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Performance Evaluation of 120 kWp On-Grid Photovoltaic Power Plants after Five Years of Operation

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Abstract
This study assesses the five-year operational performance of a 120 kWp grid-connected rooftop photovoltaic (PV) power plant with multiple locations in Blora, Central Java, Indonesia. By analyzing real-world energy yield, degradation rates, and climate-related impacts, the study identifies key environmental and technical factors influencing PV efficiency. Performance data from 2020 to 2025 show varying degrees of degradation across sites, with Widya Patra 3 showing the greatest reduction (51.09%), and Widya Patra 2 showing the least (12.5%). The study confirms that dust accumulation, shading, temperature fluctuations, and humidity have a significant impact on long-term efficiency. Climate variables such as sunshine duration, rainfall intensity, and wind speed were found to have a direct relationship with energy yield. These findings highlight the importance of regular maintenance, proactive cleaning strategies, and optimized PV system designs for better performance and sustainability in tropical climates. The study sheds light on future PV reliability improvements, guiding the implementation of climate-resilient strategies in solar energy development.

Keywords:
long-term analysis, performance degradation, photovoltaic power plant, PV efficiency, temperature effects

1. Introduction

Photovoltaic (PV) technology has advanced significantly over time, from low-efficiency silicon-based cells to advanced monocrystalline, polycrystalline, and thin-film modules with higher energy conversion rates (Puriza et al., 2021). These technological advancements have made PV systems more widely used in a variety of applications, ranging from residential to industrial-scale energy production. Despite these advancements, real-world performance is inevitably influenced by environmental factors such as dust accumulation, weather variability, shading, and temperature fluctuations, resulting in long-term efficiency losses (Asrori & Yudiyanto, 2019; Makkulau et al., 2020). Understanding the effects of these degradation mechanisms is critical for maximizing system reliability, energy yield, and economic viability over long operational periods.

Dust deposition is one of the most common issues affecting PV system performance, as it directly interferes with solar irradiance absorption and increases surface reflectance, thereby lowering energy conversion efficiency. According to studies conducted in Indonesia, dust accumulation can reduce panel efficiency by 5–15% per year (Sariman & Fitriyani, 2021; Sugiarta et al., 2020). Dust layers in urban environments like Jakarta have been found to reduce efficiency by up to 30%, whereas regular cleaning increases voltage stability by about 25% (Effendi et al., 2024). Furthermore, dust accumulation varies by region, with wet/dry pollution conditions causing power drops of up to 2.2% in Bone Bolango, Indonesia (Talawo et al., 2022). These findings highlight the importance of proactive maintenance and automated cleaning solutions to reduce dust-related losses.

Similarly, shading, whether partial or full, poses a significant challenge to PV performance by limiting irradiance absorption and causing cell mismatches, resulting in disproportionate losses in power output. According to research, partial shading of 25–75% of a PV module can cause power losses of up to 91% in a 100 Wp system (Saputra et al., 2023). In large-scale installations, shading effects can result in significant daily production losses, as seen in a 1.3 MWp plant in Sulawesi, where shadow simulations revealed energy deficits of 28.6 to 81.4 kWh per day (Parapa', 2023). Structural obstructions such as buildings and trees have also been found to contribute to significant power reductions, with studies in Jakarta reporting output losses of up to 85.3% due to shading. To mitigate these effects, optimal system design strategies—such as configuring array layouts to minimize shading and employing bypass diodes—are critical for ensuring consistent energy generation.

Aside from dust and shading, temperature fluctuations impose an additional critical performance constraint on PV systems. As surface temperatures rise above standard test conditions, the voltage output of PV modules decreases, reducing overall energy production. Monocrystalline panels lose 2.3% of their power with every 10 °C increase in temperature, whereas polycrystalline modules can lose up to 10.12% (Makkulau et al., 2020). Given that field temperatures frequently exceed 50 °C, efficiency losses can range from 10 to 25%, affecting long-term operational stability (Harahap et al., 2022). High temperatures have the greatest impact during peak midday hours (11:00–14:00), when panel temperatures can reach 50–68 °C, accelerating degradation (Asrori et al., 2022; Jaya et al., 2024).

To mitigate temperature-related losses, a variety of cooling strategies, both active and passive, have been tested. Water-based cooling systems have shown promising results, reducing panel temperatures by 4–10 °C while increasing output voltage by 2.5% (Kusumaningtyas et al., 2023). Forced air cooling with fans can increase efficiency by 0.5–3.5%, with higher airflow rates increasing power output by up to 31% (Pido et al., 2023). Hybrid cooling solutions, such as the combination of phase-change materials (PCMs) and air or water flow, have shown improved thermal management and long-term efficiency (Kusumaningtyas et al., 2023). Passive cooling methods, such as heat sinks and perforated aluminum plates, help lower temperatures by increasing heat dissipation (Sjahruddin & Bizzy, 2020; Sofijan, 2021).

Beyond thermal mitigation, new technologies like Internet of Things (IoT)-controlled cooling systems and fuzzy logic controllers are being developed to optimize cooling cycles (Kusumaningyas et al., 2024; Loegimin et al., 2020). Automated cleaning mechanisms, such as IoT-based wipers, have effectively reduced dust-related losses by 44.6% while increasing cleaning efficiency (Isyanto et al., 2023; Kusuma et al., 2020). Optimal tilt angles, like the 10 ° configuration used in Semarang, that increased irradiance capture to 1,774 kWh/m², are crucial for improving system performance (Sugiono et al., 2022). These advancements highlight the importance of incorporating smart maintenance strategies and adaptive cooling techniques into PV system designs to ensure long-term energy generation.

While short-term PV performance has been explored by Umam et al. (2021), there remains a notable gap in long-term data for rooftop systems operating in tropical climates, where elevated temperatures, high humidity, and particulate exposure can accelerate system degradation. In particular, existing research on the 120 kWp rooftop PV system lacks comprehensive assessments of cumulative environmental impacts over extended periods. This study addresses these limitations by quantifying the five-year degradation rate of the on-grid PV plant, evaluating the long-term influence of temperature fluctuations on energy yield, and expanding previous single-year weather correlations to uncover chronic efficiency losses. By doing so, it provides a more complete understanding of system resilience and performance sustainability in tropical environments.

This study provides a framework for improving the reliability and economic viability of PV systems in environmentally stressed regions by combining real-world performance trends with actionable mitigation strategies, ranging from optimized cooling techniques to adaptive maintenance protocols.

2. Methods and Materials

2.1 Study Site and System Description

This study evaluates the long-term performance of a 120 kWp grid-connected rooftop PV system installed at eight different locations in Blora, Central Java, Indonesia (latitude: -6.95°, longitude: 111.41°). The system is composed of polycrystalline silicon modules organized into 20 kWp, 10 kWp, and 5 kWp arrays, each with string inverters to maximize energy conversion efficiency. The system specifications are consistent with those outlined in the previous one-year performance evaluation (Umam et al., 2021). To investigate the effect of environmental conditions on system performance, meteorological data, such as solar irradiance and ambient temperature, were obtained from the nearest weather station and validated against regional satellite data provided by the Indonesian Meteorology Agency (BMKG). The location of the study is shown in Figure 1.

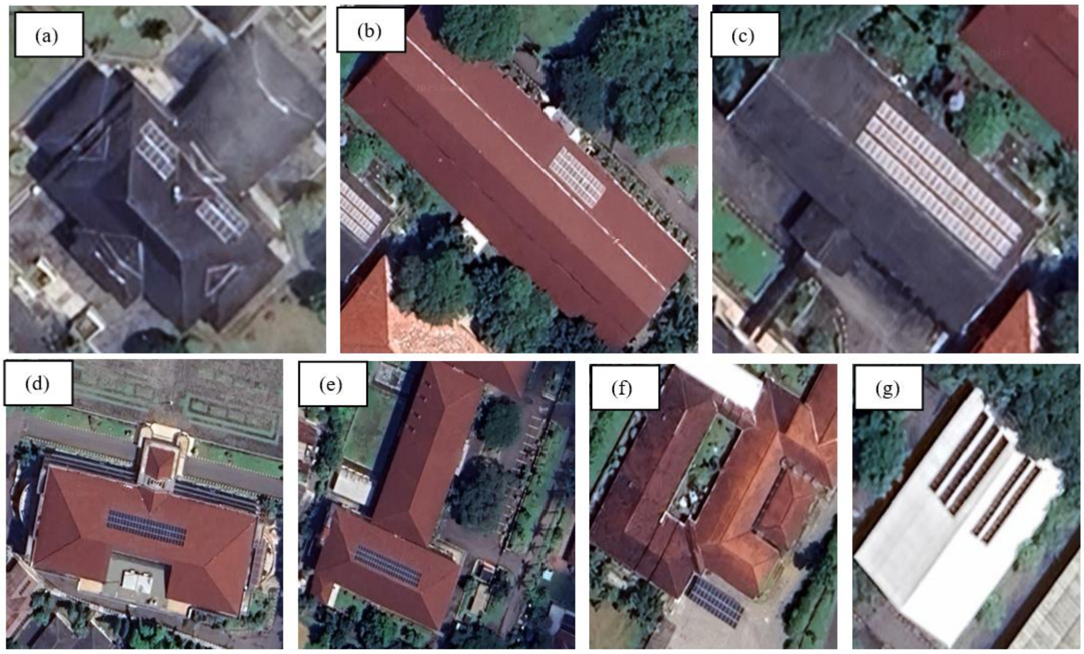

Figure 1. Locations of PV power plants (a) Widya Patra 2, (b) Migas 1, (c) Instrumentation Laboratory, (d) Main Office 4, (e) Widya Patra 3, (f) Wisma 1, (g) Electrical Laboratory.

2.2 Data Collection

Performance data for the 2020–2025 study period were obtained using the SolarmanSmart monitoring system, a platform provided by IGEN Tech Co., Ltd. Data parameters such as DC/AC power output, voltage, and current were recorded at 15-minute intervals using Suder Power Inverter MDA–1100W, allowing for a detailed analysis of energy generation trends over time. In addition, a SOLARMAN stick logger LSW-5 (USB) was used to monitor system availability and operational faults, which assisted in identifying potential disruptions and inverter failures that could affect the PV plant's efficiency. Meteorological data, which are critical in assessing PV system performance, were obtained from the BMKG's online database. During the study, key environmental variables such as global horizontal irradiance (GHI), average wind speed, sunshine duration, and ambient temperature were measured. These datasets provided detailed insights into seasonal trends and long-term climatic variations that influenced the PV plant's energy yield.

To ensure data accuracy, a structured outlier detection protocol was implemented to identify and remove erroneous records stemming from inverter downtime, shading artifacts, and sensor anomalies. This process involved applying statistical filters using z-score thresholds to flag data points that deviated significantly from expected operational patterns. For instance, sudden drops in power output during periods of high irradiance were cross-checked against meteorological inputs to confirm whether they reflected genuine system behavior or measurement errors. Time-series consistency checks were also performed to detect gaps or irregular intervals, which were either interpolated using conservative methods or excluded when interpolation posed a risked introducing bias.

2.3 Performance Metrics

To evaluate system efficiency and long-term degradation, several key performance indicators were analyzed. The Performance Ratio (PR) was calculated as the ratio of actual energy output to the theoretical maximum yield, adjusted for site-specific irradiance and system losses. This metric provides a normalized measure of system efficiency that is independent of location or system size.

The degradation rate was estimated using linear regression applied to the normalized annual yield (kWh/kWp/year). Normalization accounted for interannual weather variability by adjusting energy output based on GHI data. Specifically, each year's yield was divided by the corresponding annual GHI to isolate performance changes attributable to system aging rather than environmental fluctuations. This approach ensured that degradation trends reflected intrinsic system behavior rather than external environmental variability.

To better understand the degradation trends, the five-year dataset (2020–2025) was benchmarked against the system's initial performance in 2021 (Umam et al., 2021). This comparative analysis supported the determination of long-term efficiency decline rates while accounting for possible environmental influences on system performance. Globally, PR is calculated using Equation (1):

$$PR = \frac{Actual\ Energy}{A * r * H}\ x\ 100\% \quad (1)$$

where A is the total solar panel area (m^2); r is the solar panel yield /efficiency; and H is radiation (kWh/m^2)

In this study, the focus is on calculating the performance ratio from the time the PV power plant was installed until the present, so the performance ratio is calculated using Equation (2):

$$PR = \frac{Y_f}{Y_r}\ x\ 100\% \quad (2)$$

where Y_f is the final yield (kWh/kWp) and Y_r is the reference yield (kWh/kWp) as in Equations 3 and 4:

$$Y_f = \frac{E_{AC}}{P_{rated}} \quad (3)$$

$$Y_r = \frac{H_{POA}}{G_{STC}} \quad (4)$$

where G_{STC} is the standard test condition irradiance = 1000 W/m² *or 1 kW/m²*. Thus, Equation 2 can be written into Equation 5.

$$PR = \frac{E_{Ac}/P_{Rated}}{H_{POA}} = \frac{E_{Ac}}{P_{Rated}\ x\ H_{POA}} \quad (5)$$

where E_{AC} is the actual energy output (kWh); P_{Rated} is the installed power (kWp); and H_{POA} is the plane of array irradiance (kWh/m²).

This formulation normalizes energy output against irradiance and system capacity, allowing for consistent year-to-year comparisons despite weather variability. To estimate the degradation rate, normalized annual yields were analyzed using linear regression over the five-year period. Normalization was achieved by dividing each year's final yield by its corresponding reference yield, effectively removing the influence of fluctuating irradiance and isolating performance changes due to system aging.

2.4 Limitations

While this study provides a thorough evaluation of PV system performance, several limitations must be recognized. One challenge occurred in 2022 due to data gaps caused by partial inverter failures, which introduced inconsistencies in system monitoring. To address this issue, missing data points were interpolated using performance records from neighboring arrays, ensuring the dataset's continuity.

Furthermore, certain environmental factors, such as dust accumulation and shading effects, were identified as potential sources of efficiency losses but were not systematically measured in this study. These influences are discussed qualitatively rather than treated as direct variables in the data analysis. Despite these limitations, the study offers important insights into degradation mechanisms and performance optimization strategies for rooftop PV systems in tropical climates.

3. Results and Discussions

3.1 Performance Evaluation of the PV Power Plant

The long-term performance evaluation of the 120 kWp grid-connected rooftop PV power plant was conducted at seven locations, including Electrical Laboratory (LB3), Instrumentation Laboratory (LB2), Migas 1 (MG), Wisma 1 (WS), Widya Patra 2 (WP2), Widya Patra 3 (WP3), and the Main Office (KB). The assessment compares the average power generation during the first month of installation (October 2020) with the system's current condition (April 2025), providing insights into environmental and operational factors contributing to degradation.

Figure 2 presents the PV production results for October 2020, showing that LB3, LB2, KB, and WP3 had similar installed capacities of 20 kWp, whereas WS and MG operated at 10 kWp, and WP2 had the smallest installed capacity of 5 kWp. The consistent trend in initial performance suggests uniform environmental influences across these locations at the time of installation.

On the other hand, Figure 3 illustrates PV power plant production after five years of operation, revealing significant variations in energy output between locations. The broader spread of production values indicates performance divergence, suggesting degradation due to environmental factors—such as dust accumulation, shading, and temperature fluctuations—as well as technical aspects like inverter efficiency and maintenance practices. These degradation effects are quantified in Table 1, which compares total and average production at each location between October 2020 and April 2025.

The results indicate varied levels of degradation across the sites. LB2 initially exhibited the highest power generation (2632.25 kWh), followed by WP3 (2587.28 kWh) and KB (2571.22 kWh). By April 2025, production significantly declined, with LB2 producing 2105.49 kWh, KB 1834.16 kWh, and LB3 1674.86 kWh. WP2 showed the lowest total production at 592.81 kWh.

Conversely, based on Equation 2, WP3 exhibited the highest degradation rate at 51.09%, followed by LB3 (25.30%) and KB (20.97%). The pronounced decline in WP3's efficiency suggests potential contributing factors such as PV module degradation, excessive dust accumulation, shading effects, or insufficient maintenance. These findings highlight the necessity for continuous monitoring and optimized maintenance strategies to sustain long-term PV system performance.

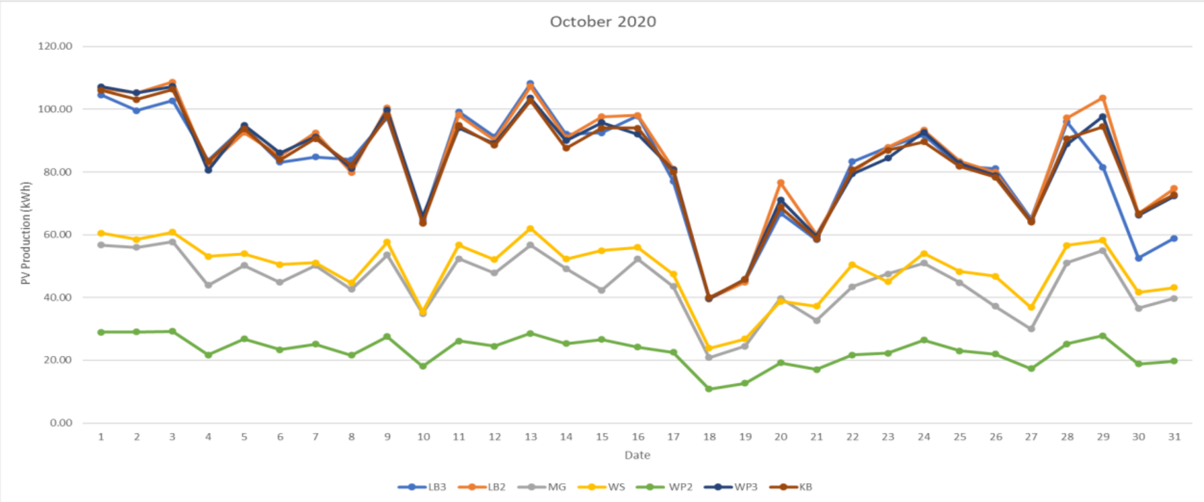

Figure 2. PV production in October 2020.

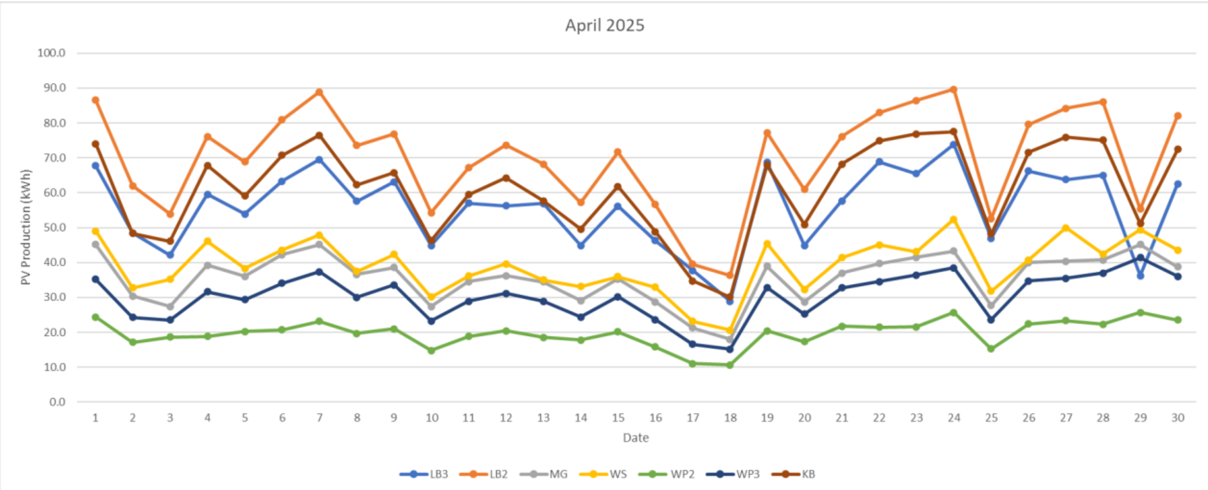

Figure 3. PV Production in April 2025.

Table 1. Comparison of the production of the PV generator at PPSDM Migas.

PV	P_{rated} (kWp)	October 2020					April 2025				
		Days	E_{AC}	Y_f	Y_r	PR	Days	E_{AC}	Y_f	Y_r	PR
LB3	20	31	2,546.43	4.11	5.2	78.98	30	1,674.86	2.79	5.2	53.68
LB2	20	31	2,632.25	4.25	5.2	81.65	30	2,105.49	3.51	5.2	67.48
MG	10	31	1,388.59	4.48	5.2	86.14	30	1,067.68	3.56	5.2	68.44
WS	10	31	1,515.33	4.89	5.2	94.00	30	1,176.73	3.92	5.2	75.43
WP2	5	31	713.33	4.60	5.2	88.50	30	592.81	3.95	5.2	76.00
WP3	20	31	2,587.28	4.17	5.2	80.25	30	909.67	1.52	5.2	29.16
KB	20	31	2,571.22	4.15	5.2	79.75	30	1,834.16	3.06	5.2	58.79

Meanwhile, Table 2 shows the annual comparison of PR in LB2. The PR in 2020, the first year of installation, was 74.84% and in 2025 it was 62.83%. This reflects a decrease of 12% after the PV system had been operating for five years.

Table 2. Annual PR of the PV system at the instrumentation laboratory (LB2).

Year	Days	E_{AC}	P_{rated}	Yf	Yr	PR
2020	92	7,160.83	20	3.89	5.2	74.84
2021	365	28,690.09	20	3.93	5.2	75.57
2022	365	27,224.56	20	3.73	5.2	71.71
2023	365	28,601.64	20	3.92	5.2	75.34
2024	366	26,738.98	20	3.65	5.2	70.24
2025	120	7,842.14	20	3.27	5.2	62.83

3.2 Effect of Climate on PV Power Plant Performance

Environmental conditions play a critical role in determining the efficiency and degradation patterns of the PV power plant. Key climate parameters—including sunshine duration, ambient temperature, rainfall, humidity, and wind speed— directly influence the long-term sustainability of energy production. These effects are evident in Table 3, which presents monthly production data from the PV system at LB2 over a five-year period.

The highest total annual production was recorded in 2021, reaching 28,690.1 kWh, with an average monthly yield of 2,390.8 kWh, suggesting favorable weather conditions. In contrast, 2025 saw the lowest total production at 7,676.9 kWh, with the lowest monthly declines observed in December 2024 (53.88 kWh) and January 2025 (54.87 kWh). Table 3 illustrates monthly production trends, reinforcing the strong correlation between sunshine duration and PV power plant output.

Table 3. Total production of the PV system in the instrumentation laboratory (LB2).

Month	Year					
	2020	2021	2022	2023	2024	2025
January		1,971.0	2,151.4	2,115.3	2,103.3	1,701.1
February		1,936.4	1,738.5	1,812.2	2,046.0	1,649.1
March		2,555.9	2,307.2	2,309.4	2,050.0	2,386.5
April		2,548.5	2,333.8	2,373.5	2,248.3	2,105.5
May		2,466.8	2,373.5	2,479.6	2,546.7	
June		2,323.0	2,281.8	2,414.1	2,208.9	
July		2,621.8	2,531.0	2,483.2	2,440.7	
August		2,839.2	2,675.9	2,680.0	2,122.9	
September		2,573.2	2,637.1	2,684.0	2,581.6	
October	2,632.3	2,730.5	2,336.7	2,650.7	2,613.6	
November	2,419.4	1,994.0	1,910.7	2,248.0	2,106.9	
December	2,109.1	2,129.9	1,947.0	2,351.6	1,670.2	
Total	7,160.8	28,690.1	27,224.6	28,601.6	26,739.0	7,676.9
Average	2,386.9	2,390.8	2,268.7	2,383.5	2,228.2	1,919.2

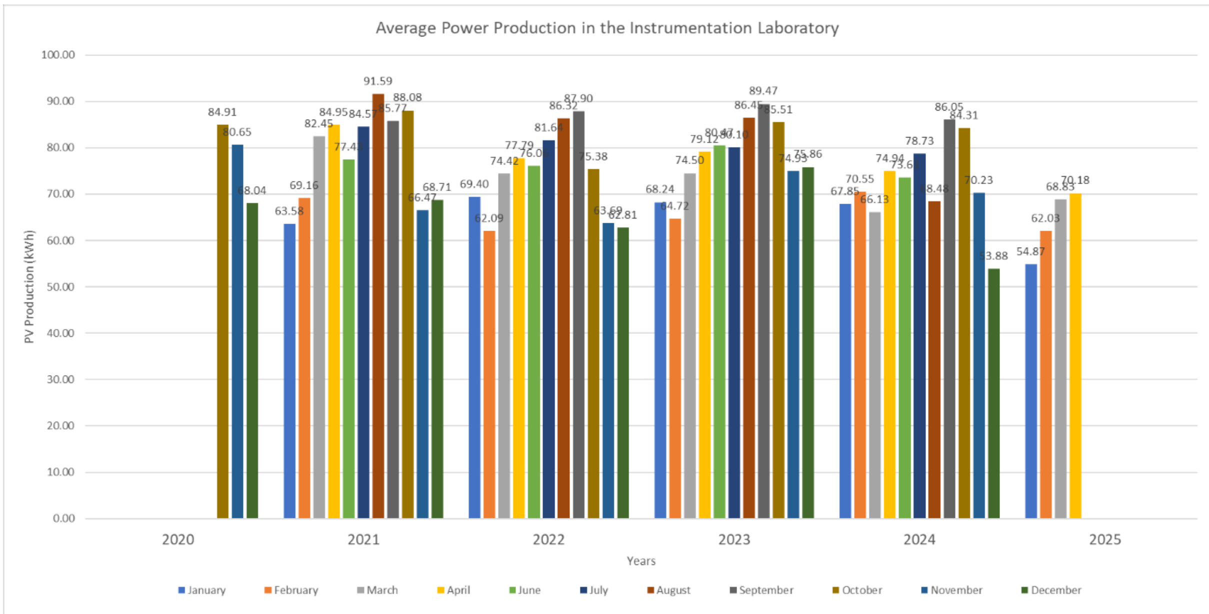

Figure 4. Average monthly power production of the PV system at LB2.

Figure 5 further demonstrates the relationship between sunshine duration and PV performance, confirming that longer solar exposure results to higher energy output. The greatest average power production was recorded in August 2021, with 8.56 hours of solar exposure per day, with only 3.18 hours of daily solar exposure, corresponding to a significantly reduced output of 53.88 kWh. These findings underscore the impact of climatic variability on PV system efficiency.

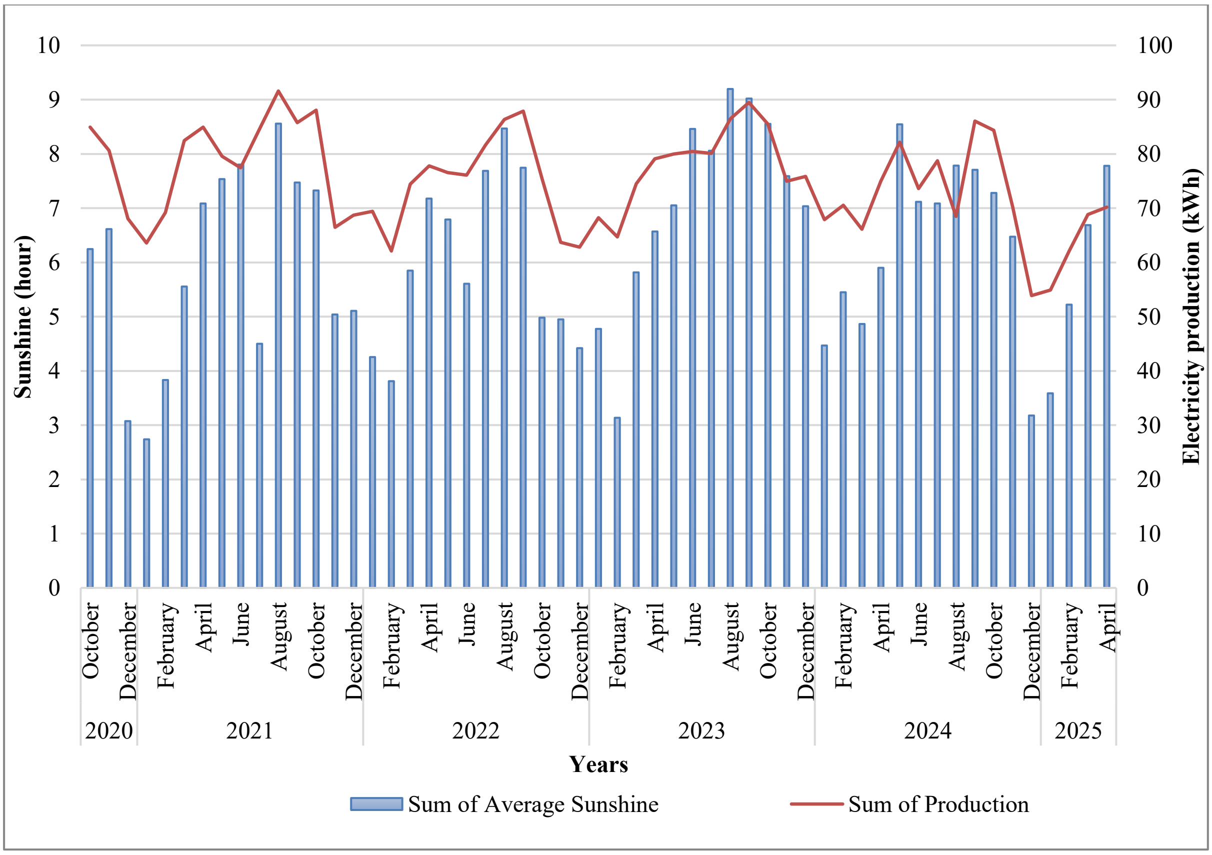

Figure 5. Correlation between sunshine duration and PV power output at LB2.

Solar irradiation has a positive correlation with temperature. As the duration of solar irradiation increases, temperature tends to rise, as shown in Figure 6. In the previous study, increasing the temperature up to 36 °C slightly increased solar cell efficiency to 12%, but efficiency decreased to 2.73% at 58 °C (Katkar et al., 2011). High temperatures generally reduce the efficiency of a solar cell because the bandgap energy in PV modules decreases at elevated operating temperatures. The effect of high temperature also reduces power output by 4% with every 10 °C increase in temperature. Moreover, electricity output could decrease from 32.1 watts to 31.9 watts after exposure to temperature ranging from 46,9 °C to 54.7 °C (Syah et al., 2022). In this study, the average operating temperature ranged from 34 °C to 52 °C, with a calculated temperature coefficient of –0.41%/°C. This means that for every 10 °C increase, the system experienced an average 4.1% reduction in energy output. These results confirm that temperature-induced losses are a significant factor in long-term performance degradation.

Month	2020	2021	2022	2023	2024	2025
January		2.74	4.25	4.77	4.47	3.59
February		3.83	3.81	3.14	5.45	5.22
March		5.55	5.85	5.82	4.86	6.69
April		7.09	7.18	6.57	5.90	7.78
May		7.54	6.79	7.05	8.55	
June		7.80	5.61	8.46	7.12	
July		4.50	7.69	8.06	7.09	
August		8.56	8.47	9.20	7.78	
September		7.47	7.74	9.02	7.71	
October	6.25	7.33	4.98	8.55	7.28	
November	6.61	5.04	4.95	7.59	6.47	
December	3.07	5.11	4.42	7.04	3.18	

(a)

Month	2020	2021	2022	2023	2024	2025
January		26.58	27.25	27.27	28.28	27.32
February		26.71	27.04	26.71	28.16	27.53
March		27.27	27.45	27.32	28.13	27.71
April		27.70	28.09	27.93	28.73	28.01
May		28.22	28.25	27.91	28.78	
June		27.21	27.34	27.96	28.14	
July		27.80	27.14	27.43	27.44	
August		27.96	27.39	27.06	27.73	
September		28.53	28.12	27.92	28.89	
October	28.73	29.10	27.81	29.34	29.95	
November	28.82	27.91	27.79	29.68	29.49	
December	27.20	27.69	27.46	28.95	27.97	

(b)

Figure 6. Average climate conditions: (a) sunshine and (b) temperature.

While sunshine duration and temperature are key determinants of PV power plant output, other climate factors—such as rainfall, humidity, and wind speed—also contribute to long-term efficiency losses. Figure 7 compares rainfall intensity between August 2021 (a high-production month) and December 2024 (a low-production month), demonstrating the inverse relationship between rainfall intensity and PV generation. While excessive rainfall reduces solar irradiation and increases panel humidity, moderate rainfall has been found to be beneficial, as it naturally cleanses dust accumulation (soiling), enhancing surface reflectance and module efficiency (Stankov et al., 2024). Yao et al. (2023) showed that PV modules experience a 16.1%–28.2% efficiency increase following heavy rainfall events (50–100 mm) compared to light rainfall conditions (<10 mm).

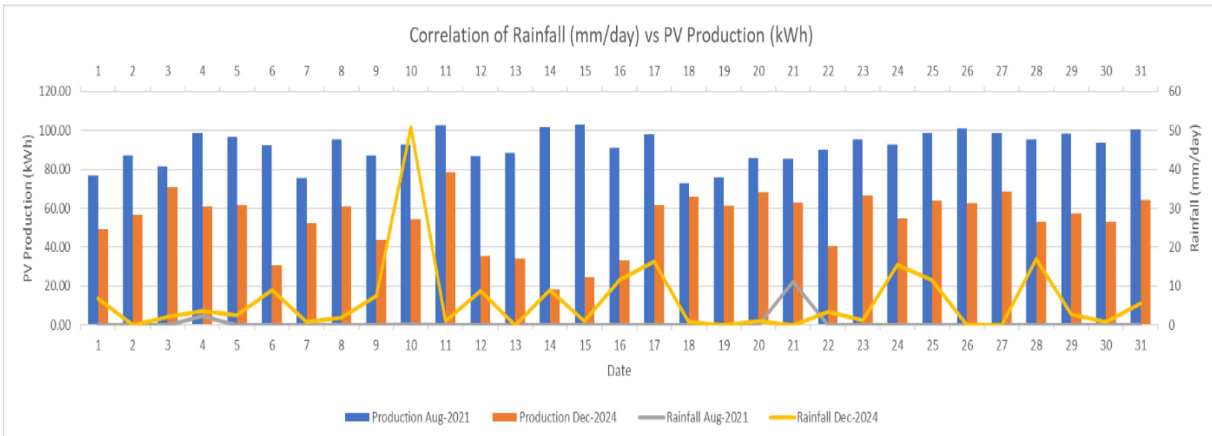

Figure 7. Correlation between rainfall intensity and PV production in August 2021 and December 2024.

Humidity also influences PV production, particularly by causing water vapor accumulation on solar panels, which can reflect and refract sunlight, reducing direct irradiation. Figure 8 compares humidity levels between August 2021 (73.5%) and December 2024 (82.71%), illustrating a negative correlation between relative humidity and PV output. Previous studies indicate that a humidity reduction from 60% to 48% can improve solar cell efficiency from 9.7% to 12.04% (Kazem et al., 2020).

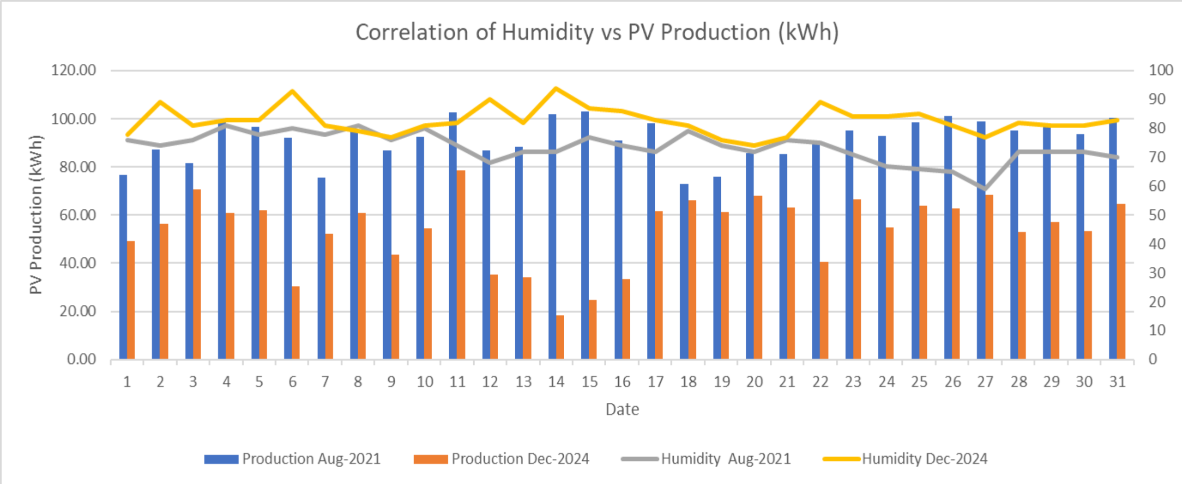

Figure 8. Correlation between humidity and PV production output in August 2021 and December 2024.

Moreover, wind conditions, such as wind speed and direction, impact PV module temperature, dust deposition, and long-term surface integrity (Hasan et al., 2022). When the wind speed is 3 m/s at an ambient temperature of 25 °C, module temperature decreases by approximately 11.0% in dusty modules compared to clean ones (Zhao et al., 2025). Wind scatters dirt and dust onto the surface of the solar panels, which can reduce transparency and prevent solar irradiation from reaching the surface of the panel (Rusănescu et al., 2023). Dust Accumulation with thermal cycling under varying wind causes surface degradation in the long term and reduces optical transmission. Figure 9 compares wind speed data for August 2021 and December 2024, revealing an average speed of 2.61 m/s in December 2024 and 2.35 m/s in August 2021. Wind movement functions as a natural cooling mechanism, reducing module temperatures and improving efficiency under extreme heat conditions.

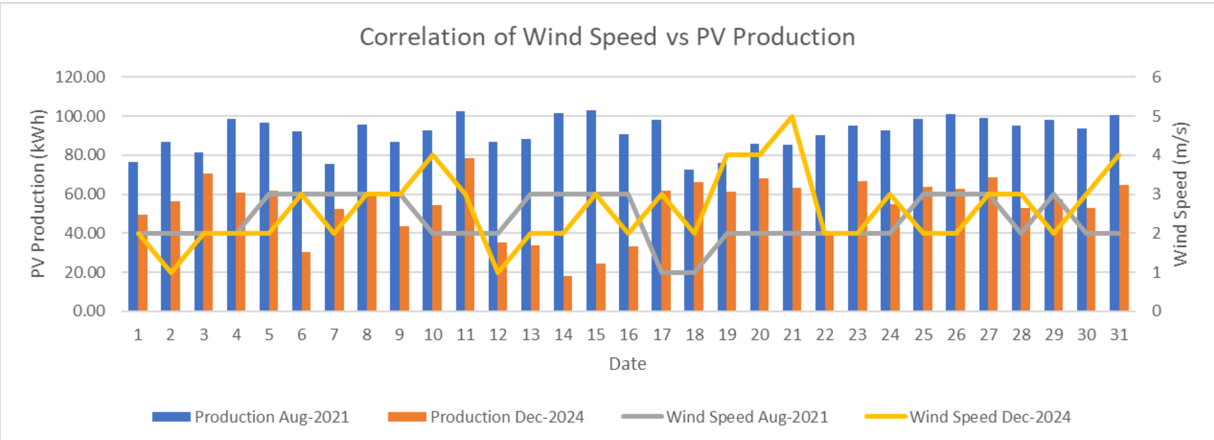

Figure 9. Correlation between wind speed and PV production in August 2021 and December 2024.

3.3 Discussion and Implications

The findings confirm that PV power plant performance degradation over time is influenced by both environmental and technical factors. While sunshine exposure is the primary driver of production fluctuations, secondary climatic effects, such as humidity, rainfall, and wind speed, also contribute to long-term efficiency losses. The significant performance divergence between installation (2020) and current output (2025) underscores the necessity for continued monitoring and intervention strategies.

Additionally, the performance disparities across sites suggest that installation-specific variables, such as shading, dust accumulation, and inverter reliability, must be considered when developing maintenance protocols. WP3 showed the steepest decline (7.8 %/year) compared to WP1 (4.2%) and WP2 (5.1%), which was attributed to three key factors: persistent vegetation shading, dust accumulation from nearby unpaved roads, and delayed inverter repairs.

Moving forward, future PV power plant designs should incorporate climate-resilient strategies, such as automated cleaning mechanisms, optimized tilt angles, and active cooling techniques to mitigate degradation and improve long-term efficiency. This study provides valuable insights into improving PV system reliability in tropical climates, contributing to sustainable energy planning and operational optimization.

4. Conclusions

This paper offers a thorough analysis of the five-year operational performance of a 120 kWp grid-connected rooftop PV power plant spread across several sites in Blora, Central Java, Indonesia. The results show how environmental and technical elements, such as dust accumulation, shading, temperature changes, and system maintenance, affect the long-term performance and degradation rate of the PV power plant.

Comparative performance data from 2020 to 2025 show varying degrees of efficiency loss across the sites. Widya Patra 3 experienced the most significant decline, with a 51.09% reduction in output, primarily due to persistent shading, high dust exposure from nearby unpaved roads, and delayed inverter repairs. In contrast, Widya Patra 2 showed the least degradation at 12.5%, benefiting from better site conditions and more consistent maintenance. These differences highlight the importance of site-specific factors, including dust exposure, shading influences, and operational stability, in defining long-term PV performance.

Variations in climate, especially in sunshine duration, temperature, rain intensity, humidity, and wind speed, have also been highlighted as major factors affecting PV power plants. We show that while high humidity and excessive rainfall lower efficiency due to increased surface reflectance and reduced irradiation, prolonged sunshine exposure increases energy generation. Moderate rain, on the other hand, has been shown to naturally reduce dust buildup, therefore enhancing energy conversion under ideal circumstances.

Although some uncontrolled variables, like dust buildup and shading, were not methodically tracked, their qualitative effect on degradation trends supports the importance of consistent maintenance, smart site planning, and better PV module designs to preserve long-term performance. The study results highlight the importance of proactive intervention strategies, including automated cleaning systems, optimal tilt angles, and active cooling technologies, to reduce degradation risks and improve PV system dependability in tropical settings.

This work offers an insightful analysis of actual degradation patterns, guiding the creation of next PV system designs suited to environmental conditions. PV power plants can attain consistent energy output and enhanced operational efficiency through climate-resilient strategies, optimal monitoring systems, and efficient maintenance procedures, thus supporting the long-term viability of solar energy as a dependable and sustainable power source.

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