CLEANING REGIMES FOR PV MODULES. COMPARISON OF METHODS, COSTS, AND EFFICACY

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ABSTRACT: The article presents a comprehensive analysis of PV module cleaning regimes tailored for Romania-like climates. Drawing on existing studies related to soiling, cleaning frequency, and economic assessments from various global regions, we identify critical factors affecting panel performance. Although many referenced studies focus on areas with highly arid or Mediterranean conditions, this article bridges those findings to the temperate-continental environment found in Romania and similar parts of Central and Eastern Europe.
The analysis suggests that, given Romania's temperate-continental climate, where rain provides natural cleaning but airborne dust and occasional snow or industrial pollution contribute to soiling, a proactive cleaning schedule—typically once every two to three months—can maximize system efficiency without incurring excessive maintenance costs.

KEY WORDS: optimization of cleaning schedule, cost-benefit analysis

1. INTRODUCTION

Photovoltaic (PV) systems are crucial components in the transition toward sustainable energy. Their performance, however, is significantly impacted by soiling – the unwanted accumulation of dust, pollen, bird droppings, and other particulates on panel surfaces. Soiling losses reduce the solar irradiance reaching the PV cells, thereby diminishing electrical output and ultimately affecting the economic viability of solar farms and rooftop installations alike [1,2].
Romania, with its temperate-continental climate marked by four distinct seasons, presents a unique set of challenges. Regions in Romania may experience moderate precipitation, periodic dust events from agricultural activities, and urban pollution that can accumulate on panel surfaces. Moreover, the transitional periods from dry to rainy seasons can exacerbate efficiency losses if panels are not suitably cleaned. Thus, understanding and implementing an optimal cleaning regime is pivotal.

This article delves into the specific factors that influence soiling in Romania-like climates, examines the methodologies and costs associated with panel cleaning, and proposes an optimized cleaning frequency that balances maintenance expenditures with revenue loss mitigation. The following sections provide detailed analysis and evidence drawn from multiple studies and supporting research data.

2. SOILING EFFECTS IN ROMANIA-LIKE CLIMATES

2.1. Nature and Rate of Soiling

Soiling on PV modules is a cumulative process and its impact is quantified by the reduction in transmittance—the fraction of sunlight reaching the cell surface. Research has shown that soiling losses can range from 1% to 30% in different locations [1,2]. In regions with high levels of airborne particulates, such as arid and semi-arid climates, the soiling rate is significantly higher. Although Romania does not experience the extreme dust storms of desert regions, the moderate dust levels from rural activities, urban pollutants, and sporadic industrial emissions still contribute to an efficiency loss of approximately 2%–5% over a month if left uncontrolled.

In Romania-like climates, rainfall plays a dual role. While rain events can naturally wash away deposited dust and particulates, long dry spells combined with agricultural dust accumulation can lead to substantial soiling losses. For instance, studies indicate that even with periodic natural cleaning by rainfall, a 5% decrease in energy yield can occur if panels are not regularly maintained [1,3].

2.2. Seasonal Variations

Romania experiences marked seasonal changes that affect panel soiling dynamics. During the spring and early summer months, agricultural activities often lead to elevated levels of dust. Additionally, pollen load during these seasons can further contribute to the particulate layer on PV surfaces. In contrast, the autumn and winter months, although benefiting from increased rainfall, can lead to a buildup of organic matter and other residues as panels are exposed to lower temperatures and occasional snowfall. The interplay of these factors necessitates a flexible and region-specific cleaning strategy.

2.3. Comparative Analysis with Other Climates

To frame Romania's conditions in a broader context, it is instructive to compare with regions discussed in the literature – table 1.

Table 1. Comparison with other climates

Region	Typical Daily Soiling Loss (%)	Natural Cleaning (Rain/Snow)	Recommended Cleaning Interval
Arid (MENA, Middle East)	0.5–0.87	Limited rain	5–7 days*
Semi-arid (Parts of India)	0.05–0.78	Moderate rain	5–12 days*
Temperate (Europe)	0.02–0.1	Frequent moderate rain	30–60 days
Romania-like Climates	~0.05–0.3 (estimated)	Seasonal rain and snow	60–90 days (proposed)

*For regions with extremely high soiling rates, cleaning cycles are aggressive to maintain performance [3].

Romania, similar to other temperate European countries, thus falls into a category where natural rain events are beneficial, but proactive cleaning remains important during prolonged dry periods.

3. PV MODULE CLEANING METHODOLOGIES

The cleaning strategy for PV modules is multifaceted, involving both operational parameters and environmental conditions. The methodologies discussed in literature range from simple manual cleaning to sophisticated automated systems. Common methods and evaluate their suitability for Romania-like conditions are further reviewed.

3.1. Manual Cleaning

Manual cleaning involves servicing solar panels using water, sponges, and soft brushes. This method offers high control over cleaning frequency and technique, which is beneficial for smaller residential or commercial installations. Manual cleaning is generally cost-effective when labor costs are low. However, safety concerns (especially for rooftop installations) and the potential for damage from improper cleaning techniques need to be carefully managed [3].

3.2. Automated and Semi-Automated Cleaning

For larger utility-scale PV farms, automated cleaning solutions using robotic systems or fixed cleaning installations have been developed. These systems can reduce labor costs and provide consistent cleaning quality. While the initial capital investment is high, the long-term maintenance cost per kW decreases significantly. Although automated systems are prevalent in arid regions with severe soiling problems, they may be less common in Romania due to moderate soiling rates6.

3.3. Water-Based Cleaning and Cleaning Agents

Water cleaning is the most common method, often complemented by non-abrasive detergents. The use of deionized or distilled water is critical to avoid depositing minerals that could reduce panel efficiency. Some studies have demonstrated that modest additions of a mild, biodegradable detergent can significantly improve cleaning effectiveness without damaging panel surfaces6.

3.4. Protective Coatings and Anti-Soiling Technologies

Another avenue is the application of hydrophobic or antistatic coatings on the PV surfaces. These coatings reduce the adhesion of dust particles, thereby lowering the rate of soiling and extending the interval between necessary cleaning events. Research findings indicate that coated PV systems can show an efficiency improvement of about 10% in the initial months compared to uncoated systems [4,5]. Such technologies are particularly promising for regions experiencing moderate soiling, like many parts of Romania.

3.5. Visual Inspection and Monitoring Systems

Continuous monitoring of energy yield through inverter data and the installation of soiling sensors are invaluable. A comparison of pre- and post-cleaning energy output allows operators to assess cleaning effectiveness and adjust frequencies accordingly. These real-time information systems help ensure that cleaning operations are triggered only when the energy losses exceed a threshold that justifies the cleaning cost6.

4. COST-BENEFIT ANALYSIS OF CLEANING REGIMES

Optimizing the cleaning schedule for PV modules requires a careful balance between the cost of cleaning operations and the potential revenue loss due to soiling-induced efficiency degradation. Several studies have produced analytical frameworks that assist in determining the optimal cleaning interval.

4.1. Economic Loss from Soiling

Soiling loss refers to the reduction in energy yield due to the deposition of dust and particulates on the panel surfaces. For example, if soiling results in a 10% reduction in output on a 10 kW system, the monetary loss can be estimated by multiplying the lost energy by the local retail electricity rate. In more extreme cases, such as those observed in parts of Asia and the Middle East, the loss can be as high as 2–5% even with optimized cleaning routes [6].

Romania, with milder soiling rates, might typically experience an annual loss of 2–4% in energy output if panels are not managed effectively. Given Romania's relatively moderate energy tariffs compared to regions with high electricity costs, the urgency of cleaning operations must be balanced against operational expenses.

4.2. Cleaning Costs

Cleaning costs vary considerably based on location, panel system size, and the chosen cleaning methodology. For instance, professional cleaning services in regions with optimized maintenance strategies typically cost between $75 and $300 per cleaning event for residential installations, while utility-scale cleaning costs are measured per kW capacity [7]. In Romania, labor costs are moderate compared to high-income regions, which could lower the cleaning cost per kW.

4.3. Formulation of the Cost Function

Researchers such as Abu-Naser [8] have derived formulas that equate the cost of cleaning to the lost revenue from efficiency degradation over time. The general idea is to determine the number of days N between cleanings by minimizing the total cost function defined as:

$$\text{Total Cost} = \text{Loss Due to Soiling Over } N \text{ Days} + \frac{P}{\text{Number of Cleaning Cycles per Year}}$$

where:

- P is the cost per cleaning operation
- The loss due to soiling is calculated based on factors such as average sun hours, system capacity, electricity tariff, and the daily loss in efficiency.

Researchers report that in highly soiled regions, optimal cleaning cycles might be as short as 5–7 days, whereas in more temperate, moderate-soiling conditions, optimal intervals extend to 60–90 days [2].

4.4. Comparative Cost Analysis

Table 2 summarizes the typical parameters for different climatic regions and how they influence cleaning frequency.

Table 2. Typical parameters for different climatic regions

Parameter	**Arid Regions (MENA)**	**Temperate Regions (Europe)**	**Romania-Like Climates (Estimated)**
Average Daily Efficiency Loss (%)	0.5–0.87	0.02–0.1	0.05–0.3
Natural Cleaning (Rainfall) Frequency	Low (infrequent)	High (regular rains)	Moderate (seasonal rains/snow)
Recommended Cleaning Interval	5–7 days	30–60 days	60–90 days
Cleaning Cost per Event (USD/kW)	Higher due to specialized tech	Moderate, manual cleaning prevalent	Moderate, potentially lower labor costs
Energy Yield Loss Impact	High (~10–15% annual)	Low (~2–4% annual)	Moderate (~3–5% annual)

*Data based on studies from multiple sources [2,3,5]

4.5. Decision Flowchart for Cleaning Cycle Optimization

The flowchart from figure 1 outlines the decision-making process for determining an optimal cleaning interval.

The flowchart illustrates the basic methodology for deciding whether and when to clean PV modules, ensuring that the cleaning regime is financially optimized based on local conditions [2].

5. CONCLUSIONS

Soiling of PV modules significantly affects energy yield, with estimated losses in the Romanian temperate-continent climate ranging from 2% to 5% per month if cleaning is not performed. Proactive cleaning regimes are essential to maintain near-peak system performance.

Regular cleaning frequency should be tailored to local conditions and soiling dynamics.

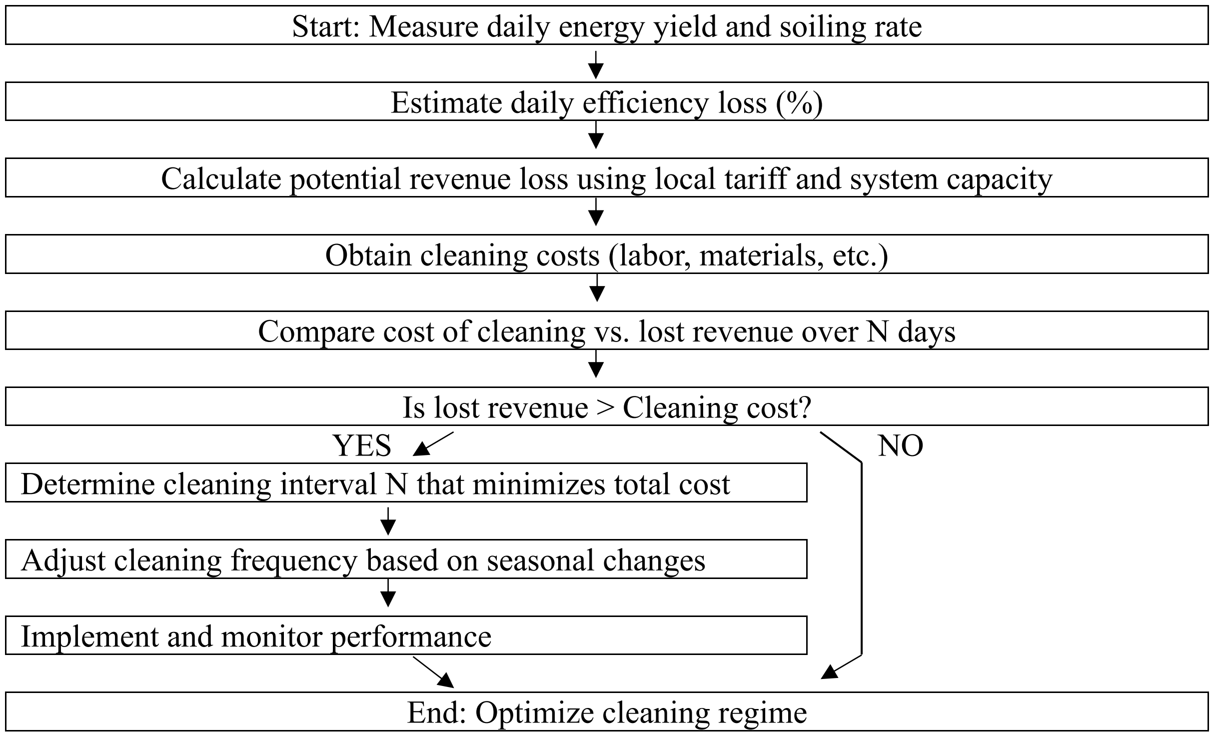

Fig. 1. Decision-making process for determining an optimal cleaning interval

For typical Romanian deployments, a cleaning interval of roughly 60–90 days is optimal, with shorter intervals during dry or dust-prone seasons and longer intervals in periods of higher rainfall or lower dust loads.

Real-time monitoring of production and soiling sensors can further refine this schedule.

Cleaning methods must balance effectiveness, safety, and total cost of ownership. Manual cleaning is suitable for small installations with controlled safety risks; automated or semi-automated cleaning reduces long-term labor costs but requires higher initial investment. Water-based cleaning with compatible additives and hydrophobic/anti-soiling coatings offer meaningful performance gains, particularly in regions with moderate to high soiling.

Anti-soiling coatings present a promising route to sustain higher initial efficiency, with potential gains around 10% in regions with moderate soiling. Durability, weathering, and maintenance implications should be incorporated into lifecycle cost analyses.

Coatings and cleaning strategies should be evaluated as part of an integrated asset management plan, combining predictive maintenance, production monitoring, and economic optimization. The goal is to maximize energy harvest while minimizing downtime and maintenance expenditures over the system's life.

Seasonal and regional variations in weather and pollution demand a dynamic, data-driven approach. Incorporate autumn/winter organic matter accumulation and spring/summer dust/pollen influx into planning, and adjust cleaning frequency accordingly.

Real-time data and decision support tools are valuable for optimizing interventions. Establish simple dashboards that track daily energy production, estimated losses due to suspected soiling, and recommended cleaning actions, enabling operators to act decisively.

The economic justification for cleaning investments hinges on the balance between marginal energy gains and maintenance costs. In Romania-like climates, the cost-effective sweet spot typically lies in proactive cleaning before substantial production losses accrue, rather than reactive cleaning after performance degradation is evident.

Stakeholder considerations, including plant owners, operators, and regulatory bodies, should emphasize risk management, safety, and environmental impact. Efficient cleaning strategies contribute to energy reliability, grid stability, and reduced water usage when optimized.

Further research opportunities include validating cleaning schedules with long-term field data, refining the cost-benefit model across diverse Romanian terrains, and exploring the performance implications of emerging coating chemistries under temperate continental conditions.

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