



## A COMPREHENSIVE PROCESS TO EFFICIENT SOLAR PHOTOVOLTAIC SYSTEM ENERGY MANAGEMENT AND MAINTENANCE

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### Abstract

*The expansion of photovoltaic systems emphasizes the crucial requirement for effective operations and maintenance, drawing insights from advanced maintenance approaches evident in the wind industry. This review systematically explores the existing literature on the management of photovoltaic operation and maintenance. Through the integration of bibliometric analysis and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, 186 articles are selected for further comprehensive review.*

*The selected articles are examined and categorized into four interconnected research domains: maintenance strategies, performance indicators, degradation modeling, and maintenance optimization and planning. The presented analysis underscores the importance of integrating maintenance strategies to enhance system effectiveness. It also emphasizes the necessity of a systematic approach that integrates reliability assessment with economic and technical considerations to optimize maintenance planning and enhance system availability and resource efficiency. This aligns with the Sustainable Development Goals for affordable, reliable, and sustainable energy, while also ensuring grid security. Furthermore, the study identifies gaps and proposes avenues for improvement, recommending a shift towards prognostic approaches and the advancement of predictive maintenance in photovoltaic systems. Key suggestions also include customizing metrics for large installations, implementing adaptive protocols that move away from traditional component-centric scheduling, and using reinforcement learning to prioritize risk and optimize long-term performance. Compared to previous reviews focusing on specific maintenance elements, this work provides a broader perspective by incorporating planning and organizational factors into the maintenance discussion.*

### 1. INTRODUCTION

The rapid global expansion of solar photovoltaic (PV) technology has transformed it from a niche energy solution into a mainstream component of modern electricity systems. Declining costs, improved module efficiencies, and strengthening policy commitments to decarbonization

have accelerated adoption across residential, commercial, and industrial applications (IEA, 2024; Fraunhofer ISE, 2022). In many developing regions—including Sub-Saharan Africa—solar PV provides an especially compelling alternative to conventional fossil-fuel generators due to its modularity, low operating costs, and capacity to support energy access for underserved households and small businesses (Keisang et al., 2021; REN21, 2022). However, while the installation of PV systems continues to increase, significant gaps persist in users' understanding of system operation, maintenance requirements, and long-term performance optimization.

Effective operation and maintenance (O&M) practices are indispensable for ensuring that PV systems meet expected energy-yield targets, minimize financial losses, and operate safely throughout their service life (Bosman et al., 2020; Hernández-Callejo et al., 2019). Research shows that inadequate or inconsistent maintenance can lead to accelerated degradation, increased downtime, safety hazards, and reduced return on investment (Aghaei et al., 2022; Koester et al., 2022). While large utility-scale plants often employ professional O&M service providers, owners of small and medium-sized enterprises (SMEs), households, and microgrid operators frequently lack access to technical guidance and practical tools needed to ensure proper system upkeep. As highlighted by Márquez (2022), many existing studies examine discrete aspects of PV maintenance—such as fault diagnosis, soiling, or degradation patterns—yet few offer an integrated, user-oriented approach that combines operational, technical, safety, and financial considerations.

The aims of this paper respond directly to these gaps by providing clear, practical, and accessible guidance on solar PV system operation, maintenance, safety, and performance monitoring. First, it seeks to equip SME owners and system operators with the knowledge required to improve energy efficiency, reduce operational costs, and extend system lifespan (Feldman et al., 2023). Second, it offers step-by-step maintenance procedures, troubleshooting methods, and advice on when professional technical assistance is warranted, drawing on established industry standards and research evidence (Walker, 2018; Livera et al., 2022). Third, the paper targets general users—including households and small businesses—by demystifying the functional principles of PV systems and promoting informed decision-making related to performance monitoring and safety (Navid et al., 2021). Finally, the paper emphasizes the importance of adhering to safety protocols, regulatory requirements, and international best practices to safeguard users and prevent accidents (Høiaas et al., 2022; Hernández-Callejo et al., 2019).

In addition to addressing technical and operational competencies, the paper highlights broader motivations for improved PV O&M, including cost savings, system reliability, and environmental sustainability. By empowering users to undertake routine maintenance and identify emerging issues early, unnecessary expenses—such as premature component failures, inefficient energy use, or preventable repairs—can be significantly reduced (Conceicao et al., 2022; Peinado-Gonzalo et al., 2020). Aligning user practices with established O&M standards also supports the long-term goals of renewable-energy adoption, including emission reduction, improved energy access, and compliance with national and international benchmarks (REN21, 2022; IEA, 2024). In this regard, the paper also serves as a crucial resource for technicians, system owners, microgrid operators, and other stakeholders who require structured, actionable, and safety-focused guidance for managing PV installations.

By integrating technical explanations, practical procedures, diagnostic tools, safety requirements, and maintenance frameworks, this paper contributes to the growing body of literature on PV system O&M. It offers a holistic and user-centered approach that prioritizes system reliability, energy performance, safety, and longevity—dimensions that are essential

for maximizing the value of solar PV investments across diverse user groups and system applications.

## **1. 2. LITERATURE REVIEW**

The literature reveals a wealth of review studies on topics related to PV O&M, as well as bibliometric studies within the solar PV research domain. Table 1 classifies the literature reviews on PV O&M- related subjects based on their scope and also categorizes the different bibliometric studies in the field of solar energy. Several review articles have conducted comprehensive investigations on monitoring and fault diagnosis techniques in the field of PV systems. Specifically, Høiaas et al. [2022] reviewed optics-based tools for large-scale PV module inspection, including fault classification and evaluations of infrared thermography and luminescence imaging technologies. These techniques are pivotal in aiding O&M operators in accurately identifying faults in PV plants. Similarly, Jaen-Cuellar et al.[2022] investigated faults in solar PV and wind power systems, analyzing their causes and impact on efficiency and maintenance costs. The study emphasized the growing utilization of data-driven techniques, such as machine learning (ML), for fault detection and diagnosis. Investigating failure and degradation modes in PV systems has also received considerable attention in the literature. Peinado Gonzalo et al.[2020] analyzed failure and degradation mechanisms in PV modules, emphasizing the identification of root causes and prevention techniques for issues such as soiling, snow deposition, corrosion, cracks, and hot spots. The study emphasized preventive maintenance techniques such as surface modifications, coatings, and fatigue analysis. Another study by Hernández-Callejo et al. [2019] discussed critical components, design factors, and O&M of PV systems, addressing energy control mechanisms, module degradation, and the influence of meteorological factors. Mitigation techniques such as uniform cooling were studied, and operational risk management was utilized to identify risks associated with electric current, fire hazards, natural events, and human factors.

Some reviews have focused on the effect of dust and soiling on PV panels and investigated various cleaning methods for enhanced performance. Conceicao et al. [2022] examined the advancement of soiling research in solar energy, covering soiling characterization, modeling, and various cleaning techniques and their influence on O&M costs. Other studies have explored various maintenance schemes for PV systems. In their study, Keisang et al. [2021] investigated O&M strategies in PV microgrid systems, including corrective, preventive, and predictive maintenance. The study focused on O&M challenges and solutions in PV microgrids in Sub-Saharan Africa, highlighting the importance of decentralized PV generation in addressing electricity access and poverty. Considerable focus has also been directed towards predictive maintenance and energy forecasting methods. For example, Ramirez-Vergara et al. [2022] looked into predictive maintenance models as an economical option for solar PV systems. The article assessed forecasting methods for critical factors such as solar irradiance and temperature, particularly highlighting the potential of ML models.

It is evident that the O&M management of PV systems lacks comprehensive research that addresses the broader challenges and complexities of maintenance. As mentioned by Márquez [2022], a comprehensive examination of maintenance management issues in solar energy systems is needed. Although Keisang et al. [2021] recognized the

importance of developing a maintenance itinerary and engaging stakeholders, their emphasis was primarily on managerial guidelines for O&M approaches. Furthermore, their assessment criteria overlooked essential technical system-related parameters, such as equipment reliability, failure rates, maintenance costs, and system availability. A successful maintenance program seeks to minimize failures, maximize production uptime, and reduce production loss through timely interventions. Once a maintenance strategy is determined, the focus shifts to scheduling, presenting an optimization challenge to ensure continuous and reliable operation of the PV system. However, there is a lack of comprehensive guidance on how to effectively coordinate the timing and sequencing of maintenance interventions and strategically integrate them within the broader operational context of a PV system. In addition, the effectiveness of O&M programs relies on the inclusion of factors such as staff coordination, required spare parts, and logistics and supply chain management, which have not received sufficient attention despite being crucial for techniques.

Madsuha et al. [2021] analyzed solar research in Indonesia, covering semiconductors, simulation, and integration of technology and regulation. In addition, a comprehensive analysis conducted by David et al. [2020] observed the evolving trends in PV energy management, discovering crucial aspects such as demand management, consumer behavior, and module materials. It is evident that the application of bibliometrics in the context of PV systems O&M management remains underexplored. The existing literature lacks detailed thematic descriptions of the management and planning of maintenance tasks, which are essential to ensure optimal performance. This gap calls for a more thorough and systematic analysis, tracking the evolving trends, and exploring key themes in PV O&M beyond the conventional domains. Embracing a holistic approach to O&M management enables a comprehensive understanding of the technical, operational, and financial elements involved. This ensures that maintenance practices are not limited to isolated tasks, but are integrated into a cohesive and efficient system.

### **3. THE PURPOSES OF O&M FOR PV SYSTEMS**

Operations and maintenance (O&M) is critical for keeping solar photovoltaic systems performing at their best over their lifetime. While we often think of solar as a “set it and forget it” technology, proper maintenance ensures systems meet production targets, maintain warranties, and operate safely.

Proper O&M serves several key purposes for PV systems:

- a. Maximizes system availability and minimizes downtime
- b. Helps meet expected financial and energy production targets
- c. Maintains equipment warranties
- d. Ensures system safety and manages liability
- e. Provides data to inform future design decisions

The solar industry increasingly recognizes that O&M shouldn't be an afterthought—it should be factored into system design and budgeting from the beginning. This approach ultimately saves money by improving reliability and reducing maintenance costs. PV maintenance requires a balanced approach between prevention and reaction. Preventative maintenance provides the foundation of system care—scheduled, predictable work that maintains health and meets warranty requirements. Like dental hygiene, it's about addressing small issues before they become major problems. Reactive maintenance, though sometimes unavoidable, typically

costs more and creates unplanned disruptions.

The most effective O&M strategies emphasize prevention while maintaining readiness for quick reaction when necessary. Even with rigorous preventative protocols, external factors like severe weather, wildlife damage, or equipment failures will occasionally demand immediate attention. The goal isn't eliminating reactive maintenance entirely, but rather minimizing its frequency through thoughtful prevention, which ultimately improves system reliability while reducing lifetime maintenance costs.

There are three critical diagnostic tools that should be in every solar technician's toolkit: They are:

(a) *I-V Curve Tracers*: I-V curve tracers measure the relationship between current and voltage in a PV circuit, providing insight into how modules are performing. This tool allows technicians to:

- Test PV array performance independent of the inverter
- Establish baseline data at commissioning
- Verify performance against manufacturer specifications
- Troubleshoot specific issues with modules or strings

A key advantage is the ability to detect problems that wouldn't show up using basic multimeter tests. For example, a module with a third of its cells bypassed due to damage would show normal open-circuit voltage and short-circuit current readings with a multimeter, but the I-V curve would reveal the issue through characteristic "humps" or "notches."

(b) *Thermal Imaging*: Thermal cameras have become an essential tool for O&M providers due to their efficiency and ease of use. They detect temperature differences that indicate potential issues in both PV modules and electrical equipment. Two main applications include:

- a. *Aerial thermal imaging* efficiently evaluates large arrays to identify modules or strings with issues. Drones or aircraft equipped with thermal cameras can quickly scan entire systems to find anomalies.
- b. *Handheld thermal imaging* is ideal for examining electrical equipment like combiners, inverters, and terminations, as well as for targeted troubleshooting of specific modules.

Common issues that thermal imaging can detect include non-operating strings or modules, bypass diode failures, cell hotspots, loose electrical connections, and blown fuses. It's important to remember that thermal imaging shows symptoms rather than causes—additional troubleshooting is typically needed to determine the underlying problem.

(c) *Insulation Resistance Testing*: Insulation resistance testing measures how well insulation prevents leakage of electrical current. This testing:

- Verifies conductor integrity during commissioning
- Establishes baseline data for future comparisons
- Helps locate ground faults during troubleshooting

For PV systems specifically, insulation resistance testing can identify which module or section of wiring has a ground fault. By systematically measuring voltages between the

array's conductors and ground, technicians can pinpoint fault locations with remarkable precision.

#### **4. PRACTICAL GUIDELINES FOR FIELD TESTING**

PV maintenance requires a balanced approach between prevention and reaction. Preventative maintenance provides the foundation of system care—scheduled, predictable work that maintains health and meets warranty requirements. Like dental hygiene, it's about addressing small issues before they become major problems. Reactive maintenance, though sometimes unavoidable, typically costs more and creates unplanned disruptions.

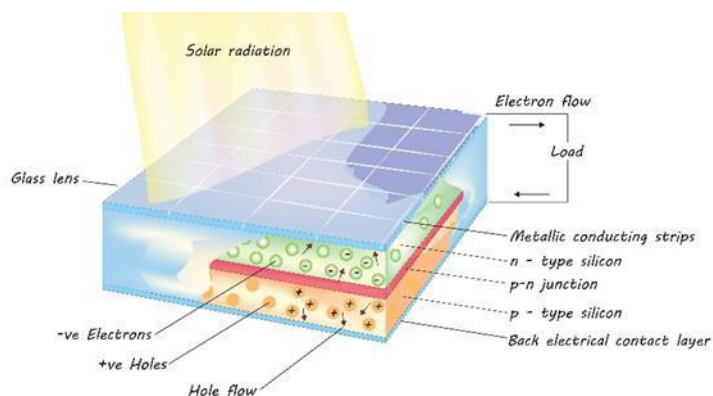
The most effective O&M strategies emphasize prevention while maintaining readiness for quick reaction when necessary. Even with rigorous preventative protocols, external factors like severe weather, wildlife damage, or equipment failures will occasionally demand immediate attention. The goal isn't eliminating reactive maintenance entirely, but rather minimizing its frequency through thoughtful prevention, which ultimately improves system reliability while reducing lifetime maintenance costs. Effective solar O&M requires both proper planning and the right diagnostic tools. I-V curve tracers, thermal cameras, and insulation resistance testers provide complementary data that helps technicians identify and resolve issues efficiently.

As the solar industry continues to mature, comprehensive O&M strategies become increasingly important to ensure systems perform reliably over their 25+ year lifespan. Investing in proper maintenance practices and diagnostic tools ultimately protects the long-term value of these renewable energy assets.

### **5.0 OVERVIEW OF SOLAR PV SYSTEM**

#### **5.1 The Scope of Solar PV Systems Covered / What are the fundamentals of PV Systems**

Photovoltaic (PV) solar energy conversion is a process that utilizes semiconductor materials, which are predominantly composed of silicon, to transform sunlight into electrical energy. The fundamental principle behind solar PV technology is the photovoltaic effect. Electrons within the semiconductor material of the solar cells are energized when sunlight strikes the material, generating an electrical current.



**Figure 1.** Photovoltaic Effect © KKT Madhusanka | Dreamstime

Solar panels are constructed from solar cells as their fundamental components. In most cases, these cells are constructed from silicon, a readily available material with advantageous semiconductor characteristics. Solar cells can be monocrystalline,

polycrystalline, or thin film, each with different efficiencies and costs.

*Monocrystalline Solar Cells:* Made from a single crystal of silicon, these cells are highly efficient and recognizable by their uniform black color and rounded edges. They are ideal for spaces with high energy demands and limited area.

*Polycrystalline Solar Cells:* Constructed from multiple silicon fragments melted together, these cells have a distinct blue, speckled appearance. They are less efficient than monocrystalline cells but more cost-effective.

*Thin-Film Solar Cells:* Composed of photovoltaic material layers on a substrate, these are lightweight and flexible. They are less efficient but excellent for large-scale or portable applications. Solar cells are assembled into larger units known as solar panels or modules. These panels are typically what you see on rooftops or in solar farms.

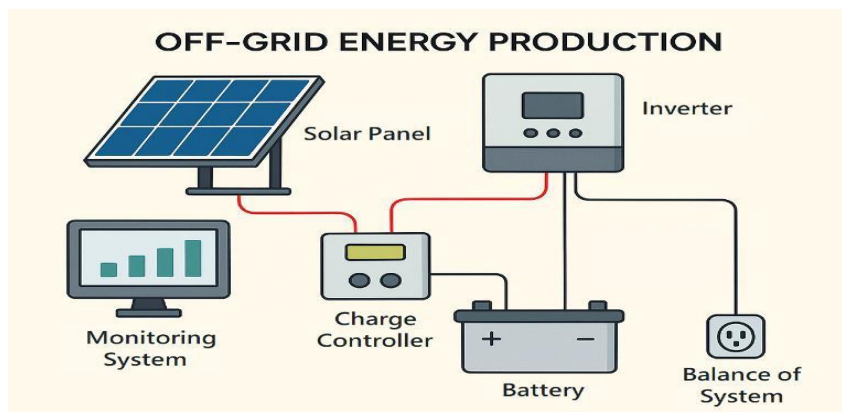


**Figure 2.** Types of solar cells – monocrystalline at the bottom, polycrystalline at the top. Source: <https://amplussolar.com/blog/complete-guide-about-types-of-solar-panels/>

## 5.2 Components of Solar PV Systems

Regardless of the size and location of an installation, the basic components needed to guarantee a correct and safely functioning Solar PV system are the same.

Additional components can be included to increase the performance and efficiency of the overall system.



**Figure 3.** Off-grid solar power system with battery storage. OpenAi (2025). ChatGPT (May 27 Version)

**Table 1. Components of Solar PV Systems**

Fundamental components	Description
Solar Panels (PV Modules)	<i>Function:</i> Capture sunlight and convert it into direct current (DC) electricity. <i>Types:</i> Monocrystalline, polycrystalline, and thin-film solar panels, each with different efficiencies and cost. Typically installed on rooftops, ground mounts, or solar farms.
Inverters	<i>Function:</i> Convert DC electricity generated by the solar panels into alternating current (AC) electricity. It is essential for the usability of solar energy in standard electrical systems and for feeding electricity into the grid. <i>Types:</i> String inverters, microinverters, and hybrid inverters.
Mounting Systems	<i>Function:</i> Securely hold solar panels in place. It needs to be robust and weather-resistant and may need to be angled for optimal sun exposure. <i>Types:</i> Fixed mounts, tracking mounts, and ground-mounted systems.
Electrical Components	Include wiring, fuses, circuit breakers, and disconnect switches. <i>Function:</i> Ensure safe operation and connectivity of the solar PV system and protect against electrical surges and faults.
Balance of System	All other components that are required to ensure the proper functioning of the solar PV system, such as grounding equipment, conduits, junction boxes, etc.
Additional components	Description
Batteries	<i>Function:</i> Store excess electricity produced by solar panels for use when there is no sunlight (e.g., at night or during cloudy days). <i>Types:</i> Lead-acid, lithium-ion, and flow batteries, with varying capacities, lifespans, and costs. Important: Particularly important for off-grid systems or grid-tied systems with a self-consumption focus.
Charge Controllers	<i>Function:</i> Regulate the voltage and current coming from the solar panels to the batteries, preventing overcharging and damage to the batteries. <i>Types:</i> Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT), with MPPT being more efficient. Important: fundamental in case batteries are connected to the PV system.
Monitoring Systems	<i>Function:</i> Track the performance of the solar PV system, including energy production, system health, and efficiency. <i>Types:</i> Onsite and remote monitoring systems, often accessible via smartphone apps or web interfaces.

Grid Interconnection Equipment (grid-tied)	Includes specific types of inverters and safety equipment that meet grid standards and regulations. <i>Function:</i> Safely and legally connect the solar PV system to the public electricity grid. <i>Important:</i> Needed for PV systems connected to the public grid.
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Each component in a solar PV system *must be carefully selected and integrated* to ensure maximum efficiency, safety, and longevity of the system.

### **5.3 System Layout and Configuration**

Designing a solar PV system involves several key considerations to ensure optimal performance, safety, and efficiency. The form and design of the system can vary considerably depending on factors such as the application (residential, commercial, industrial), location, available space, and unique energy requirements. For instance, residential systems often prioritize aesthetics and space efficiency, utilizing rooftop installations to maximize available area, whereas commercial systems may focus on larger-scale energy production, often employing flat-roof or ground-mounted setups. In industrial applications, high energy demands and robust infrastructure lead to extensive ground-mounted arrays or hybrid systems with backup storage. Location plays a critical role, as areas with high solar irradiance favor optimal panel tilt angles and orientations for maximum sunlight capture, while regions prone to extreme weather require reinforced structures. Available space determines the layout, with limited areas requiring compact, high-efficiency panels, while open spaces allow for expansive installations. Finally, unique energy requirements, such as off-grid or grid-tied systems, influence the inclusion of storage batteries, inverters, and backup systems to meet specific energy reliability and usage patterns.

### **5.4 Solar Panels Arrangement**

Select panels of either monocrystalline, polycrystalline, or thin-film type, considering their efficiency, cost, and space requirements. To fully tap into the potential of an installation, it is important to consider carefully where those are placed and their inclination angle as both aspects influence the energy ultimately produced under the same weather conditions.

*Orientation and Tilt:* there is no standard value that can be applied to all installations as orientation depends on the geographical location. In the Northern Hemisphere, solar panels are commonly positioned facing south and angled at a degree similar to the latitude of the area to optimize sunlight absorption. Likewise, in the southern hemisphere, panels face North.

*Shading:* Ensuring that there are no barriers such as trees, buildings, or other objects that block sunlight over the sun hours.

## 5.5 Mounting Structure



**Figure 5.** Mounting Structure

PV systems are mounted on stable structures that secure them fixed in the best possible positioning. The main options are:

1. *Roof-mounted systems* take advantage of the built environment and are typically found in residential or industrial settings. These systems necessitate a robust roof that can support them and hence structure reinforcement may be needed.
2. *Ground-mounted systems* are employed where there is insufficient or inappropriate roof space. Land space is necessary and therefore considerations regarding the environmental impact of the installation should be considered.

It is also possible to include in the installation a tracking system that detects the trajectory of the sun and rotates PVs toward its direction, enhancing efficiency but also leading to an increase of the costs.

## 5.6 Inverter and their placement

Inverters are fundamental to convert the electricity produced by the PVs and make them



**Figure 6.** White inverter for solar cell system

There are several types of inverters:

1. *String inverters*, which manage multiple panels together and are suitable for smaller systems.
2. *Central inverters* are for large commercial systems.
3. *Microinverters*, which are attached to each panel for increased efficiency and monitoring.
4. *Solar Inverter*, typically designed to work directly with solar panels, optimizing energy production using maximum power point tracking (MPPT).
5. *Battery Inverter*, designed to manage and integrate energy storage systems, enabling stored energy to be utilized during power outages or at night.

Additionally, hybrid inverters, or multi-mode inverters, play a crucial role in certain solar photovoltaic (PV) systems. They integrate the features of a conventional solar inverter and a battery inverter allowing for effectively handling energy derived from solar panels, the electrical grid, and battery storage devices.

### 5.7 Battery storage

Solar energy is an intermittent source as it depends on the presence of sunlight. Batteries allow us to store the energy produced and not directly consumed to use it later when the sun is not present. These are fundamental in case the system is off grid, meaning that it is not connected to the public grid that could compensate for the electricity need when electricity produced by the PV is not available anymore.



**Figure 8.** Modern battery for solar systems ©Alexey Arama Dreamstime.com

Some considerations related to the storage are:

1. *Position*: the inverter for easy integration into the system and far from hot places.
2. *Size and Capacity*: The size of the battery storage system is determined based on energy production, the needs and the desired autonomy (how long the system can run without sunlight).
3. *Integration*: Battery storage must be smoothly incorporated with the PV system to enable energy storage and utilization during periods of low solar production.

Batteries are not the only way to store energy. Other options are hydrogen storage, compressed air storage and thermal storage.

### 5.8 Charge Controller

Charge controllers are important to ensure healthy batteries, preventing their degradation due to wrong voltage or overload of energy. Those are usually installed between the solar panels and the batteries. The specific layout and configuration of a solar PV system can

vary greatly based on individual requirements and constraints. It's essential to engage with qualified solar professionals to design and install a system that meets the specific needs of the site and the users effectively.

## 6. SAFETY PRECAUTIONS

### 6.1 Personal Protective Equipment (PPE)

The utilization of Personal Protective Equipment (PPE) is essential in guaranteeing the safety of persons engaged in the operation and maintenance of Solar Photovoltaic (PV) systems. PV systems incorporate electrical elements and are frequently deployed in open-air settings, presenting diverse hazards. A comprehensive analysis of the essential PPE employed in PV systems is presented in the Table below.

**Table 2.** Personal Protective Equipment (PPE)

Category	Description
Electrical Insulated Gloves	<i>Purpose:</i> Protect against electric shocks when handling electrical components of the solar PV system. <i>Specification:</i> Should be rated for the specific voltage levels encountered in the system.
Safety Glasses or Goggles	<i>Purpose:</i> Protect the eyes from harmful solar radiation, dust, debris, and accidental splashes of cleaning or maintenance chemicals. <i>Specification:</i> Should have UV protection and be impact resistant.
Hard Hats	<i>Purpose:</i> Protect the head from falling objects, especially when working under or near solar panels installed at height. <i>Specification:</i> Should meet industry safety standards.
Protective Footwear	<i>Purpose:</i> Protect feet from falling objects, sharp edges, and electric shocks. <i>Specification:</i> Should be sturdy, have electrical insulation, and possibly steel toes for enhanced protection.
Sun Protection Gear	<i>Purpose:</i> Protect against prolonged exposure to the sun, which is common during outdoor work. It can include long-sleeved shirts, sun hats, and sunscreen.
Respiratory Protection	<i>Purpose:</i> Protect against inhalation of harmful dust, especially during cleaning or maintenance activities. <i>Specification:</i> Dust masks or more advanced respirators, depending on the level of exposure.
Protective Clothing	<i>Purpose:</i> General protection against cuts, abrasions, and other minor injuries. <i>Specification:</i> Durable material, possibly with reinforced areas for additional protection

The selection of PPE should be based on a thorough risk assessment, considering the specific tasks, the environment, and the potential hazards associated with the operation and maintenance of solar PV systems. Regular training on the proper use and maintenance of PPE is also essential to ensure safety.

### 6.2 Electrical safety

Ensuring electrical safety is of utmost importance when operating and maintaining PV systems. Although these systems are eco-friendly, they require careful management of high-voltage power, which can present significant dangers if mishandled.

Below are essential factors and procedures to guarantee electrical safety:

- a) A comprehensive understanding of PV system constituent parts, including solar panels, inverters, DC/AC converters, batteries (if applicable), and wiring systems. Acquiring this knowledge aids in the recognition of possible dangers. To ensure solid knowledge of electrical principles and becoming acquainted with the PV being used appropriate training and certifications are necessary for everyone engaged in the installation, operation, or maintenance of PV systems. Moreover, the utilization of Personal Protective Equipment (PPE) presented in the section above is imperative to consistently employ suitable PPE to mitigate the likelihood of electric shock and other forms of harm.
- b) Ensure equipment conformity to national and municipal electrical codes, as well as industry standards established by organizations like the Institute of Electrical and Electronics Engineers (IEEE) or the International Electrotechnical Commission (IEC).
- c) *Set electrical lockout and tagout procedures:* Enforce lockout/tagout protocols to guarantee the safe de-energization of the system during maintenance or repair. This serves as a precautionary measure to avoid unintentional activation of the system.
- d) *Apply safe installation practices:* It is important to make sure that all components are placed according to the guidelines provided by the manufacturer and the electrical codes of the local area. Ensuring proper grounding and bonding is crucial for minimizing the likelihood of electric shock.
- e) *Labelling and Signage:* It is important to mark electrical components with information such as power ratings and warning signs. This helps to alert and remind personnel about potential hazards.
- f) *Be aware of weather-related risks:* It is important to understand that PV systems can produce electrical energy even when the weather is cloudy. Additionally, be aware of the increased risk of electrical hazards during wet or stormy weather.
- g) *Maintenance of battery Safety (for systems with storage):* If the system incorporates energy storage components, it is crucial to handle and maintain batteries correctly, as they may pose extra risks such as chemical leakage or thermal runaway.
- h) *Schedule periodic maintenance and inspections:* Routinely examine and uphold the PV system to guarantee its optimal functionality. This entails inspecting for impaired cables, insecure linkages, and indications of corrosion.

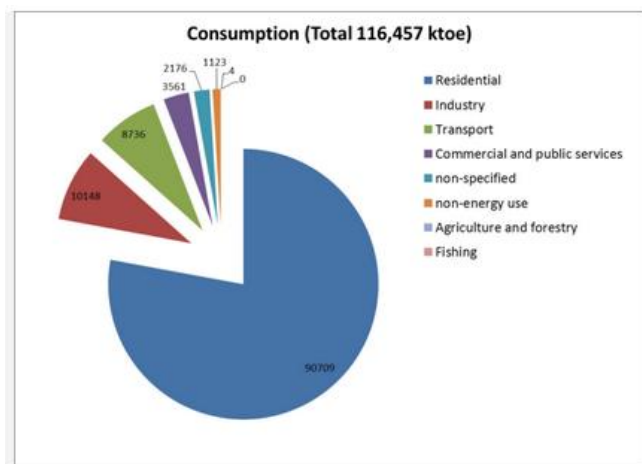
### **6.3 Regular operation procedures**

The routine functioning of solar PV systems generally entails the activities of monitoring, conducting maintenance checks, and assuring optimal system performance. Although solar PV systems typically require minimal maintenance, it is essential to follow regular operational practices to ensure optimal performance and promptly detect any potential problems. Below is a 10 points summary of the standard operating procedures for solar PV systems.

1. *Visual Examination:* Inspect the solar panels for any apparent signs of damage, such as fractures, discolouration, or the accumulation of debris and vegetation. Examine the mounting systems for any indications of looseness or impairment. Make sure that there are no obstacles such as fallen branches or heavy debris on the panels.
2. *Performance Monitoring:* Examine the energy production statistics obtained from the inverter or monitoring system. Analyze the daily production with anticipated performance benchmarks using records and weather conditions. Monitor for any substantial declines in energy generation, as these may indicate potential problems with the solar panels or inverter.



**Figure 9.** Dusty and Weathered Solar Panel Array. Source: <https://cleanenergy4africa.org/solar-energy-and-dust-control/>



**Figure 10.** Nigeria Energy Situation:

Source: [https://energypedia.info/wiki/Nigeria\\_Energy\\_Situation](https://energypedia.info/wiki/Nigeria_Energy_Situation)

3. *Inverter inspection:* Ensure proper functioning of the inverter. Typically, inverters are equipped with an indicator light or display panel that provides real-time information about their present functioning state. Pay attention to any atypical sounds emanating from the inverter, since they may suggest internal malfunctions.
4. *Battery systems inspection (if applicable):* verify the charge levels of systems equipped with battery storage and verify that they fall within the recommended range. Observe any indicators or notifications regarding battery functionality.
5. *Connections inspection:* Verify that all electrical connections are firmly attached and there are no indications of excessive heat, such as discoloration or wire melting. It is advisable to approach this task with caution. The assistance of a professional is highly recommended, as it has inherent risks.
6. *Solar Panel Cleaning:* Periodically clean solar panels when they accumulate excessive dust, bird droppings, or other debris to ensure optimal efficiency. Utilize suitable cleaning techniques, such as employing gentle brushes and mild soapy water, while

refraining from using abrasive substances or harsh chemicals.

7. *Shading inspection:* Monitor the panels for any newly occurring shading problems, which may be attributed to the growth of trees, recent construction activities, or other obstacles. The presence of shading can greatly diminish the effectiveness of a solar PV system.
8. *Environmental factors:* Take into consideration the prevailing meteorological conditions. Following severe weather phenomena such as storms or significant rainfall, it may be imperative to conduct supplementary inspections and sanitation procedures.
9. *Documentation:* Keep a detailed record of daily performance metrics, inspections, and all maintenance tasks. This record is extremely valuable for monitoring and evaluating the functioning of the system over some time, as well as for recognizing any patterns or problems that may arise.
10. *Professional Maintenance Services:* Ensure to regularly schedule professional inspections and maintenance services, since certain areas of system check-up and maintenance necessitate specialized expertise and equipment.

#### **6.4 Routine Maintenance Practice**

The execution of regular maintenance procedures is critical in ensuring the optimal operation and durability of solar PV systems. This will also ensure its maximal performance and fasten the return on investment. By dividing these responsibilities into distinct subsections, a comprehensive strategy for system maintenance is achieved. The classification of these maintenance duties is described in more detail below.



*Figure 11: Solar PV maintenance. Source: <https://rkwindmast.com/c/can-you-power-wash-solar-panels.html>*

#### **6.5 PVs cleaning and inspection scheduled**

*Frequency:* Typically, every 6–12 months, more often in dusty or bird-prone areas.

##### *6.5.1 Cleaning:*

- *Method:* Use soft brushes or sponges and mild soapy water. Avoid abrasive materials and high-pressure water sprays.
- *Focus Areas:* Remove debris, dirt, and bird droppings from solar panels.

## **6.6 Inspection:**

- *Visual Checks:* Look for cracks, discoloration, or delamination in panels.
- *Mounting and Racking Systems:* Ensure all bolts and supports are secure.
- *Shading:* Check for new shading issues due to tree growth or new constructions.
- *Grounding and Bonding:* Ensure these are intact for safety and system performance.

## **6.7 Inverter Maintenance**

- *Frequency:* Monthly (minimum), Detailed Checks Quarterly
- *Visual Inspection:* Check for any error messages on the display, signs of overheating, or physical damage. Inspect mounting integrity and ensure the inverter is secure and not vibrating.
- *Performance Monitoring:* Verify status indicators (LEDs) and LCD/online display for any warning/error codes and confirm proper DC input voltage and AC output voltage levels for any unusual drops or inconsistencies.
- *Ventilation:* Ensure the inverter is well-ventilated and free from dust, moisture and debris.
- *Firmware Updates:* Keep the inverter's firmware updated as per manufacturer's recommendations.

## **6.8 Battery Maintenance (for systems with storage)**

- *Frequency:* Monthly, with Detailed Capacity Testing Annually

### *Inspection:*

- *Performance Monitoring:* measure and record individual battery voltages and string voltages.
- *Room Inspection:* Confirm battery room ventilation, temperature, and absence of leaks or fire hazards

As mentioned in Table 1, the two main types of batteries used in PV systems are lead-acid and lithium-ion. Each of these two types requires different precautions:

### *Lead-Acid Batteries:*

- *Water Levels:* Regularly check and top up water levels in flooded lead-acid batteries.
- *Terminal Checks:* Clean and tighten battery terminals to prevent corrosion and ensure good connections.
- *State of Charge:* Regular monitoring to avoid overcharging or deep discharging.

### *Lithium-Ion Batteries:*

- *Temperature Monitoring:* Ensure they are operating within the recommended temperature range.
- *Software:* Keep battery management system software up to date.
- *Visual Inspection:* Check for any signs of swelling or damage.

### *Electrical Connections Check*

- *Frequency:* Every 6 Months (or quarterly in high-humidity, dusty, or corrosive environments) When verifying the electrical connection, it is important to check the following:
  - *Tightness of Connections:* Ensure all electrical connections are tight and secure and perform torque checks on terminal screws and cable lugs
  - *Corrosion Inspection:* Look for any signs of corrosion on terminals and connections.
  - *Temperature Inspection:* Check for any signs of overheating (discoloration, melting insulation).

- *Wiring Inspection:* Check for any signs of fraying, rodent damage, or wear on the wiring and conduct insulation resistance testing (especially after major rain/dust events).
- *Safety Checks:* Ensure all safety switches, circuit breakers, surge protection devices and disconnects are functioning properly.

## 7. TROUBLESHOOTING COMMON ISSUES

### 7.1 Diagnostic Steps for Common Problems

**Table 3.** Common issues

Issue Category	Symptoms	Diagnostic Steps	Suggested Actions
Reduced Power Output	Lower-than-usual energy production	<ol style="list-style-type: none"> <li>1. Inspect for shading or obstructions.</li> <li>2. Check for dirt or debris on panels.</li> <li>3. Monitor the inverter for error messages.</li> <li>4. Review historical performance data.</li> </ol>	<ul style="list-style-type: none"> <li>• Clean panels</li> <li>• remove obstructions.</li> <li>• reset, or troubleshoot inverter.</li> </ul>
Inverter Issues	Error messages, no power output	<ol style="list-style-type: none"> <li>1. Refer to the manual for error codes.</li> <li>2. Perform power cycling.</li> <li>3. Check the inverter's ventilation.</li> </ol>	<ul style="list-style-type: none"> <li>• Reset the inverter.</li> <li>• ensure proper ventilation.</li> <li>• contact a professional if the error persists.</li> </ul>
Battery-Related Issues	Poor charging, battery not holding charge	<ol style="list-style-type: none"> <li>1. Check charge levels.</li> <li>2. Inspect connections.</li> <li>3. For lead-acid, check water levels.</li> </ol>	<ul style="list-style-type: none"> <li>• Tighten connections.</li> <li>• refill water (if applicable)</li> <li>• professional battery check.</li> </ul>
Panel Damage	Visible damage, reduced panel output	<ol style="list-style-type: none"> <li>1. Visual inspection.</li> <li>2. Check the electrical output with a multimeter.</li> </ol>	<ul style="list-style-type: none"> <li>• Replace damaged panels.</li> <li>• professional assessment.</li> </ul>

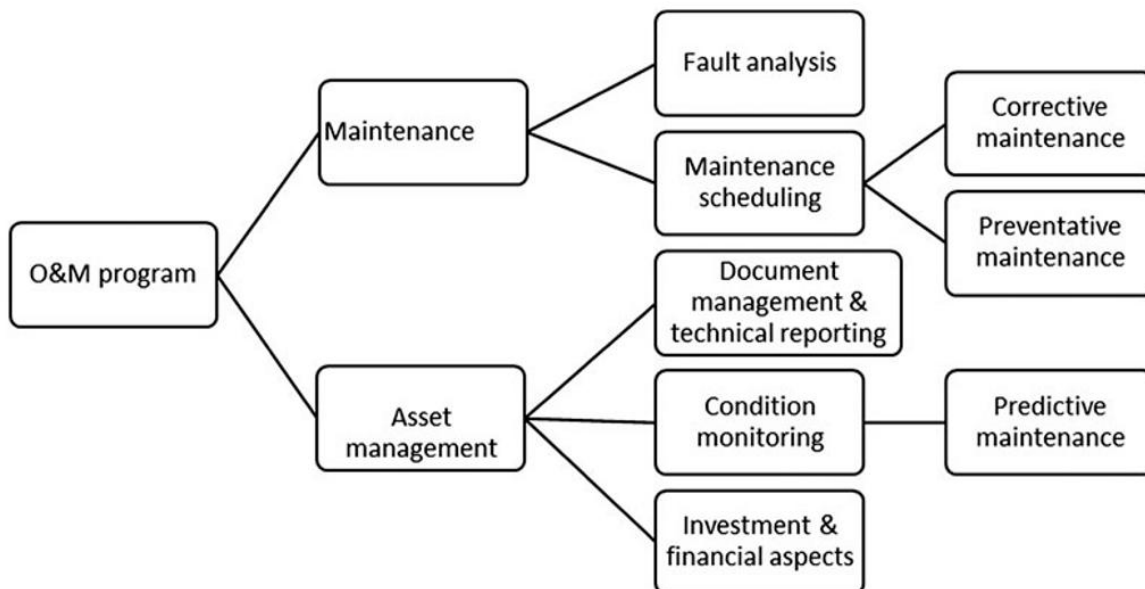
### When to Contact a Professional Technician

**Table 4.** Assistance by Professional Technician

Issue	Description	Professional Assistance Needed When
Physical Damage	Cracks, discolouration, or other damage to components	Damage is significant and affects system performance.
Electrical Concerns	Wiring or connection issues	Problems are complex or high-risk (e.g., inverter failure).
Battery Issues	Problems with charging or battery health	Issues persist despite basic troubleshooting, or if safety risk is present.
Safety Risks	Any issue requiring work at heights or with high voltage	Safety risks are involved, or specialized knowledge is required.

## 8. DISCUSSION

The increase in the implementation of solar PV systems has indirectly led to improvements in maintenance methods. Researchers have created advanced technologies and tools for enhanced and precise system fault diagnostics, troubleshooting, and timely remedial responses by incorporating features for document management, technical reporting, fault analysis, maintenance scheduling, and financial reporting (Gilabert and Arnaiz 2006; Efthymiou et al., 2012; Abbassi et al., 2015). Operations and maintenance, being a highly technical facet of solar photovoltaic technology, depends on the system's size, specific design, and contextual location. These complexities result in variations in maintenance implementation methods across diverse locations and distinct installation needs. A maintenance management framework is essential to implement remedial measures promptly to prevent downtime and prolong the overall system's service life. Figure 6 delineates the essential components for establishing a comprehensive maintenance program.



**Figure 6.** Diagram illustrating the principal components of a maintenance program (Eltawil and Zhao 2010; Hirsch et al., 2018).

Mgonja, C. T. and Saidi, H. conducted a study on off-grid solar photovoltaic systems in public facilities (Mgonja and Saidi 2017), emphasising maintenance management systems to assess the effectiveness of their deployment. This assessment utilised a case study methodology to present a model that underscores the necessity for collaborative efforts among all pertinent stakeholders engaged in SPV systems from the planning to the disposal phase. The proposed model seeks to enhance field maintenance practices through the active engagement of stakeholders in promoting a proactive maintenance culture, emphasising that the delayed implementation of a maintenance management scheme during the initial project phase adversely affects long-term sustainability. The British Standards Institution (BSI, 2010) emphasises that continuous and comprehensive planning is essential for the successful implementation of solar PV installations, from project conception through construction,

supervision, inspections, and commissioning duties.

The fragmentation of responsibility directly contributes to the efficacy of the operation and maintenance of solar photovoltaic microgrids. The workflow, encompassing the early identification of impending failure and the swift deployment of maintenance personnel equipped with appropriate tools and spare parts, necessitates a collaborative effort among asset managers, plant operators, and field technicians (Averbukh et al., 2013; Tejwani et al., 2014). The schematic illustrates that the operator is only responsible for operations and maintenance, while the Asset Manager oversees the managerial and financial aspects of the microgrid operations (Palit and Sarangi 2014). This paradigm ensures sustainability through the accountability it fosters.

Frameworks for Implementing the Operation and Maintenance Program SPV plants, being capital-intensive projects, necessitate effective management to address risks and uncertainties, and crucially, require an individual accountable for fulfilling the project objectives, whether economically based or focused on energy yield security (C 2010; Gonzalo et al., 2020).

The problematic and defective operational circumstances frequently experienced by solar PV fleets are particularly concerning. In the pursuit of enhanced system dependability and long-term sustainability in solar PV systems, an appropriate operational model must be selected. These models exist to guarantee the effective enforcement and execution of the existing O&M strategy while assessing and analysing criteria for success or failure. Operations and maintenance (O&M) can be conducted via various alternatives, including third-party O&M companies or in-house teams, known as maintenance management models (Bosman et al., 2020; Solar Power Europe [SPE] 2018).

Table 3 illustrates that each option possesses distinct advantages and disadvantages, necessitating a judicious decision in the selection of the approach to plant operation, as it will significantly influence subsequent positive or negative repercussions. A decision-making dilemma arises including risk exposure, labour, initial and subsequent costs, quality control, and intellectual capital, necessitating clear and decisive resolution. For example, when an organisation possesses existing O&M-related assets such as skilled personnel, hardware, software, and infrastructure, it may be prudent to use an in-house O&M delivery model to leverage these resources. Outsourcing operations and maintenance is perceived as a cost-saving measure; however, it can lead to complications when the contractor sacrifices quality by utilising inferior or substandard components, adversely affecting overall system performance. A setback may also arise from the installer's bias in notifying the owner of system malfunctions or failures, as this may reflect poorly on their workmanship (installation and design). Furthermore, issues may arise if the installers cease operations, thereby

nullifying any post-installation services, including possible warranty claims.

**TABLE 3.** Different models for handling operation and maintenance requirements.

O&M execution model (Epri 2010)	
In-house	Third party
Description	
In this model, the company and or institution owning or hosting the solar PV system is in charge of ensuring optimal performance and smooth operation and takes care of any maintenance needs.	Also termed as outsourced to an external contractor, who is charge of the ensuring the clients needs for reliable electricity supply without interruption is met. The contractor carries out any maintenance needs and any system upkeep activities necessary, including warranty claims.
Advantages	
Better Vicinity on personnel\Equipment Issue.	Lower Upfront Costs, Greater Flexibility.
Improved Quality Control.	Lower Upfront risks.
Ability to leverage existing utility assets.	Less Drain on Utility Labor Force
Workforce training.	
Company has command of solar PV O&M process	
Disadvantages	
Higher upfront costs	Lack of involvement means to knowledge or skills transfer.
Increased risk	
Workforce knowledge\resource ramp up	Cost may be overinflated
	Dependent on Outsourced Contractors

The intricacies of SPV microgrids, as highlighted in the preceding paragraphs, require that the operations and maintenance of the installations be managed by qualified professionals. This will guarantee the system undergoes judicious administration and fulfils expectations by mitigating risks and uncertainties. The proficient professionals function as both operations and maintenance practitioners, employed by the clients. Their responsibility is to collect data on the current performance and operations of the installations, conduct requisite analysis, diagnosis, troubleshooting, and maintenance on the SPV microgrid. The involvement of expatriates in executing the O&M operations can occur through two methods: In-house or Third-party models, each possessing distinct advantages and disadvantages as highlighted in Table 3. Nevertheless, due to the differing aims and resources, the decision rests with the system owner, guided by the project development team, with the primary aim of safeguarding the capital investment. The decision hinges on the system owner's perspective about the installation and application; for example, a commercial SPV microgrid within an industry possessing an existing maintenance team may prefer a Hybrid model. This innovative method for managing operations and maintenance involves an agreement between the system owner and the solar service firm to undergo a transitional phase during which training and knowledge transfer occur to the utility or organization's personnel. This concept significantly benefits system owners by reducing the entire lifecycle cost of Solar PV installations, particularly for extended contracts with third-party organisations.

## 9. CONCLUSION AND GENERAL RECOMMENDATIONS

Solar photovoltaic (SPV) technology is rapidly advancing in both development and implementation, propelled by declining leveled costs of power and

supportive governmental policies such as feed-in tariffs. Although solar PV microgrids are inherently lower-risk systems than traditional power generating methods, they face distinct hazards related to financial, operational, and technical factors. In contrast to conventional PV systems, the reliability, safety, and efficiency of SPV microgrids are enhanced by the incorporation of additional protective devices, power conditioning, and modulation electronics. Furthermore, the distribution lines serving remote customers and the intricacies of interconnection networks, exemplified by relevant microgrid topologies such as radial, ring, and tree architectures, contribute to the demands for monitoring, inspection, troubleshooting, and repair. Consequently, a comprehensive approach to Operations and Maintenance (O&M) and a suitable framework to demonstrate its connection to the fundamental success of solar photovoltaic systems is essential. This encourages stakeholders to develop and refine systems design, operational strategies, and maintenance planning and execution methods to guarantee optimal system availability, dependability, safety, effectiveness, and efficiency.

Comprehending the diverse configurations, control architectures, and operational modes in SPV microgrids is essential for analysing the maintenance needs of these systems. Furthermore, many obstacles arise in the functioning of SPVM, contingent upon installation site, component design, and system optimisation objectives. Finally, a definitive evaluation and assessment framework for the maintenance program is essential, encompassing critical metrics for system utilisation, as well as baseline parameters for comparative analysis and performance evaluation. Maintenance is a perpetual endeavour, particularly in the evolving domain of SPV microgrids; therefore, an Operations and Maintenance (O&M) program must be adaptable if it fails to achieve established objectives.

### **9.1 General Recommendations**

The following recommendations are noted in this article:

- *Documentation:* Keep detailed records of all maintenance activities.
- *Professional Inspection:* At least once a year, have a professional technician inspect and service the system.
- *Safety First:* Always prioritize safety, especially when working with electrical components or at heights.

Regular maintenance is crucial for optimizing the efficiency, ensuring safety, and prolonging the lifespan of solar PV systems. Certain operations can be managed by the system owner, however, duties related to electrical components should be performed by competent personnel. Routine maintenance not only extends the lifespan of the system but also guarantees that it functions at its highest level of efficiency, resulting in the most

### **9.2 Conclusions**

The conclusions arrived at in this paper include:

- a. To maintain quality control and safety standards, it is important that only qualified personnel work on PV installations. The authors suggest minimum skill and knowledge guidelines for PV technicians.
- b. Safety is a serious concern when servicing PV installations. Early PV

systems often had maximum system voltages less than 50 Vdc, but 1,000 Vdc systems are now allowed by code in commercial and large-scale installations.

- c. Qualified personnel should always work in teams of two people when working on live equipment, and there should always be at least two qualified persons trained in cardiopulmonary resuscitation on the jobsite.
- d. Not all installations have appropriate signage, and qualified persons must be trained to recognize potential hazards with or without signage present.
- e. System uptime and availability is a key objective of O&M, and inverters that are offline can have a dramatic negative impact on the ROI of a PV system.
- f. Low power production also impacts ROI, and O&M personnel need effective strategies for identifying and correcting problems quickly.

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### **Conflicts of Interest**

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

### **References**

- Aghaei, M., Fairbrother, A., Gok, A., Ahmad, S., Kazim, S., Lobato, K., Oreski, G., Reinders, A., Schmitz, J., Theelen, M., et al. (2022). Review of degradation and failure phenomena in photovoltaic modules. *Renewable and Sustainable Energy Reviews*, 159, 112160. <https://doi.org/10.1016/j.rser.2022.112160>
- Bosman, L. B., Leon-Salas, W. D., Hutzal, W., & Soto, E. A. (2020). PV system predictive maintenance: Challenges, current approaches, and opportunities. *Energies*, 16(3). <https://doi.org/10.3390/en13061398>
- Conceicao, R., Gonzalez-Aguilar, J., Merrouni, A. A., & Romero, M. (2022). Soiling effect in solar energy conversion systems: A review. *Renewable and Sustainable Energy Reviews*, 162, 112434. <https://doi.org/10.1016/j.rser.2022.112434>
- Feldman, D., Dummit, K., Zuboy, J., & Margolis, R. (2023). *Spring 2023 solar industry update*. National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy23osti/86215.pdf>
- Fraunhofer Institute for Solar Energy Systems. (2022). *Photovoltaics report*. <https://www.ise.fraunhofer.de>
- Hernández-Callejo, L., Gallardo-Saavedra, S., & Alonso-Gómez, V. (2019). A review of photovoltaic systems: Design, operation and maintenance. *Solar Energy*, 188, 426–440. <https://doi.org/10.1016/j.solener.2019.06.017>
- Høiaas, I., Grujic, K., Imenes, A. G., Burud, I., Olsen, E., & Belbachir, N. (2022). Inspection and condition monitoring of large-scale photovoltaic power plants: A review of imaging technologies. *Renewable and Sustainable Energy Reviews*, 161, 112353. <https://doi.org/10.1016/j.rser.2022.112353>
- IEA. (2024). *Renewables 2024: Analysis and forecasts to 2030*. International Energy Agency. <https://www.iea.org/reports/renewables-2024>

- Jaen-Cuéllar, A. Y., Elvira-Ortiz, D. A., Osornio-Rios, R. A., & Antonino-Daviu, J. A. (2022). Advances in fault condition monitoring for solar photovoltaic and wind turbine energy generation: A review. *Energies*, *15*(15). <https://doi.org/10.3390/en15155404>
- Keisang, K., Bader, T., & Samikannu, R. (2021). Review of operation and maintenance methodologies for solar photovoltaic microgrids. *Frontiers in Energy Research*. <https://doi.org/10.3389/fenrg.2021.730230>
- Koester, L., Lindig, S., Louwen, A., Astigarraga, A., Manzoloni, G., & Moser, D. (2022). Review of photovoltaic module degradation, field inspection techniques and techno-economic assessment. *Renewable and Sustainable Energy Reviews*, *165*, 112616. <https://doi.org/10.1016/j.rser.2022.112616>
- Livera, A., Theristis, M., Micheli, L., Fernandez, E. F., Stein, J. S., & Georghiou, G. E. (2022). Operation and maintenance decision support system for photovoltaic systems. *IEEE Access*, *10*, 42481–42496. <https://doi.org/10.1109/ACCESS.2022.3168140>
- Márquez, F. P. G. (2022). Maintenance management in solar energy systems. *Energies*, *15*(10). <https://doi.org/10.3390/en15103727>
- Navid, Q., Hassan, A., Fardoun, A. A., Ramzan, R., & Alraeesi, A. (2021). Fault diagnostic methodologies for utility-scale photovoltaic power plants: A state-of-the-art review. *Sustainability*, *13*(4). <https://doi.org/10.3390/su13041629>
- Peinado-Gonzalo, A., Pliego-Marugán, A., & García Márquez, F. P. (2020). Survey of maintenance management for photovoltaic power systems. *Renewable and Sustainable Energy Reviews*, *134*, 110347. <https://doi.org/10.1016/j.rser.2020.110347>
- REN21. (2022). *Global status report 2022*. Renewable Energy Policy Network for the 21st Century. <https://www.ren21.net>
- Walker, A. (2018). *Best practices for operation and maintenance of photovoltaic and energy storage systems* (NREL/TP-7A40-73822). National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy19osti/73822.pdf>
- Agortimevor, D. K. (2023). *Practical operation & maintenance (O&M) manual on solar PV systems for rural clinics (CHPS compounds) in Kwahu Afram Plains District, Ghana*. GIZ Green People's Energy Project. [https://gruene-buergerenergie.org/wp-content/uploads/Practical-Operation-Maintenance-Manual\\_Final.pdf](https://gruene-buergerenergie.org/wp-content/uploads/Practical-Operation-Maintenance-Manual_Final.pdf)
- Ahmed, R., Sreeram, V., Mishra, Y., & Arif, M. (2020). A review and evaluation of the state-of-the-art in PV solar power forecasting: Techniques and optimization. *Renewable and Sustainable Energy Reviews*, *124*, 109792. <https://doi.org/10.1016/j.rser.2020.109792>
- Aghaei, M., Fairbrother, A., Gok, A., Ahmad, S., Kazim, S., Lobato, K., Oreski, G., Reinders, A., Schmitz, J., Theelen, M., et al. (2022). Review of degradation and failure phenomena in photovoltaic modules. *Renewable and Sustainable Energy Reviews*, *159*, 112160. <https://doi.org/10.1016/j.rser.2022.112160>
- Alimi, O. A., Meyer, E. L., & Olayiwola, O. I. (2022). Solar photovoltaic modules' performance reliability and degradation analysis—A review. *Energies*, *15*(165964). <https://doi.org/10.3390/en15165964>
- Aria, M., & Cuccurullo, C. (2017). Bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*. <https://doi.org/10.1016/j.joi.2017.08.007>
- Azad, A., & Parvin, S. (2022). Bibliometric analysis of photovoltaic thermal (PV/T) system: From citation mapping to research agenda. *Energy Reports*, *8*, 2699–2711. <https://doi.org/10.1016/j.egy.2022.01.182>
- Bermejo, J. F., Fernández, J. F. G., Pino, R., Márquez, A. C., & López, A. J. G. (2019). Review and comparison of intelligent optimization modelling techniques for energy forecasting and condition-based maintenance in PV plants. *Energies*, *12*(21). <https://doi.org/10.3390/en12214163>
- Bosman, L. B., Leon-Salas, W. D., Hutzal, W., & Soto, E. A. (2020). PV system predictive

- maintenance: Challenges, current approaches, and opportunities. *Energies*, 16(3). <https://doi.org/10.3390/en13061398>
- Bouckaert, S., Pales, A. F., McGlade, C., Remme, U., Wanner, B., Varro, L., D'Ambrosio, D., & Spencer, T. (2021). *Net zero by 2050: A roadmap for the global energy sector*. International Energy Agency. <https://iea.blob.core.windows.net/assets/063ae08a-7114-4b58-a34e-39db2112d0a2/NetZeroBy2050-ARoadmapfortheGlobalEnergySector.pdf>
- Calderón, A., Barreneche, C., Prieto, C., Segarra, M., & Fernández, A. I. (2021). Concentrating solar power technologies: A bibliometric study. *Frontiers in Mechanical Engineering*, 7, 682592. <https://doi.org/10.3389/fmech.2021.682592>
- Chen, Q., Wang, Y., Zhang, J., & Wang, Z. (2020). The knowledge mapping of concentrating solar power development based on literature analysis technology. *Energies*, 13(8), 1988. <https://doi.org/10.3390/en13081988>
- Conceicao, R., Gonzalez-Aguilar, J., Merrouni, A. A., & Romero, M. (2022). Soiling effect in solar energy conversion systems: A review. *Renewable and Sustainable Energy Reviews*, 162, 112434. <https://doi.org/10.1016/j.rser.2022.112434>
- David, T. M., Rizol, P. M. S. R., Machado, M. A. G., & Buccieri, G. P. (2020). Future research tendencies for solar energy management using a bibliometric analysis, 2000–2019. *Heliyon*, 6(7). <https://doi.org/10.1016/j.heliyon.2020.e04452>
- Dhanraj, J. A., Mostafaeipour, A., Velmurugan, K., Techato, K., Chaurasiya, P. K., Solomon, J. M., Gopalan, A., & Phoungthong, K. (2021). An effective evaluation on fault detection in solar panels. *Energies*, 14(22). <https://doi.org/10.3390/en14227770>
- Elomari, Y., Norouzi, M., Marín-Genescà, M., Fernández, A., & Boer, D. (2022). Integration of solar photovoltaic systems into power networks: A scientific evolution analysis. *Sustainability*, 14(15), 9249. <https://doi.org/10.3390/su14159249>
- Feldman, D., Dummit, K., Zuboy, J., & Margolis, R. (2023). *Spring 2023 solar industry update*. National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy23osti/86215.pdf>
- Fraunhofer Institute for Solar Energy Systems. (2022). *Photovoltaics report*. <https://www.ise.fraunhofer.de>
- Hernández-Callejo, L., Gallardo-Saavedra, S., & Alonso-Gómez, V. (2019). A review of photovoltaic systems: Design, operation and maintenance. *Solar Energy*, 188, 426–440. <https://doi.org/10.1016/j.solener.2019.06.017>
- Høiaas, I., Grujic, K., Imenes, A. G., Burud, I., Olsen, E., & Belbachir, N. (2022). Inspection and condition monitoring of large-scale photovoltaic power plants: A review of imaging technologies. *Renewable and Sustainable Energy Reviews*, 161, 112353. <https://doi.org/10.1016/j.rser.2022.112353>
- IEA. (2024). *Renewables 2024: Analysis and forecasts to 2030*. International Energy Agency. <https://www.iea.org/reports/renewables-2024>
- Jamil, W. J., Abdul Rahman, H., Shaari, S., & Salam, Z. (2017). Performance degradation of photovoltaic power system: Review on mitigation methods. *Renewable and Sustainable Energy Reviews*, 67, 876–891. <https://doi.org/10.1016/j.rser.2016.09.072>
- Jaen-Cuellar, A. Y., Elvira-Ortiz, D. A., Osornio-Rios, R. A., & Antonino-Daviu, J. A. (2022). Advances in fault condition monitoring for solar photovoltaic and wind turbine energy generation: A review. *Energies*, 15(15). <https://doi.org/10.3390/en15155404>
- Kazem, H. A., Chaichan, M. T., Al-Waeli, A. H., & Sopian, K. (2020). A review of dust accumulation and cleaning methods for solar photovoltaic systems. *Journal of Cleaner Production*, 276, 123187. <https://doi.org/10.1016/j.jclepro.2020.123187>
- Keisang, K., Bader, T., & Samikannu, R. (2021). Review of operation and maintenance methodologies for solar photovoltaic microgrids. *Frontiers in Energy Research*. <https://doi.org/10.3389/fenrg.2021.730230>
- Kim, J., Rabelo, M., Padi, S. P., Yousuf, H., Cho, E. C., & Yi, J. (2021). A review of the

- degradation of photovoltaic modules for life expectancy. *Energies*, 14(14). <https://doi.org/10.3390/en14144278>
- Koester, L., Lindig, S., Louwen, A., Astigarraga, A., Manzolini, G., & Moser, D. (2022). Review of photovoltaic module degradation, field inspection techniques and techno-economic assessment. *Renewable and Sustainable Energy Reviews*, 165, 112616. <https://doi.org/10.1016/j.rser.2022.112616>
- Livera, A., Theristis, M., Micheli, L., Fernandez, E. F., Stein, J. S., & Georghiou, G. E. (2022). Operation and maintenance decision support system for photovoltaic systems. *IEEE Access*, 10, 42481–42496. <https://doi.org/10.1109/ACCESS.2022.3168140>
- Luque, A., & Hegedus, S. (Eds.). (2011). *Handbook of photovoltaic science and engineering*. Wiley.
- Madsuha, A. F., Setiawan, E. A., Wibowo, N., Habiburrahman, M., Nurcahyo, R., & Sumaedi, S. (2021). Mapping 30 years of sustainability of solar energy research in developing countries: Indonesia case. *Sustainability*, 13(20), 11415. <https://doi.org/10.3390/su132011415>
- Márquez, F. P. G. (2022). Maintenance management in solar energy systems. *Energies*, 15(10). <https://doi.org/10.3390/en15103727>
- Navid, Q., Hassan, A., Fardoun, A. A., Ramzan, R., & Alraeesi, A. (2021). Fault diagnostic methodologies for utility-scale photovoltaic power plants: A state-of-the-art review. *Sustainability*, 13(4). <https://doi.org/10.3390/su13041629>
- Olorunfemi, B. O., Ogbolumani, O. A., & Nwulu, N. (2022). Solar panels dirt monitoring and cleaning for performance improvement: A systematic review on smart systems. *Sustainability*, 14(17), 10920. <https://doi.org/10.3390/su141710920>
- Osmani, K., Haddad, A., Lemenand, T., Castanier, B., & Ramadan, M. (2020). A review on maintenance strategies for PV systems. *Science of the Total Environment*, 746, 141753. <https://doi.org/10.1016/j.scitotenv.2020.141753>
- Peinado-Gonzalo, A., Pliego-Marugán, A., & García Márquez, F. P. (2020). Survey of maintenance management for photovoltaic power systems. *Renewable and Sustainable Energy Reviews*, 134. <https://doi.org/10.1016/j.rser.2020.110347>
- Pillai, D. S., Shabunko, V., & Krishna, A. (2022). A comprehensive review on building integrated photovoltaic systems: Emphasis on technological advancements, outdoor testing, and predictive maintenance. *Renewable and Sustainable Energy Reviews*, 156, 111946. <https://doi.org/10.1016/j.rser.2021.111946>
- PV Education. (2024). *Introduction to solar PV systems*. <https://pveducation.org>
- Ramirez-Vergara, J., Bosman, L. B., Wollega, E., & Leon-Salas, W. D. (2022). Review of forecasting methods to support photovoltaic predictive maintenance. *Clean Engineering and Technology*, 8, 100460. <https://doi.org/10.1016/j.clet.2022.100460>
- Rediske, G., Michels, L., Siluk, J. C. M., Rigo, P. D., Rosa, C. B., & Bortolini, R. J. F. (2022). Management of operation and maintenance practices in photovoltaic plants: Key performance indicators. *International Journal of Energy Research*, 46(6), 7118–7136. <https://doi.org/10.1002/er.7737>
- Renewable Energy Policy Network for the 21st Century (REN21). (2022). *Global status report 2022*. <https://www.ren21.net>
- Ren, Z., Verma, A. S., Li, Y., Teuwen, J. J., & Jiang, Z. (2021). Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, 144, 110886. <https://doi.org/10.1016/j.rser.2021.110886>
- Saikia, K., Vallès, M., Fabregat, A., Saez, R., & Boer, D. (2020). A bibliometric analysis of trends in solar cooling technology. *Solar Energy*, 199, 100–114. <https://doi.org/10.1016/j.solener.2020.02.013>
- Shafiee, M., & Sørensen, J. D. (2019). Maintenance optimization and inspection planning of

- wind energy assets: Models, methods, and strategies. *Reliability Engineering and System Safety*, 192, 105993. <https://doi.org/10.1016/j.res.2017.10.025>
- Shen, Y., Ji, L., Xie, Y., Huang, G., Li, X., & Huang, L. (2021). Research landscape and hot topics of rooftop PV: A bibliometric and network analysis. *Energy and Buildings*, 251, 111333. <https://doi.org/10.1016/j.enbuild.2021.111333>
- Tusar, M. I. H., & Sarker, B. R. (2022). Maintenance cost minimization models for offshore wind farms: A systematic and critical review. *International Journal of Energy Research*, 46(4), 3739–3765. <https://doi.org/10.1002/er.7425>
- Walker, A. (2018). *Best practices for operation and maintenance of photovoltaic and energy storage systems* (NREL/TP-7A40-73822). National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy19osti/73822.pdf>
- Zwane, N., Tazvinga, H., Botai, C., Murambadoro, M., Botai, J., de Wit, J., Mabasa, B., Daniel, S., & Mabhaudhi, T. (2022). A bibliometric analysis of solar energy forecasting studies in Africa. *Energies*, 15(15), 5520. <https://doi.org/10.3390/en15155520>

