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The Effect of Roof Slope and Orientation on The Performance of Grid PV Plants in Central Java, Indonesia

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ABSTRACT

This study presents a comprehensive five-year performance analysis of four 20 kWp grid-connected rooftop photovoltaic plants in Central Java, Indonesia, to evaluate the impact of roof slope and orientation. The investigated PV installations were configured with different orientations and tilt angles due to building constraints, namely LB3 (Northwest 315° / Southeast 135°) with a tilt angle of 20°, WP3 (Northeast 30°) with a tilt angle of 30°, KB (Northeast 15°) with a tilt angle of 30°, and LB2 (Northeast 45°) with a tilt angle of 20°. The research identifies an optimal configuration of 20° tilt with a Northeast (45°) orientation, yielding a peak DC power of 15.2 kW and demonstrating the highest initial and long-term energy production. However, this investigation reveals that one system with a near-optimal geometry failed, reducing its performance ratio by over 58% due to a single-array fault, while a suboptimal dual-orientation system maintained higher production through consistent operation. The data conclusively shows that performance degradation and component failure can outweigh the advantages of an optimal roof design. The study concludes that the viability of rooftop PV in Central Java depends on a dual strategy: prioritising optimal roof geometry to maximise energy potential and implementing a proactive operations and maintenance regime to protect the investment. These findings provide evidence-based guidance for stakeholders to optimise both the design and lifetime performance of solar energy systems.

Keyword: Rooftop PV; Roof Orientation; Tilt Angle; Performance; Central Java

1. INTRODUCTION

The global transition towards renewable energy is imperative to mitigate climate change and ensure sustainable development. Among various alternatives, solar photovoltaic (PV) technology has emerged as a leading solution due to its scalability, decreasing costs, and abundant resource availability. Indonesia, a country blessed with year-round high solar irradiation, has significant potential for solar energy generation. To harness this potential, the Indonesian government has actively promoted the adoption of PV systems, particularly through rooftop installations, to contribute to the national energy mix and achieve its renewable energy targets.

Central Java, a populous and industrially developing province, is a critical region for implementing solar energy projects. However, a primary challenge in urban and suburban settings is integrating PV systems into existing building infrastructure. Unlike ground-mounted solar farms, which can be optimised for maximum solar exposure, rooftop PV systems are constrained by the predetermined slope (tilt angle) and orientation (azimuth angle) of the building's roof. These geometric factors directly influence the amount of solar irradiance incident on the panel surface, thereby significantly affecting the system's energy yield.

Extensive research has been conducted to determine the optimal tilt and azimuth angles for PV modules. The general rule of thumb suggests that the optimal tilt angle is approximately equal to the location's latitude for maximising annual energy yield. However, in equatorial regions like Indonesia, which experience minimal seasonal variation in the sun's path, the optimal configuration often favours shallower tilt angles. Simulation-based studies using PVsyst and Helioscope software have demonstrated this trend across various Indonesian cities. For example, Rido Sukma Ramdani & Artiyasa (2024) found that an 8° tilt facing South was optimal for an on-grid system in Sukabumi, West Java—an area geographically close to Central Java. Similarly, Sugiono et al. (2022) identified a 10° tilt as optimal for rooftop PV systems in Semarang, Central Java, using Helioscope. These findings are particularly relevant as they reflect local conditions and software methodologies applicable to this study.

Further supporting this trend, Dyah Afriyani et al. (2019) and Ali & Basri (2022) used PVsyst to analyse the impacts of tilt and irradiance in various Indonesian contexts, linking tilt angle to performance ratio. International studies such as (Tuama et al., 2021) also validate the use of PVsyst, reinforcing its credibility and global applicability. Collectively, these simulation studies suggest that shallow tilt angles of 8 °- 10 ° are consistently optimal for rooftop PV systems in Java.

Complementing simulation results, experimental studies provide empirical validation under real-world conditions. Rita Hariningrum (2021) observed that a 0° tilt produced peak output between 10:00 and 15:00 in Semarang, highlighting the influence of daily solar variation. (Wirajati & Natha, 2021) found that a 15° tilt yielded the highest power output in Bali, while Fikri Nugroho et al. (2022) and Mardani et al. (2022) reported optimal tilts of 15° and 10°, respectively, in East Java. These results reinforce the shallow-angle trend and provide a robust empirical basis for comparison.

Theoretical and international literature further contextualises these findings. Babatunde et al. (2017) emphasised the combined impact of tilt, orientation, and environmental factors such as dust on PV performance. Yunus Khan et al. (2020) reviewed global tilt optimisation strategies, noting that optimal angles often approximate local latitude, while H.M.S. Husein et al. (2004) established the long-standing importance of tilt and orientation in PV design. In the Indonesian context, Pangestuningtyas D.L et al. (2020) modelled seasonal variation in Semarang, finding different optimal angles for rainy versus dry seasons—an important consideration for Central Java's climate.

Beyond conventional fixed-mount systems, niche studies have explored alternative technologies and analytical methods. Sadewo et al. (2022) demonstrated the yield-maximising potential of solar trackers, though fixed mounts remain more practical and economical for rooftop installations. Samsurizal et al. (2019) and Kurniawan et al. (2019) introduced regression-based modelling approaches, offering analytical depth for tilt optimisation. Despite this body of knowledge, a clear research gap remains. While simulation studies exist for other Indonesian locations, a comprehensive, empirical investigation quantifying the real-world performance of existing on-grid PV systems with different fixed-roof geometries in Central Java is lacking (Umam et al., 2025). Crucially, the long-term impact of system degradation and failures relative to the initial geometric advantages has not been thoroughly examined.

Therefore, this study bridges this gap by leveraging a five-year dataset from four operational 20 kWp rooftop PV plants in Cepu, Central Java. Moving beyond theoretical models, it offers evidence-based insights into how roof geometry and system health jointly affect energy yield. The objectives are to compare performance across different fixed-roof configurations, quantify energy losses due to design limitations and system faults, and provide practical recommendations for optimising rooftop PV planning and maintenance.

The findings of this study are expected to provide actionable insights for PV installers, architects, policymakers, and investors, enabling more accurate energy forecasts and highlighting the critical link between initial design, ongoing maintenance, and long-term project viability.

2. METHOD

This study employs a comparative case-study approach to analyse four existing 20 kWp grid-connected rooftop PV plants in Cepu, Central Java, Indonesia. The sites provide a natural experiment, featuring variations in roof orientation and slope as detailed in Table 1. All systems utilise polycrystalline silicon modules and comparable string inverter technology, ensuring a consistent technological basis for comparing geometric effects.

Electrical performance data, including daily AC energy output (kWh), was collected from the inverters' integrated monitoring systems. Meteorological data, ambient temperature, and wind speed were obtained from the nearest weather station of the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG). To enable site-specific performance analysis, the Plane of Array irradiance for each unique roof geometry was calculated from the GHI data using standard solar geometric models.

Table 1. Orientation and Slope of the Studied PV Plants

Location	Orientation	Slope
LB3	Northwest (315°) and Southeast (135°)	20°
WP3	Northeast (30°)	30°
KB	Northeast (15°)	30°
LB 2	Northeast (45°)	20°

The technical specifications of the photovoltaic modules and inverter used in this study (LB3, WP3, KB, LB2) are summarised in Table 2.

Table 2. Product specification

Modul Name	YL280P-29b
Module type	Polycrystalline silicon
Maximum Power (Pmax)	280 WP
Voltage at Maximum Power (Vmpp)	31.4 V
Current at Maximum Power (Impp)	8.92A
Open Circuit Voltage (Voc)	38.2 V
Panel Efficiency	17.1%
Inventer Model	SOFAR 11KTL-X
Max. DC Input Voltage	1000V
Operating MPPT Voltage Range	160-960
Nominal Grid Voltage	3/N/PE, 230/400V
Nominal Grid Frequency	50/60 Hz
Nominal Output Power	10000W
Max Output Power	11000VA

The primary metric for evaluating and comparing the performance of the four PV plants is the Specific Yield (Y_f), which is calculated as:

$$Y_f = E_{AC} / P_{rated} \quad (1)$$

where:

- E_{AC} is the total AC energy output over the period (kWh),
- P_{rated} is the installed capacity of the system (kWp).

The Specific Yield, expressed in kWh/kWp, normalises energy production by system size, enabling direct comparison between installations. Furthermore, the Performance Ratio (PR) was calculated to assess each system's overall efficiency, independent of solar resource variability. The PR is defined as:

$$PR = (Y_f / Y_r) * 100\% \quad (2)$$

where:

- Y_f is the Final Yield (kWh/kWp), as defined above.
- Y_r is the Reference Yield (kWh/kWp), calculated as H_{POA} / G_{STC}, where H_{POA} is the total in-plane irradiation received by the array (kWh/m²), and G_{STC} is the irradiance at Standard Test Conditions (1 kW/m²).

This real-world study acknowledges certain limitations. Unquantified variables such as partial shading, minor maintenance discrepancies, and varying soiling rates may introduce uncertainty into the comparative analysis. The findings are also specific to the climatic conditions of Cepu, Central Java, during the study period.

3. RESULTS AND DISCUSSION

An analysis of the initial performance data from October 2020 provides a baseline comparison of the four rooftop PV system configurations under near-ideal, start-of-life conditions. As summarised in Table 2, all systems demonstrated high and consistent performance, with Performance Ratios (PR) exceeding 78.9%, confirming good installation quality and the general viability of rooftop PV in Central Java.

All four systems demonstrated high and consistent performance in their initial state, with Performance Ratios exceeding 78.9%. This indicates that the installations were of good quality and that all configurations are viable for solar energy generation in Central Java. However, the small but measurable variations in Final Yield (Y_f) and PR reveal the influence of geometric layout.

Table 3. Performance Comparison of PV Plants at Initial Operation (October 2020)

Location	**P_{rated} (kWp)**	**October 2020**				
		Days	**E_{AC} Production (kWh)/month**	**yf**	**yr**	**PR (%)**
Electrical Laboratory (LB3)	20	31	2546.43	4.11	5.2	78.98
Instrumentation Laboratory (LB2)	20	31	2632.25	4.25	5.2	81.65
Widya Patra 3 (WP3)	20	31	2587.28	4.17	5.2	80.25
Main Office (KB)	20	31	2571.22	4.15	5.2	79.75

Table 4. Performance Comparison of PV Plants After 5 Years of Operation (September 2025)

Location	**P_{rated} (kWp)**	**September 2025**				
		Days	**E_{AC} Production (kWh)/month**	**yf**	**yr**	**PR (%)**
Electrical Laboratory (LB3)	20	30	2137.84	3.56	5.2	68.52
Instrumentation Laboratory (LB2)	20	30	2515.46	4.19	5.2	80.62
Widya Patra 3 (WP3)	20	30	1049.42	1.75	5.2	33.64
Main Office (KB)	20	30	2121.72	3.54	5.2	68.00

The performance data, ranked from highest to lowest yield, is as follows:

- LB2: 4.25 kWh/kWp/day
- WP3: 4.17 kWh/kWp/day
- KB: 4.15 kWh/kWp/day
- LB3: 4.11 kWh/kWp/day

The top-performing system, LB2 (Northeast 45°, 20° tilt), suggests that a Northeast orientation is highly effective for this location, as shown in Figure 1. In the southern hemisphere, the sun's path is predominantly in the northern sky.

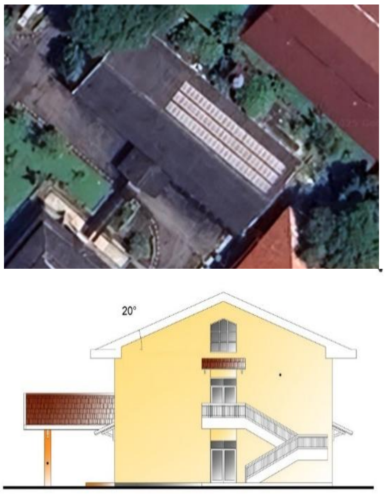

Figure 1. The orientation and tilt angle of the Instrumentation Laboratory (LB2)

Therefore, orientations facing North to Northeast receive more direct sunlight throughout the day than those facing other directions. The superior performance of LB2 over the other Northeast-facing systems (WP3 and KB) indicates that its specific combination of a 45° azimuth and 20° tilt was the most optimal among the configurations studied, as shown in Figure 2.

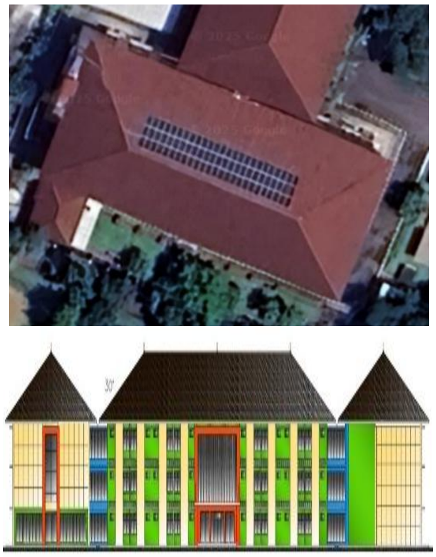

Figure 2. The orientation and tilt angle of Widya Patra 3 (WP3)

Moreover, a direct comparison can be made between systems with similar orientations but different tilts. LB2 vs WP3 (Northeast 30°, 30° tilt): LB2 produced a slightly higher yield (4.25 vs 4.17 kWh/kWp/day). This suggests that, for a Northeast orientation at Central Java's latitude (~-7°), a shallower 20° tilt angle may be more optimal than a steeper 30° angle. This aligns with the general principle that optimal tilt angles in equatorial regions are often relatively shallow.

LB2 vs. KB (Northeast 15°, 30° tilt): The significantly better performance of LB2 highlights that both azimuth and tilt play a role, as shown in Figure 3. While KB faces closer to true North (which is theoretically ideal in the southern hemisphere), its steeper 30° tilt appears less optimal than LB2's 20° tilt, resulting in a lower energy yield.

Figure 3. The orientation and tilt angle of the Main Office (KB)

The electrical Laboratory (LB3) has a unique dual-orientation configuration, with panels facing Northwest (315°) and Southeast (135°). This system recorded the lowest yield of the four, as shown in Figure 4. This is expected, as during October (a spring month in the southern hemisphere), neither the Northwest nor the Southeast faces the sun's path for extended periods. A split array effectively elongates the production curve, generating more power in the early afternoon (Southeast) and late afternoon (Northwest) but sacrificing peak production at midday when solar irradiance is highest. This result indicates that while a dual-orientation setup can be a practical solution for roofs with limited space, it typically results in a 5-7% reduction in total energy yield compared to a single, well-oriented array like LB2.

Figure 4. The orientation and tilt angle of the Electrical Laboratory (LB3)

Therefore, the Instrumentation Laboratory configuration produced the highest energy yield under Central Java's climatic conditions. The analysis confirms that even small variations in orientation and tilt can lead to measurable differences in output. For rooftop PV planning in this region, prioritising a Northeast-to-North-facing roof plane with a relatively shallow tilt angle (around 20°) is recommended to maximise energy production.

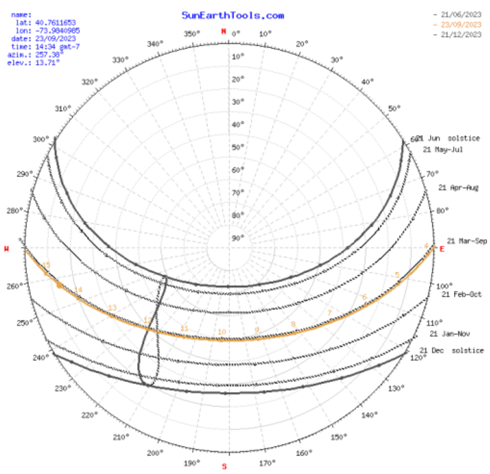

Figure 5. Solar Path Diagram

The solar path diagram shows that the sun travels across the southern part of the sky at high elevations throughout the year due to Central Java's low latitude. The high solar altitude suggests that moderate tilt angles are more suitable for maximising irradiance capture. The analysis also shows that a Northeast orientation aligns well with the solar trajectory during peak irradiance periods. This observation supports the empirical findings of this study, which show that the configuration with a 20° tilt and a 45° Northeast orientation produced the highest energy output among the investigated PV systems.

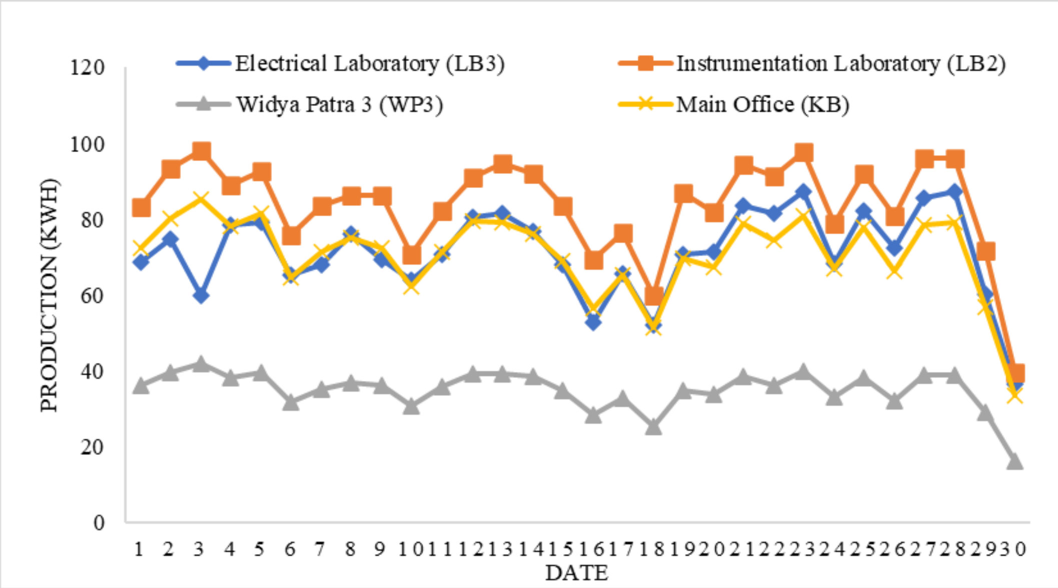

Figure 6. Comparison of PV Production in September 2025

A one-way analysis of variance (ANOVA) was performed to determine whether there are significant differences in mean photovoltaic (PV) energy production among the four monitored systems: Electrical Laboratory (LB3), Instrumentation Laboratory (LB2), Widya Patra 3 (WP3), and Main Office (KB).

Descriptive statistics reveal noticeable differences in average energy production across the systems. The Instrumentation Laboratory (LB2) recorded the highest mean value (83.85), followed by the Electrical Laboratory (LB3) (71.26) and the Main Office (KB) (70.72). In contrast, Widya Patra 3 (WP3) exhibited a substantially lower mean production (34.98). The observed variances indicate moderate dispersion within each group; however, differences in mean values suggest potential systematic performance variations among installations.

The ANOVA results indicate that the between-group sum of squares (SS = 39,847.05) is considerably larger than the within-group sum of squares (SS = 12,582.37), suggesting that most of the total variability in PV production is attributable to differences among systems rather than random variation within systems.

The calculated F-value ($F = 122.45$) greatly exceeds the critical F-value ($F_{crit} = 2.68$) at $\alpha = 0.05$. Additionally, the p-value (8.50×10^{-36}) is far below the significance threshold ($p < 0.05$).

Therefore, the null hypothesis (H_0), which states that there is no significant difference in mean PV production among the four systems, is rejected. These results confirm that statistically significant differences exist in the energy production performance of the evaluated PV installations. The substantial disparity in energy production, particularly the significantly lower output from the WP3 system, may indicate a fault affecting one of the PV arrays.

Table 5. Summary of PV Production in September 2025

Location	***Count***	***Sum***	***Average***	***Variance***
Electrical Laboratory (LB3)	30	2137.84	71.26133333	131.0199361
Instrumentation Laboratory (LB2)	30	2515.46	83.84866667	158.7140809
Widya Patra 3 (WP3)	30	1049.42	34.98066667	27.68625471
Main Office (KB)	30	2121.72	70.724	116.4545076

Table 6. Results of the One-Way ANOVA Test for PV Production in September 2025

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	39847.05479	3	13282.3516	122.4533181	8.5E-36	2.682809
Within Groups	12582.3686	116	108.4686948			
Total	52429.42339	119				

Furthermore, the module temperature data provides critical insights into the operational conditions and thermal performance of the four PV plants, directly linking to their energy yield and long-term degradation, as illustrated in Figure 5. Temperature is a key factor influencing photovoltaic efficiency, and its impact becomes especially pronounced under high irradiance conditions typical of Central Java's climate.

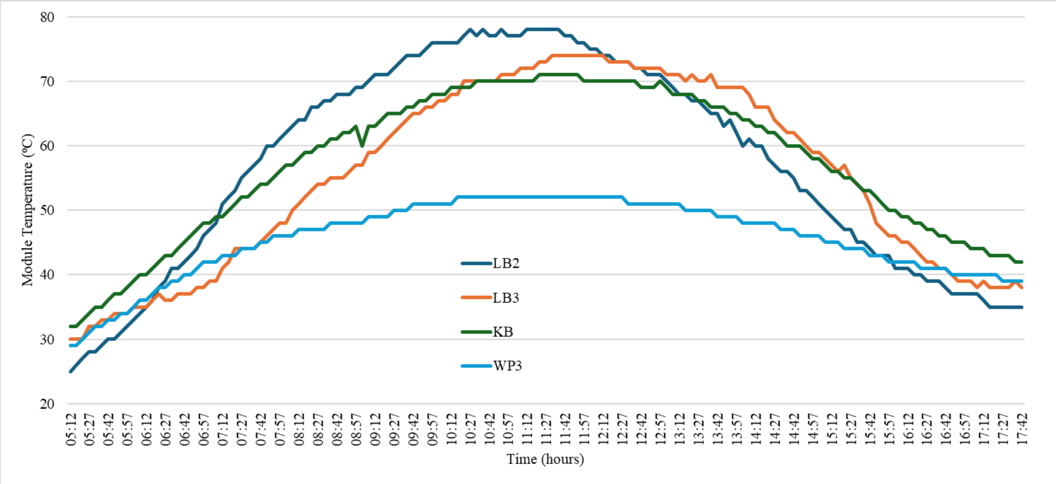

Figure 7. Module Temperature Profiles on a Clear-Sky Day

A significant and consistent temperature differential was observed across the four systems throughout the day, establishing a clear thermal hierarchy. The LB2 system recorded the highest module temperature, peaking at 78°C. Closely following was the KB system, which reached 71°C, while LB3 (dual orientation) reached 74°C. In stark contrast, the WP3 system maintained the lowest peak temperature at just 52°C. The most striking outcome is the 26°C difference between LB2 and WP3, a substantial thermal gap with profound implications for both instantaneous performance and long-term module degradation.

This temperature disparity directly affects conversion efficiency. For polycrystalline silicon modules, performance typically declines by -0.3% to -0.5% per °C increase in temperature. Applying a conservative coefficient of -0.4%/°C, the 26°C difference between LB2 and WP3 translates to an approximate 10.4% reduction in instantaneous efficiency for LB2 at peak irradiance. In other words, despite receiving more sunlight, LB2's modules were significantly less efficient at converting it into electricity during the hottest part of the day.

LB2, the system with the highest overall energy yield, operates under the most thermally stressful conditions. Its superior geometric configuration enables it to capture substantially more solar irradiance, which compensates for the efficiency losses caused by elevated temperatures. This underscores the complex interplay between irradiance capture and thermal effects, highlighting that optimal energy yield is not solely a function of temperature minimisation but also of strategic orientation and tilt that maximise solar exposure.

Furthermore, the daily performance profiles recorded on 23 September 2025 under clear-sky conditions provide a definitive side-by-side comparison of the four PV plants. As shown in Figure 6, this dataset isolates the influence of roof geometry and system health by eliminating weather variability, thereby providing a reliable benchmark for evaluating energy production potential across configurations.

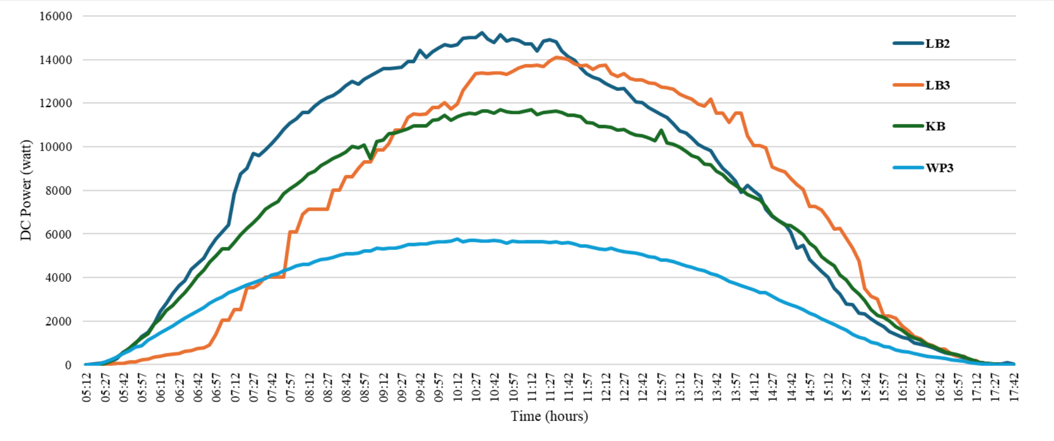

Figure 8. DC Power Output on a Clear-Sky Day (23 September 2025)

The data reveal a distinct performance hierarchy among the functioning systems. LB2, configured with a 20° tilt and Northeast 45° azimuth, achieved the highest peak DC power output at approximately 15.2 kW. KB followed with 11.6 kW, while LB3—despite its dual-orientation layout—reached 14.0 kW. WP3, with a 30° tilt and Northeast 30° azimuth, recorded the lowest peak at just 5.8 kW. These results confirm that the LB2 configuration is the most effective for solar energy capture in Central Java, outperforming KB by over 3.6 kW (a 31% margin) at peak. Moreover, LB2 maintained a consistently higher power curve throughout the day, reinforcing its geometric advantage.

The performance of LB3 highlights the inherent trade-offs of a dual-orientation array. While its peak power is respectable, its production curve is notably flatter and more symmetrical than those of LB2 and KB. This is attributable to its split-facing design: Southeast-facing panels peak in the morning, while Northwest-facing panels peak in the afternoon. As a result, LB3 avoids a pronounced midday spike, which is typically associated with maximum irradiance. Although this configuration may offer operational benefits such as load balancing, it sacrifices peak performance during the most productive solar hours.

A visual comparison of the area under the power curves between LB2 and LB3 quantifies the energy loss associated with dual-orientation setups. Between 09:00 and 14:00—when solar irradiance is highest—LB3 consistently underperforms relative to LB2. This gap represents the practical cost of accommodating roof constraints that prevent a unified, optimally oriented array. While dual-orientation may be necessary in certain architectural contexts, its impact on daily energy yield must be carefully considered during system design and feasibility assessment.

4. CONCLUSION

This study has demonstrated the critical factors governing the performance of rooftop PV systems in Central Java. The results indicate that system configuration and operational reliability are key factors affecting PV performance.

Roof geometry influences the potential energy production of rooftop PV systems. The configuration of a 20° tilt with a 45° Northeast orientation was unequivocally identified as optimal, yielding a peak power of 15.2 kW and the highest initial energy production. In contrast, a dual-orientation setup incurred a quantifiable 5-7% energy penalty due to its inability to maximise peak irradiance.

System reliability and maintenance define the practical floor of performance. The research revealed that the initial advantage of an optimal roof can be entirely negated by component failure. The WP3 installation experienced a 58% reduction in performance ratio to a single-array fault—serves as a stark warning. This failure was identified through power output data and abnormal temperature patterns. This finding indicates that system faults can significantly reduce PV output, regardless of the system's initial configuration.

Overall, the results suggest that both system design and operational maintenance play important roles in maintaining stable PV performance. Proper system configuration and regular monitoring are therefore essential for ensuring reliable operation of rooftop PV systems in tropical regions.

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