Performance analysis and evaluation of a 10.6 kWp grid-connected photovoltaic system in Serpong

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Abstract. The grid-connected Photovoltaic (PV) System was installed in the rooftop of Energi Building, PUSPIPTEK in 2017 located in Serpong, South Tangerang. The System consists of 40 modules @265 Wp, a 10 kWh battery system, and a 10250 kW grid-tie inverter. This study presents the performance analysis of the PV system based on the eight-months monitored data from July 2019 to February 2020. The evaluated parameters of the PV system include yields, performance ratio, capacity factor, energy efficiency, and average daily energy output of the PV system. The results show that the average value of the performance ratio and capacity factor during the eight-months monitored period were 82.42% and 14.07% with average values of the array ($Y_a$), final ($Y_f$) and reference ($Y_r$) yields were 3.49 kWh/kWp/d, 3.38 kWh/kWp/d, and 4.12 kWh/kWp/d, respectively. Meanwhile, the average daily energy output of the PV system during the eight-months monitored period was 36.92 kWh per day with the average values of the module ($\eta_{PV}$), system ($\eta_{sys}$), and inverter ($\eta_{inv}$) efficiency was found to be 15.29%, 14.77%, and 96.63%, respectively. Compared with previous studies in the literature, these results indicated that the grid-connected PV system installed in Energi Building PUSPIPTEK Serpong exhibited good performance.

Nomenclature

| Symbol       | Definition                                      |
|--------------|-------------------------------------------------|
| $E_{DC}$     | DC energy output, kWh                            |
| $E_{AC}$     | AC energy output, kWh                            |
| $E_{AC,m}$   | Monthly total AC energy output, kWh              |
| $Y_a$        | Array yield, kWh/kWp/day                         |
| $Y_f$        | Final yield, kWh/kWp/day                         |
| $Y_r$        | Reference yield, kWh/kWp/day                     |
| $P_{PV,rated}$ | Nominal power of PV system, kWp                  |
| $H_t$        | Global solar radiation, kWh/m\textsuperscript{2} |
| $H_R$        | Reference irradiance of the PV, kW/m\textsuperscript{2} |
| $PR$         | Performance ratio, %                             |
| $CF$         | Capacity factor, %                               |
| $CF_m$       | Monthly capacity factor, %                       |
| $\eta_{PV}$  | PV module/array efficiency, %                    |
| $\eta_{sys}$ | PV system efficiency, %                          |
| $\eta_{inv}$ | Inverter efficiency, %                           |
| $S$          | PV module/array area, m\textsuperscript{2}      |
| $L_C$        | Array capture losses, kWh/kWp/day                |
| $L_S$        | System losses, kWh/kWp/day                       |
1. Introduction
The implementation of solar photovoltaic (PV) energy in the world has developed rapidly. REN21 reported that the global capacity of the PV system reached 405 GW in 2017, and increased to 505 GW in 2018. The top five countries with the highest capacity of the PV system are China, the United States, Japan, Germany, and India with a capacity of 176.1 GW, 62.4 GW, 56 GW, 45.3 GW, and 32.9 GW, respectively [1]. The total capacity of the PV system in Indonesia reached 135 MW until 2019 with solar energy potential reached 207.8 MW. This amount is around 0.02 % of the total solar energy potential in Indonesia [2]. This capacity will be increased to pursue the target of RUEN scenario with targeted PV system installation was 6.379 MW in 2025 and 45.000 MW in 2050 [3].

Evaluation of the PV system's performance is essential to study. This study was needed to know how a good PV system works. In recent years, the performance of the PV system was evaluated and investigated in many countries in the world. The performance of a grid-connected PV system depends on various things such as cell technology, inverters, and installation configuration. It also depends on the weather parameters as global irradiance, ambient temperature, and soiling losses as analyzed by the investigator of the performance of PV grid-connected in Morocco and Brazil [4-5]. Also, the performance of various solar PV module technology in Malaysia and Peru was evaluated [6-7]. On the other hand, research on the performance of PV systems has never been found in Indonesia, especially research that assesses the parameters of PV system performance standards.

This paper assesses and analyzes the performance of a 10.6 kWp grid-connected PV rooftop system installed in the Energi Building, PUSPIPTEK located in Serpong, South Tangerang. The objective of this study is to analyze the performance parameters of the PV rooftop system located in Serpong in terms of performance parameters standard such as yields, performance ratio, capacity factor, energy efficiency, and average daily energy output. In the end, the results of this study are compared with the results of the previous study located in other countries.

2. PV System Description
2.1. Configuration of PV System
In 2017, a grid-connected PV rooftop system was installed on the top of the Energi Building, PUSPIPTEK, Serpong, South Tangerang. This rooftop PV system started to operate in December 2017. The PV system consists of 40 units of 265 Wp polycrystalline PV modules with specifications as shown in Table 1. The 20 modules connected in series to form one PV string, then 2 PV strings are connected in parallel to form a PV system with a capacity of 10.6 kWp. The configuration of the PV system is shown in Fig. 1.

| Table 1. PV module specification under standard test condition (STC) |
|---------------------------------------------------------------|
| **Parameter**        | **Specification**        |
| Nominal max. power (Pmax) | 265 W                  |
| Opt. operating voltage (Vmp) | 30.6 V               |
| Opt. operating current (Imp) | 8.66 A                |
| Open circuit voltage (Voc) | 37.7 V               |
| Short circuit current (Isc) | 9.23 A                |
| Module efficiency    | 16.47 %                |
| Operating temperature | -40 °C++80 °C          |
| Maximum system voltage | 1000 V (IEC)1000 V (UL) |
| Power tolerance      | 0 - +5 W              |
Figure 1. The configuration of 10.6 kWp grid-connected PV rooftop system in Energi Building

The PV system works at 600 VDC voltage. This system equipped with a 10 kWh battery system. The PV system connected to the Sunny Tripower TL10000 grid-tie inverter with a maximum AC power of 10250 kW to convert DC voltage, the power output from the PV module to AC voltage. The power output from the inverter connected directly to the PLN network. This system is also equipped with a weather station to record the data of solar intensity, module temperature, ambient temperature, and wind speed [8].

2.2. Weather Conditions at Location of PV System

The PV system installed on the rooftop of Energi Building, PUSPIPTEK located in Serpong with a longitude 106°38’-106°47’ E and latitude 06°13’30”-06°22’30” S. Based on the data of Photovoltaic Geographical Information System (PVGIS), the global horizontal irradiation and ambient temperature at Serpong during 2016 are shown in Figure 2.

Figure 2. Monthly irradiance and ambient temperature in Serpong during 2016

3. Performance Parameters of PV System

The performance of the PV system is evaluated according to several parameters. Based on IEC61724, standard parameters for evaluating the performance of grid-connected PV systems are energy production of the PV system (\(E_{DC}\)), array yield (\(Y_a\)), final yield (\(Y_f\)), reference yield (\(Y_r\)), performance ratio (\(PR\)), capacity factor (\(CF\)), energy efficiency and system losses [4-5].

3.1. Energy Productions

The energy production of the PV system is the energy generated by the PV array during a specific time. The amount of this energy affected by solar radiation and module temperature. In this study, the energy production calculated in average daily energy during the monitored period.
3.2. Yields
Yields of the PV system divided into array yield, final yield, and reference yield. The yields indicate the actual operation of the array relative to the nominal capacity of the PV system [5].

3.2.1. Array yield ($Y_a$)

can be interpreted as the amount of DC energy delivered by the PV system divided by the nominal power of the PV system. The $Y_a$ represents the time that the PV system must be operating with its nominal power to produce the energy generated, measured in kWh/kWp [5]. The array yield equation is given as [4-5]:

$$Y_a = \frac{E_{DC}}{P_{pv,\text{rated}}}$$  \hspace{1cm} (1)

Where $E_{DC}$ is a total of DC energy delivered by the PV system (kWh) and $P_{pv,\text{rated}}$ is the nominal power of the PV system (kWp).

3.2.2. Final yield ($Y_f$)

Final Yield is a ratio of total AC energy delivered by the PV system during a specific period and nominal power of the PV system. It exhibits how many hours a day the PV system must operate at its nominal power to generate the same amount of energy as was recorded. It measured in kWh/kWp [4]. The final yield is given as [4-5]:

$$Y_f = \frac{E_{AC}}{P_{pv,\text{rated}}}$$  \hspace{1cm} (2)

Where $E_{AC}$ is a total of AC energy generate by PV system (kWh) and $P_{pv,\text{rated}}$ is the nominal power of the PV system (kWp).

3.2.3. The reference yield

Reference yield is the comparison of the global solar radiation ($H_t$) and the PV system’s reference irradiance ($H_R$). The value of $H_R$ is 1 kW/m² [4-5]. Reference yield is a quantity of the theoretical energy available at a certain location during a specified period time, measured in kWh/kWp [5]. The reference yield equation is below:

$$Y_r = \frac{H_t}{H_R}$$ \hspace{1cm} (3)

3.3. Performance Ratio (PR)

The performance ratio (PR) represents the whole losses effect on the normal power output of a PV system. The PR values depending on module temperature, imperfect utilization of incident solar radiation also the failures of the system components. The PR value represents how close the PV system to its ideal performance during real operation. PR of the PV systems independent of location, tilt angle, orientation, and their nominal power capacity [4-5]. PR value varies from 0.6 to 0.8. It does not indicate the number of energy produced by the PV system. The PV system with high PR in low solar irradiation place may produce less energy than a PV system with low PR in a high solar irradiation location vice versa [9]. PR is defined as a ratio of final yield and reference yield [4-5]. PR also defined as the energy output $E_{AC}$ divided by the nameplate DC power $E_{DC}$ obtained in the Standard Test Condition [10]. PR obtained by the equation below

$$PR = \frac{Y_f}{Y_r} \times 100\%$$  \hspace{1cm} (4)

3.4. Capacity Factor (CF)

Capacity Factor (CF) is the comparison between real energy generated by the PV system ($E_{AC}$) and theoretically rated energy or the number of energy produced by the PV system if it is operated at full
nominal power for 24 h per day. The monthly capacity factor ($CF_m$) can be calculated using equations below

$$CF_m = \frac{E_{AC,m}}{P_{PV,\text{rated}} \times 24 \times D}$$

(5)

Where $E_{AC,m}$ is the amount of the PV system energy delivered to the grid in a certain month, and $D$ is the number of days in a certain month.

3.5. Energy Efficiency
PV system efficiencies include a PV module, system, and inverter efficiency. The equation of PV module, system, and inverter efficiency, respectively are shown below [4-5].

$$\eta_{pv} = \frac{E_{DC}}{H_t \times S} \times 100\%$$

(6)

$$\eta_{sys} = \frac{E_{AC}}{H_t \times S} \times 100\%$$

(7)

$$\eta_{inv} = \frac{E_{AC}}{E_{DC}} \times 100\%$$

(8)

3.6. Array Capture Losses ($L_c$) and System Losses ($L_s$)
Array capture losses are due to the losses on PV array [4]. While system losses are due to DC into AC conversion by inverter [11]. These losses are given as

$$L_c = Y_r - Y_a$$

(9)

$$L_s = Y_a - Y_f$$

(10)

4. Results and Discussion
Performance of a 10.6 kWp grid-connected PV system analyzed based on monitored data during eight months from July 2019 to February 2020. Data of the PV and weather station system recorded on 5 minutes intervals. The data are available on the monitoring system and able to download in CSV file. The data include PV power (DC power), inverter output power (AC power), and radiation. These data used to calculate average daily energy, yields, performance ratio, capacity factor, efficiencies, and losses. The results of DC and AC average daily energy, performance ratio, capacity factor, also module, system, and inverter efficiency are shown in Table 2.

| Months  | DC Energy ($E_{DC,d}$) kWh/day | AC Energy ($E_{AC,d}$) kWh/day | Performance Ratio ($PR$) | Capacity Factor ($CF$) | Module Efficiency ($\eta_{pv}$) | System Efficiency ($\eta_{sys}$) | Inverter Efficiency ($\eta_{inv}$) |
|---------|-------------------------------|-------------------------------|--------------------------|-------------------------|-------------------------------|-------------------------------|-------------------------------|
| Jul-19  | 38.62                         | 38.15                         | 87.58                    | 15.00                   | 15.89                         | 15.69                         | 98.77                         |
| Aug-19  | 39.09                         | 38.33                         | 82.69                    | 15.07                   | 15.12                         | 14.82                         | 97.99                         |
| Sep-19  | 42.32                         | 41.59                         | 83.59                    | 16.35                   | 15.25                         | 14.98                         | 98.23                         |
| Oct-19  | 41.21                         | 40.52                         | 81.66                    | 15.93                   | 14.88                         | 14.63                         | 98.33                         |
| Nov-19  | 41.75                         | 41.00                         | 79.45                    | 16.12                   | 14.52                         | 14.24                         | 98.07                         |
| Dec-19  | 34.52                         | 33.47                         | 80.03                    | 13.16                   | 14.76                         | 14.34                         | 96.89                         |
| Jan-20  | 29.77                         | 27.57                         | 82.50                    | 10.84                   | 15.95                         | 14.78                         | 92.74                         |
| Feb-20  | 30.28                         | 28.15                         | 83.88                    | 11.06                   | 16.23                         | 15.03                         | 92.64                         |
4.1. Energy Production

The average daily DC energy of the PV system is the amount of energy generated by the PV system on average in one day. While average daily AC energy is the amount of output energy from inverter on average in one day. The value of monthly average daily DC energy during monitored period varied from 29.77 kWh/day in January 2020 to 42.32 kWh/day in September 2019 and the value of monthly average daily AC energy of the PV system is varied from 27.57 kWh/day in January 2020 to 41.59 kWh/day in September 2019. The average daily energy during the monitored period was found 37.20 kWh/day for DC energy and 36.10 kWh/day for AC energy. The amount of energy output influenced by the decreasing number of sun hours because of the number of cloudy days during the monitored period [4]. In September 2019, the PV system produced the highest energy because it is on the dry season with high solar intensity. While in January 2020, the amount of PV system energy production is lowest among other months because the season was changed to rainy season with high-intensity rainfall. The amount of output energy also affected by global solar radiation. Figure 3 shows the trend of average daily energy following the trend of global solar radiation.

![Figure 3. Average daily energy production of a 10.6 kWp grid-connected PV rooftop system in the Energi Building and global solar radiation during September 2019](image)

The other parameter influencing PV energy production is module temperature. Figure 3 shows that the higher PV energy production on September, 11th with the close irradiance to September, 21st. This is due to the high irradiance combined with lower temperature on September, 11th compared to the high irradiance with higher temperature in September, 21st. On September, 11th, global solar radiation reached 5.80 kWh/m² and module temperature reached 43.04 °C, while in September, 21st, global solar radiation reached 5.60 kWh/m² and module temperature reached 45.16 °C. Energy production on September, 11th reached 53.20 kWh, while on September, 21st reaches 48.38 kWh. The trend of module temperature during September 2019 showed in Figure 4.
4.2. Yields

The monthly average daily array yield, final yield, and reference yield of the 10.6 kWp grid-connected PV system in the Energi Building from July 2019 to February 2020 are shown in Figure 5. The figure shows that the highest array yield and final yield happened in September 2019, while highest reference yield happened in November. The monthly average daily array yield varied from 2.80 kWh/kWp/d in January 2020 to 3.99 kWh/kWp/d in September 2019. The monthly average daily final yield varied from 2.60 kWh/kWp/d in January 2020 to 3.92 kWh/kWp/d in September 2019. The monthly average daily reference yield varied from 3.17 kWh/kWp/d in February 2020 to 4.87 kWh/kWp/d in November 2019. The array yield and final yield values in January and February are lower than other months, because of the low irradiance and the reduced sun hours in this month. The highest array and final yield recorded in September 2019, but the highest reference yield recorded in November 2019. This condition shows that in November, the PV system has higher losses so that causes the lower array and final yield in November than September. The average value of array yield, final yield, and reference yield during the eight-month monitored period are 3.51 kWh/kWp/d, 3.41 kWh/kWp/d, and 4.14 kWh/kWp/d, respectively. In previous research in Brazil, the monthly average value of array yield, final yield and reference yield during the one-year monitored period are 4.9 kWh/kWp/d, 4.6 kWh/kWp/d, and 5.6 kWh/kWp/d, respectively [5].
4.3. Performance Ratio (PR)

PR shows the ratio of the energy transferred to the grid after the reduction of energy losses such as soiling, shadowing, and thermal losses, etc. It does not indicate the number of energy generated by the PV system. Figure 6 shows that PR does not represent the number of energy production of the PV system. The PV system with high PR in low solar irradiation place may produce less energy than a PV system with low PR in a high solar irradiation location vice versa [9]. The value of PR affected by losses in conversion of solar energy into electricity (DC energy) and the losses in conversion of DC into AC energy. In this study, monthly average PR of the PV system varied from 79.45% in November 2019 to 87.58% in July 2019 with an average of 82.67%. It means that the PV system able to convert 82.67% of incident solar energy into useful electricity. While 17.33% of the solar energy concerning the PV array is not converted to electricity due to losses or component's defect. In the other study, the PR of a grid-connected PV system in China was varied from 80% to 85% [12]. While the annual average monthly PR of the PV system in Eastern India was 78% [9].

![Figure 6](image_url)

**Figure 6.** The value of Performance Ratio (PR) of a 10.6 kWp grid-connected PV rooftop system in Energi Building compared to energy production from July 2019 to February 2020

4.4. Capacity Factor (CF)

In this study, CF calculated monthly and its average during the eight-month monitored period. The monthly CF of the PV system in Serpong was varied from 10.84% in January 2020 to 16.35% in September 2019 with an average of 14.19%. This value illustrated the amount of time during a monitored period if the PV system is producing energy at its full power output. It means that the PV system capable of generating full power energy in about 34.62 days of the eight-month monitored period (July 2019-February 2020). The value of the capacity factor compared to energy production shows in Figure 7. The capacity factor of the PV system varies depending on the location and affected by solar radiation. The typical capacity factor is in the range of 0.15 to 0.4 [5]. In Morocco, the capacity factor varied from 6.55% to 21.42% [4]. In northeastern Brazil, capacity factor varied from 15.5% to 23.1% [5].
Figure 7. The value of Capacity Factor (CF) of a 10.6 kWp grid-connected PV system in Energi Building compared to energy production from July 2019 to February 2020

4.5. Energy Efficiencies
The calculated efficiencies of this PV system included module ($\eta_{PV}$), system ($\eta_{sys}$), and inverter ($\eta_{inv}$) efficiency, the results have shown in Figure 8. Module efficiency ranged from 14.52% in November 2019 to 16.23% in February 2020, system efficiency ranged from 14.24% in November 2019 to 15.69% in July 2020 and inverter efficiency ranged from 92.64% in February 2020 to 98.77% in July 2019. The average of the module, system, and inverter efficiency are 15.32%, 14.81%, and 96.71%, respectively. The module efficiency value decreased from July 2019 to November 2019, because of the dry season so that the PV system covered by dust. Whereas, the value of module efficiency increased from December 2019 to February 2020 because the dust on the PV module was swept away by rainwater that causes the PV module more efficient. The inverter efficiency tends to decrease from July 2019 to December 2019 and drastically decrease in January and February 2020. This caused by the failure of the inverter component that causes higher system losses on the inverter. The value of system efficiency influenced by module and inverter efficiency. The results show that system efficiency smoothly decreases in July until November 2019 and smoothly decreases in December 2019 until February 2020. These values are higher than the efficiency value of the grid-connected PV system in Morocco, where the lowest value of modules efficiency is 11.80% in September and the highest value is 13.22% in February, the lowest value of system efficiency is 11.41% in September and the highest value is 12.93% in February, whereas the lowest value of inverter efficiency is 96.7% in February and the highest value is 96.8% in December [4].
4.6. Losses

The losses evaluated in this study are array capture \((L_C)\) and system \((L_S)\) losses. Monthly \(Y_f\) with corresponding \(L_C\) and \(L_S\) have shown in Figure 9. The figure shows that the \(L_C\) value increased in July 2019 and reached the highest in November 2019. This increasing due to the dry season which started in July 2019 and ended in November 2019, so that dust and soiling covered the array PV during this period. In January and February 2020, high-intensity rain swept the dust and soil in the array PV, so that the array PV became clean and caused lower \(L_C\) in these months. The \(L_S\) value influences the inverter efficiency, where the higher \(L_S\) causes lower efficiency. It can be seen that in January and February 2020, the \(L_S\) reached the highest value so that caused the lower inverter efficiency in these months (see Figure 8). The \(L_C\) values of the PV system in this study varied from 0.32 kWh/kWp/d in February 2020 to 0.93 kWh/kWp/d in November 2019. The \(L_S\) values of the PV system varied from 0.04 kWh/kWp/d in July 2019 to 0.20 kWh/kWp/d in February 2020. The average \(L_C\) and \(L_S\) are 0.63 kWh/kWp and 0.10 kWh/kWp. Losses in other PV systems in Morocco have observed: the \(L_C\) varied from 0.025 kWh/kWp in February to 0.76 kWh/kWp in September. The \(L_S\) ranged from 0.14 kWh/kWp in January and 1.89 kWh/kWp in May [4].

### Figure 9. Monthly final yield \((Y_f)\) with corresponding array capture losses \((L_C)\) and system losses \((L_S)\) of the 10.6 kWp grid-connected PV system in Energi Building from July 2019 to February 2020

5. Conclusion

In this paper, the performance of a 10.6 kWp grid-connected PV rooftop system installed in the Energi Building, PUSPIOTEK Serpong, South Tangerang has been observed and evaluated. The average daily energy during the eight-months monitored period was 37.20 kWh/day for DC energy (PV output) and 36.10 kWh/day for AC energy (inverter output) with the average values of the array \((Y_a)\), final \((Y_f)\), and reference \((Y_r)\) yields were 3.51 kWh/kWp/d, 3.41 kWh/kWp/d, and 4.14 kWh/kWp/d, respectively. The average performance ratio \((PR)\) during the eight-months monitored period was found 82.67% with the average of the module \((\eta_{PV})\), system \((\eta_{sys})\), and inverter \((\eta_{inv})\) efficiency were found to be 15.32%, 14.81%, and 96.71%, respectively. Meanwhile, the average capacity factor \((CF)\) during the eight-months monitored period was about 14.19%. Compared with existing studies in the literature, these results indicated that the grid-connected PV system installed in the Energi Building, PUSPIOTEK Serpong exhibited good performance.
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