Performance Analysis of 120 kWp Grid-Connected Rooftop Solar Photovoltaic System in Central Java

Mukhamad Faeshol Umam[1], Ferry Purwo Saputro[1], Muhammad Rizqi Al Asy'ari[2], Sesi Selia[2], Amrullah Farad Sunaryo[2], Umi Yuliatin[3]

[1]*Pusat Pengembangan Sumber Daya Manusia Minyak dan Gas Bumi, Cepu*

[2]*Enerka Bhumi Pratama, Jakarta Selatan*

[3]*Politeknik Energi dan Mineral Akamigas, Cepu*

INFORMASI NASKAH

Diterima : 15 Oktober 2021
Direvisi : 16 November 2021
Disetujui : 19 November 2021
Terbit : 30 November 2021

Email korespondensi:
mukhamad.umam@esdm.go.id

Laman daring:
https://doi.org/10.37525/mz/2021-2/298

ABSTRACT

This study examines the performance of a solar power plant with a total capacity of 125 KWp, which operates for one year in Blora, Central Java. The ability of this power plant is a total of PV modules with 20 kWp, ten kWp, and five kWp capacities spread across eight locations. The annual performance of the rooftop solar power plant is measured automatically by the converter installed in each module. The resulting data from inverters are compared to the meteorological conditions from the meteorological agency. This research will investigate the influence of climate on the power generated, the efficiency of the equipment in a power plant, and the effect of pseudo motion of the sun. It was found that there were variations in energy output throughout the year, and it was concluded that the maximum annual energy was produced in July-August. In addition to weather, other factors need to be investigated further to determine the causes of variations in solar PV output.

Keywords: *solar, central java, performance*

ABSTRAK

Penelitian ini mengkaji kinerja pembangkit listrik tenaga surya dengan total kapasitas 125 KWp yang beroperasi selama satu tahun di Blora, Jawa Tengah. Kemampuan pembangkit listrik ini berupa total modul PV dengan kapasitas 20 kWp, sepuluh kWp, dan lima kWp yang tersebar di delapan lokasi. Kinerja tahunan pembangkit listrik tenaga surya atap diukur secara otomatis oleh konverter yang dipasang di setiap modul. Data yang dihasilkan dari inverter dibandingkan dengan kondisi meteorologi dari badan meteorologi. Penelitian ini akan menyelidiki pengaruh iklim terhadap daya yang dihasilkan, efisiensi peralatan pada pembangkit listrik, dan pengaruh gerak semu matahari. Ditemukan adanya variasi keluaran energi sepanjang tahun, dan disimpulkan bahwa produksi energi tahunan maksimum terjadi pada bulan Juli-Agustus. Selain cuaca, faktor lain perlu diteliti lebih lanjut untuk mengetahui penyebab variasi keluaran PV surya.

Kata Kunci: PLTS, Jawa Tengah, Kinerja

INTRODUCTION

The need for electricity in Indonesia and the world in this globalization makes the energy demand rise sharply. While many governments try to reduce fossil fuels to mitigate catastrophic climate changes, renewable energy became the first to develop energy generators. Based on Indonesian government policies, it is estimated that 40% of electricity demand will be generated from renewable energy in 2030 (Setiadi et al., 2019). From many renewable sources in Indonesia, solar energy is one of the promising renewable energy sources (Sibagariang et al., 2020). Solar energy is part of renewable energy that can reduce limited reserves of fossil-based fuels and impact greenhouse gas (GHG) emissions from the combustion process (Tarigan, 2020). Therefore, solar energy in Indonesia should be rapidly developed due to its relatively high and stable daily radiation every year and its location between the equator (Tarigan et al., 2014). Under the Ministry of Energy and Mineral Resources (ESDM), the Indonesian government has planned to develop solar energy for electricity of 6.5 GW by 2025 and 45 GW by 2050, or 22% of the solar potential of 207.9 GW (ESDM, 2016)

To date, many potential areas have been developed include on java island. The potential for solar PV on java island is still relatively high, despite being not the most significant in the country. The java island is the most populous, so that the most effective potential for rooftop solar PV to be developed. This rooftop method can be seen from the high solar PV capacity in several areas in java. The National Energy General Plan reports that Indonesia's average solar PV potential reaches 4.80 kWh/m2/day (Sukarso & Kim, 2020). Indonesia is also a tropical country, where all areas get sunshine throughout the year (Handayani & Ariyanti, 2012). Moreover, large-scale solar power plants are expected to be installed in the Java system under future grid plans (Setiadi et al., 2019). Potential areas for solar power development are Surabaya East Java (Tarigan et al., 2014), Bali (Tanoto et al., n.d.) and Central Java (Syahputra & Soesanti, 2020). The construction of power generation sources must be planned to develop solar PV power plants and possibly used for long-term investments (Quentara & Suryani, 2017). Therefore, the development of PV solar must be well prepared, starting from selecting the network installation system (Tarigan, 2020).

Further, electrical grid installation systems are classified into on-grid and off-grid systems (Hossain & Ali, 2013). An on-grid photovoltaic system was chosen for this study and has been developed to support the national electricity supply (Setiadi et al., 2019). The advantage of this application is that the on-grid solar power plant system does not have to provide sufficient electricity for the needs of the power properties as in the off-grid system (Bimantoro et al., 2019). On the other hand, off-grid mini-grid PV requires a storage system to maintain electrical supply to satisfy the demand. The off-grid solar power plant is commonly implemented in remote areas that have not received electricity from PLN (Syahputra & Soesanti, 2020).

A significant transformation is being experienced by solar PV, especially for modern power systems, such as renewable energy generation (REG), battery energy storage system (BESS), high voltage DC transmission, electric vehicles (Setiadi et al., 2019). For daily needs, a Direct current system (DC) must be converted into alternating current (AC) with an inverter (Dzulfikar & Broto, 2016). This inverter must be connected to the electrical system at home to save electricity excess electricity (Dzulfikar & Broto, 2016). Inverters are divided into inverters for off-grid solar PV systems and inverters for on-grid solar PV systems (Sasongko et al., 2021). The inverter on the connected on-grid system is usually related to the electricity distribution network, so it must have synchronization capability (phase matching) and draw power from the available electricity distribution network (Sasongko et al., 2021).

Table 1. Potential recources of solar irradiance in Java Island[1]

Province	Location	Time measurement	Elevation (m)	Slope	Azimuth	Global Irradiance (W/m^2)
Jakarta	Jakarta Utara	2005-2016	2	10	30	213.07
Banten	Tangerang	2005-2016	17	10	30	202.93
	Lebak	2005-2016	35	10	30	201.54
West Java	Bogor	2005-2016	269	10	30	198.51
	Bandung	2005-2016	718	10	30	200.75
Central Java	Semarang	2005-2016	17	10	30	215.72
Yogyakarta	Yogyakarta	2005-2016	104	10	30	216.29
East Java	Pacitan	2005-2016	75	10	30	215.76

The rooftop solar photovoltaic systems are becoming a fundamental global energy system (Sasongko et al., 2021). Rooftop PV systems are smaller than ground-mounted rooftop PV systems, systems commonly applied to the roofs of residential, commercial, or industrial building complexes (Goel, 2016). The successful implementation of rooftop solar PV systems in many countries has been influenced by technical and policy or regulatory (Tarigan, 2020). Currently, regulations for the rooftop solar PV system have been introduced (Government of Indonesia, 2018), namely the ESDM Ministerial Regulation or ESDM Regulation No 49/2018. The regulation encourages and supports users such as communities, public and commercial buildings to generate electricity by using PV systems installed in a planned manner on the roof of the building (Syanalia & Winata, 2018). The resulting energy can be exported or fed into the utility grid (Tarigan, 2020). However, the energy produced can vary depending on the size of the building and the available roof space (Syanalia & Winata, 2018). Rooftop solar PV technology can also improve decarbonization and energy security by making the most of today's public space (Syanalia & Winata, 2018)

Solar PV power is affected by Earth-Sun distance, solar declination, hour angle (ω) of sunlight, average ambient temperature, ambient temperature, rainfall, relative humidity, cloud cover, longitude, latitude, and other disturbances in space (Nasruddin et al., 2018). Thus, one of the disadvantages of solar PV systems, especially on a large scale, requires land or open space to install solar modules (Tarigan, 2020). This problem could

[1] Data from https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY

be solved by installing solar PV on the roof of the building. This installation strategy has become popular in recent years, fueled by the downward trend of PV prices and the growing market for rooftop solar PV (Abreu et al., 2019).

However, solar roof PV in urban areas with enough electricity is still less attractive in Indonesia (Tarigan et al., 2014). Also, solar power can only be used from morning to evening (Naimah et al., 2020). Hence, there is a problem regarding the timing mismatch between peak demand and rooftop PV solar energy generation (Rosyad et al., 2020). It is necessary to take additional steps to accumulate solar irradiation during sunny days and then store it in the embedded phase transition (Handayani & Ariyanti, 2012). Rooftop solar PV also can not be hindered by a higher field horizon, as it can shorten the period of the Sun (Tarigan, 2018). From some estimations, only a tiny part of solar PV can be applied to buildings (Tarigan, 2020). The feasibility of rooftop solar PV, especially for on-grid systems, can occur when the price of fuel resources decreases (Siswantoro et al., 2021). Other obstacles that can also hinder solar PV utilization include technical problems with inverters, wiring, inverters, and light ballasts (Naimah et al., 2020). Moreover, solar energy systems for distributed roofs usually have relatively small capacities (Sasongko et al., 2021). Currently, on-grid solar rooftops are not economically feasible in Indonesia as the selling price is low, and the initial investment and maintenance costs are pretty high (Siswantoro et al., 2021).

Many factors affect the application of a roof solar PV system. For instance, technical, policies, or regulatory aspects play an essential role in rooftop solar PV development (Tarigan, 2020). The Indonesian government's policy regarding the use of PV systems in rooftop buildings should be established to support the National Energy Policy by 2025, increasing the role of new and renewable energy by 36% by 2050 (Sasongko et al., 2021). In this regard, the regulation of the rooftop solar PV system has been recently introduced by the Government of Indonesia (2018), namely the Decree of Minister of Energy and Mineral Resources No. 49/2018. This regulation supports and encourages users, communities, public and commercial buildings to generate electricity using PV systems installed on the roofs of buildings (Sasongko et al., 2021). State Electricity Company (PLN) has also proposed a proposed net-metering regulation for solar PV customers. The law contains procedures for interconnecting customer electrical facilities to the PLN network (Sasongko et al., 2021). In this regulation, the customer can export excess energy generated from the PV rooftop to the grid owned by PLN (Rosyad et al., 2020). The energy produced can be exported into the utility grid (Sasongko et al., 2021). This export price can be multiplied by 35% of the retail price (Rosyad et al., 2020).

METHOD

The energy generated by a solar power generation system is influenced by many factors such as radiation effects, temperature, shade, system design, tilt angle, sunlight intensity, and other factors. This report shows the performance of solar power plants with a total capacity of 125 kWp installed on the roofs of buildings belonging to the oil and gas human resource development center spread over 8 locations with different faces but with similar slope angles. Output factors to be analyzed include total power (kW), DC voltage (V), AC voltage (V), and frequency. This data will be compared every month and against weather data from BMKG. Details of the installed solar panels are as follows:

a. Plant ID : 783458
b. Name : PLTS PPSDM MIGAS
c. Location : Central Java
d. Plant Type : Industrial Rooftop
e. The angle of Tilt : 10°
f. Constructing Cost: 1.735.138.000 IDR
g. System Type : All on Grid
h. Benchmark Price : 1467 IDR/kWh
i. Total Capacity : 125kWp
j. Time Zone : (UTC+07:00)
k. 20 kWp 3 Phase
   - Main office corridor (KB)
   - Oil Laboratory Building (LB1)
   - Electric Laboratory Building (LB3)
   - Instrumentation Lab. Building (LB2)
   - Widya Patra III Parking (WP3)
l. Ten kWp 3 phase

- Migas 1 building corridor (MG)
- Wisma 1 Parking (WS)

m. Five kWp 1 phase

- Widya Patra II Building (WP2)

The location of each solar panel is shown in Figures 1 to 8.

Figure 1. Location of KB[2]

Figure 2. Location of LB1[3]

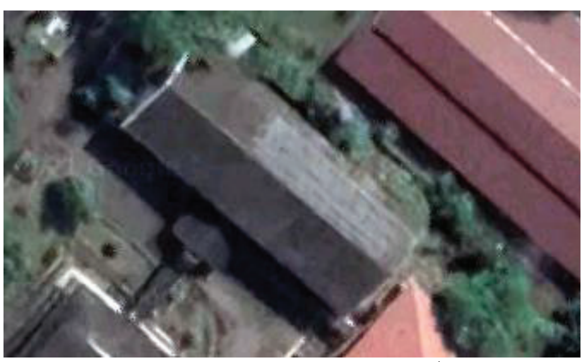

Figure 3. Location of LB2[4]

Figure 4. Location of LB3[5]

Figure 5. Location of MG[6]

Figure 6. Location of WP2[7]

Figure 7. Location of WP3[7]

[2]Courtesy of Google Maps https://www.google.com/maps/@-7.1407615,111.6003173,245m/data=!3m1!1e3
[3]Courtesy of Google Maps https://www.google.com/maps/@-7.1407615,111.6003173,245m/data=!3m1!1e3
[4]Courtesy of Google Maps https://www.google.com/maps/@-7.1407615,111.6003173,245m/data=!3m1!1e3
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[7]Courtesy of Google Maps https://www.google.com/maps/@-7.1328388,111.5947065,246m/data=!3m1!1e3
[8]Courtesy of Google Maps https://www.google.com/maps/@-7.1371988,111.6011182,245m/data=!3m1!1e3

Figure 8. Location of WS[9]

The data presented in this paper is the output data from the inverter, which is connected to the Solarman data center (Solarman, 2021) with WiFi and internet media. Data stored on Solarman servers is available in daily, weekly, monthly and yearly data. However, the unstable WiFi connection and internet network allows the data to be misleading.

The data will then be compared with the weather variation data during the test. Historical weather was also analyzed during the trial to determine how much change in weather trends in Central Java. In addition to the anticipated output differences, the uncertainty of the conditions under which the resulting data is complete or partially missing will be analyzed roughly. These data anomalies and discrepancies in meteorological data may cause errors in the measured results.

RESULT AND DISCUSSION

A. Influence of Climate on Generated Power

This research compares the inverter output data with weather (meteorological) data. This study also analyzes the relationship between climate and the performance of solar PV that is currently operating. Besides the climate effect on the daily power generated by rooftop solar PV, it is assumed that the rainfall also contributed as one factor that hinders the maximum solar PV capacity. Another factor is the shades of the cloud that make the lowest point of sunshine on certain days. It is assumed that other factors should be considered because there are many anomalies found in the field.

However, this paper will focus on weather and the power generated. The LB3's daily developed power chart is shown in Figure 10 that indicates the electrical power has decreased in performance even to the point of not producing power on certain days. On the other hand, from late December to March, the power production did not fall as in the previous month. When compared with weather data as a parameter in these months, the rainfall was also relatively high, possibly because of the season's transition.

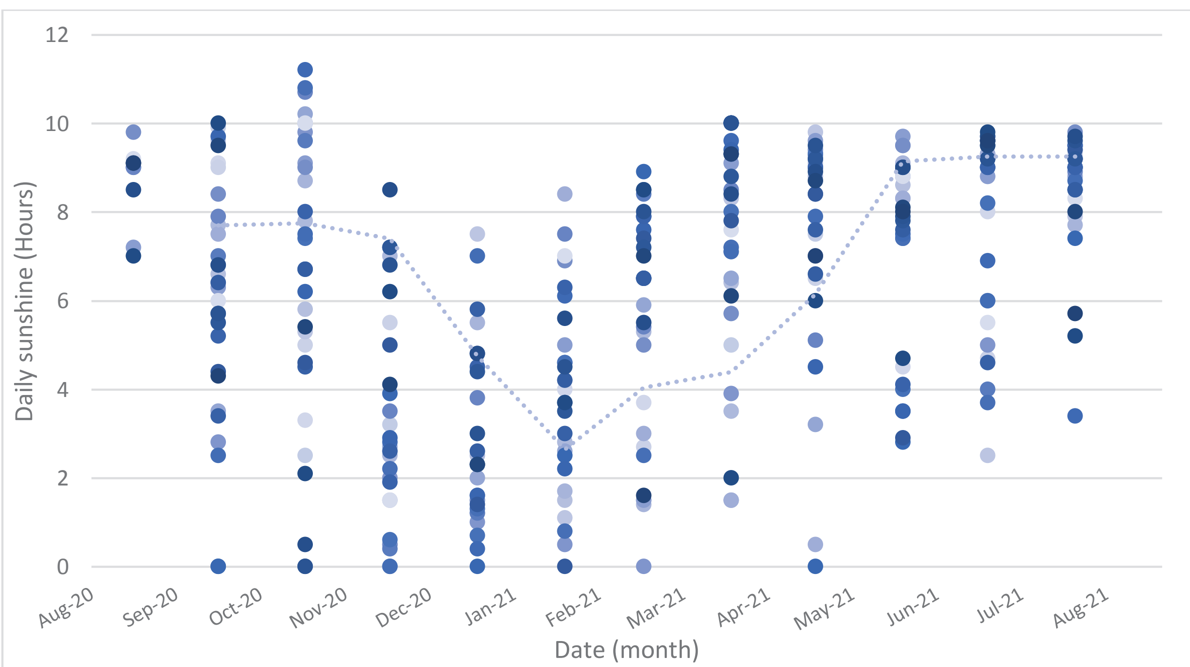

Figure 9. Daily sunshine in central java from 1 September 2020 to 31 August 2021 with uneven sunshine hours throughout the month indicated by different colors (BMKG, 2021)

[9] Courtesy of Google Maps https://www.google.com/maps/@-7.1431901,111.5858262,247m/data=!3m1!1e3

This research also compares the daily solar radiation value in figure 9, where the radiation is relatively low in December, January, and February. This low solar radiation is compared to the trend of solar rooftop PV power production in Figure 10. The electrical power that can be stable is generated from the radiation value that has a high intensity in the dry season months. The location factor is also considered to look at the climate in the study area so that the data obtained may show a shorter or even longer duration of solar radiation than the radiation calculated nationally. Solar rooftop PV equipment starts to supply electricity at around 06.00 and stops at approximately 15.30. The period of this power production is usually influenced by sunrise and sunset times, cloudy weather, rainfall, a wind that moves rain-carrying clouds, on-shore breeze, and other related matters.

The basic principle of this solar PV system, the sunlight is converted and directed to DC power and transformed by the inverter to AC. In an on-grid system, if the sunlight varies and the duration of the irradiation is small or blocked, the building utilizes the power from another power plant because it is still connected to the grid system. Hence, in this on-grid system, the climatic factors have less influence on the power used by the building. However, because of the utilization of energy from the grid, economic efficiency will be reduced.

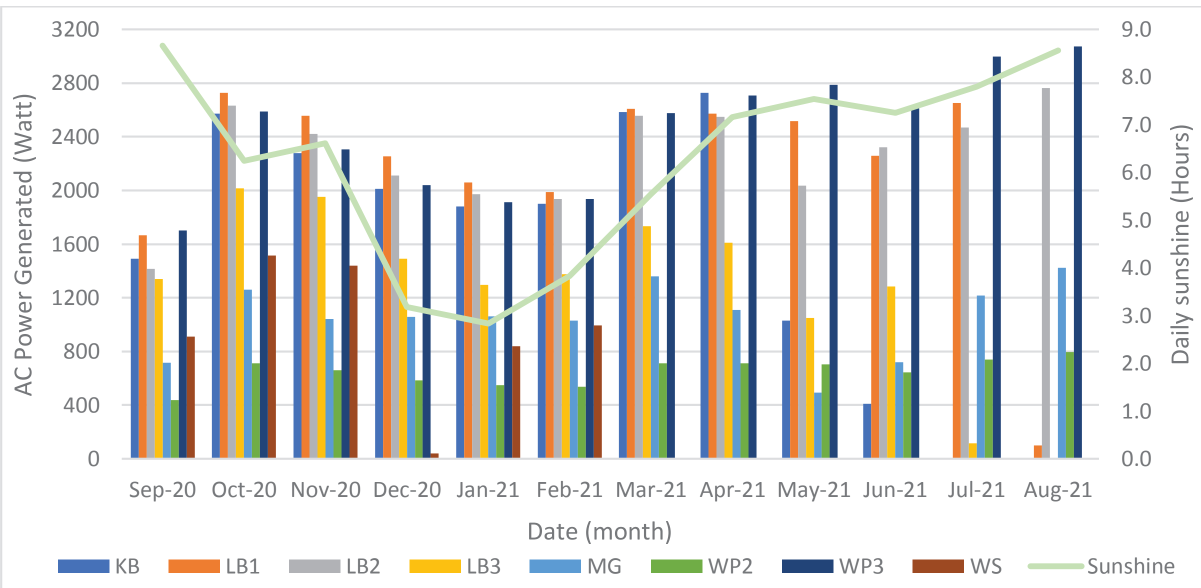

Figure 10. Power generated per solar PV module from 15 September 2020 to 31 August 2021 compared with average daily sunshine.

Furthermore, Figure 11 explains how rainfall in Indonesia does not have sufficient stability. High rain climates are not suitable for solar plant productivity, especially rooftop solar PV. Therefore, precipitation is highly affecting the trend of electricity generated. On the other hand, a low rainfall climate will increase the performance of solar PV to produce electricity. Thus, the maximum energy is obtained in April, May, June, July, August, September, and October because the rain in April, May, June, July, August is relatively low.

Figure 11 also shows some anomalies like rainfall in October that increases considerably in November, December, and January makes much heavy rain in these three months. However, it decreases again in February and drastically increases again in March.

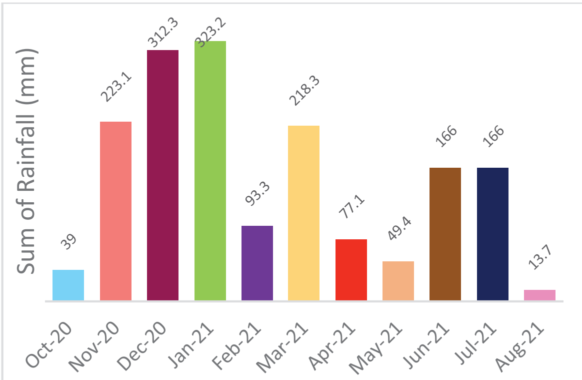

Figure 11. The rainfall per month (BMKG, 2021)

It is estimated that this anomaly occurs because the rain-carrying clouds begin to form gradually. In February, the transition season begins to appear to be the dry season. During this time, wind intensity, greenhouse gas effects, an on-shore breeze can also contribute to weather conditions in Indonesia.

This weather trend was also related to electricity consumption. The analyzed electricity usage data in PPSDM Migas, as shown in figure 12, indicates that electricity consumption begins to decline from October to February. It is assumed that although the weather is not perfect, solar rooftop PV can gradually reduce electricity consumption from PLN. From February to March, electricity consumption declined quite sharply, although the rainfall was relatively high. Aside from the climate transition in February to March, it is estimated that the rain duration was short, so the energy generated can be optimized. Hence, the solar energy during the day was sufficient to fill the electricity needs.

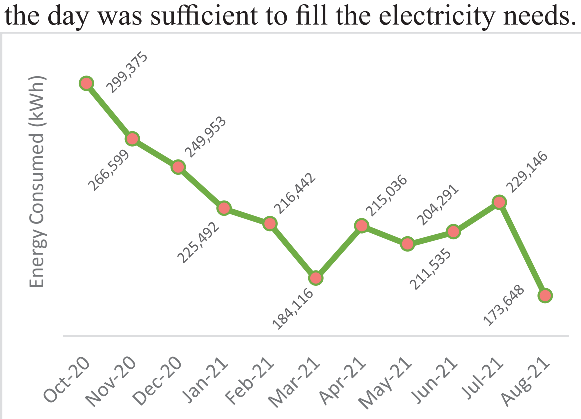

Figure 12. Electricity consumption in PPSDM Migas from October 2020 to August 2021.

In the coming months, the electricity used was moving slowly. Although electricity consumption rose again in July, it fell again in August. Furthermore, the electricity consumption increased again in April. Besides the “work from home” policy that is in place in March, it is estimated that from March to April, there is still a transitional process so that the performance of solar rooftop PV cannot be measured precisely while the electricity consumption increases again.

Several factors might also influence the instability of electricity consumption. Overall, if compared to the month before installing solar rooftop PV, the electricity usage from the grid is very high, reaching the figure of 300,000 kWh. Meanwhile, after the installation of solar rooftop PV, electricity consumption is far below 250,000 kWh. It also can be seen that although electricity consumption continues to experience instability, rooftop solar PV still provides electricity supply, making PLN electricity usage not as high as before using solar rooftop PV.

B. Equipment Efficiency in Power Generation

The solar rooftop PV module at PPSDM Migas is the on-grid system. It is observed that the PV module is suitable for climate conditions in Central Java. The solar PV module is installed with a tilt angle of 10°, which is the most effective position to capture sunlight.

The effectiveness of the PV module is also affected by the position of the building and its surroundings. Buildings with an open place to set up solar PV rooftops and not blocked by other buildings or trees will be able to catch the sunlight more, while the PV Module can convert the sunlight properly. However, the performance of the PV module to capture sunlight can also experience several challenges. For example, the solar PV module location in LB3 and WP2, as shown in Figure 4 and Figure 6, is very close to the trees. As a result, the PV module cannot receive sunlight ideally at certain hours cause shadows to block the sunlight. This problem can affect the average power production data that is converted to the inverter. Figure 13 shows that the power production begins to decline at 02.00 PM. The data also indicates that the estimated catch of the PV module begins to decrease at the time. Thus, it is concluded that apart from sunlight, several factors, such as the presence of shadows from other objects, also affect the average power production. It is also estimated that PV module quality, age of PV modules, and maintenance of PV modules can also reduce the efficiency of PV module performance.

Further, this study investigates the efficiency of the inverter, which converts DC power to AC. Figure 14 shows the efficiency and the productivity of the inverter from the daily power expended. The daily energy produced shows a decrease in the rainy season starting in October, and it increases again in February. While in that period, the climate in Central Java is experiencing a transition period between rainy and dry seasons. The effectiveness of the inverter can also be seen from the average daily power production from figure 14 when the seasons change from dry to rainy. Conversely, the power increased again in the transition from rainy to dry season. For example, in WP3, the power increase from around 1500 Watts to 3074 Watts. The variations in daily data also occur in other buildings, which means that the intensity of the sunlight varies from time to time.

However, the anomaly in the data could be misleading to the conclusion on inverter efficiency. One possible factor in the accuracy of the data is data transmission. Therefore, the efficiency of a system is highly dependent on how the inverter's ability to restore data. In addition, efficiency is also influenced by the robustness of rooftop solar PV. This study assumed that because the inverter is new and well-maintained, the performance of the inverter should still be relatively good.

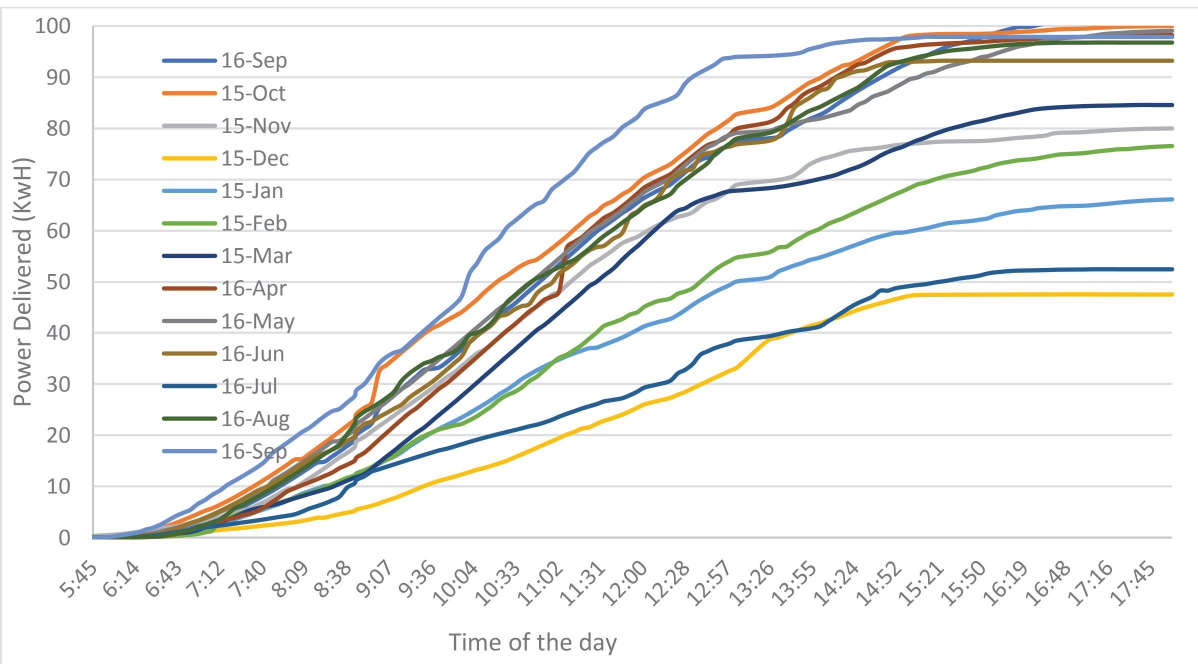

Figure 13. Power generation in a day throughout the year from the WP3 module.

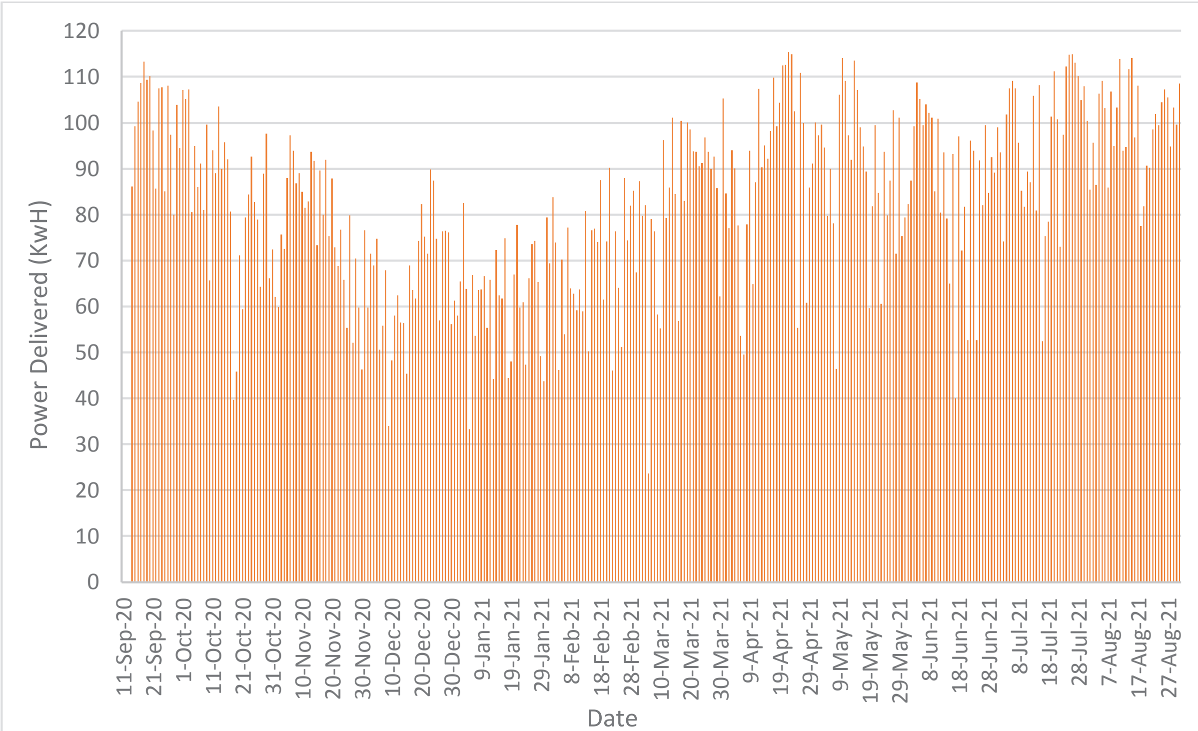

Figure 14. Daily power delivered from WP3 module from 15 September 2020 to 31 August 2021.

This study also analyzes the transmitted power's daily data, which can also illustrate how efficient the inverter is. In the daily data, the energy sent by the inverter can convert DC to AC and then will be transferred the power to the network. Figure 13 shows power from the sunlight starts to increase from morning to evening. Although the power generated fluctuated, the inverter can accumulate the power so that the power generated is maximum and can be utilized.

C. The effect of the apparent motion of the sun

The daily energy capture data collected shows that the peak of the maximum energy generated shifts every month, as shown in figure 15. This change is due to the apparent motion of the sun. The apparent annual activity of the sun is the apparent movement of the sun that seems to move from south to north and back to south every year. The earth revolves around the sun on a tilted axis so that the tilted towards the sun is sometimes the north pole and sometimes the planet's south pole. This phenomenon causes the sun not to rise and set in the same position throughout the year, and the seasons change in the northern and southern hemispheres. When the north part of the earth is tilted towards the sun, it gets more light and the days are longer, resulting in summer in the land of the four seasons. On the other hand, there is winter in the southern part of the earth simultaneously.

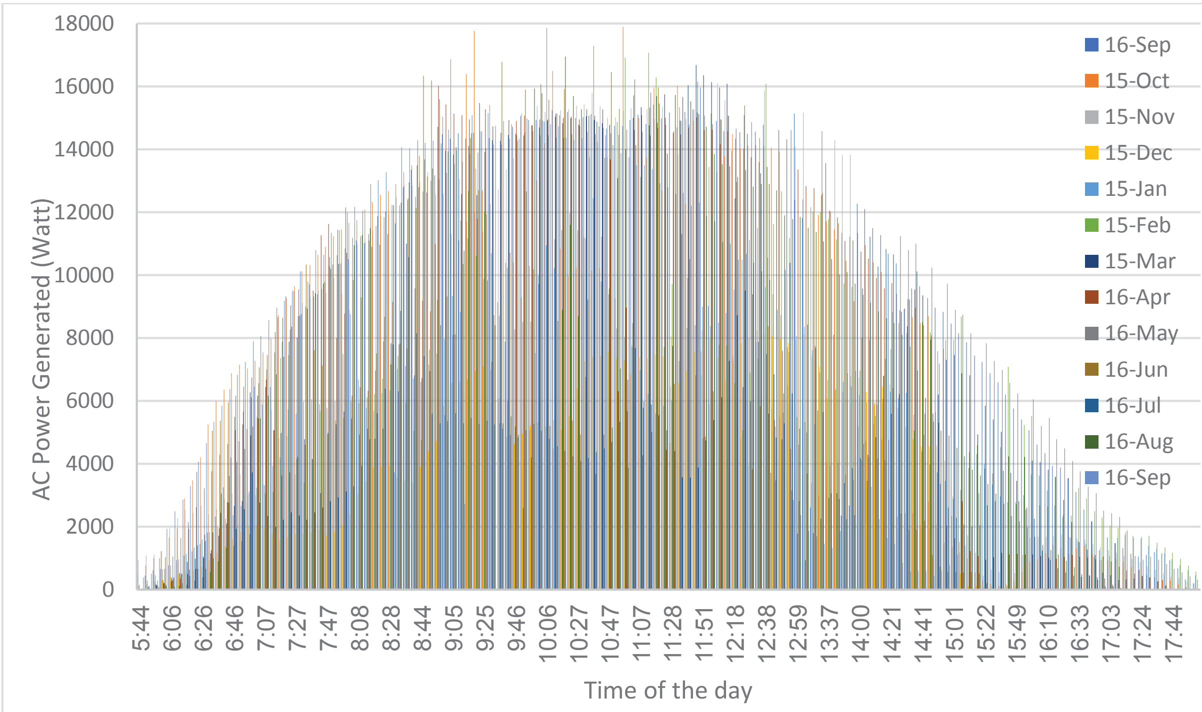

Figure 15. The comparison of daily power generated throughout the year from the WP3 module.

The research location on java island, slightly south of the equator, can still capture maximum sunlight throughout the year. When the sun reaches its northernmost point in this apparent motion, the northern equinox occurs between June 20th–22nd. In that month the equipment starts to deliver electricity at around 06.00 AM and stops at about 15.30. In contrast, the solstice occurs when the sun reaches its southernmost point between December 20th–23rd. In that month the equipment starts to deliver electricity at around 05.30 AM and stops at approximately 16.30. The midpoint between the two, called the equinox, occurs in March and September. In that month the equipment starts to deliver electricity around 05.30 AM and stops at around 17.00

SUMMARY

The performance of a 125 KWp solar power plant operating for one year in Central Java has been investigated in this study. As found in previous studies, there is a climate influence on the generated electricity trend. Maximum energy is obtained in April, May, June, July, August, September, and November. In contrast, the minimum power is obtained in December, January, and February. March and October are months with medium energy absorption. The months of October and November may be an anomaly because the rainy season hasn't started, but the sun's rays are not maximal. This anomaly might be because clouds begin to form before the rainy season.

Furthermore, the data displayed shows some data inconsistencies displayed by each PV module. These irregularities may be due to the efficiency of each piece of equipment in the power plant. Inconsistent data can also be caused by differences in angle, direction towards the PV panel, or cloud cover. However, cloud approach differences are very unlikely because these buildings are relatively close to each other. Technical errors in transmitting, receiving, and storing data that depend on wireless communication channels via WiFi are also likely to cause data to be inconsistent. The operator needs to check the connection and make sure the communication from the inverter to the server is running smoothly without a hitch.

Finally, it was found that the sun's apparent motion causes variations in the daily data regarding the length of irradiation and the maximum energy generation time. The months where the sun is above the equator, namely March and September, are the most extended time solar panels are exposed to sunlight. In contrast, the sun's shortest shine is recorded in June where the sun's position is north of the equator. This data is consistent with the fact that the location of this study is south of the equator.

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