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Assessment of Performance Ratio Variation in a 225 kWp Rooftop PV System Exposed to Industrial Fly Ash at PT Jaya Energi

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Abstract-This study evaluates monthly monitoring data from a 225 kWp grid-connected rooftop photovoltaic (PV) system at PT Jaya Energi, an industrial facility where boiler-derived fly ash may contribute to module soiling. Data from Huawei FusionSolar were analyzed for September–December 2025 and May–August 2026; January–April 2026 was excluded from the comparison because frequent rainfall and cloud cover could affect irradiance and remove accumulated dust. The recorded monthly Performance Ratio (PR) ranged from 54.9% to 60.3% during September–December 2025 and from 46.8% to 54.4% during May–August 2026. Within the latter period, PR decreased from 54.4% in May to 46.8% in August, a reduction of 7.6 percentage points (13.97% relative to May). This trend indicates lower recorded system performance, but it cannot be attributed exclusively to fly-ash soiling because direct soiling measurements and controlled clean/soiled comparisons were unavailable. The daily energy log recorded 0.00 kWh fed to the grid on each listed date; this supports zero recorded daily export but does not prove that instantaneous reverse power was absent at all times. The findings support further site-specific monitoring before a fixed cleaning interval or definitive zero-export performance claim is established.

Keywords: Rooftop PV, Soiling, Fly Ash, Performance Ratio, Zero Export

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1. Introduction

Solar photovoltaic (PV) technology converts solar irradiance into electricity and is increasingly used to supply on-site demand. For industrial rooftop systems, performance depends not only on module and inverter characteristics but also on environmental conditions, maintenance practices, and the relationship between PV generation and facility load [1].

Rooftop PV systems in industrial facilities can be exposed to airborne particles generated by nearby processes. At PT Jaya Energi, solid residues from the combustion of spent bleaching earth (SBE) used as boiler fuel include fly ash and bottom ash. Deposited particles may reduce the optical transmittance of module cover glass and thereby reduce energy yield. However, the magnitude of this effect at a particular site depends on particle properties, humidity, rainfall, wind, module tilt, and cleaning history; these factors should be considered when interpreting operational monitoring data [2], [3].

In its production process, PT Jaya Energi utilizes SBE waste from CPO processing residues as fuel for the factory boiler to generate thermal energy. The final combustion process yields dense solid particulate byproducts, namely fly ash and bottom ash. The characteristics of industrial fly ash dust include extremely fine particle sizes, high opacity, and strong adhesive properties when interacting with local air humidity. The adhesion of this type of dust to solar modules drastically reduces the transmittance of the cover glass, thereby decreasing the solar irradiance intensity that can be converted into electrical energy by the photovoltaic cells [3]. Research and development in PV performance under various working conditions must thrive, the constant threat of dust soiling on PV surfaces and other

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pertinent environmental elements undermines the consistency of power yield [4].

Ambient temperature and solar irradiance significantly affect the power output of PV modules. Solar irradiance and module temperature affect PV output and can also influence comparisons of monthly performance. Performance Ratio (PR) normalizes energy yield against the available solar resource, but it does not by itself isolate soiling from shading, equipment availability, sensor uncertainty, or other system losses. Accordingly, a decline in monthly PR is evidence of a change in normalized system performance, not a direct measurement of fly-ash deposition unless supported by dedicated soiling measurements or a suitable clean reference [5], [6], [7].

Field studies have documented performance losses associated with fly-ash and other forms of PV soiling, while review studies emphasize that accumulation and removal rates vary with local environmental conditions and cleaning practices [5], [6], [9]. In tropical environments, rainfall may remove part of the deposited material, whereas relatively dry periods can allow dust to accumulate. For this reason, the present study compares two selected observation windows rather than treating the intervening months as a continuous degradation record. The module condition shown in Figure 1 provides site context, but visual evidence alone does not quantify soiling loss.

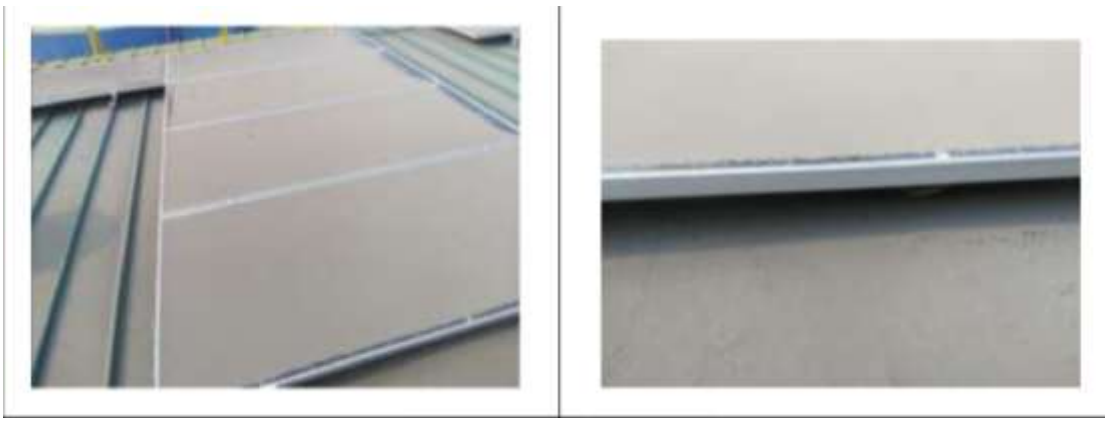


Figure 1. Solar modules contaminated by fly ash accumulation

The fine particle size and physicochemical characteristics of fly ash can enhance its deposition and adhesion on PV module surfaces. In humid environments, moisture-induced capillary forces may promote particle agglomeration and strengthen adhesion, resulting in persistent soiling layers that reduce the optical transmittance of the module surface [8].

Industrial grid-connected PV installations may use export-limitation controls to prevent net energy export to the utility grid. In this study, zero-export performance is assessed using the available daily "Fed to grid" energy records. A daily value of 0.00 kWh indicates that no daily export was recorded at the data resolution provided; it does not necessarily demonstrate that reverse power flow was absent at every instant. Claims about control response therefore require time-resolved measurements at the point of common coupling and, where available, verification of the inverter or export controller logs [7].

2. Method

2.1 Research Design and System Specification

This study uses a quantitative-descriptive case-study approach to examine a 225 kWp grid-connected rooftop PV installation at PT Jaya Energi. The system is connected to a PLN supply with a stated capacity of 1,110 kVA. Monthly monitoring data were obtained from Huawei FusionSolar for September–December 2025 and May–August 2026. January–April 2026 was excluded from the comparative analysis because frequent rainfall and cloud cover during that interval could affect irradiance and potentially remove accumulated dust. The analysis focuses on recorded PR, energy yield,

irradiation, and module temperature. Daily energy records were separately examined to describe recorded grid export. The study is observational; it does not include direct fly-ash sampling, soiling sensors, or controlled comparisons between clean and soiled modules.

A key limitation is that physical sampling of the fly-ash layer was not conducted because rooftop access was subject to site health-and-safety requirements. In addition, no dedicated soiling sensor or optical-transmittance measurement was available. Therefore, the observed PR changes cannot be attributed exclusively to fly ash; thermal effects, irradiance variation, rainfall, shading, equipment operation, and other factors may also contribute. The monitoring windows are discontinuous and should not be interpreted as a continuous eight-month degradation trajectory [6]. Dust thickness is not measured directly but is estimated based on the reduction in the PR value observed before and after cleaning [9].

The primary components of the system consist of 409 units of Trina Solar TSM-DE19 550 Wp monocrystalline photovoltaic modules and 3 units of Huawei string inverters (1 unit of SUN2000-115KTL and 2 units of SUN2000-30KTL, with a total inverter capacity of 175 kW). From this system configuration, the system's DC/AC ratio is calculated as follows:

$$\text{DC/AC Ratio} = \frac{P_{DC,\text{nom}}}{P_{AC,\text{nom}}} = \frac{225\ \text{kWp}}{175\ \text{kWac}} = 1{,}29 \quad (1)$$

The proportion of the PV system capacity relative to the connected PLN power capacity is expressed as:

$$\text{Capacity precentage} = \frac{225\ \text{kWp}}{1.110\ \text{kVA}} \times 100\% = 20.27\% \quad (2)$$

The spatial arrangement, rooftop orientation, and sensor distribution of the 225 kWp PV installation at the industrial site are depicted in Figure 2.



Figure 2. Image of research location

2.2 Monitoring and Data Collection

Monitoring data were exported from Huawei FusionSolar. The available records contain monthly values for theoretical yield, sun hours, PV generation yield, irradiation, PR, and average module temperature. The irradiance data monitored through the FusionSolar interface are presented in Figure 3. The platform data were used as reported; no independent sensor calibration or reconstruction of missing periods was performed. The immediate post-cleaning PR was not available as a measured baseline, so September 2025 is treated below as the highest PR observed in the first monitoring window, not as a verified clean-module reference [7].

The analysis compares September–December 2025 with May–August 2026. The monthly PR values are compared descriptively, while acknowledging that differences in weather and operating conditions can influence the results. The study does not claim that the selected windows isolate fly-ash soiling from all other performance-loss mechanisms.

Monitoring was performed at intervals following site cleaning between 2025 and 2026. For this analysis, September–December 2025 and May–August 2026 were selected as the two observation windows. January–April 2026 was excluded because frequent rainfall and cloud cover could affect irradiance and potentially wash accumulated dust from module surfaces. This selection reduces the risk of directly comparing observations with very different rainfall conditions, but it does not establish that the selected months represent a controlled dry-season experiment or a continuous soiling-accumulation period.



Figure 3. Irradiance data monitored via the FusionSolar interface.

Monitoring the impact of fly ash soiling accumulation was conducted periodically post-cleaning from August 2025 through August 2026. However, to optimize analysis efficiency and eliminate data redundancy, this study applied a purposive sampling method, narrowing its focus to the May–August 2026 period. The exclusion of data from January to March 2026 was based on climatological factors, as the Indonesian region typically hits the peak of the rainy season during these months, bringing heavy precipitation. This high rainfall triggers an uncontrolled natural self-cleaning effect that flushes the solar module surfaces, which would distort the accuracy of the dust accumulation rate data caused purely by industrial operations. Thus, the May–August 2026 period was selected because it captures the transition into the dry season—creating an ideal framework to observe the long-term peak soiling phase and maximum performance degradation without rain intervention.

To quantify the exact impact of soiling on system performance, the relative and total PR reductions were calculated against the highest observed PR. Generally, the percentage of energy loss due to soiling (soiling loss) is expressed using the following equation:

$$L_{soiling} = \frac{PR_{initial} - PR_{final}}{PR_{initial}} x100\% \quad (3)$$

where PR_reference is the selected observed reference PR and PR_later is the PR in the later observation. Because a verified immediately post-cleaning PR and direct soiling measurements were unavailable, the results are reported as relative PR reductions rather than definitive fly-ash soiling losses [6], [10].

PR is a normalized indicator of PV system performance and should be calculated consistently with the applicable monitoring methodology, including clearly defined energy and irradiance periods. In this study, the monthly PR values supplied by the monitoring platform are analyzed as reported. The calculation inputs, units, averaging method, and time resolution should be documented in the final submission so that the reported values can be independently reproduced. Relevant PV performance-monitoring literature provides context for interpreting normalized yield and operational losses [7]

Table 1 summarizes the monthly performance data for September–December 2025. Table 2 summarizes the available data for May–August 2026. The two tables represent separate observation windows and should not be described as a continuous monitoring series.

Table 1. PV system performance data after cleaning (Sep 2025 baseline)

Period	Average Theoretical Yield (kWh)	Average Sun Hours (H)	Average PV Generation Yield (kWh)	Average Irradiation (kWh/㎡)	Average PR Performance Ratio(%)	Average Temperature(°C)
Sep-25	1219.02	10.4	735.59	5.419	60.3%	32
Oct-25	1186.33	10.6	702.38	5.274	59.2%	32.6
Nov-25	1085.61	10.5	630.80	4.826	58.1%	32.3
Dec-25	1254.12	10.3	688.29	5.575	54.9%	33

Table 2. PV system performance data 8 months post-cleaning.

Period	Average Theoretical Yield (kWh)	Average Sun Hours (H)	Average PV Generation Yield (kWh)	Average Irradiation (kWh/㎡)	Average Performance Ratio (%)	Average Temperature (°C)
May-26	965.13	10.0	523,323	4.290	54.4%	31.8
Jun-26	920.02	9.6	494,045	4.095	53.7%	30.3
Jul-26	859.01	9.7	441,369	3.819	51.4%	29.7
Aug-26	835.00	9.5	390,526	3.712	46.8%	30.2

3. Result and Discussion

3.1 Analysis of PV Performance Degradation

The highest PR recorded in the September–December 2025 observation window was 60.3% in September 2025. PR subsequently decreased to 54.9% in December 2025. In the later observation window, PR decreased from 54.4% in May 2026 to 46.8% in August 2026. These observations indicate lower recorded normalized performance in the later months, but the data do not isolate fly-ash deposition as the sole cause. The decline in the PR during the May–August 2026 period is detailed in Table 3.

Table 3. Decline Performance Ratio (May–August 2026)

Period	Performance Ratio (%)	Description
May-26	54.4	Highest Value
Jun-26	53.7	
Jul-26	51.4	
Aug-26	46.8	Lowest Value

Relative PR reduction within the observed soiling period (using May 2026 as the initial reference point against August 2026 as the lowest point):

$$L_{1_soiling} = \frac{54.4\% - 46.8\%}{54.4\%} x100\% = 13{,}97\% \quad (4)$$

Total PR reduction relative to the cleanest post-cleaning condition (using the overall highest baseline from September 2025 against the lowest point in August 2026):

$$L_{2_soiling} = \frac{60.3\% - 46.8\%}{60.3\%} x100\% = 22{,}38\% \quad (5)$$

Between May and August 2026, PR decreased from 54.4% to 46.8%, an absolute reduction of 7.6 percentage points and a relative reduction of approximately 13.97% (7.6/54.4 × 100). Comparing the highest PR observed in September 2025 (60.3%) with the August 2026 value (46.8%) gives an absolute difference of 13.5 percentage points and a relative reduction of approximately 22.39% (13.5/60.3 × 100). The latter comparison is between two observed monthly values; September 2025 is not a verified clean-module baseline. Neither percentage should be interpreted as a direct, independently measured fly-ash soiling loss. A detailed relative PR reduction during the observed period and relative PR reduction between the two reference periods is summarized in Table 4.

Table 4. Summary of PR reductions

Comparison	Absolute Decrease (% points)	Relative Decrease (%)	Duration
Within the soiling period (May–Aug 2026)	7.6	≈ 13.97%	4 Months
The optimal baseline (Sep 2025 → Aug 2026)	13.5	≈ 22.38%	12 Months

The appropriate cleaning interval cannot be determined from the available PR data alone. The comparison covers two observation windows: September–December 2025 and May–August 2026. January–April 2026 was excluded because frequent rainfall and cloud cover could affect solar irradiance and potentially remove accumulated dust. Consequently, the selected windows provide a descriptive comparison under differing environmental conditions rather than a continuous monitoring record. During May–August 2026, PR decreased by 7.6 percentage points, from 54.4% to 46.8%; this corresponds to a 13.97% relative reduction from the May value.

Direct soiling measurements, controlled comparisons between clean and soiled modules, and verified post-cleaning PR data were unavailable. Therefore, the observed PR decline cannot be attributed exclusively to fly-ash accumulation. Changes in irradiance, rainfall, module temperature, shading, equipment availability, and other operating conditions may also have contributed [6]. A fixed cleaning schedule should be determined only after additional monitoring quantifies soiling-related losses and an economic assessment compares recoverable energy value with cleaning costs.

Cleaning-schedule optimization generally involves balancing the value of energy lost while modules are soiled against the cost of cleaning. In the present study, the required site-specific inputs—including a directly measured soiling-loss rate, cleaning cost per cycle, and value of recovered electricity—are not available. Therefore, the cited optimization framework can guide future analysis but cannot yet support a numerical optimal cleaning interval for this PV system [11].

3.2 Analysis of Fly Ash Dust Impact on the 225 kWp PV System Power Output

Evaluating variations in the Performance Ratio across different operational phases provides a granular view of how fly ash dust affects overall efficiency. Calculations were executed by applying the determined Performance Ratio (PR) values across five repetitive iterations over different months to ensure statistical accuracy [12]. The technical analysis of the power output was calculated using the following formula:

$$P(t) = P_{peak} \times \left(\frac{I(t)}{1000}\right) \times PR \quad (6)$$

Where:

P(t) = Power output at time t (Watts).
P_peak = Installed PV capacity (225 kWp).
I(t) = Instantaneous solar irradiance (805.9 W/m²).
1000 W/m² = Standard Test Condition (STC) solar irradiance intensity.
PR = Performance Ratio.

Calculation of $P(t)$:

Under Optimal / Clean Conditions (PR = 60.3%)

$$P(t) = 225 \times \left(\frac{805.9}{1000}\right) \times 0.603$$

$$P(t) = 225 \times 0.8059 \times 0.603$$

$$P(t) \approx (109.34\ \text{kW})$$

Under Soiled / Dirty Conditions (PR = 46.8%):

$$P(t) = 225 \times \left(\frac{805{,}9}{1000}\right) \times 0{,}468$$

$$P(t) = 225 \times 0.8059 \times 0.468$$

$$P(t) \approx (84.86\ \text{kW})$$

At an assumed irradiance of 805.9 W/m², the simplified calculation gives approximately 109.34 kW for PR = 60.3% and 84.86 kW for PR = 46.8%. These are illustrative estimates based on the stated equation and common irradiance, not directly measured instantaneous outputs. The difference should not be attributed exclusively to fly-ash soiling because the selected PR values were recorded in different months and under potentially different operating conditions.

3.3 Zero Export and Load Absorption Characteristics

The system is configured for zero-export operation. The Zero Export function on the inverter regulates the current and voltage supplied to the grid and consumed by the load [13]. Table 5 lists daily energy records in which the "Fed to grid" field is 0.00 kWh for every date shown. This supports the conclusion that no daily grid-export energy was recorded in the listed dataset. However, daily totals do not establish that instantaneous reverse power was absent at every moment, nor do they independently verify the dynamic response of the export-limitation controller. Time-resolved measurements at the point of common coupling and controller/inverter event logs would be needed for stronger validation.

Table 5. Historical dataset log for electrical energy and PV generation.

Date	Production consumption (kWh)	Generated by PV (kWh)	Fed to grid (kWh)	Consumed by appliances (kWh)
2025-08-01	14781.50	547.48	0.00	15328.98
2025-08-02	15481.83	449.61	0.00	15931.44
2025-08-03	15373.65	524.22	0.00	15897.87
2025-08-04	14707.38	493.67	0.00	15201.05
2025-08-05	14512.63	442.16	0.00	14954.79
2025-08-06	14791.20	503.19	0.00	15294.39
2025-08-07	15554.29	450.29	0.00	16004.58
2025-08-08	14001.14	423.20	0.00	14424.34
2025-08-09	13851.41	502.16	0.00	14353.57
2025-08-10	15062.24	600.12	0.00	15662.36
2025-08-11	16044.26	601.69	0.00	16645.95
2025-08-12	15946.78	627.78	0.00	16574.56
2025-08-13	16151.31	571.89	0.00	16723.20
2025-08-14	15856.82	599.66	0.00	16456.48
2025-08-15	14916.41	643.92	0.00	15560.33
2025-08-16	12411.55	629.46	0.00	13041.01
2025-08-17	14728.77	609.08	0.00	15337.85
2025-08-18	14720.21	377.77	0.00	15097.98
2025-08-19	14897.94	467.02	0.00	15364.96
2025-08-20	8095.96	743.00	0.00	8838.96
2025-08-21	11757.28	601.86	0.00	12359.14
2025-08-22	13466.47	727.88	0.00	14194.35
2025-08-23	13133.00	758.14	0.00	13891.14
2025-08-24	13327.39	694.77	0.00	14022.16
2025-08-25	14707.41	752.37	0.00	15459.78
2025-08-26	14564.43	655.63	0.00	15220.06

2025-08-27	14571.96	630.67	0.00	15202.63
2025-08-28	15728.49	630.28	0.00	16358.77
2025-08-29	16091.76	680.00	0.00	16771.76
2025-08-30	15877.84	728.33	0.00	16606.17
2025-08-31	15902.72	732.41	0.00	16635.13

Across all dates listed in Table 5, recorded energy fed to the grid is 0.00 kWh per day. This is consistent with the intended zero-export operating mode during the logged period, but it does not prove that the zero-export control operated flawlessly at every instant. The daily data also show that the listed PV generation (approximately 377.77–758.14 kWh/day) was lower than the recorded facility energy demand values. The energy-balance column headings and measurement boundaries should be verified against the original monitoring export before publication, because the reported "Production consumption" and "Consumed by appliances" values appear to differ by the PV generation amount.

For context, even during the lowest logged production load baseline (August 20, 2025), the minimum internal energy consumption was 8,095.96 kWh, while the PV system contributed 743 kWh. Because the PV system's generation capacity is significantly smaller than the overall industrial load profile, the system naturally operates in a safe self-penetration mode, minimizing any risk of triggering a grid connection trip due to reverse power.

4. Conclusion

The monitoring data show a decline in recorded PR across the selected observation windows. In September–December 2025, monthly PR decreased from 60.3% to 54.9%; in May–August 2026, it decreased from 54.4% to 46.8%, a reduction of 7.6 percentage points or 13.97% relative to May. Comparing September 2025 with August 2026 gives a difference of 13.5 percentage points, equivalent to a 22.39% relative reduction; however, September 2025 is the highest observed value, not a verified clean-module baseline. Because the observation windows are discontinuous and direct soiling measurements and controlled clean/soiled comparisons were unavailable, these PR changes cannot be attributed exclusively to fly ash or used to establish a constant monthly degradation rate. A site-specific cleaning interval should therefore be set only after additional monitoring quantifies soiling-related losses and an economic assessment compares the value of recoverable energy with cleaning costs. For zero-export operation, the daily log records 0.00 kWh fed to the grid on each listed date, which supports zero recorded daily export but does not establish that instantaneous reverse power was absent at all times. Time-resolved power measurements at the grid connection and export-controller logs are recommended to validate zero-export performance more rigorously.

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