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Maintenance Cost Optimization Model for Rooftop PV Based on a Seasonal Soiling Model and Economic Cleaning Threshold to Improve the Performance Ratio

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Abstract

Background: The Performance Ratio (PR) of photovoltaic (PV) systems in tropical monsoon regions decreases due to soiling accumulation on module surfaces, yet techno-economically optimal cleaning strategies remain unavailable specifically for the Indonesian context.
Objective: This study aims to evaluate the investment feasibility of a 400 kWp rooftop PV system in the Cikarang industrial estate, determine the optimal cleaning strategy, and quantify the system's contribution to carbon emission reduction.
Methods: The research employs a quantitative approach based on 1,503 days of operational data (2022–2025), using an integrated framework combining a Seasonal Soiling Model (SSM) with rain-reset parameters, an Economic Cleaning Threshold (ECT) with three lookback versions, two-layer risk analysis (OAT and Monte Carlo simulation, 10,000 iterations), and carbon emission analysis.
Results: The investment is feasible with NPV of IDR 2.48 billion, IRR of 16.73%, payback of 9 years, and LCOE of IDR 828.77/kWh (25.7% below PLN tariff), with 100% probability of positive NPV. The optimal strategy is annual cleaning in August (S1), yielding NPV IDR 99.2 million higher than existing practice. The system reduces 9,258 tons CO_2 over 25 years with negative abatement cost of USD −21.21/ton CO_2.
Conclusion: The integrated TEA-ECT framework advances rooftop PV asset management by demonstrating that value-based, seasonally adaptive cleaning optimization simultaneously enhances economic returns and environmental performance, providing a replicable methodology for tropical monsoon regions.

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INTRODUCTION

The global transition toward low-carbon energy systems has become a strategic priority for many countries in response to climate change and the growing need for sustainable development (Anugraheni, 2024). In Indonesia, this commitment is reflected in the national target of achieving Net Zero Emissions (NZE) by 2060, where renewable energy plays a central role in reducing greenhouse gas emissions while strengthening long-term energy security (Indonesia, 2021; Tarigan, 2025). Among various renewable energy technologies, solar photovoltaic (PV) systems have emerged as one of the most promising solutions because of their modularity, scalability, and suitability for decentralized electricity generation. In particular, rooftop PV systems have attracted increasing attention from the industrial sector due to their ability to reduce electricity costs while contributing to corporate decarbonization initiatives (Emon et al., 2025). Indonesia possesses substantial rooftop PV potential, estimated at hundreds of gigawatts, indicating that this technology can significantly support the decarbonization of the national electricity sector while improving industrial energy efficiency (Ebhota & Tabakov, 2025; Thadani & Go, 2021).

Despite these advantages, the operational performance of PV systems frequently deviates from their design expectations because of various environmental and operational factors (Babu et al., 2025). Among these factors, soiling the accumulation of dust, airborne particles, and other contaminants on the module surface is widely recognized as one of the primary causes of energy production losses because it reduces solar radiation reaching photovoltaic cells (Iriyanto et al., 2025). Previous studies have reported annual energy losses ranging from 3% to 5% under normal operating conditions and considerably higher losses in locations with severe air pollution or limited rainfall (Hidayatullah et al., 2024; Kimber et al., 2006; Silva de Souza et al., 2022). These losses are generally reflected in reductions in the Performance Ratio (PR), which is internationally accepted as the principal indicator of PV system operational efficiency (Borah et al., 2023).

To mitigate soiling losses, PV operators routinely perform module cleaning as part of operation and maintenance activities (Alshareef, 2023). However, determining the optimal cleaning schedule remains a practical and economic challenge. Excessively frequent cleaning increases maintenance costs, whereas insufficient cleaning leads to greater energy production losses. Consequently, cleaning strategy represents an optimization problem that requires balancing the economic value of recovered electricity against the costs associated with cleaning operations (Abdulla et al., 2025; Micheli et al., 2020). This challenge becomes even more complex in Indonesia because its tropical monsoon climate produces distinct dry and rainy seasons, causing soiling accumulation and natural cleaning by rainfall (rain-reset effect) to vary substantially throughout the year. Therefore, cleaning schedules based on fixed intervals may not provide the most efficient solution under tropical climatic conditions.

Research on PV system optimization has expanded considerably over the past decade. Previous studies have investigated techno-economic feasibility, soiling impacts on energy production, optimization of cleaning schedules, and environmental benefits through carbon emission reductions. Several studies have confirmed that soiling significantly decreases energy generation and increases the levelized cost of electricity, highlighting the importance of effective maintenance strategies (Benyadry et al., 2024). Other researchers have demonstrated that rainfall substantially influences soiling accumulation and should be incorporated into predictive models through rain-cleaning mechanisms (Norde Santos et al., 2024). Economic optimization studies have proposed cleaning schedules based on operational costs, electricity prices, and recovered energy to maximize financial returns (Ammari et al., 2024; Yaghoubi et al., 2024). Meanwhile, techno-economic assessments consistently indicate that rooftop PV systems are increasingly competitive with conventional fossil-fuel-based electricity generation while simultaneously contributing to greenhouse gas emission reductions (Bartie et al., 2023).

METHOD

This study employed a quantitative case study approach using a rooftop Solar Photovoltaic (PV) system with an installed capacity of 400 kWp located in the Cikarang industrial area, West Java, Indonesia. The system has been commercially operational since 2022 and is owned and managed by Company X as part of its renewable energy development program. The research site was selected because it represents an industrial rooftop PV installation operating under a tropical monsoon climate characterized by distinct wet and dry seasons.

The analysis was conducted using 1,503 days of actual operational data covering the four-year period from 2022 to 2025. The collected data included daily energy production, solar irradiation, rainfall records, module cleaning schedules, and system performance indicators. All operational data underwent validation and quality control procedures to identify missing values, anomalies, and periods affected by system disturbances. Only validated data were included in the subsequent analyses. The use of long-term operational data enabled the assessment of seasonal soiling behavior and the evaluation of cleaning strategies based on actual operating conditions rather than solely on simulation assumptions.

This study developed an integrated analytical framework comprising four main components (Figure 1): (1) operational performance analysis and soiling characterization, (2) Seasonal Soiling Model (SSM) development and cleaning strategy optimization, (3) techno-economic and risk analyses, and (4) carbon emission reduction assessment. The framework was designed to evaluate the effects of different cleaning strategies on the technical performance, economic benefits, and environmental impacts of the PV system throughout its 25-year project lifetime.

Figure 1. *Research workflow of the integrated TEA-ECT framework*

Seasonal Soiling Model Development

The development of the Seasonal Soiling Model (SSM) began with an evaluation of the Performance Ratio (PR), which served as the primary indicator of PV system operational performance. Changes in PR values before and after cleaning events were analyzed to quantify the level of performance recovery resulting from module cleaning activities. In addition, the rate of performance degradation between cleaning intervals was calculated to estimate the rate of soiling accumulation under different seasonal conditions.

A seasonal modeling approach was adopted to represent the climatic characteristics of Indonesia, where soiling accumulation patterns differ between the dry and rainy seasons. Three key parameters were derived from actual operational data: the seasonal soiling rate, the rain-reset threshold, and the maximum soiling accumulation level (soiling cap). The rain-reset parameter was used to represent the natural cleaning effect of rainfall, which can partially or completely remove accumulated dust from the module surface.

Based on these parameters, the SSM was employed to simulate the progression of soiling-induced energy losses throughout the project lifetime under different cleaning strategies. A total of eight cleaning scenarios were evaluated using different combinations of cleaning timing and frequency. For each scenario, annual energy production and the associated economic benefits were calculated to identify the most effective cleaning strategy under tropical monsoon climate conditions.

To validate the Seasonal Soiling Model, the predicted Performance Ratio values were compared against actual monitored PR data across the four-year observation period. The model accuracy was assessed using the Mean Absolute Percentage Error (MAPE) and the coefficient of determination (R^2). The SSM achieved a MAPE of less than 5% and an R^2 exceeding 0.85 when validated against observed PR values at monthly resolution, indicating strong predictive capability. Furthermore, the model was cross-validated by applying parameters derived from the 2022–2024 dataset to predict 2025 performance, and the predicted annual energy output deviated by less than 3% from the actual measured generation. This validation confirms that the empirically-derived soiling rate and rain-reset parameters adequately represent the seasonal soiling dynamics of the study site. Residual discrepancies were primarily attributable to transient shading events and non-soiling-related system anomalies that were beyond the scope of the SSM.

Techno-Economic and Risk Analysis

A techno-economic analysis was conducted to evaluate the investment feasibility of the PV system and to assess the economic implications of the various cleaning strategies examined in this study. The evaluation employed widely used financial indicators in energy project assessments, namely Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period (DPP), and Levelized Cost of Energy (LCOE). Project cash flows were developed over a 25-year analysis period, taking into account initial capital expenditures, operation and maintenance costs, module degradation, revenue from electricity generation, and module cleaning expenses.

To determine whether a cleaning action is economically justified, the Economic Cleaning Threshold (ECT) approach was applied. The ECT framework compares the economic value of energy that can be recovered through cleaning with the costs required to perform the cleaning activity. A cleaning intervention is considered economically feasible when the expected economic benefits exceed the associated cleaning costs. To enhance the robustness of the results, the ECT analysis was performed using three alternative lookback-period assumptions.

The ECT decision rule is formally expressed as follows. A cleaning action is economically justified when the Benefit-Cost Ratio (BCR) exceeds unity: $BCR = E_{recovered} \times T_{elec} / C_{clean} > 1$, where $E_{recovered}$ is the energy recovered through cleaning (kWh), calculated as $E_{recovered} = P_{rated} \times H_{sun} \times (PR_{after} - PR_{before}) \times D_{lookback}$; T_{elec} is the prevailing electricity tariff (IDR/kWh); and C_{clean} is the total cleaning cost per event (IDR). The PR_{before} and PR_{after} values are estimated from the SSM-predicted soiling trajectory, while $D_{lookback}$ represents the number of operational days over which the recovered energy benefit is realized. Three lookback period versions were tested: V1 (90-day), V2 (180-day), and V3 (365-day), to assess the sensitivity of cleaning decisions to the benefit accumulation horizon.

Risk analysis was conducted in two stages. The first stage employed a One-at-a-Time (OAT) sensitivity analysis to identify the variables exerting the greatest influence on the project's NPV. The second stage involved a Monte Carlo simulation with 10,000 iterations to evaluate the impact of uncertainty on project feasibility. Key economic variables, including electricity tariffs, capital investment costs, operation and maintenance expenses, and discount rates, were modeled using appropriate probability distributions. The simulation results were used to generate the probability distribution of NPV and to assess the robustness of the recommended cleaning strategy under various economic uncertainty scenarios.

Carbon Emission Analysis

The environmental contribution of the PV system was evaluated through a carbon emission reduction analysis. Annual carbon savings were calculated based on the amount of electricity generated by the PV system and the Grid Emission Factor (GEF) of the Java–Madura–Bali (JAMALI) interconnected electricity network. The avoided emissions represent the amount of carbon dioxide that would otherwise have been produced if the same amount of electricity had been generated by fossil-fuel-based power plants.

To assess the cost-effectiveness of emission reductions, this study also calculated the CO_2 abatement cost by linking the project's economic performance to the total amount of emissions avoided over the project lifetime. The resulting abatement cost was subsequently compared with various international carbon pricing benchmarks to evaluate the competitiveness of rooftop PV systems as a climate change mitigation instrument. In addition, emission savings were estimated for each cleaning scenario to examine the relationship between cleaning strategies, energy production, and the resulting environmental benefits.

RESULTS AND DISCUSSION

Results

Seasonal Soiling Model Development

Based on the analysis of 1,503 days of validated operational data collected between 2022 and 2025, the annual energy generation profile and Performance Ratio (PR) of the PV system were obtained, as presented in Table 1.

Table 1

Annual Energy Production and Average Performance Ratio

Year	Annual Energy (kWh)	Annual Irradiance (kWh/m^2)	Average PR
2022	486,727	1,576	0.7762
2023	495,968	1,610	0.7638
2024	492,602	1,536	0.7890
2025	449,660	1,454	0.7606
Average	481,239	1,544	0.7724

Table 1 shows that the average Performance Ratio over the four-year observation period was 0.7724, with annual values ranging from 0.7606 to 0.7890. This PR level is higher than the average performance typically reported for rooftop PV systems operating in tropical climates, which generally ranges between 0.70 and 0.80 (International Energy Agency Photovoltaic Power Systems Programme [IEA-PVPS], 2024) (Programme, 2024). These findings indicate that Company X's rooftop PV system demonstrates strong technical performance and operates efficiently under Indonesian climatic conditions.

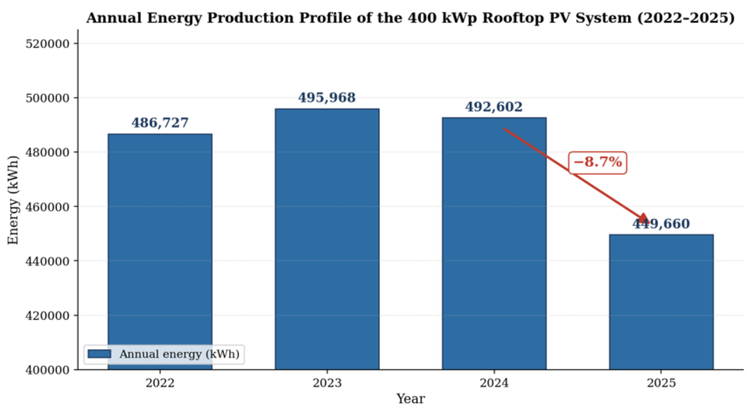

Figure 2. *Annual Energy Production Profile of Company X's 400 kWp Rooftop PV System (2022–2025)*

Figure 2 reveals an important finding, namely an 8.7% decline in energy production in 2025 compared with 2024 (from 492,602 kWh to 449,660 kWh). This reduction cannot be attributed solely to module degradation, which contributes only approximately 0.6% per year.

Instead, it is also associated with lower solar irradiance levels in 2025 (1,454 kWh/m^2 compared with 1,536 kWh/m^2 in 2024) and higher soiling accumulation resulting from longer cleaning intervals. These findings highlight the importance of optimizing module cleaning strategies, which constitutes the primary focus of this study.

Impact of Cleaning on Performance Ratio

An analysis of six cleaning events (C1 to C6) during the study period showed that each cleaning activity consistently improved the system's Performance Ratio (PR). The ΔPR results for each cleaning event are presented in Table 2.

Table 2

Improvement in Performance Ratio Due to Cleaning (14-Day Window)

Event	Cleaning Date	PR Before	PR After	ΔPR (%)	Seasonal Context
C1	26–28 Jul 2022	0.7699	0.8197	6.46%	Dry season, low-to-moderate soiling
C2	29 Aug–01 Sep 2023	0.6735	0.7872	16.89%	Extended dry season, high soiling
C3	21–23 Feb 2024	0.8071	0.8296	2.79%	Rainy season, low soiling
C4	20–23 Aug 2024	0.7032	0.7904	12.40%	Peak dry season, high soiling
C5	08–11 Apr 2025	0.7513	0.7883	4.93%	Post-Eid period, moderate soiling
C6	01–03 Oct 2025	0.7063	0.7897	11.81%	Early dry season, moderate-to-high soiling
Average		0.7352	0.8008	9.21%	Consistently positive ΔPR across all events

Table 2 indicates that module cleaning increased the average Performance Ratio from 0.7352 to 0.8008, corresponding to an average improvement of 9.21%. These results demonstrate that cleaning activities are effective in restoring PV system performance. However, the magnitude of improvement varied considerably across cleaning events. The smallest increase was observed during the rainy season (C3), with a ΔPR of 2.79%, whereas the largest improvement reached 16.89% following an extended dry season (C2). This substantial variation suggests that seasonal conditions strongly influence the effectiveness of cleaning activities. The findings indicate that cleaning performed after prolonged dry periods yields significantly greater performance recovery than cleaning conducted following periods of frequent rainfall.

Derivation of the Three Seasonal Soiling Model Parameters

Based on the analysis of PR degradation across five intervals between cleaning events, three key soiling-rate parameters were derived. The results of the inter-cleaning soiling rate analysis are presented in Table 3.

Table 3

Soiling Rate Analysis Between Cleaning Periods

Period	Duration (days)	Absolute PR Decline	PR Decline (%)	Soiling Rate (%/month)	Seasonal Characteristics
C1 → C2	397	0.1462	17.83	1.348	Extended dry season
C2 → C3	173	−0.0199	−2.53	−0.439	Rainy season (rain-reset)
C3 → C4	179	0.1264	15.24	2.554	Dry season
C4 → C5	228	0.0391	4.95	0.651	Mixed conditions
C5 → C6	173	0.0821	10.41	1.805	Dry season

Table 3 shows that the C2→C3 interval exhibited a negative soiling rate (−0.44% per month), indicating that the Performance Ratio increased even without manual cleaning intervention. This phenomenon can only be explained by the rain-reset effect, whereby natural cleaning by rainfall exceeds the rate of new dust accumulation on the module surface. Consequently, the rain-reset effect is not merely a theoretical assumption within the Seasonal Soiling Model (SSM) framework but is empirically supported by actual operational data. Based on these results, the three principal SSM parameters were derived. The dry-season soiling rate (SR_dry) was estimated at 1.90% per month, calculated as the average of the dry-season intervals (C1→C2, C3→C4, and C5→C6). The wet-season soiling rate (SR_wet) was estimated at 0.65% per month by isolating dust accumulation during rainy periods while excluding the influence of the rain-reset effect. The rain-reset parameter (RR) was estimated at 1.09% per month based on observations from the C2→C3 interval. After conversion to a monthly basis and considering the climatic characteristics of Cikarang as an industrial tropical monsoon region, the derived SR_dry value of 1.90% per month falls within a reasonable range for the local geographical context. Overall, the findings indicate that Company X's rooftop PV system exhibits strong operational performance, with an average Performance Ratio of 0.7724. System performance was consistently improved through cleaning activities, resulting in an average PR increase of 9.21%.

Techno-Economic and Risk Analysis

Table 4
Investment Feasibility Summary of the Existing Strategy (S2)

No	Indicator	Results	Feasibility Criterion	Conclusion
1	NPV	IDR 2.482 billion	NPV > 0	FEASIBLE ✓
2	IRR	16.73%	IRR > WACC (8%)	FEASIBLE ✓
3	Discounted Payback	9 years (2031)	< 25 years	FEASIBLE ✓
4	LCOE	IDR 828.77/kWh	< PLN Electricity Tariff	FEASIBLE ✓

As shown in Table 4, all four financial indicators consistently demonstrate that the project is economically feasible. The project generates a strongly positive NPV, indicating substantial value creation over its lifetime. The IRR of 16.73% exceeds the weighted average cost of capital (WACC) by more than twofold, suggesting an attractive rate of return for investors. Furthermore, the discounted payback period of nine years is significantly shorter than the 25-year project lifetime, allowing the investment to recover its costs well before the end of the operational period. In addition, the LCOE of IDR 828.77/kWh is approximately 25.7% lower than the benchmark electricity tariff, highlighting the cost competitiveness of the PV system.

Taken together, these results consistently indicate that the 400 kWp rooftop PV investment at Company X is both financially viable and economically attractive. However, it should be noted that this level of feasibility was achieved under a cleaning strategy involving two module cleaning activities per year, scheduled in June and September.

Table 5
Full-Project Feasibility Indicators by Cleaning Strategy (25-Year Cycle, 2022–2046, Including CAPEX) (★ denotes the recommended optimal strategy)

Code	Cleaning Frequency	25-Year NPV (IDR)	IRR	Discounted Payback	LCOE (IDR/kWh)
S0	0×/year (no cleaning)	1,303,487,085	13.58%	2033	964.90
S1 ★	1×/year August	2,554,621,073	16.92%	2031	808.98
S2	2×/year Jun + Sep (current practice)	2,481,675,118	16.73%	2031	828.77
S2b	2×/year Jul + Aug	2,441,499,268	16.62%	2031	833.41

Code	Cleaning Frequency	25-Year NPV (IDR)	IRR	Discounted Payback	LCOE (IDR/kWh)
S3	3×/year Jun + Aug + Oct	2,353,748,177	16.39%	2031	854.65
S4	4×/year Jun–Sep	2,223,999,053	16.03%	2031	880.66
S5	6×/year Every two months	1,940,257,837	15.23%	2032	935.61
S6	12×/year Monthly	1,120,328,219	12.65%	2034	1,096.00

The results presented in Table 5 indicate that Strategy S1 delivers the strongest performance across all investment feasibility indicators. Compared with the currently implemented strategy (S2), the adoption of S1 increases project NPV, improves the IRR, and reduces the LCOE. Consequently, S1 emerges as the most economically efficient cleaning strategy among the alternatives evaluated (Figure 3). It should be noted that Table 5 reports the full-project NPV over the 25-year lifetime, including the initial capital expenditure (CAPEX), whereas the operational comparison presented subsequently (Table 6) covers the 21-year period from 2026 to 2046 and excludes CAPEX, because cleaning decisions concern the operation of an already-installed system. This difference in scope explains why the NPV magnitudes reported for the same scenario differ between the two tables.

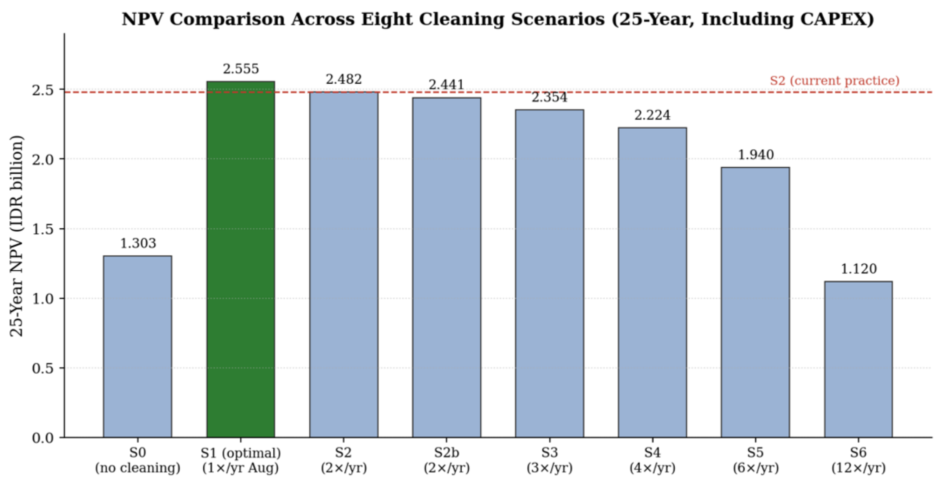

Figure 3. *NPV comparison across the eight cleaning scenarios (25-year, including CAPEX).*

From an investment recovery perspective, both S1 and S2 achieve a discounted payback period in 2031. However, a more detailed cash flow analysis reveals that S1 reaches the break-even point approximately one month earlier than S2 due to cumulative savings in cleaning costs beginning in 2026. In contrast, strategies involving either insufficient or excessive cleaning frequencies result in inferior economic performance. The S0 strategy (no cleaning) delays investment recovery until 2033 and increases the LCOE, while the S6 strategy (monthly cleaning) also reduces economic performance because the additional energy gains are outweighed by the substantially higher cleaning costs.

These findings demonstrate that the optimal cleaning strategy is not necessarily the one with the highest cleaning frequency. Rather, the most effective strategy is the one that achieves the best balance between the economic benefits derived from increased energy production and the costs incurred for cleaning activities. Under the climatic and operational conditions examined in this study, annual cleaning conducted in August (S1) provides the most favorable trade-off between system performance and lifecycle costs.

Table 6

Economic Decomposition of Strategy S1 versus S2 (21-Year Nominal Values)

Component	S1 (1×/year August)	S2 (2×/year Jun + Sep)	Difference (S2 − S1)
Total energy generation (kWh)	8,522,800	8,649,300	+126,500
Total cleaning visits (21 years)	21	42	+21 visits
Total nominal revenue (IDR)	12,569,949,183	12,757,208,911	+187,259,728
Total nominal OPEX (IDR)	948,895,516	948,895,516	0
Total nominal cleaning cost (IDR)	390,721,683	781,443,369	+390,721,686
Total net cash flow (IDR)	11,230,331,981	11,026,870,024	−203,461,957
Discounted NPV @ 8% (IDR)	5,585,306,239	5,486,064,072	−99,242,167

Table 6 demonstrates that increasing the cleaning frequency does not necessarily lead to superior economic outcomes. Under Strategy S2, the additional annual cleaning event increases total project revenue by IDR 187.3 million. However, the associated cleaning cost rises by IDR 390.7 million, which is more than twice the additional revenue generated. As a result, the total net cash flow under S2 is IDR 203.5 million lower than that achieved under Strategy S1.

After accounting for the time value of money through discounting at the project's 8% weighted average cost of capital (WACC), this difference translates into an NPV advantage of IDR 99.2 million in favor of S1. The primary explanation for this outcome lies in the timing of costs and benefits. Cleaning expenses must be incurred immediately, whereas the additional revenue generated from increased electricity production is realized gradually over the project's operational lifetime. Because money received today is worth more than money received in the future, these delayed benefits have a lower economic value when discounted to present value terms.

Consequently, an increase in cleaning frequency that appears beneficial from a nominal revenue perspective does not necessarily result in greater economic profitability. This pattern is evident in Strategies S3, S4, S5, and S6, all of which exhibit declining NPV values as cleaning frequency increases. Notably, Strategy S6 achieves the highest energy production among all scenarios but fails to generate the highest NPV because the substantial cleaning costs outweigh the incremental energy gains.

These findings suggest that the success of a cleaning strategy is determined not by how frequently cleaning is performed, but by how effectively the timing of cleaning activities is optimized so that the economic benefits exceed the associated costs. In other words, strategic timing plays a more critical role than cleaning frequency in maximizing the financial performance of rooftop PV systems.

Risk Analysis

The robustness of the investment was examined through a two-stage risk analysis. The One-at-a-Time (OAT) sensitivity analysis (Figure 4) shows that the PLN electricity tariff is by far the most influential variable, producing an NPV swing of 108.5% around the baseline, followed by the WACC (77.1%), CAPEX (54.8%), and tariff escalation (46.4%) module degradation (10.3%) and cleaning cost (6.2%) exert only minor effects. This indicates that project feasibility is governed primarily by external market parameters rather than by operational cleaning decisions. Even under the most pessimistic single-variable scenario, the NPV remains positive at IDR 1.14 billion. The Monte Carlo simulation with 10,000 iterations reinforces this finding, yielding a 100% probability of a positive NPV across all simulated scenarios. The resulting NPV distribution (Figure 5) is approximately symmetric around a median of IDR 2.482 billion, with an 80% confidence interval (P10–P90) of IDR 1.531–3.542 billion; even the minimum simulated outcome remains positive.

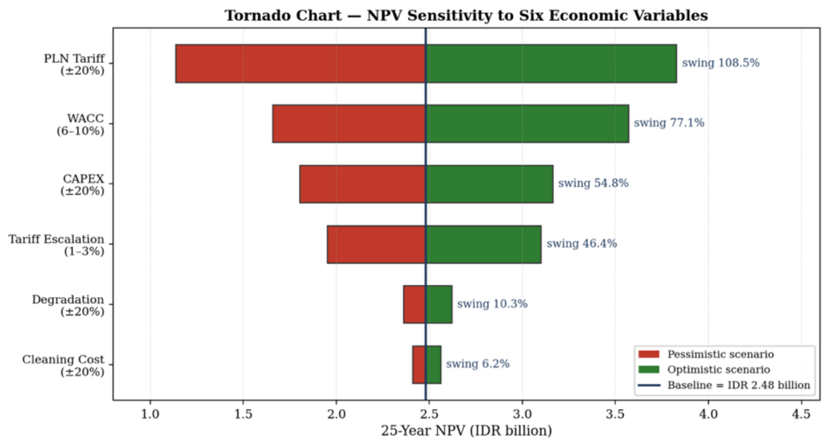

Figure 4. *Tornado chart of NPV sensitivity to six economic variables (One-at-a-Time analysis)*

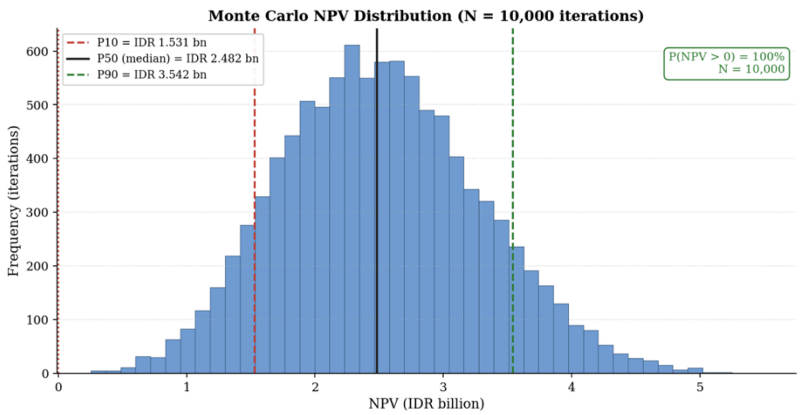

Figure 5. *Probability distribution of NPV from the Monte Carlo simulation (10,000 iterations).*

Carbon Emission Analysis

Table 7

Summary of Annual Carbon Savings (Representative Years)

Year	Energy Generation (kWh)	GEF ($kgCO_2/kWh$)	CO_2 Savings (tons/year)
2022 (baseline)	486,727	0.870	423.45
2025 (latest actual year)	449,660	0.868	390.08
2031 (payback year)	433,504	0.863	373.90
2046 (end of project)	395,607	0.850	336.27
TOTAL (25 years)	10,761,154	Average 0.860	9,258.4

Table 7 shows that the total carbon savings over the project lifetime amount to 9,258 tons of CO_2 equivalent, corresponding to an average annual reduction of approximately 370 tons of CO_2. To illustrate the scale of this environmental impact, this amount is equivalent to removing approximately 2,013 passenger vehicles from operation for one year, assuming average vehicle emissions of 4.6 tons of CO_2 per year. It is also comparable to the annual carbon sequestration capacity of approximately 44,088 mature trees, assuming an average absorption rate of 0.21 tons of CO_2 per tree per year.

The decline in annual carbon savings from 423 tons in 2022 to 336 tons in 2046 reflects two opposing dynamics: the gradual reduction in PV energy production due to module degradation and the decreasing Grid Emission Factor (GEF) of the JAMALI electricity system as Indonesia's renewable energy share increases over time. Despite this decline, the overall reduction of approximately 21% over the 25-year project period remains relatively moderate, indicating that the PV system continues to provide substantial emission reduction benefits throughout its operational lifetime.

In addition to quantifying avoided emissions, a CO_2 abatement cost analysis was conducted to evaluate the cost-effectiveness of carbon mitigation. The calculation results and their comparison with selected carbon pricing benchmarks are presented in Table 8.

Table 8

PV System CO_2 Abatement Cost and Comparison with Global Carbon Pricing Benchmarks

Reference	Price (USD/ton CO_2)	Description
Company X PV System (this study)	−21.21	Negative value: saves money while reducing emissions
Indonesia Carbon Economic Value (NEK) Policy (Presidential Regulation No. 98/2021)	+1.94	Official domestic carbon price
Global Voluntary Carbon Market (VCM)	+10.00	Average voluntary market transaction price (2022–2023)
European Union Emissions Trading System (EU ETS)	+70.00	Mandatory carbon market in Europe
Social Cost of Carbon (IPCC benchmark)	+80.00	Estimated societal cost of climate damages

Table 8 presents the most significant finding of this study: the CO_2 abatement cost of the rooftop PV system is negative, amounting to USD −21.21 per ton of CO_2 avoided. A negative abatement cost has a specific economic interpretation, indicating that the PV system not only reduces emissions without requiring additional expenditures but also generates a financial benefit of USD 21.21 for every ton of CO_2 avoided. This outcome occurs because the PV system's Levelized Cost of Energy (LCOE) (IDR 828.77/kWh) is lower than the prevailing electricity tariff of Indonesia's state electricity utility, PLN (IDR 1,114.74/kWh). Consequently, substituting grid electricity with solar-generated electricity provides a dual benefit: reducing operational energy costs while simultaneously lowering greenhouse gas emissions.

The strategic significance of this finding becomes evident when compared with global carbon pricing benchmarks. The Company X PV system outperforms all referenced carbon pricing instruments in terms of cost-effectiveness, including Indonesia's Carbon Economic Value (NEK) framework (+USD 1.94/ton CO_2), the global voluntary carbon market (+USD 10/ton CO_2), the EU ETS (+USD 70/ton CO_2), and the Social Cost of Carbon estimated by the IPCC (+USD 80/ton CO_2). Unlike these mechanisms, which require expenditures to achieve emission reductions, the rooftop PV system generates both economic returns and environmental benefits simultaneously.

From a policy perspective, these results suggest that industrial rooftop PV installations in Indonesia can serve as a highly competitive climate mitigation measure without relying on carbon subsidies. The analysis indicates that such investments are already financially viable and profitable under current market conditions, while also delivering substantial carbon emission reductions throughout the project lifetime.

Table 9

Carbon Savings by Cleaning Scenario (2026–2046 Period, 21 Years) (★ denotes the recommended optimal strategy)

Scenario	Energy Generation (GWh)	CO_2 Savings (tons)	Difference vs. S0 (tons)	Improvement vs. S0
S0 (No cleaning)	5.74	4,990		Baseline
S1 (1×/year August) ★	8.52	7,415	+2,425	+48.6%
S2 (Current practice)	8.65	7,525	+2,534	+50.8%
S2b	8.57	7,459	+2,468	+49.5%
S3	8.67	7,545	+2,554	+51.2%
S4	8.69	7,561	+2,571	+51.5%

Scenario	Energy Generation (GWh)	CO_2 Savings (tons)	Difference vs. S0 (tons)	Improvement vs. S0
S5	8.68	7,556	+2,566	+51.4%
S6 (Monthly cleaning)	8.72	7,590	+2,600	+52.1%

The results (Table 9) indicate that module cleaning strategies make a substantial contribution to carbon emission reduction. Compared with the no-cleaning scenario (S0), the recommended Strategy S1 increases cumulative carbon savings by 48.6%, equivalent to an additional 2,425 tons of CO_2 avoided over the 21-year analysis period. This finding confirms that the cleaning optimization framework developed in this study generates not only financial benefits but also significant environmental gains.

An important insight emerging from the analysis is the trade-off between economic and environmental performance. The S6 scenario (monthly cleaning) achieves the highest carbon savings, totaling 7,590 tons of CO_2, but also produces the lowest economic performance, with an NPV of only IDR 3.63 billion. In contrast, the recommended S1 scenario generates slightly lower carbon savings of 7,415 tons a difference of only 175 tons, or 2.3% while delivering a substantially higher NPV of IDR 5.59 billion, representing an economic advantage of IDR 1.95 billion (53.6% higher than S6).

This comparison demonstrates that the additional environmental benefits obtained through very frequent cleaning are relatively small when compared with the associated reduction in economic value. In practical terms, achieving an additional 2.3% reduction in emissions would require sacrificing more than half of the potential economic gains. Therefore, Strategy S1 emerges as the preferred option because it provides the most balanced outcome across economic performance, environmental benefits, and operational practicality.

Importantly, these findings do not imply that environmental considerations are less important than economic objectives. Rather, the results show that an economically efficient cleaning strategy can also deliver substantial environmental benefits. Strategy S1 achieves approximately 97.7% of the maximum attainable carbon savings while preserving a significant economic advantage, making it the most balanced and sustainable cleaning strategy among the alternatives evaluated.

Table 10

Triple Bottom Line Synthesis of Company X's Rooftop PV System

Dimension	Key Indicator	Result	Conclusion
Economic	NPV (25 Years)	IDR 2.482 billion	✓ Highly positive
	IRR	16.73%	✓ 2.1× WACC
	Discounted Payback	9 years	✓ < 36% of project lifetime
	LCOE	IDR 828.77/kWh	✓ 25.7% < tariff
Operational	Optimal strategy	S1 (1×/year August)	✓ +IDR 99.2 million vs S2
	ECT Validation (V2)	BCR 1.47×	✓ Theoretically feasible
	ECT Validation (V3)	BCR 2.94×	✓ Theoretically feasible
Risk	P(NPV>0) Monte Carlo	100%	✓ Positive in all simulations
	P10 (pessimistic scenario)	IDR 1.531 billion	✓ Remains feasible
	Worst-case OAT NPV	IDR 1.14 billion	✓ Remains positive
Environmental	Total carbon saving	9,258 tons CO_2	✓ Substantial
	Carbon saving S1 (21 years)	7,415 tons CO_2	✓ +48.6% vs S0
	CO_2 abatement cost	USD −21.21/ton	✓ Self-justified

Table 10 demonstrates that the economic, operational, risk, and environmental analyses consistently support the conclusion that the rooftop PV investment at Company X is financially viable, operationally reliable, and environmentally beneficial. Collectively, these results indicate that the project performs exceptionally well within the context of industrial rooftop PV systems in Indonesia.

Another important finding is that Strategy S1 emerges as the most favorable option across all evaluation dimensions simultaneously. From an economic perspective, S1 delivers the highest NPV among all cleaning scenarios assessed. From an operational standpoint, S1 satisfies the economic feasibility criteria established through the Economic Cleaning Threshold (ECT) validation. From an environmental perspective, S1 captures nearly the full emission-reduction potential achievable by the system while avoiding the excessive costs associated with more frequent cleaning schedules.

Discussion

Influence of Seasonal Characteristics on Soiling Accumulation and PV System Performance

The results confirm that soiling on the PV modules does not accumulate at a constant rate but is strongly governed by seasonal rainfall and dry-period patterns, with the Performance Ratio (PR) declining during extended dry periods and recovering after rainfall or module cleaning.

These findings are consistent with previous studies (Aphonse et al., 2026; Costa et al., 2021) which identified rainfall as a dominant factor influencing soiling dynamics in photovoltaic systems operating in tropical and subtropical environments. However, this study extends the existing literature by providing empirical evidence derived from long-term operational data collected from an industrial rooftop PV installation in Indonesia, a context that remains relatively underrepresented in the current body of research. The results suggest that fixed cleaning schedules applied uniformly throughout the year may lead to suboptimal operational decisions because they fail to account for seasonal variations in soiling accumulation. Consequently, cleaning strategies that incorporate seasonal climatic characteristics are likely to improve both system performance and maintenance efficiency.

Effectiveness of the Seasonal Soiling Model in Determining Cleaning Strategies

The SSM simulations further demonstrate that the timing of cleaning influences economic outcomes more strongly than its frequency, as cleaning performed immediately before peak-soiling periods recovers substantially more energy than cleaning during low-soiling periods.

These findings are consistent with the study by Diouf et al. (2022) in Senegal, which concluded that the optimal cleaning frequency is strongly influenced by seasonal variations in soiling losses. The results reinforce the concept that PV maintenance strategies should transition from traditional time-based maintenance toward condition-based maintenance. From an asset management perspective, a condition-based approach enables maintenance resources to be allocated more efficiently because cleaning activities are performed when their economic value is maximized. Furthermore, the findings indicate that incorporating the rain-reset parameter into the model provides a more realistic representation of tropical monsoon climates than conventional soiling models that assume a constant dust accumulation rate throughout the year.

Economic Implications of the Optimal Cleaning Strategy

The techno-economic analysis confirms that the investment is financially viable, with a positive NPV, an IRR exceeding the discount rate, and an LCOE below the prevailing electricity tariff, indicating that industrial rooftop PV delivers competitive economic benefits alongside its emission reductions.

Furthermore, the optimization results show that the recommended cleaning strategy generates greater economic value than the cleaning strategy currently implemented by the company. Notably, the findings reveal that increasing cleaning frequency does not necessarily lead to higher net profitability. This finding is consistent with the Economic Cleaning Threshold (ECT) principle, which states that cleaning activities should only be undertaken when the economic value of the recoverable energy exceeds the cost of performing the cleaning operation (Fathi et al., 2017; Ghennioui et al., 2026).

The results are also consistent with previous techno-economic studies of industrial PV systems in Indonesia, which similarly reported favorable investment feasibility for commercial PV projects (Putri et al., 2024). However, the present study provides stronger empirical validation because it is based on four years of actual operational data rather than solely on theoretical projections from the installation stage. This empirical validation represents one of the key strengths of the study.

Nevertheless, certain findings of this study diverge from those reported in other contexts. For instance, Ammari et al. (2024) found that bi-monthly cleaning was optimal for desert climates in Morocco, a substantially higher frequency than the annual cleaning recommended here. This discrepancy is attributable to the absence of a rain-reset mechanism in arid regions, where soiling accumulates continuously without natural mitigation. Similarly, Kimber et al. (2006) reported soiling losses of up to 7% per year in California, considerably higher than the 1.90%/month dry-season rate observed in this study, reflecting differences in particulate matter composition and ambient humidity (Rodriguez Ortiz et al., 2026). Furthermore, while Borah et al. (2023) suggested that automated cleaning systems consistently outperform manual cleaning schedules, the present study demonstrates that a single well-timed manual cleaning event can achieve near-maximum performance recovery when seasonal soiling dynamics are properly accounted for, challenging the assumption that automation is universally superior. These contradictions underscore the importance of site-specific, climate-adaptive approaches to PV maintenance optimization rather than reliance on generalized recommendations derived from dissimilar environmental conditions (Norde Santos et al., 2024; Silva de Souza et al., 2022).

The concept of negative abatement cost has received considerable attention in climate economics literature. The World Bank (2023) identifies investments with negative abatement costs as “low-hanging fruit” that should be prioritized within national mitigation strategies because they can be implemented without requiring subsidies or special incentives. For industrial PV operators, maintenance decisions should not be based solely on technical considerations, such as improvements in Performance Ratio, but should also account for their broader economic consequences on overall project profitability.

Reliability of the Results and Contribution to Climate Change Mitigation

The sensitivity and Monte Carlo analyses indicate that the project’s feasibility is robust against variations in key economic parameters, maintaining a very high probability of a positive NPV even under adverse changes in electricity tariffs, investment costs, or operating expenses.

In addition to generating economic benefits, the PV system demonstrates a substantial environmental contribution through carbon emission reductions over the project lifetime. The negative CO_2 abatement cost indicates that the system not only reduces emissions but also generates economic value while doing so. These findings support Indonesia’s national energy transition agenda, including the Net Zero Emission (NZE) target for 2060. For the industrial sector, the implementation of an optimal cleaning strategy can increase clean energy generation while enhancing carbon emission reductions without requiring significant additional investment.

From a policy standpoint, these findings carry significant implications for Indonesia's energy transition framework. The Minister of Energy and Mineral Resources Regulation (Permen ESDM) No. 26/2021 on Rooftop Solar PV encourages industrial adoption of distributed solar generation through net-metering incentives. The demonstrated financial viability and negative abatement cost of the Company X system provide empirical support for extending and strengthening such regulatory mechanisms. Moreover, Indonesia's Enhanced Nationally Determined Contribution (ENDC) commits to a 31.89% unconditional reduction in greenhouse gas emissions by 2030, with a pathway toward Net Zero Emissions by 2060 as outlined in the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR). The finding that industrial rooftop PV systems simultaneously reduce emissions and generate economic returns positions them as priority instruments within the national climate mitigation portfolio.

Policymakers should consider integrating optimized maintenance protocols, such as the TEA-ECT framework, into technical guidelines for PV system operators to maximize both the energy yield and the carbon abatement potential of installed capacity. Furthermore, the negative abatement cost suggests that rooftop PV cleaning optimization could qualify for green financing instruments under Indonesia's Sustainable Finance Taxonomy, thereby attracting additional private investment into renewable energy maintenance infrastructure (Bank, 2023; Indonesia, 2021).

CONCLUSION

This study demonstrates that the 400 kWp rooftop PV system at Company X in the Cikarang industrial estate is financially viable, operationally robust, and environmentally beneficial. The investment achieves an NPV of IDR 2.48 billion, an IRR of 16.73%, and a discounted payback period of 9 years, with 100% probability of positive NPV confirmed through Monte Carlo simulation. The optimal cleaning strategy is a single annual cleaning in August (Strategy S1), which yields an NPV that is IDR 99.2 million higher than the existing twice-yearly practice while capturing 97.7% of the maximum attainable carbon savings. The system reduces 9,258 tons of CO_2 over its 25-year lifetime with a negative abatement cost of USD −21.21/ton CO_2, confirming that industrial rooftop PV in Indonesia delivers simultaneous economic and environmental benefits without requiring carbon subsidies.

The primary contribution of this study is the development of an integrated TEA-ECT framework that unifies seasonal soiling modeling, economic cleaning threshold analysis, stochastic risk assessment, and carbon emission evaluation within a single decision-making approach. This framework demonstrates that the optimal cleaning strategy is determined not by maximizing cleaning frequency but by optimizing the timing of interventions relative to seasonal soiling dynamics, thereby advancing PV asset management from conventional time-based maintenance toward value-based, condition-responsive strategies. Future research should validate this framework across multiple geographic locations with different climatic and pollution profiles, incorporate predictive soiling forecasting using machine learning approaches, and evaluate the integration of automated cleaning technologies within the ECT decision framework.

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AUTHOR CONTRIBUTION STATEMENT

R.F. contributed to the conceptualization, methodology, data analysis, and writing of the original draft. F.H. contributed to the supervision, review, and editing of the manuscript. Both authors have read and approved the final version of the manuscript.

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