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Performance Analysis of Multi-Oriented Residential Rooftop PV System in Indonesia Towards Net Zero Emission by 2060

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ABSTRACT

Performance of 5 kWp Multi-Oriented Photovoltaic (PV) Power Plant installed in one of the houses in Jakarta, Indonesia has been obtained by evaluating the performance of the rooftop PV Power Plant system. To calculate the impact of the system on Net Zero Emissions (NZE), it is necessary to evaluate the performance to determine the quality of the installed system's performance by calculating the Performance Ratio (PR) and the Capacity Factor (CF). The data needed to calculate PR and CF consist of PV array outputs; irradiation that falls on the surface of the array, ambient temperature and PV module temperature. These data were collected for one year from January to December 2022. From the calculation, the system yields 76.07% PR, 11.13% CF, and CO_2 emissions reduction was 3,703.63 kg/year. As a comparison and reference, a PR and CF system calculation is carried out with PVSyst software which simulation results can be used to design a PV Power Plant system with the proper orientation both multi and single oriented for optimal performance. The technical quality of a good PV Power Plant system is needed to support the achievement of Indonesia's target towards NZE in 2060. The results of the study show that compared to the system PR, the performance evaluation of the PV Power Plant system based on CF systems is more appropriate to be used as a benchmark because it is more oriented to the output system which is directly proportional to the reduction of CO_2 emissions.

1. INTRODUCTION

The largest energy supply in Indonesia is currently fossil fuel, it increases high air pollution (CO_2 emissions) globally. In 2014, Indonesia's Greenhouse Gas Emissions (GHG) were recorded at 464.4 million tons of CO_2 emissions (RUEN 2017). One of the solutions to this problem is by utilizing renewable energy, namely solar energy. Solar energy is a very potential energy resource as an alternative energy that is clean and environmentally friendly.

NZE target in 2060 is very likely to be achieved by the transition of energy use from fossil-fuel to renewable energy. In the electricity sector, the first step that can be done is by the use of renewable energy with a portion of 45% total energy demand. Installation of 100 GW PV Power Plant can be done in the next 10 years and the use of rooftop PV Power Plant is 2% of the total load demand in 2025. In 2030 carbon emissions will continue to increase around 200 Mtons of CO_2 emissions as a result of coal power plants that are still under construction, however the share of coal power plants will decrease from 60% to 45%. In the next stage, the use of coal will be reduced by 12% at 2035, 4% in 2040 and replaced by 100% renewable energy in 2060 with a portion of 88% PV Power Plant. Using this energy scenario, the carbon produced by the fossil generator will decrease until it reaches NZE [1].

With an average of 4.8 kWh/m^2/day irradiation that can be used for PV Power Plant in Indonesia [2] and no additional land is needed for installation, the rooftop PV Power Plant is very potential to be used in the residential area or official industry. The rooftop PV Power Plant system has other advantages including: direct sunlight access, the roof surface is generally high positioned which will minimize shadows on the surface of the PV module, does not require additional land because the solar module is placed on the roof so the investment value of the PV Power Plant system becomes cheaper. It also does not interfere with home landscapes and hinder daily activities and close to customers as well as to electric grid, because customers are connected to the system, so there is no need for transmission or distribution system costs. The application of this technology requires several prerequisites, such as the quality of the roof structure, the orientation of the roof and the installed electricity subscription [3].

The community has great interest on using the rooftop PV Power Plant, showed by the increasing number of customers until the end of November 2022 to 6,461 customers with a total capacity installed to 77.6 MWP. There is also an average increase per month of 2.4 MW during 2022 [4]. It is also the result of support from Indonesian Government with the existence of Ministry of Energy and Mineral Resources Regulation No. 26 year 2021 regarding the rooftop PV Power Plant.

Various types of rooftop PV Power Plant systems have been designed and commercialized in the market with different characteristics and prices. Monitoring and evaluation of this kind of system becomes important because it will determine the characteristics and behavior with temperature, spectral mismatch in an outdoor environment, as well as to find out the performance of the system and anticipate the damage. Monitoring and evaluation can provide useful information about PV Power Plant system operations and can determine what needs to be done to improve its performance [5]. Improving the performance of the PV Power Plant system, supported with national and international climate change policies, PV Power Plant is expected to contribute substantially to the future global energy mix [6].

PV Power Plant performance can be evaluated by three parameters: system efficiency, energy yield and performance ratio [7]. Several PV Power Plant system performance analysis has been carried out in previous studies: PV Power Plant in Morocco [8], PV Power Plant in Brazil [9], PV Power Plant in France [10]and at locations with similar climate and humidity as Indonesia, namely in Ghana [6]. Evaluation of PV Power Plant performance in Indonesia has not been carried out, one of the studies that have been conducted regarding this is the evaluation of the grid-tied PV Power Plant system is based on energy yield [11]. Evaluation of the rooftop PV Power Plant system in this study was carried out by calculating PR, which is the ratio of the actual energy output to the theoretical energy output [12] and the system's CF which is the ratio of actual power produced by solar energy within a certain period of time and the maximum power may be produced by the system, expressed in percentage.

2. RESEARCH MATERIALS AND METHODS

2.1 System description

The 5 kWp rooftop PV Power Plant system consists of 10 units of 500 WP solar modules with an arrangement of 2 strings in parallel (Table 1). The first string consists of a series of 6 modules facing north while the second string consists of a series of 4 modules facing south. The DC current output of the two strings is connected to 4.2 kVA inverter which will produce AC electricity. The AC electricity produced by the inverter is connected to the grid through main distribution panel (Table 2). The configuration of the rooftop PV Power Plant system can be seen in Figures 1-3.

2.1.1 PV module

Table 1. PV module specification

Parameter	Value
Peak Power-$P_{Max}(W_P)$	500
Power Tolerance – P_{max}(W)	0 ~ 5
Maximum Power Voltage- V_{mpp}(V)	42.8
Maximum Power Current – I_{mpp}(I)	11.69
Open Cicuit Voltage – V_{OC}(V)	51.7
Short Circuit Current – I_{SC}(A)	12.28
Modul Efficiency ŋ – (%)	20.7

2.1.2 Inverter

Table 2. Inverter specification

Type	4200TL - X
Capacity	4.2 kW
Input Data	**Value**
Max recommended PV power plant power (STC)	5880 W
Max DC voltage	550 V
Start Voltage	100 V
MPP Work voltage range/nominal voltage	80 V-550 V/360 V
Max. input current	12.5 A/12.5 A
Max. short circuit current	16 A/16 A
Number of independent MPP Tracker/string per MPP tracker	2/1
Output AC	
Rated AC output power	4200 W
max ac apparent power	4200 VA
Max output current	19 A
AC nominal voltage	230 V (160-300 V)
AC grid frequency	50 Hz/60 Hz±5 Hz

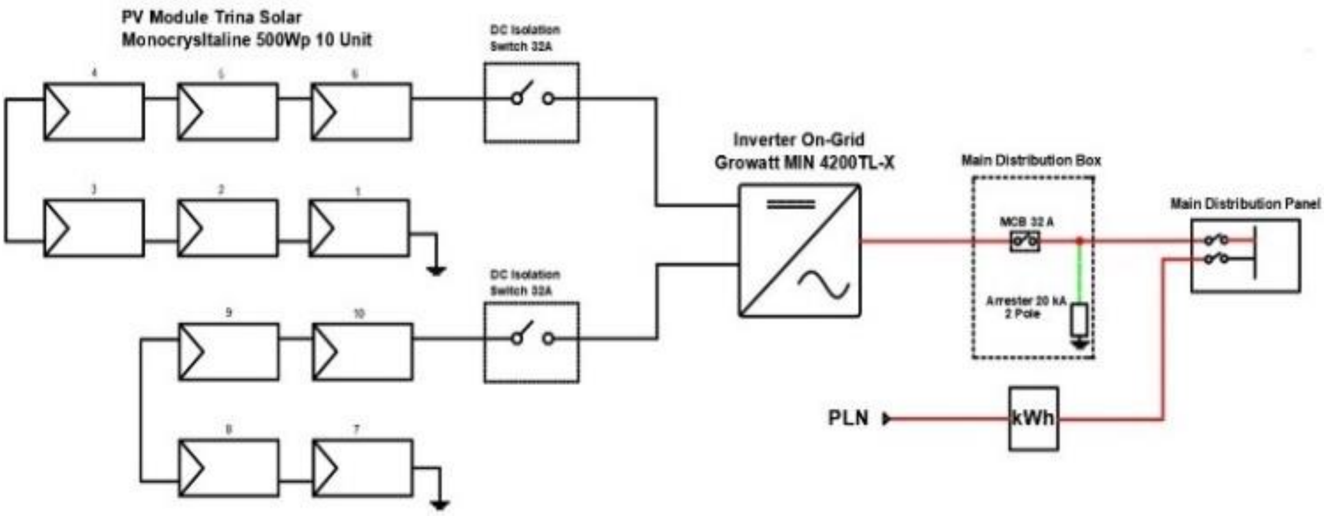

Figure 1. Single line diagram

Figure 2. Installed rooftop PV power plant system

Figure 3. Rooftop PV power plant inverter installation

2.1.3 Irradiation and ambient temperature

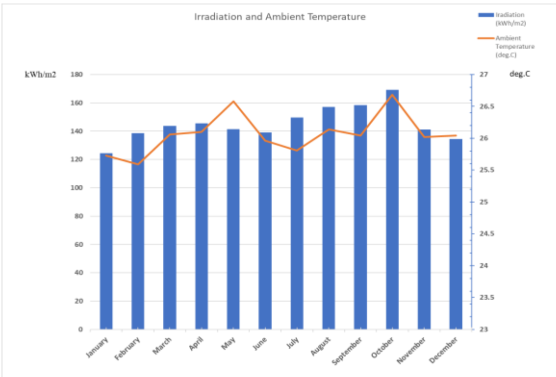

Figure 4. Monthly average irradiation and ambient temperature

Assessment and analysis of climate data in the location of the study is an important step in PV Power Plant system performance analysis. Meteorological data is obtained from various sources and software. In this study, rooftop PV Power Plant is located in a residential area in South Jakarta, with coordinates of 6.26816° S and 106.79514° E. Solar irradiation monthly average data (kWh/m^2/day) and the ambient temperature is taken from Meteonorm 8.0 in 2014 can be seen in Figure 4 above, the average ambient temperature for one year was 26.1°C, with the highest temperature occurred in October of 26.68°C. Likewise, the highest irradiation also occurred in October of 169.3 kWh/m^2, or an average of 5.5 kWh/m^2 per day.

2.2 Performance ratio

Performance ratio (PR) is quality measurement of on-grid PV Power Plant that does not depend on location, therefore it is often described as a quality factor. PR is declared in percent and describes the relationship between the actual and theoretical energy output of PV Power Plant. Thus, PR shows the actual proportion of energy available to be exported to the network after deducting power losses from conversion operations by different components such as PV modules, inverters, and cables. Weather conditions, especially ambient temperatures are also an influencing factor. PR can be defined as the final result divided by the results of the reference, as the formula below:

$$PR = \frac{Yf}{Yr} \quad (1)$$

Y_f is defined as the total AC energy produced by the PV Power Plant system for a certain time period divided by the measured output power of the installed PV Power Plant system. Y_f price is defined as:

$$\begin{gathered}\mathrm{Yf} = Eac/(Ppv\ rated)\ \text{(kWh/kWp)} \\ \mathrm{E_{AC}}\text{=AC energy output (kWh).}\end{gathered} \quad (2)$$

Y_r is the total in-plane insolation or horizontal insulation in-plane global divided by reference irradiation in standard temperature conditions that is 1 kWh/m^2. This is a measure of theoretical energy available at certain locations over a certain period of time. Reference results can be calculated by:

$$Yr = Ht/Hr \text{ (kWh/kWp)} \quad (3)$$

where, H_t=Solar radiation that falls in the field of photovoltaic array; H_r=reference irradiation [13].

2.3 Capacity factor

Capacity Factor (CF) is the ratio between the energy produced by the PV Power Plant (E_{AC}) and energy system that is assessed theoretically or the amount of energy produced by the PV Power Plant system if it is fully operated nominal power for 24 hours per day. Monthly CF can be calculated:

$$CF = \frac{Eac}{Ppv\ rated\ \times 24 \times D} \quad (4)$$

where, E_{AC} is the amount of energy of the PV Power Plant system sent to the network in a certain month, and D is the number of days in a certain month [14].

2.4 Carbon emission reduction

The amount of emission reduction is calculated from the system energy output which is then converted to CO_2 emissions reduction with a multiplier factor of 0.76 kg/kWh [15].

2.5 PVSyst

PVSyst is a PV Power Plant simulation software that can estimate the final output results of the PV Power Plant at the location and configuration of certain systems. In this study, licensed PVSyst 7 is used.

2.6 Data acquisition and processing

The measured energy is the result of all energy generated from the system installed at the measurement location during the test period [16]. After the rooftop PV Power Plant system operates for approximately one and a half years, an energy output analysis is performed, radiation measurement, system's PR calculation is based on actual data compared to the results of PVSyst 7. CF of the system is calculated using measurement data during the measurement period. This system was installed in August 2021, but data analysis was conducted from January to December 2022. Data was taken at an interval of 5 minutes. In this paper, PV Power Plant system performance evaluation method is done by comparing the PR and CF system between the measurement results on the installed system with the results of the PVSyst software simulation and further comparing it with the installation of the PV Power Plant with ideal PV module orientation (single-oriented) which is seen in the flow diagram in Figure 5.

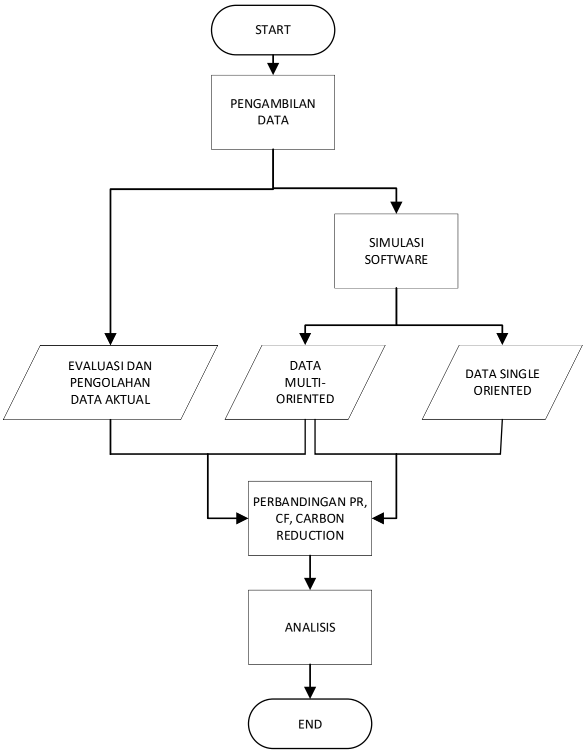

Figure 5. The 5kWp rooftop PV power plant system evaluation method

3. RESULTS AND DISCUSSION

3.1 Comparison of 5 kWp PV power plant performance from actual data and PVSyst simulation

Actual PR and CF of 5 kWp PV Power Plant System will be compared with PVSyst simulation results. The differences will be analyzed further to determine the factors that cause these differences.

Actual data on energy production and the average module temperature in the PV Power Plant in 2022 can be seen in Figure 6. The average monthly energy output was 495.61 kWh, while the average PV Power Plant module temperature was 47.17°C.

The PV Power Plant output simulation uses PVSyst software using parameters as shown in Table 1.

There is significant difference between the actual data and PVSyst simulation data (Table 4). The first difference is the irradiation data, which has almost similar pattern to Meteonorm 8.0 radiation value of 1742.7 kWh/m^2/year far exceeding the actual radiation value of 1396.5 kWh/m^2/year. This can be caused by Meteonorm limitations in predicting weather.

In PV Power Plant output, the pattern that occurs both in actual data and PVsyst simulation is identical with irradiation patterns. Whereas PR has a slightly different pattern from the irradiation and output of PV Power Plant, especially in January, where the actual data system has a large energy output but has a low PR (Figure 7). This is due to reduced system efficiency especially due to high temperatures of modules operating at high irradiation therefore resulting high temperatures as well.

In other comparative parameters, the system's CF has the same pattern as irradiation and PV Power Plant output. A slight difference that occurs is caused by differences in the number of days in each month.

Table 1. PVSyst simulation parameters

No.	Parameter	Value
1	Coordinate	-6.26° S and 106.79° E
2	Albedo	20%
3	Solar module tilt	30°
4	PV module orientation	0° & 180° (North and South facing)
5	PV module quantity	10
6	Total capacity	5 kWp
7	Inverter capacity	4.2 kVA
8	Shading	without shading
9	Soiling loss	5% [2]
10	Diode loss	0.7V (typical)
11	Mismatch loss	2% (typical)
12	LID-Light induced degradation	2% (typical)
13	Strings mismatch loss	0.1% (typical)
14	Wiring loss	0.2% (DC) dan 1.3% (AC)
15	Module quality loss	0.8% (typical)

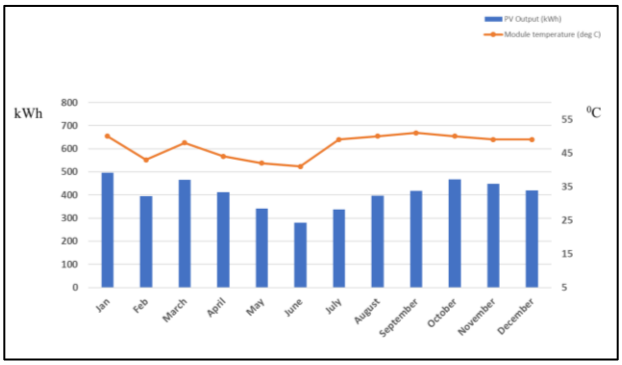

Figure 6. Energy output and average module temperature in the PV power plant

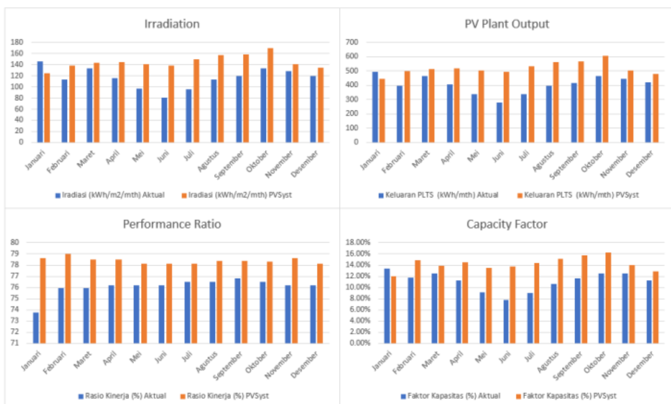

Figure 7. Output comparison, PR and CF between actual data and PVSyst simulation

Table 4. PVSyst parameters of actual calculation results and simulation results (Multi-oriented)

Month	Irradiation (kWh/m²/month)		PV Power Plant Output (kWh/month)		Performance Ratio (%)		Capacity Factor (%)	
	Actual	PVSyst	Actual	PVSyst	Actual	PVSyst	Actual	PVSyst
January	145.79	124.4	495.7	447	73.77	78.6	13.33%	12.02%
February	112.89	138.6	395.1	500	75.94	79	11.76%	14.88%
March	133.23	143.7	466.3	515	75.94	78.5	12.53%	13.84%
April	115.8	145.4	405.3	521	76.22	78.5	11.26%	14.47%
May	97.34	141.3	340.7	504	76.22	78.1	9.16%	13.55%
June	80.34	139	281.2	496	76.22	78.1	7.81%	13.78%
July	96.37	149.6	337.3	533	76.5	78.1	9.07%	14.33%
August	113.54	157.2	397.4	563	76.5	78.4	10.68%	15.13%
September	119.57	158.5	418.5	567	76.79	78.4	11.63%	15.75%
October	133.51	169.3	467.3	605	76.5	78.3	12.56%	16.26%
November	128.06	141.2	448.2	506	76.22	78.6	12.45%	14.06%
December	120.06	134.5	420.2	480	76.22	78.1	11.30%	12.90%
Total	**1396.5**	**1742.7**	**4873.2**	**6237**	-	-	-	-
Average	**116.4**	**145.2**	**406.1**	**519.8**	**76.1**	**78.4**	**11.13%**	**14.25%**

3.2 Comparison of multi and single oriented 5 kWp PV power plant performance from PVSyst simulation

Actual PR and CF of 5 kWp PV Power Plant System will be compared with PVSyst simulation results. The differences will be analyzed further to determine the factors that cause these differences.

The PV Power Plant output simulation uses PVSyst software using the same parameters in the previous section as shown in Table 1 except in the module orientation that only faces north (Azimuth=0°) in the single Oriented variant.

The simulation parameters other than solar modules orientation are the same, the irradiation of the two systems being compared is identical. The output of PV Power Plant shows a different trend, where the multi -oriented system (North and South) will give a greater output when the sun is in the South of equator (October - February), while the single oriented system (North) will give a greater output when the sun is in the north of equator (March - September). This is because the sun will be right above the equator (equinox) in March and September [17, 18].

The maximum output of the solar module will increase if the incident angle of sunlight is always perpendicular (90°) to the surface of the panel. But in reality, solar irradiation varies based on latitude and sun declination for one year. The axis of the earth's rotation has a slope of around 23.45° to the plane of the earth's orbit to the sun, with the height of the sun in the sky varies every day. To find out the maximum height of the sun (in degrees) when the sun reaches the sky (α), the following formula is used [18]:

$$\alpha = 90° - lat + \delta \text{ (Northern Hemisphere)}$$
$$\alpha = 90° + lat - \delta \text{ (Southern Hemisphere)}$$

where, lat is a latitude (coordinate) location of PV Power Plant installed in degrees and Δ is the angle of sun declination (-23.45 ° s.d. 23.45 °). If the maximum angle of the sun (α) is known, the slope of the PV module (β) can also be known. However, α alone is not enough to determine the optimal PV module orientation, the angle of the solar module must form with respect to the earth's surface (β), can be obtained by: β=90°-α.

Table 5. PVSyst simulation results in multi-oriented and single oriented

Month	Irradiation (kWh/m²/month)		PV Power Plant Output (kWh/month)		Performance Ratio (%)		Capacity Factor (%)	
	PVSyst Multi	PVSyst Single	PVSyst Multi	PVSyst Single	PVSyst Multi	PVSyst Single	PVSyst Multi	PVSyst Single
January	124.4	124.4	447	394	78.6	78.3	12.02%	10.59%
February	138.6	138.6	500	465	79	78.8	14.88%	13.84%
March	143.7	143.7	515	527	78.5	78.4	13.84%	14.17%
April	145.4	145.4	521	588	78.5	78.6	14.47%	16.33%
May	141.3	141.3	504	615	78.1	78.5	13.55%	16.53%
June	139	139	496	634	78.1	78.9	13.78%	17.61%
July	149.6	149.6	533	672	78.1	78.8	14.33%	18.06%
August	157.2	157.2	563	659	78.4	78.6	15.13%	17.72%
September	158.5	158.5	567	605	78.4	78.4	15.75%	16.81%
October	169.3	169.3	605	586	78.3	78.2	16.26%	15.75%
November	141.2	141.2	506	454	78.6	78.4	14.06%	12.61%
December	134.5	134.5	480	407	78.1	77.8	12.90%	10.94%
Total	**1742.7**	**1742.7**	**6237**	**6606**	-	-	-	-
Average	**145.2**	**145.2**	**519.8**	**550.5**	**78.4**	**78.5**	**14.25%**	**15.08%**

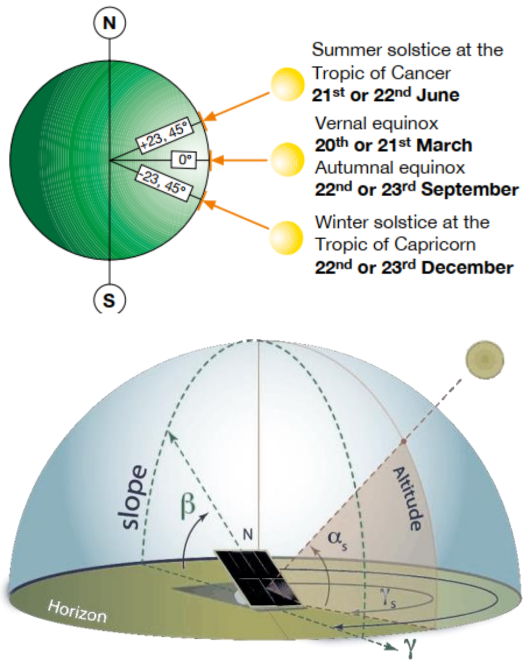

Figure 8. Declination, altitude of the sun and its relation to the tilt of the solar module [19]

With solar declination (Δ) which varies between -23.45° to 23.45° throughout the year as shown in Figure 8, so an annual average can be taken at 0°. So, the calculation will produce the module slope angle (β) as follows:

$$\beta = 90° - \alpha$$
$$\beta = 90° - (90° + lat - \delta)$$
$$\beta = -lat$$

This approach produces an optimal module tilt angle which is equivalent to the degree of latitude (coordinates) of the location of PV Power Plant which is 6.26816° S in this study. Solar module installations on the rooftop PV Power Plant may use the optimal module tilt angle or following the slope of the existing roof. The use of the ideal module tilt angle with the addition of the module mounting structure will increase the output and performance of the system at the expense of installation aesthetics. While PV module tilt angle equivalent to the existing roof slope, as in this study where the PV Power Plant system is installed with tilt angle of the existing roof slope of 30°.

Data in Table 5 shows the output of PV Power Plant equivalent to the system's CF and is not equivalent to the system's PR. This is due to the system's PR which is closely related to the efficiency of the PV Power Plant, so that the increase in PV Power Plant production due to high irradiation will reduce the efficiency of the system due to high temperatures which indirectly will decrease the PR of the system [20].

3.3 Carbon reduction

Compensation for the CO_2 emissions reduction from the 5 kWp rooftop PV Power Plant system at this location is the amount of energy output system multiplied by a factor of 0.76 kg/kWh. So that with the system's energy output as much as 4,873.2 kWh/year, will be equivalent to CO_2 emissions reduction by 3,703.63 kg/year.

CO_2 emissions reduction values above equivalent to energy output and system's CF and are not equivalent to system's PR values in which PV Power Plant PR is a parameter of PV Power Plant system efficiency.

4. CONCLUSIONS

CO_2 emissions reduction values of 3,703.63 kg/year equivalent to energy output and system's CF and are not equivalent to the system's PR where system's PR is a parameter of the PV Power Plant system efficiency. Increased PV Power Plant production due to high irradiation will reduce system efficiency due to high temperatures which will then indirectly decrease the PR of PV Power Plant system.

The right solar module orientation will directly affect the output of the PV Power Plant system which is reflected in the system's CF (not from system's PR). So, comparing to the PR, the system's CF is more suitably used as benchmark of the PV Power Plant system in supporting NZE targets in 2060. Further research is needed at other geographical locations, especially locations with different climate or coordinate (latitude) positions.

To achieve the target of installing 100 GW PV Power Plant system in the next 10 years, in addition to the technical good quality PV Power Plant, Government policies support are also needed so that the target of Indonesian Government of Net Zero Emission by 2060 can be achieved.

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