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Analysis of the Impact of Wind and the Environmental Temperature on the Performance of a Rooftop Solar PV System: A Case Study of 52.2 kWp PT PLN Research and Development Center Rooftop PV Systems

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Abstract

To support the rooftop PV program and anticipate changes in the characteristics of the PLN electricity system due to the increasing number of rooftop PV customers, the PLN Research and Development Center has compiled a study related to rooftop PV performance analysis in 2021. This study aimed to observe the influence of weather parameters on the performance of rooftop PV systems which is carried out according to IEC 61724-1:2017. The measured parameters are solar irradiance, the surface temperature of the PV module, ambient temperature, wind speed, and direction. The analysis was performed under three different weather conditions: cloudy, rainy, and sunny skies. Monocrystalline type PV module that was installed for two years shows good performance. In rainy conditions, the highest efficiency of the PV array is 16.1% – 16.69% because the environmental temperature and the temperature of the PV module when it rains is the lowest compared to sunny and cloudy conditions. In sunny skies, the highest inverter efficiency is obtained, around 97.9 – 98.84%, due to very high solar irradiation (more than 1000 W/m²), so the inverter works more optimally than in rainy and cloudy conditions. The highest average wind speed is obtained in sunny conditions, which is 3.28 m/s with the same wind direction, namely the West-Northwest. However, the influence of the wind is not significant to provide a cooling effect to the rooftop PV.

Keywords: *efficienc; performance ratio; rooftop PV*

Abstrak

Analisis Pengaruh Angin dan Suhu Lingkungan Terhadap Kinerja Sistem PV Surya Atap: Studi Kasus 52,2 kWp Pusat Penelitian dan Pengembangan PT PLN Sistem PV Atap. Untuk mendukung program PLTS Atap dan mengantisipasi perubahan karakteristik sistem kelistrikan PLN akibat bertambahnya jumlah pelanggan PLTS Atap, Puslitbang PLN telah menyusun kajian terkait analisis kinerja PLTS Atap pada tahun 2021. Penelitian ini bertujuan untuk mengamati pengaruh parameter cuaca terhadap kinerja sistem PV atap yang dievaluasi berdasarkan IEC 61724-1:2017. Parameter yang diukur adalah iradiasi matahari, suhu permukaan modul PV, suhu lingkungan, dan kecepatan dan arah angin. Analisis dilakukan dalam tiga kondisi cuaca yang berbeda: berawan, hujan, dan cerah. Modul PV tipe monokristalin yang telah terpasang selama 2 tahun menunjukkan performa yang baik. Pada kondisi hujan, efisiensi tertinggi dari array PV adalah 16,1% - 16,69%, karena temperatur lingkungan dan temperatur modul PV pada saat hujan adalah yang paling rendah dibandingkan dengan kondisi cerah dan mendung. Pada saat langit cerah diperoleh efisiensi inverter tertinggi yaitu sekitar 97,9 - 98,84%, hal ini disebabkan karena iradiasi matahari yang sangat tinggi (lebih dari 1000 W/m²), sehingga inverter bekerja lebih optimal dibandingkan pada kondisi hujan dan mendung. Kecepatan angin rata-rata tertinggi diperoleh pada kondisi cerah, yaitu 3,28 m/s dengan arah angin yang sama, yaitu Barat-Barat Laut, namun pengaruh angin tidak signifikan untuk memberikan efek pendinginan pada PLTS atap.

Kata kunci: efisiensi; PV atap; rasio kinerja

INTRODUCTION

As a vast country, Indonesia has a lot of solar resources due to its location. Solar irradiation intensity on the country's surface ranges from 4.6 kWh/m^2/day to 7.2 kWh/m^2/day [1]. Indonesia has a vast potential to create electricity from solar energy, with a capacity of roughly 207.8 GWp. According to the government's plan, solar power penetration will continue to rise dramatically in the future Indonesian electricity system, owing to planned cost reductions in solar photovoltaic technologies [2].

Solar PV technology is one of the most effective, sustainable, and inexpensive ways to obtain energy from renewable sources. Utilizing solar photo-voltaic, particularly for PV rooftop systems, also brings many benefits for industry players; it is possible to make an energy-saving potential of circa 16 percent for industries that use solar PV rooftops [3]. The trend of using solar energy, especially rooftop PV, is increasing yearly. The government of Indonesia has intensively encouraged the rooftop PV program since 2018. To support and anticipate changes in the characteristics of the PLN electricity system due to the massive increase in the number of rooftop PV customers, the PLN Research Institute built a rooftop PV system in 2019.

Several studies on the performance of rooftop solar PV systems have been carried out such as a performance ratio monitoring of rooftop PV systems, rooftop PV system design, and technical and economic analysis of rooftop PV systems in Indonesia, for example, investigation of 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 on the performance of a solar power plant with a total capacity of 125 kWp, which operates for one year in Blora, Central Java [4] the simulation used PV Syst 7.0 by inputting the location, specifications, and configuration of the PV module, inverters, such as actual conditions in the field without shading on 25 kW rooftop solar PV at Misbahul Ulum Building, Lhokseumawe City [5], design process a low-rooftop PV plant’s data monitoring and its Performance Ratio (PR) calculation using free open-access whilst following on the International standard IEC 61724 on 10.6 kWp rooftop solar PV at Puspitek BRIN, Serpong [6]. Building integrated photovoltaic for rooftop and facade applications in Indonesia that employed the Sunny Web Design software and econometric spreadsheet program to calculate the energy generation and required specifications of BIPV [7]. Technical, economic, and environmental analysis of the residential scale of the rooftop PV system in Surabaya, Indonesia, has been conducted based on the data from a built installation of rooftop on-grid PV using SolarGIS PV planner, RETSCreen, and PVsyst simulation tools [8]. At the same time, no studies include experimental results on PV performance in the Jakarta region and the interaction of this PV with the environment in this region.

As previously stated, previous studies are more likely to be used for PV performance analysis; however, the literature quantifies the impact of wind and the environmental temperature on the performance of a rooftop solar PV system is still scarce, particularly in Indonesia. There has never been a study of the performance analysis of solar PV systems installed in the PT PLN Research Institute.

Therefore, this paper presents an experimental study with a critical analysis of a PV module based on silicon for three days under variable climatic conditions (clear, cloudy, and rainy); the experimental analysis was carried out to evaluate the actual performance under actual conditions in Jakarta. Furthermore, the performance parameter of rooftop PV systems calculated includes annual energy output, array yield, final yield, reference yield, performance ratio, and system efficiency. It is expected that this study can be used as input in planning for installing rooftop solar PV systems in other buildings in Jakarta.

METHOD

This PV system was installed in the main building of PT PLN Research Institute, located in South Jakarta, Indonesia. The system was equipped with 174 PV modules (mono-crystalline silicon) using two inverters, with a total generating capacity of 52.2 kWp, and started its operation in early December 2019. The study in this present work is carried out by literature reviews, measurement, data analysis, and mathematical calculation according to IEC 61724-1:2017. In this context, AC power, DC power, and solar irradiance are used to calculate the performance of the rooftop PV system.

Description of PV system

The research location of the rooftop PV system at the main building in PT PLN Research Institute, South Jakarta, Indonesia. The latitude and longitude of the site are 6°15'17.3"S 106°50'04.7"E, respectively. The PV system as shown in **Figure 1**, was installed with a capacity of 52.2 kWp, covering a total surface area of 283.08 m^2 and inclined at 25° towards the north and south. The rooftop PV system consisted of 24 mono-crystalline silicon modules, the PV module and array specifications are shown in **Table 1.** The Jiangsu Solarman INE-300-60M modules were each of 300 Wp capacity and comprised 60 solar cells made of the mono-crystalline silicon water.

Figure 1. Front view of 52.2 kWp rooftop PV

The modules had an efficiency of 18.44% under STC (Standard Test Condition) and were arranged in 2 sub-systems (array). The total capacity of this PV rooftop is 52.2 kWp with 174 PV modules which each array capacity as follows:

a) Subsystem I: Total capacity is 27 kW and was arranged in 5 parallel strings, with 18 modules connected in series in each string (90 PV modules).
b) Subsystem II: Total capacity is 25.2 kWp and was arranged in 4 parallel strings, with 21 modules connected in series in each string (84 PV modules).

In our installation, we used a string inverter architecture. In this architecture, an inverter is placed at the end of each chain which aims to increase the number of DC/DC converters which leads to the possibility of extracting the maximum power. The main specification of the PV module and inverter are shown in **Table 1.**

The system has 2 inverters, each capacity of 33 kW. The inverter had a rated maximum efficiency of 98% and maximum AC power of 33,000 W. The three-phase Trannergy TRM033KTL inverter was used to convert DC to AC which was fed into the main building's utility grid system through a panel distribution.

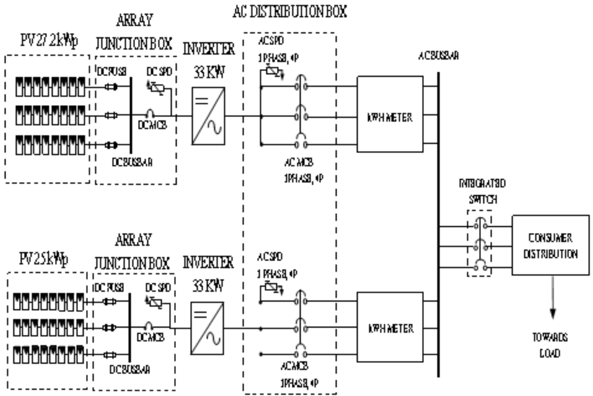

Figure 2. Schematic block diagram of PV system

Figure 2 shows the schematic block diagram of the installed PV system. The current from the PV array enters the array junction box, which combines the current with a short circuit current protection system and excessive load on the array junction box. From the array junction box, then enter into the inverter. The AC voltage generated by the inverter then enters the distribution box in the main building and the installed distribution network system.

Table 1. PV module and inverter specifications

PV Module/Array		Inverter	
Parameters	*Specification*	Parameters	*Specification*
Type	*Mono-crystalline silicon*	***Input***	
Maximum power (P_{max})	*300 Wp*	Maximum dc power	*35,000 W*
Maximum power voltage (V_{mp})	*32.1 V*	Maximum dc voltage	*1000 V*
Maximum power current (I_{pm})	*9.35 A*	PV - voltage range at MPPT	*250 to 800 V*
Open circuit voltage (V_{oc})	*39.7 V*	***Output***	
Short circuit current (I_{sc})	*9.65 A*	Maximum ac power	*33,000 W*
Maximum system voltage (V_{dc})	*1000 V*	***Efficiency***	
Module efficiency	*18.44%*	Maximum efficiency	*98.5%*
Module area	*1.626 m²*	Europian efficiency	*98%*
NOCT	*45 °C*	***Weight***	*47 kg*

Weather monitoring and data acquisition

A set of meteorological sensors connected to the data logger was installed to measure meteorological parameters such as solar radiation and the temperature of the modules (**Figure 3**). The instrument is an RT1 smart rooftop monitoring by Kipp & Zonen, which combined solar irradiation with PV module temperature measurement (duo-sensor). The device can measure plane-of-array (POA) irradiance from 0 to 2000 W/m^2, to within ±1 W/m^2. The solar radiation sensor was installed at the same tilt angle and orientation as the PV array to measure plane of array (POA) irradiance.

Figure 3. The RT1 irradiance sensor monitoring

To determine module temperature, a sensor was installed on one module, and it was placed centrally on the back sheet as shown in **Figure 4**. The module's temperature was measured by a surface mount temperature sensor. The PV module's temperature sensor is a 10-k negative temperature coefficient (NTC) with a measurement range of -20 to +100°C, ±1 °C, with a measurement uncertainty of ±0.015 °C. **Figure 5** shows Smart Weather Sensor Lufft type WS500-UMB, the ambient temperature, wind speed, and direction sensors are suitable for industrial and professional uses.

The installation was daily monitored by using a dedicated weather data monitoring system with an integrated data logger (SPL-XYS 2 module device). Data was recorded in 1-minute intervals in the data logger and was recorded, averaged, and stored all data collected, before being transferred to a specialized PC. The monitoring of the different measurements assured by 1 PC (is a mini PC or single board computer platform that runs a PC-like OS such as Windows). The recorded parameters provide information about the power levels, DC/AC currents, and voltages as well as the metrological parameters. Data acquisition from the PV system can be accessed through the Trannergy website and directly download from the inverter, where the data is used to calculate PR using a mathematical equation.

Figure 4. The temperature sensor

Figure 5. Smart Weather Sensor - Lufft type WS500-UMB

RESULTS AND DISCUSSION

To analyze the energy-related performance of a rooftop PV system, some important parameters are to be computed using data collected during its operation in a given location. These parameters include the total energy generated by the PV system (E_{AC}), the array yield (Y_A), final yield (Y_F), reference yield (Y_R), system efficiency, and performance ratio (PR). These normalized performance indicators are relevant since they provide a basis for comparing PV systems under various operating conditions.

Energy Output

The energy output from the 52.2 kW rooftop PV system was monitored and recorded every month from the accumulation of daily energy production. The recording period (for this study) was from January to December 2021. **Figure 6** presents the total monthly output energy by the rooftop PV system. It is seen that the monthly total energy generated by the PV system over the monitored period varied between 4,065.53-5,384.17 kWh. The peak of energy production is reached for October 2021 with 5,384.17 kWh. At the same time, the minimum energy generated for June 2021 with 4,065.53 kWh. The total annual energy delivered to the grid by the system was about 56,677.4 kWh. By taking 365 days for one year, the daily average energy output is about 155.28 kWh. The annual specific energy final is determined as 1,085.77 kWh/kWp. The specific energy can be used to compare the performance of PV systems installed in the same climatic conditions.

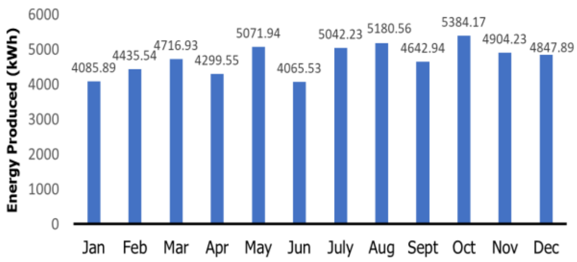

Figure 6. The total monthly output energy by the rooftop PV system

Energy output in different weather

Figure 7 Shows the variation in energy output on different days (clear, rainy, and cloudy). Total energy production in December 2021 was 4,857.89 kWh, with an average daily production in December 2021 of 156.38 kWh. The clear skies or sunny day energy production occurred on December 2nd, 2021, at 272.68 kWh. The clear day is characterized by irradiation during the noon, and it correlated to maximum energy production during the day, and this leads to an increase in the ambient temperature and the temperature of the modules. Rainy and cloudy days are characterized by low irradiation and relatively low temperatures. The rainy day energy production occurred on December 7th, 2021, at 81.30 kWh, and the cloudy day energy production on December 10th, 2021, was about 182.6 kWh.

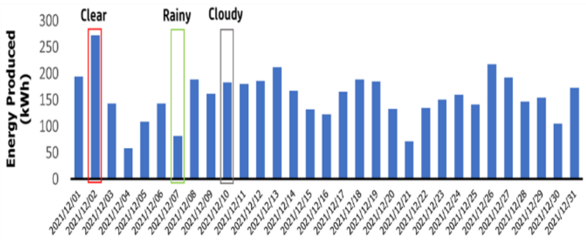

Figure 7. The variation of energy output on different days (clear, rainy, and cloudy)

During a clear day, the powers are higher and similar to solar irradiations compared to a cloudy and rainy day where the fluctuations of solar irradiation conducted fluctuations of the system's powers. The PV modules generate more power at relatively high temperatures (clear day noon), but at low temperatures (cloudy and rainy days) generate less power. During the three days, the array efficiencies are higher when rainy days, even though they generated less power than on clear and cloudy days. During the other two days (cloudy and rainy days), we observed that the solar irradiation has an irregular shape and the wind speed is lower than the clear day, which explains the slight difference between the ambient temperature and the temperatures of the modules.

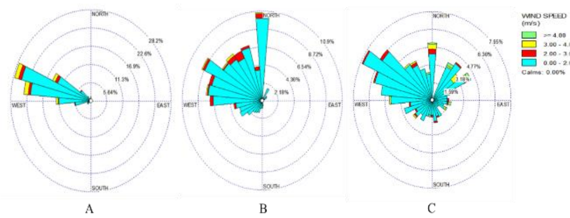

Figure 6. Wind speed and direction on different days (clear (A), rainy (B), and cloudy (C)

Figure 6 (clear (A), cloudy (B), and rainy (C)) shows wind speed and direction on different days. The highest wind speed was obtained in clear skies, which amounted to 3.28 m/s. Although the high wind speed only occurs in 1 direction (West Northwest), this reduces the PV module temperature less.

Performance of the PV systems

Table 2. Daily PV array efficiency, inverters efficiency, and system efficiency on different days

Day	Sub System	Solar Irradiance (kWh/m²)	Ambient Temp (°C)	Module Temp (°C)	Wind speed (m/s)	PV Array Eff. (%)	Inverter Eff. (%)	PV System Eff. (%)
Clear Day 02/12/2021	27 kWp	7.6	31.99	46.80	3.28	13.78	97.90	13.49
Rainy Day 07/12/2021		2.04	26.56	31.95	1.50	16.69	92.66	15.47
Cloudy Day 10/12/2021		4.84	28.83	40.16	1.71	14.54	95.67	13.91
Clear Day 02/12/2021	25.2 kWp	7.6	31.99	46.19	3.28	13.50	98.84	13.34
Rainy Day 07/12/2021		2.04	26.56	30.69	1.50	16.13	93.49	15.08
Cloudy Day 10/12/2021		4.84	28.83	39.06	1.71	14.99	96.22	14.43

Table 2 shows the solar irradiance, the ambient and the module temperature, the wind speed, PV array, inverter, and PV system efficiencies for the two subsystems during the three days. On a rainy day, the two subsystems have good PV array efficiency between 16.1% – 16.69%, compared with the two other days because the environmental temperature factor and the temperature of the PV module when it rains is the lowest compared to clear and cloudy conditions. The highest inverter efficiency obtained on a clear day is around 97.9 – 98.84%, this is due to very high solar irradiation (more than 1000 W/m²), so the inverter works more optimally than in rainy and cloudy conditions.

Table 3. Daily PV array losses, system losses, and performance ratio on different days

Day	Sub System	Reference Production (kWh/kWp/day)	PV Array Production (kWh/kWp/day)	Final Production (kWh/kWp/day)	PV Array Losses (%)	System Losses (%)	Performance Ratio (%)
Clear Day 02/12/2021	27 kWp	7.6	5.68	5.56	1.92	0.12	73.18
Rainy Day 07/12/2021		2.04	1.85	1.71	0.19	0.14	83.88
Cloudy Day 10/12/2021		4.84	3.81	3.65	1.02	0.90	75.42
Clear Day 02/12/2021	25.2 kWp	7.6	5.56	5.50	2.04	0.06	72.34
Rainy Day 07/12/2021		2.04	1.78	1.67	0.26	0.12	81.76
Cloudy Day 10/12/2021		4.84	3.93	3.78	0.90	0.15	78.24

The reference, the PV array, the final yields, the PV array losses, the systems losses, and the Performance Ratio (PR), are shown in **Table 3.** The results show that maximal values of the reference, the PV array, and the final yields for the two sub-systems are registered during the clear day. The highest array losses occurred for the PV rooftop system in clear skies; this result can be explained due to the high ambient temperature and PV module temperature. The performance ratio does not vary linearly with solar irradiation but is also affected by ambient and PV module temperatures. The PR is maximal on a rainy day at around 81.76 – 83.88% because of the decrease in array losses caused by the decrease in module temperature.

CONCLUSION

The experimental results show that the two PV subsystems behave differently depending on the day. These differences are mainly due to the variations of the weather condition, the tilt angle of the rooftop PV, etc. The obtained results show that the PV array's efficiency is greatly affected by the ambient temperature and the surface temperature of the PV module, while the efficiency of the inverter is greatly affected by solar irradiation. In rainy conditions, the highest efficiency of the PV array is 16.1% – 16.69% because the environmental temperature factor and the temperature of the PV module when it rains is the lowest compared to sunny and cloudy conditions. In clear skies, the highest inverter efficiency is obtained, namely 97.9 – 98.84%; this is due to very high solar irradiation (more than 1000 W/m²), so the inverter works more optimally than in rainy and cloudy conditions. The highest average wind speed is obtained in sunny conditions, 3.28 m/s, with the same wind direction, namely the West-Northwest. However, the influence of the wind is not significant to provide a cooling effect on the PV rooftop.

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