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Beyond the Broom: Reimagining O&M as the Neural Core of Long-Term Solar Plant Performance

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Abstract: **Among all renewable energy sources, solar energy is witnessing rapid growth. Its applications vary by location, including rooftop (RCC and tin-shed), ground-mounted, floating, and carport systems. While India has made significant progress in solar installations, the operations and maintenance (O&M) aspects are often overlooked. This paper highlights the importance of O&M practices in sustaining system performance over the standard 25-year lifespan. Real-world data from rooftop solar installations in northern India has been analyzed to support the discussion.**

Keywords: **Performance Ratio, Predictive Maintenance, Remote Monitoring System (RMS), O&M Analytics**

(I) INTRODUCTION

The solar industry is growing faster than ever whether it's massive utility-scale plants or small rooftop setups, more and more people are starting to see solar as a reliable way to generate electricity. With sunlight being so abundant, especially in countries like India, solar photovoltaic (PV) systems have become one of the most promising sources of clean energy. It's not just about going green anymore it's about saving money, gaining energy independence, and investing in a long-term solution. Over the past decade, the use of solar energy worldwide has grown rapidly [1].

As of 31st July 2025, India's installed solar power capacity has reached an impressive 119.02 GW [2]. This clearly shows how fast the country is embracing clean energy. But while installation numbers look great on paper, one of the biggest challenges that consumers especially rooftop owners are facing today is reliability. And reliability, in simple terms, is directly tied to how many units your solar plant actually produces over time. Installing a solar system is not just a one-time investment where one sets it and forgets it. People often assume that if they've used top-quality panels, inverters, and did the installation through a reputed vendor, their job is done. But that's only half the story. No matter how good the hardware is, if the system isn't properly maintained, it won't perform optimally. And that directly affects the Return on Investment (ROI) in the long run.

This is where Operation & Maintenance (O&M) plays a crucial role. Unfortunately, O&M is still widely misunderstood. Many think it only means cleaning panels or fixing faults when something breaks. But in reality, O&M is much more than that it's about regularly monitoring system performance, analysing data, spotting small inefficiencies before they become big issues, and making sure your plant is always running at its best. Data is the heart of this whole process. Without proper data and more importantly, without knowing how to read and act on that is just a guesswork and not O&M analytics and guesswork doesn't give ROI. A well-maintained plant, backed by strong data analysis, is the only way to ensure solar continues to deliver what it promised at the time of installation.

(II) THE BROOM MODEL: TRADITIONAL O&M

This model consists of the 5 aspects that limits the visibility of Solar O&M.

(i) Visual Inspection: It is the first and foremost activity during the process of preventive maintenance and corrective maintenance. In this process all the balance of systems visually inspected to figure out any abnormality/damage and actions are taken accordingly.

(ii) Periodic Cleaning: The soil and dust accumulate on the solar panel and as a result its efficiency gets severely affected. So, the regular cleaning is done to improve the functionality of solar panels. In the areas with minimal to no dust the practice of 3 cleaning cycles in a month is followed and in the dusty areas 4 or more cleaning cycles are done depending upon the site conditions and the level of dust.

(iii) Manual Fault Identification: When a fault occurs in a solar plant and the monitoring system fails to identify the exact issue, manual fault detection becomes necessary. This involves on-site inspection using standard tools and visual checks to locate the problem. The common problems in the system which can be identified in one go are: dirty or shady solar panels, loose or burnt MC4 connectors resulting in an open circuit, rodent damage (wires cut by rats), improper earthing, and SPD failure.

(iv) Corrective Maintenance: It is done when the fault is detected causing the breakdown. For example loose connections of nut and bolts in the busbar of ACDB can cause sparking and eventually melting the lugs and the Low AC Voltage or Phase Fault will appear in the inverter alarms. Until and unless the coorective maintenance is not done the system will be in breakdown causing the generation loss which eventually leads to the poor ROI.

(v) Skill Gaps: Apart from the above mentioned 4 activities one major challenge that often comes up is the presence of skill gaps. These gaps can make even simple tasks inefficient or prone to errors. For example, if a technician hasn't been properly trained to identify certain faults in the system, they might miss early signs of damage, leading to bigger issues later. Addressing these skill gaps through proper training and upskilling programs is essential to improve overall system reliability.

(III) SOLAR O&M AS THE "NEURAL CORE" – NEW PARADIGM

Just like the human brain governs the body through sensory inputs, processing, memory, reflexes, and decision-making, a solar O&M system also relies on similar functions to ensure continuous and efficient plant operation. The parallels are as follows:

(i) Sensory input: Sensors play a vital role in capturing key environmental and system parameters such as solar irradiance, module temperature, and string voltage. Remote Monitoring Systems (RMS) continuously track plant performance, while IV curve tracing helps assess panel health by analyzing current-voltage behavior. Additionally, thermographic imaging is used to detect hotspots and cell-level damage in modules, ensuring early identification of performance issues.

(ii) Processing: O&M analytics functions as the brain's processing unit, it interprets incoming data to evaluate system performance, detect anomalies, and prioritize corrective actions. Third-party data loggers further enhance this by enabling functions like DG synchronization, zero-export control, and real-time alarm detection, helping to minimize underperformance and unplanned downtime.

(iii) Short-term memory: Modern solar inverters are equipped with onboard memory that logs alarm events along with timestamps. These logs can be accessed via the inverter interface or associated mobile applications. Reviewing this short-term alarm history helps O&M teams identify recurring faults, analyze downtime trends, and respond with appropriate maintenance actions.

(iv) Long-term memory: Just as the brain stores long-term experiences for better decision-making, an intelligent O&M framework relies on historical data including degradation rates, seasonal weather patterns, and equipment failure records to build predictive models. These insights are essential for forecasting performance and planning preventive interventions.

(v) Reflexes: Similar to human reflexes that act instantly to protect the body, a well-integrated solar plant responds to critical faults through automated shutdowns, system alerts, and immediate technician dispatch. This rapid response helps prevent equipment damage and reduces energy generation losses.

(vi) Decision-making Based on continuous data inputs, the O&M system can schedule predictive maintenance, trigger load management, and execute remote controls to optimize plant operation. These decisions improve system efficiency, reduce manual intervention, and extend the overall life of the solar asset.

(IV) DATA-DRIVEN DECISION MAKING IN SOLAR O&M

As discussed in the previous section the O&M Analytics is the heart and soul of Solar O&M as everything is based upon data. The one and only thing which influence the decision making in this area is real-time authentic data.

(i) Real time monitoring platforms: There are various platforms that enables us to monitor the plants remotely such as DelREMO, SuryaLog, Qantum etc. Not only they show the real time data in the forms of tables and graphs but also record the data of previous days in the form of daily data, weekly data, monthly data, and annual data so they can be accessed as per the user's convenience.

(ii) KPI tracking: The tracking of Key Performance Indicators such as Performance Ratio (PR), Capacity Utilization Factor (CUF), Downtime can be tracked by these monitoring platforms itself. If the low performance is detected in these parameters then the analysis is done to figure out the root cause. On the basis of generation and dust issues the cleaning cycles in a month is decided.

(iii) Case Study (A real story of the commercial solar plant):

How a PR drop was detected early due to RMS in June 2024?
A 290 kW solar plant has been installed at a factory located in of the North-East Indian states. This area is heavily affected by dust, which frequently accumulates on the solar panels. As a result, a thick layer of dust settles on the panels, leading to reduced power generation and a lower Performance Ratio (PR). This issue was detected through the Remote Monitoring System (RMS) integrated with the Weather Monitoring System (WMS). The data for a period of 10 days is as follows:

Date	Generation (kWh)	Irradiance	PR
10-06-2024	942	4.35	74.67%
11-06-2024	247	1.3	65.51%
12-06-2024	846	4.4	66.30%
13-06-2024	861	4.42	67.17%
14-06-2024	930	4.26	75.27%
15-06-2024	938	4.32	74.87%
16-06-2024	623	3.42	62.81%
17-06-2024	929	4.21	76.09%
18-06-2024	932	4.26	75.44%
19-06-2024	709	3.36	72.76%

A reduction in Performance Ratio (PR) was observed on 12-06-2024 and 13-06-2024 due to dust accumulation on the solar panels. In response, the site engineer prioritized panel cleaning, which led to an improvement in PR on 14-06-2024 and 15-06-2024. By analyzing the data, most plant-related issues can be identified, enabling informed and effective decision-making to address them.

All site-specific information has been anonymized to ensure client confidentiality while preserving the integrity of the data analysis.

(V) AUTOMATION IN O&M AND SYSTEM LONGEVITY

O&M and system longevity go hand in hand. The brain doesn't waits to be told, it reacts. So should O&M in solar plants. The following aspects of automation in O&M ensures the smooth functioning of the solar plants:

(i) Robotic Cleaning: It ensures uniform and regular cleaning of PV modules, especially useful in dusty or remote regions and reduces manual labour, water usage, and downtime. It also maintains consistent irradiance-to-energy conversion by minimizing soiling losses.
(ii) Drones for inspection: Thermographic (IR) imaging detects hotspots, PID, diode failures, and other thermal anomalies quickly. Visual imaging identifies physical damage, module cracks, or cable issues from an aerial view. It enables fast and accurate diagnostics over large solar fields, reducing inspection time drastically.

(iii) Auto Ticketing Systems: It is one of the most amazing concepts in which faults and alarms from SCADA or inverter systems are automatically converted into tickets and assigned to relevant O&M Engineer. It supports real-time fault logging, priority-based resolution, and closure tracking which in turn minimizes human error and improves response time and accountability.

(iv) Smart Inverter-Based Auto-Triggers: Inverters with built-in intelligence can perform auto-isolation of faulty strings or MPPT channels. Auto-triggers can initiate protective actions (like shutdown or derating) under abnormal grid or thermal conditions. It Supports remote diagnostics, event logging, and predictive maintenance using inverter analytics.

By ensuring the smooth O&M the problem of hotspots, PID, cable burnouts, and MPPT losses can be solved.

Even after so much of debate and discussions the O&M always remains an unsung part.

(V) A case study of two different 3 years old system with and without O&M: This case study compares two different solar plants, both commissioned in April 2022 in one of the North Indian cities. One plant has a capacity of 300 kW, and the other is 280 kW, a normal difference of 20 kW in DC capacity (kW_p). Both are RCC rooftop commercial systems, installed by the same installer, in the same month, and in the same city.

What is the only difference at both of these plants?

One plant has been properly maintained through dedicated O&M services, while the other has not.

So, when the installer, commissioning month, and location are all the same, where did things go wrong?

Issues	With O&M	Without O&M
Ground Fault	Whenever the plant encountered a ground fault, the site engineer resolved it on the same day.	Little to no awareness of the Remote Monitoring System (RMS); the fault was detected late, resulting in significant generation loss.
Soiling loss	Dedicated solar module cleaning team used the proper cleaning equipment for the solar module cleaning every week.	No dedicated team; local factory workers occasionally used conventional water pipes, only removing the top layer of dust.
Fault occurrence	Strategic and timely preventive maintenance was performed quarterly. As a result, no major faults occurred over the 3-year period.	Frequent breakdowns were reported, including MC4 connector burnouts, sparking in the ACDB, and lug failures due to loose connections.
Analytics and Data-Collection	O&M activities were backed by performance analytics, enabling early detection and resolution of issues.	No data analytics were performed; issues were addressed only after they escalated significantly.
Safety-Concerns	A safety engineer conducted quarterly site visits to identify and mitigate potential risks or hazards.	No safety audits were performed, and risks remained unidentified and unaddressed throughout the period.

This is a real case study. When the issues started becoming frequent at the plant that was not under O&M, the owner finally decided to opt for structured maintenance to improve the system's performance and credibility which is crucial. While the generation loss that occurred earlier is irreversible, such issues can be avoided in the future provided that O&M is carried out consistently and as per schedule.

*Specific locations have been anonymized to maintain confidentiality, without impacting the accuracy or relevance of the findings.

(VI) SAFETY, FIRE RISK & COMPLIANCE AS COGNITIVE FUNCTIONS

In solar operations and maintenance (O&M), safety must always come first regardless of timelines or work pressure. Protecting both human life and solar infrastructure is the top priority before initiating any activity on-site. Most major losses in solar plants occur due to human negligence or poor maintenance practices, which can be prevented with basic awareness and regular system checks. Below are four key areas that must be addressed proactively to avoid safety incidents and equipment failures:

(i) SPD Failure Detection: Surge Protection Devices are installed in both the DCDB (DC Distribution Box) and ACDB (AC Distribution Box) to safeguard equipment from sudden voltage spikes typically caused by lightning or switching events. If an SPD fails and goes unnoticed, the system is left exposed to damaging surges. Fortunately, most SPDs come with a visual status indicator commonly green for healthy and red for faulty. This makes it easy for even non-technical personnel on-site to identify a problem just by observing the indicator. However, it's critical that failed SPDs are replaced immediately to maintain protection levels.

(ii) Ground Fault Monitoring: Also known as insulation fault or PV ISO fault, this occurs when damaged cable insulation allows current to leak to the ground. This typically results in the inverter shutting down and displaying an insulation alarm. Ground faults can be identified through remote monitoring systems or on-site by measuring the floating voltage at the string level. Once the faulty string is located, the issue is often resolved by isolating the damaged portion and reconnecting it using MC4 connectors or by replacing the affected cable segment. Regular insulation resistance checks can prevent such faults from escalating.

(iii) Earthing resistance monitoring: One area that's gaining more attention from site engineers is earthing resistance monitoring. Over time, ground connections can deteriorate due to corrosion, soil conditions, or poor workmanship, and if left unchecked, they can significantly increase the risk of fault currents going undetected or finding unintended paths leading to equipment damage or even fires. By continuously monitoring earth resistance, one can actively reduce risk and ensuring the grounding system is doing what it's supposed to do under real-world conditions.

(iv) Policy compliance auto-checks (future idea): Another concept that's emerging and one that could really change the current compliance is automated policy compliance checks. While still more of a future-forward idea, the potential is huge. Imagine a system that can cross-check live plant data against O&M protocols, grid codes, or internal safety standards, and flag deviations in real time before they turn into issues. It shifts the role of compliance from a periodic audit to a live, self-correcting process. This function can create a significant impact treating safety not as an afterthought, but as an integrated, intelligent part of the solar plant's brain.

(VII) FUTURE VISION: AUTONOMOUS, SELF HEALING SOLAR PLANTS

(i) AI agents handling O&M: AI will play a key role in automating O&M by continuously monitoring system health, identifying faults, and predicting failures before they occur. Machine learning models will analyze real-time data from sensors to optimize performance, reduce downtime, and eliminate the need for routine manual inspections, resulting in higher efficiency and lower operational costs.

(ii) Digital Twins: A digital twin is a virtual replica of the physical solar system that operates in parallel with it. It enables real-time performance tracking, predictive analysis, and simulation of various scenarios without risking actual hardware. Engineers can remotely test updates or troubleshoot faults, leading to more accurate diagnostics, faster repairs, and improved system reliability over time.

(iii) Blockchain-based service logs: Using blockchain technology for service logs ensures all maintenance and operational activities are recorded in a secure, tamper-proof, and transparent manner. This builds trust among stakeholders and allows for traceability of every service event. Smart contracts can automate maintenance schedules, while decentralized records ensure no single point of failure or data manipulation risk.

(iv) Decentralized O&M microservice networks: Instead of relying on centralized control, decentralized O&M microservices will allow different parts of the solar system to manage specific tasks independently. Each microservice will handle a dedicated function like fault detection, cleaning, or performance analysis communicating through standardized protocols. This increases modularity, fault tolerance, and scalability, especially in large, distributed solar installations.

(VIII) CONCLUSION

As the solar sector matures, it's clear that operations and maintenance (O&M) is no longer a secondary task it is the neural core that defines long-term system reliability, performance, and ROI. Traditional models like "broom-based" maintenance no longer suffice in a world where even minor inefficiencies can lead to major generation losses. With data-driven analytics, AI integration, and automation, O&M is evolving from reactive upkeep to intelligent, proactive system governance. Concepts like digital twins, automated fault detection, and blockchain-based logging aren't futuristic anymore they're becoming operational necessities. For engineers on the ground, this means retraining our perspective: from just keeping systems running to engineering ecosystems that think, react, and heal themselves. This shift isn't optional, it's inevitable. And those who adapt will define the next phase of India's solar success story.

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