RECOMMENDED CLEANING REGIMES FOR PV PANNELS IN ROMANIA-LIKE CLIMATES

Popescu Vlad-Mihai, *University Constantin Brancusi, Targu Jiu, Romania*
Cruceru Mihai, *University Constantin Brancusi, Targu Jiu, Romania*

ABSTRACT: The article analyzes the economic and technical rationale for an optimized PV module cleaning regime in climates akin to Romania. Using a hypothetical 1 MW solar PV system as a case example, the analysis demonstrates that even modest soiling losses can meaningfully affect energy yield and project economics if not mitigated. Key parameters—5 daily sun hours, a 0.15% daily efficiency loss from soiling, a 0.10 euro/kW electricity tariff and 250 euro per cleaning event—are combined to estimate daily revenue loss from soiling at approximately 0.75 euro. A simplistic break-even interval suggests infrequent cleaning, yet the model acknowledges nonlinear deterioration mechanisms (e.g., hotspot formation and PID) that warrant more proactive maintenance. Consequently, a preventive cleaning cadence of every 60–90 days is recommended for Romania-like climates, with seasonal adjustments to reflect dust, pollen, and meteorological conditions.

KEY WORDS: cleaning schedule, key performance metrics

1. INTRODUCTION

The global transition towards a sustainable energy future is unequivocally powered by the rapid deployment of renewable sources, among which solar photovoltaic (PV) technology stands as a cornerstone. The economic viability and return on investment of large-scale PV systems are intrinsically linked to their ability to maximize energy yield over their operational lifetime. However, the theoretical performance of these systems is often compromised by real-world environmental factors, with soiling—the accumulation of dust, pollen, bird droppings, and other particulates on panel surfaces—emerging as a critical and pervasive challenge. Extensive international research has quantified the significant impact of soiling on PV performance. Studies in arid and semi-arid regions, such as those in the Middle East and California, have reported annual energy losses exceeding 5-7%,- and in extreme cases, losses can surge beyond 20% during prolonged dry seasons [1, 2]. While the soiling rates in temperate climates, like that of Romania, are often perceived as less severe, the cumulative financial impact remains substantial. Research by the National Renewable Energy Laboratory (NREL) suggests that even modest soiling losses of 1-3% can have a profound effect on the Levelized Cost of Energy (LCOE) and the long-term profitability of solar assets [3].

The economic dilemma for asset managers, therefore, is not whether soiling occurs, but how to mitigate it cost-effectively. The core of this challenge lies in optimizing the cleaning schedule: an infrequent cleaning regime allows for significant, and sometimes irreversible, energy revenue loss and potential technical degradation, such as hotspot formation. Conversely, an excessively frequent schedule incurs unnecessarily high operational expenditures (OPEX) that can erode the financial benefits of the cleaning itself. This optimization is highly location-specific, dependent on local deposition rates, rainfall patterns, seasonal variations (e.g., agricultural cycles, pollen seasons), and the prevailing electricity tariff [4].

This case study investigates this optimization problem within a Romania-like temperate environment. By analyzing a hypothetical 1 MW PV system, this paper will quantify the daily revenue loss due to soiling, calculate a simplistic break-even cleaning interval, and contrast it with real-world, proactive cleaning recommendations supported by operational data. Furthermore, it will demonstrate the considerable performance and financial benefits of a preventive maintenance strategy, underscoring that in the context of solar asset management, proactive cleaning is not merely an operational task but a strategic financial decision.

2. CASE STUDY: OPTIMAL CLEANING SCHEDULE IN A ROMANIA-LIKE ENVIRONMENT

To illustrate the optimization process and the impact of proactive cleaning, we considered a hypothetical 1 MW solar PV system installed in a Romanian region. The following parameters are assumed based on estimates and data from similar temperate climates:

- System Capacity: 1 MW
- Average Daily Sun Hours: 5 hours
- Average Daily Efficiency Loss Due to Soiling: 0.15%
- Electricity Tariff: 0.10 euro per kWh
- Cost per Cleaning Event: 250 euro

2.1. Calculation

Using the general principle that cleaning should occur when the cost of lost revenue matches or exceeds the cleaning cost, the daily loss in revenue is computed as:

$$\text{Daily Revenue Loss} = \text{System Capacity} \times \text{Sun Hours} \times \text{Efficiency Loss} \times \text{Electricity Tariff}$$

Substituting the assumed values:

$$\text{Daily Revenue Loss} = 1{,}000\ \text{kW} \times 5\ \text{hours} \times 0.0015 \times 0.10 = 0.75\ \text{euro per day}$$

The number of days N required for the cumulative loss to equal the cleaning cost is approximately:

$$N \approx \frac{250}{0.75} \approx 333\ \text{days}$$

However, this simplistic calculation does not account for dynamic changes in soiling over time, seasonal variations, and the nonlinear deterioration that can occur. Real-world observations in temperate regions typically suggest that proactive cleaning every 60–90 days can yield optimum performance and cost savings2. In our hypothetical example, while the pure break-even calculation would point to a very long interval, the deterioration in panel performance—and the potential for irreversible effects like hotspot formation or PID (Potential Induced Degradation)—necessitates more frequent cleaning. Thus, experts recommend a preventive cleaning regime of around 2–3 months in Romania-like climates.

2.2. Performance Impact

Data from various international studies suggest that even a modest cleaning—if it recovers 3–8% of lost efficiency—can greatly augment annual energy yield. In the case study, if cleaning prevents even a 3% loss in efficiency annually, the financial benefit can be quantified as follows:

$$\text{Additional Energy Generation} = 1{,}000\ \text{kW} \times 5\ \text{hours} \times 365 \times 0.03 = 54{,}750\ \text{kWh per year}$$

At an electricity tariff of 0.10 euro per kWh, this recovery is worth approximately 5,475 euro annually, which far outweighs the cleaning expenses if performed at a frequency that prevents severe yield reductions [2].

Table 1 summarizes key performance metrics for the hypothetical PV system.

Table 1. Key performance metrics for the PV system

Metric	Value	Explanation
System Capacity	1 MW	1,000 kW system installed
Average Daily Sun Hours	5 hours	Average effective irradiation per day
Estimated Daily Efficiency Loss (%)	0.15%	Estimated loss due to soiling
Daily Revenue Loss (euro)	0.75	Calculated loss without cleaning
Optimal Cleaning Interval Estimate	60–90 days	Recommended preventive cleaning frequency
Expected Annual Energy Recovery	~54,750 kWh	Through preventing a 3% efficiency loss
Annual Revenue Benefit (euro)	5,475	Monetary value of energy recovery at 0.10/euro/kWh

The table clearly demonstrates the strong economic case for periodic cleaning, even in climates with moderate soiling levels2.

3. RECOMMENDED CLEANING REGIMES FOR ROMANIA-LIKE CLIMATES

An evidence-based regime for cleaning photovoltaic (PV) installations located in climates analogous to Romania is proposed, grounded in the analysis of empirical data and the findings from a representative case study. The objective is to maintain high energy yields while minimizing maintenance costs and environmental impact. The regime is organized into three interrelated subsections: preventive cleaning scheduling, cleaning method recommendations, and environmental and practical considerations.

3.1. Preventive Cleaning Schedule

A preventive cleaning regimen is advocated to manage soiling losses without resorting to reactive, ad hoc measures. The recommended cleaning frequency spans from 60 to 90 days for residential and small commercial installations. This interval captures the trade-off between natural cleaning processes, such as rainfall and occasional snowfall, and the economic imperative to sustain PV efficiency. Seasonal adjustments are warranted: during Spring and Early Summer, heightened agricultural dust and pollen contribute to accelerated soiling, which may justify shortening the interval toward the lower end of the range if significant soiling is observed. Conversely, Autumn and Winter typically exhibit more frequent natural cleansing due to precipitation, allowing for an interval near 90 days unless urban pollution or industrial emissions produce elevated soiling rates. Weather-responsive cleaning is essential, with monitoring sensors or inverter performance data employed to dynamically adapt schedules in response to unexpected dust events or prolonged dry spells. In regions subject to episodic heavy dust events from construction or industrial activities, unscheduled cleaning should be considered promptly after such events to mitigate yield losses.

3.2. Cleaning Method Recommendations

Cleaning methodologies should be aligned with system size, exposure, safety, and cost considerations. For rooftop installations in residential neighbourhoods, manual cleaning using deionized water, soft sponges, and microfiber cloths is recommended, with explicit emphasis on safety practices. Larger commercial systems or utility-scale installations warrant consideration of semiautomated cleaning systems, given their demonstrated reliability in comparable European contexts. The adoption of protective coatings—hydrophobic and antistatic treatments—should be evaluated as a means to reduce soiling severity; regular inspection of coating integrity should accompany the cleaning schedule, with the expectation that such coatings extend the interval between cleaning events by decreasing particulate adhesion. Integrated monitoring should be employed to continuously evaluate soiling impacts, with a predefined performance threshold (for example, a 5% drop in daily yield relative to expected performance) serving as a trigger for cleaning interventions. This approach ensures that cleaning is administered in a data-driven, cost-effective manner.

3.3. Environmental and Practical Considerations

Environmental stewardship must be embedded in cleaning practices. Water usage should be judicious, with a preference for closed-loop recycling systems or low-water cleaning methods, particularly in regions where water conservation is critical. Maintenance records should be meticulously kept, including detailed logs of cleaning events, observed performance improvements, and any deviations from expected energy yields; such documentation facilitates refinement of cleaning intervals over time and supports warranty considerations if necessary. Local adaptation is essential, given that Romania's climate exhibits significant regional variation between mountainous areas and plains; therefore, environmental assessments at the local level should inform the precise calibration of cleaning frequencies and methodologies.

4. POLICY IMPLICATIONS AND STRATEGIC RECOMMENDATIONS

The economic and technical benefits associated with optimized PV module cleaning extend beyond individual installations and bear relevance for national energy policy and regulatory design. This section outlines how policymakers and energy regulators can promote cleaner maintenance practices in a manner that enhances system reliability, energy output, and long-term market sustainability. The discussion encompasses subsidies and financial incentives, regulatory guidelines, research and development (R&D), and strategic collaboration among stakeholders.

4.1. Subsidies and Financial Incentives

Public financial support can shift the cost-benefit balance in favor of more frequent and effective cleaning by reducing upfront and operating costs. Subsidies or low-interest loans could be targeted at PV system operators to facilitate the deployment of automated cleaning systems or the procurement of protective coatings. Such support is anticipated to yield higher energy production, thereby improving the overall efficiency of the solar fleet. In addition, incentive programs should consider integrating maintenance performance indicators into feed-in tariff schemes or other renewable energy incentives. Operators that sustain high performance through optimized cleaning could receive performance bonuses, creating incentives for best practices across the industry.

4.2. Regulatory Guidelines

Clear, standardized guidelines are essential to harmonize maintenance practices across diverse installations. The development of Standard Operating Procedures (SOPs) tailored to Romania's climatic conditions would provide a reference framework for routine PV module cleaning. These SOPs should be disseminated to both residential and commercial PV operators to promote consistency and safety. Furthermore, mandatory reporting mechanisms for maintenance records from large-scale PV installations could be established to furnish a national database of PV maintenance practices. Aggregated data would enable more precise regional cleaning recommendations and facilitate evidence-based policy refinement.

4.3. Research and Development

Local R&D initiatives are central to understanding the nuanced impact of soiling in varied Romanian climates. Collaboration among universities, research institutions, and industry stakeholders is encouraged to generate robust empirical evidence that informs optimal cleaning intervals and the development of innovative cleaning technologies. Demonstration projects should be funded to compare cleaning methodologies and technologies under real-world conditions across multiple regions. Outcomes from these pilots would guide future investments and policy decisions, ensuring that innovations translate into practical, scalable solutions.

4.4. Strategic Collaboration

The realization of integrated maintenance solutions benefits from strategic collaborations among PV manufacturers, cleaning service providers, and technology developers. Such partnerships should aim to minimize energy losses and maximize lifecycle performance through coordinated maintenance strategies. Public awareness campaigns are instrumental in communicating the long-term benefits of proactive cleaning, including cost savings and reduced system degradation. By elevating awareness among the public and PV owners, these efforts can contribute to improved grid reliability and enhanced renewable energy penetration.

5. CONCLUSION

The analysis herein demonstrates that the optimization of PV module cleaning regimes in climates similar to Romania constitutes both a technical and an economic imperative. The principal findings are as follows.

Soiling dynamics in a temperate-continental climate are characterized by seasonal variations, moderate baseline dust levels, and natural cleansing via rain and occasional snowfall. Consequently, cleaning intervals should be longer than those appropriate for arid regions but more proactive than those typical of locales with high rainfall. An optimal preventive cleaning frequency of 60 to 90 days is recommended to sustain high PV performance while balancing cleaning costs with the energy yield recovered.

The spectrum of cleaning methodologies ranges from manual cleaning with deionized water to automated, robotic cleaning systems; selection should be guided by system size, localized soiling rates, safety considerations, and economic constraints.

From an economic perspective, well-calibrated cleaning regimes can mitigate substantial energy losses, with the potential to avert even 3–5% annual efficiency losses, translating into meaningful financial gains over the system lifetime.

Policy measures—including subsidies, regulatory guidelines, and targeted R&D initiatives—can support the broader adoption of optimal cleaning practices, thereby improving the financial performance and sustainability of the renewable energy sector.

REFERENCES

[1] Mosbah, C. A., Kermadi, M., Gama, A., & Yettou, F. (2025). Smart and cost-effective optimisation of photovoltaic cleaning schedules. *Energy and Buildings*, 116184.

[2] Chiteka, K., Arora, R., Sridhara, S. N., & Enweremadu, C. C. (2020). A novel approach to Solar PV cleaning frequency optimization for soiling mitigation. *Scientific African*, *8*, e00459.

[3] Chiteka, K., Arora, R., Sridhara, S. N., & Enweremadu, C. C. (2020). Cleaning cycle optimisation in non-tracking ground mounted solar PV systems using Particle Swarm Optimisation. *International Journal for Simulation and Multidisciplinary Design Optimization*, *11*, 9.

[4] Kumar, M., Verma, D., Aggarwai, Y., Agarwal, D., & Tomar, A. (2024). Review of Various Photovoltaic Cleaning Methods. In *Advancement of Intelligent Computational Methods and Technologies* (pp. 114-119). CRC Press.

[5] Alghamdi, A. S., Bahaj, A. S., Blunden, L. S., & Wu, Y. (2019). Dust removal from solar PV modules by automated cleaning systems. *Energies*, *12*(15), 2923.

[6] Li, D., King, M., Dooner, M., Guo, S., & Wang, J. (2021). Study on the cleaning and cooling of solar photovoltaic panels using compressed airflow. *Solar Energy*, *221*, 433-444.

[7] Khadka, N., Bista, A., Adhikari, B., Shrestha, A., Bista, D., & Adhikary, B. (2020). Current practices of solar photovoltaic panel cleaning system and future prospects of machine learning implementation. *IEEE Access*, *8*, 135948-135962.

[8] Abuzaid, H., Awad, M., & Shamayleh, A. (2022). Impact of dust accumulation on photovoltaic panels: a review paper. *International Journal of Sustainable Engineering*, *15*(1), 264-285.

[9] Racoceanu., C. THE ROLE OF FOSSIL FUELS IN THE CURRENT ENERGY CRISIS, Annals of the" Contantin Brancusi " University of Târgu Jiu, Engineering Series, vol. 3(2022) , pag.63-66, ISSN: 1842-4856.

[10] Racoceanu., C. REDUCTION OF GREENHOUSE GAS EMISSIONS, Annals of the" Contantin Brancusi " University of Târgu Jiu, Engineering Series, vol. 3(2021) , pag.17-20, ISSN: 1842-4856

[11] Racoceanu., C. STUDY ON BENSON STEAM GENERATOR WET FLUE GAS DESULPHURIZATION, Annals of the" Contantin Brancusi " University of Târgu Jiu, Engineering Series, vol. 3(2022) , pag.67-70, ISSN: 1842-4856

[12] Racoceanu., C. EXERGY ANALYSIS OF POWER EQUIPMENT – PART II: EXERGY EFFICIENCY OF THE COMBUSTION PROCESS, Annals of the" Contantin Brancusi " University of Târgu Jiu, Engineering Series, vol. 3(2021) , pag.65-68, ISSN: 1842-4856

[13] Racoceanu Cristinel, ENERGY BALANCE MEASUREMENTS FOR AUXILIARY INSTALLATIONS OF LARGE POWER ENERGY GROUPS, Annals of the „Constantin Brancusi" University of Targu Jiu, Engineering Series, No. 2/2017, pag. 27 -31 , ISSN 1842 –4856.

[14] Racoceanu Cristinel, STUDY ON INFLUENCE OF ENERGY EFFICIENCY OF A STEAM BOILER BENSON ON ENVIRONMENTAL POLLUTION, Fiability&Durability, no.2/2017, pag.35-40, ISSN 1844-640X.

[15] Racoceanu Cristinel, STUDY ON THE ENERGY BALANCE OF THE ELECTRO-PUMPS WITH CONDENSATION FOR THE ENERGY GROUPS IN CONDENSATION OPERATING WITH INFERIOR COAL, Annals of the „Constantin Brancusi" University of Targu Jiu, Engineering Series, No. 3/2016, pag.19-23, ISSN 1842 – 4856.