse and reflected solar irradiance. The solar irradiance that gives the highest contribution is the beam solar irradiance. It is due to the beam solar irradiance goes out the sun and penetrates the chromospheres, atmosphere and directly arrive the object on earth surface. There is no barrier material when the beam solar irradiance arrive the object on earth surface. The minimum, maximum and average beam solar irradiance are 877 W/m^2, 1052 W/m^2 and 968.3 W/m^2, respectively. The second contribution of solar irradiance is diffuse solar irradiance. The minimum, maximum and average diffuse solar irradiance are 55.39 W/m^2, 115.9 W/m^2 and 88.21 W/m^2, respectively. The third contribution of solar irradiance is reflected solar irradiance. The minimum, maximum and average reflected solar irradiance are 0.3 W/m^2, 12.7 W/m^2 and 4.7 W/m^2, respectively.

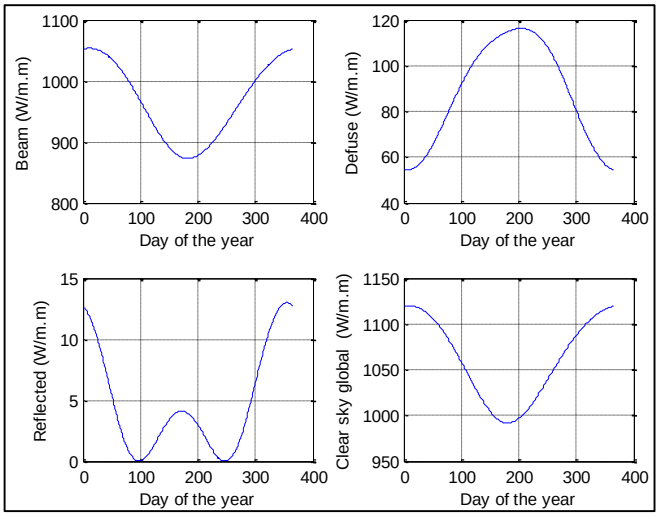

Fig 3: Solar irradiance throughout the year in Semarang

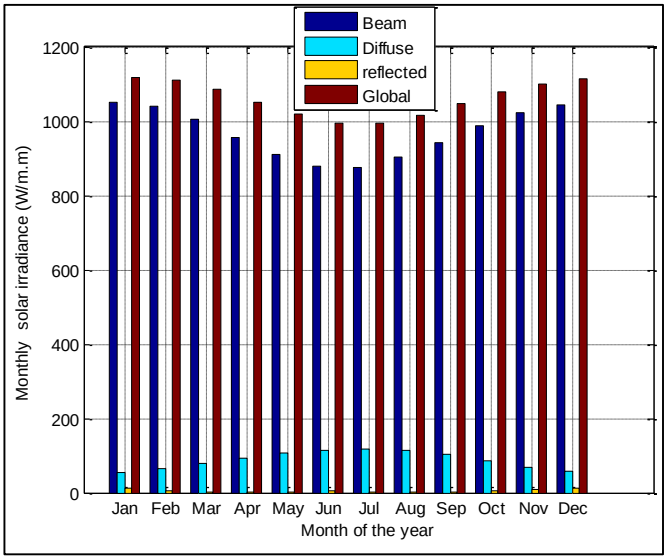

Fig 4: Monthly beam, diffuse, reflected and clear sky global solar irradiance throughout the year in Semarang

3.2 PV Module Performance

3.2.1 Validation of the Mathematical Modeling Using PSpice

The mathematical modeling of PV module performance is validated using PSpice software, the data of PV module as shown in Table 1 is simulated for condition of solar irradiance and temperature are 1000 W/m^2 and 25 ^{0}C, respectively. The current-voltage and power-voltage curve are shown in Figure 5 and 6.

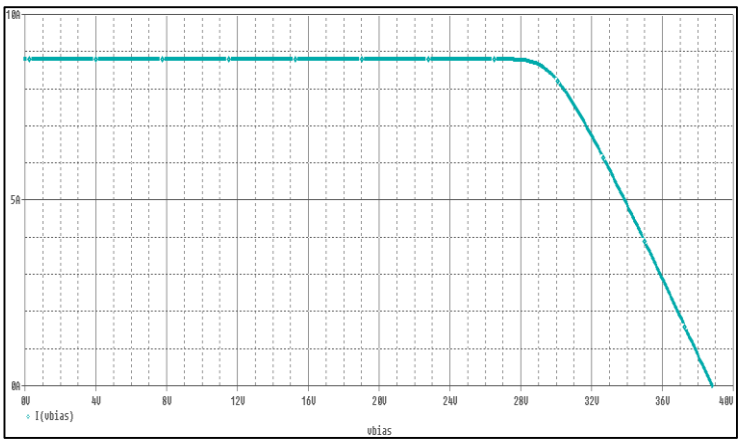

Fig 5: Current – voltage curve of 250 W YGE PV module at STC

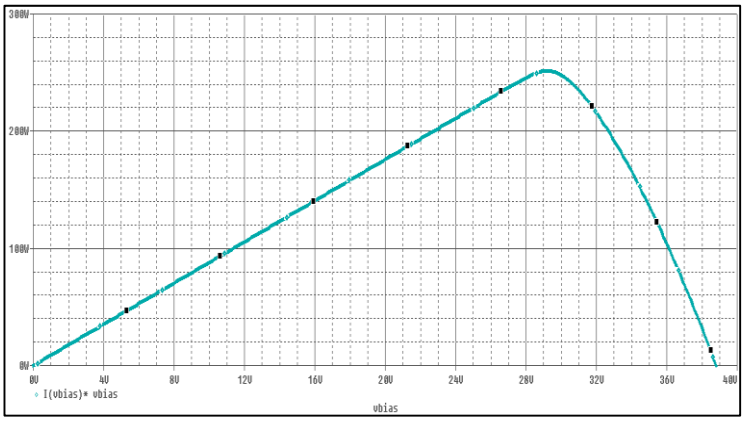

Fig 6: Power – voltage curve of 250 W YGE PV module at STC

The PV module performance for solar irradiance of 1000 W/m^2 of and temperature of 25 ^{0}C are shown in Table 2.

Table 2: The PV module performance for 1000 W/m^2 of solar irradiance and 25 ^{0}C of temperature

Electric Characteristics	Data Sheet	Simulation
Short circuit current (A)	8.79	8.79
Open circuit voltage (V)	38.40	38.85
Maximum power (W)	250.00	251.18

The PV module characteristics can be validated using statistical analysis, exactly using percentage error (^{e}) [15]. A relative percentage error between -10% and +10% is considered acceptable. Based on electric characteristics as shown in Table 1, the percentage error of the short circuit current, the open circuit voltage and the maximum power are 0 %, 1.17% and 0.47 %. These percentage errors indicate that the simulation of PV module performance is considered acceptable. The positive percentage error indicates tendency under-simulate to the data sheet of PV module. The model described in this simulation is based on Standard Test Condition (STC) defined with nominal solar irradiance level 1000 W/m^2 and nominal temperature 25 ^{0}C of Air Mass (AM) 1.5 G solar spectral contents. This STC according to the electrical characteristics of a PV module from the value of the main PV magnitudes available for a commercial module: short circuit current, open circuit voltage, maximum power and the number of cells connected.

3.2.2 Electrical Power Generated by PV Module in Semarang

The electrical power generated by 250 W YGE PV module is simulated based on the reported annual temperature of 26.9^{0}C by [7] and average beam solar irradiance of 968.3 W/m^2 in Semarang. The current-voltage curve and power-voltage curve are shown in Figure 7 and Figure 8, respectively. The figures show that the short circuit current, open circuit voltage, and maximum power of 250 W YGE PV module are 8.51 A, 38.56 V and 243.2 W, respectively. 250 W YGE PV module has dimension of 1.65 m x 0.99 m or 1.64 m^2, an area of 1 km^2 in Semarang can be installed around 610,000 units of 250 W YGE PV module. The total of 250 W YGE PV modules will generate the electrical power of 148.352 MW.

The solar irradiance affects the performance of PV module. Under constant temperature, if the solar irradiance increases, thus the value of the open circuit voltage, maximum power of PV module will increase. The open circuit voltage scales logarithmically with the short circuit current which, in turn scales linearly with the solar irradiance resulting in a logarithmic dependence of the open circuit voltage with the solar irradiance. The solar irradiance effect on the electrical characteristics of PV module is much larger in the short circuit current than in the open circuit voltage.

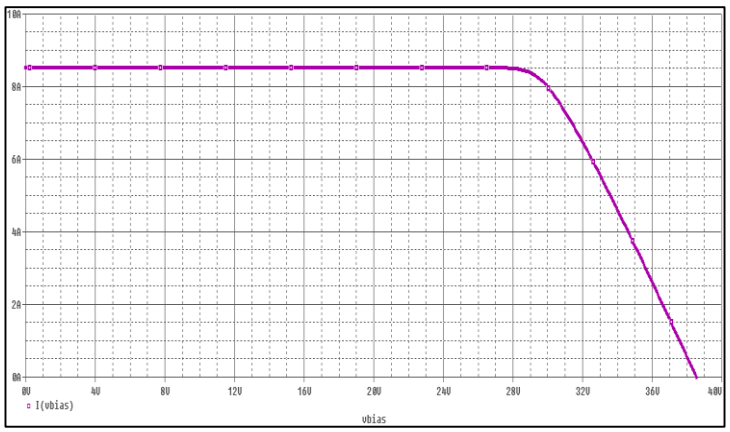

Fig 7: Current – voltage curve of 250 W YGE PV module at average clear sky global solar irradiance of 968.3 W/m^2 and annual temperature of 26.9 ^{0}C in Semarang

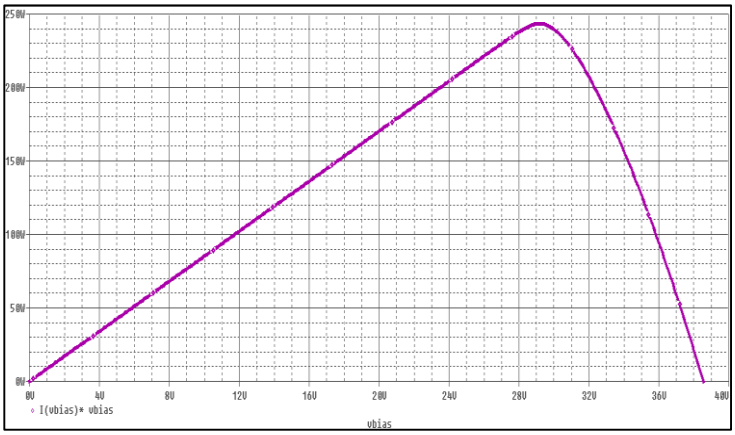

Fig 8: Power – voltage curve of 250 W YGE PV module at average clear sky global solar irradiance of 968.3 W/m^2 and annual temperature of 26.9 ^{0}C in Semarang

4. Conclusion

The minimum, maximum and average clear sky global solar irradiance are 991.8 W/m^2, 1120 W/m^2 and 1061 W/m^2, respectively. Based on the reported annual temperature of 26.9^{0}C and the beam solar irradiance of 968.3 W/m^2 in Semarang, if 250 W YGE PV module is simulated using PSpice, thus it will generate the electrical power of 243.2 W. It has dimension of 1.65 m x 0.99 m or 1.64 m^2. An area of 1 km^2 in Semarang can be installed around 610,000 units of 250 W YGE PV module. The total of 250 W YGE PV modules will generate the electrical power of 148.352 MW.

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