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Reliability and maintainability analysis of Solar Photovoltaic Systems in rural regions: A narrative review of challenges, strategies, and policy implications for sustainable electrification

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Abstract

The increasing adoption of solar photovoltaic (PV) systems plays a critical role in advancing sustainable energy, particularly in regions with limited or no grid access. However, the long-term performance, reliability, and maintainability of these systems in challenging environments remain a pressing concern. This narrative review investigates key factors impacting the sustainability of solar PV systems, focusing specifically on Uganda's Lango region. The study identifies significant challenges, including harsh environmental conditions, limited availability of certified components, and insufficient maintenance infrastructure, which collectively lead to system inefficiencies and reduced operational lifespans. To address these challenges, the review evaluates strategies such as the implementation of preventive and predictive maintenance practices, capacity-building programs for local technicians, and the introduction of government-supported policies aimed at reducing the cost of quality components. Furthermore, the findings underscore the importance of strengthening local supply chains, promoting community-led maintenance initiatives, and expanding technical support networks. The study concludes that a multi-pronged approach integrating technical, policy, and community-driven solutions is vital for enhancing the resilience, viability, and longevity of solar PV systems in resource-constrained settings. These recommendations offer actionable pathways to ensure sustained energy access and foster the broader adoption of solar PV technology in underserved regions.

1.0 Introduction

The rapid expansion of solar photovoltaic (PV) systems has positioned them as a cornerstone in the shift towards sustainable energy generation. With global efforts focused on reducing greenhouse gas emissions and diversifying energy sources, solar PV technology offers a viable solution due to its renewable nature and minimal operational emissions [1]. However, as solar PV systems become more integral to energy infrastructures, ensuring their long-term maintainability and reliability has emerged as a critical area of study [2,3]. Maintainability and reliability analysis of solar PV systems is essential to optimize performance, reduce downtime, and extend system lifespans. These analyses help identify the factors that contribute to system failures and inefficiencies, allowing for the development of preventive maintenance strategies and enhanced design practices [4]. Factors such as environmental conditions, component quality, and operational stresses play significant roles in the reliability of PV systems. Moreover, the high initial investment in solar PV installations underscores the need for robust maintenance strategies to ensure sustained returns and operational stability. Solar PV systems generate electricity directly from sunlight through the photovoltaic effect, where photons striking a semiconductor material (typically silicon) release electrons, creating an electric current as illustrated in Figure 1.

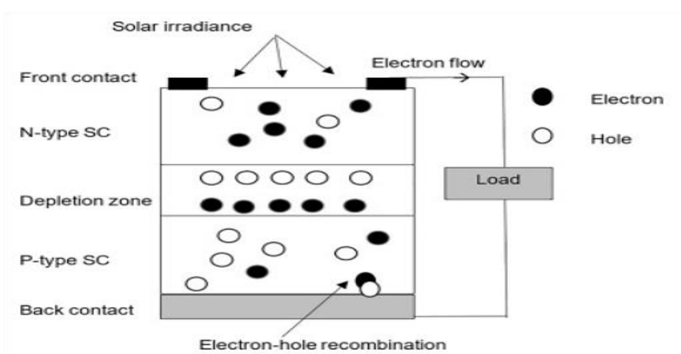

Figure 1: Working Principles of Solar PV System [5]

As illustrated in Figure 1, the energy conversion process in solar photovoltaic systems takes place in semiconductor materials, typically silicon, within a solar cell. This process begins with photon absorption, where sunlight, composed of light particles called photons, strikes the surface of the solar cell. These photons transfer their energy to electrons in the silicon atoms. Next is the excitation of electrons which occurs when the energy from the photons excites the electrons, providing them with enough energy to break free from their atomic bonds and create electron-hole pairs [6,7]. The flow of electrons is then facilitated by the cell's electric field, directing these free electrons through an external circuit to generate an electric current (I) as they return to the P-type layer of the cell, completing the circuit. This current, when paired with the voltage (V) across the cell, gives a power output (P) as in equation (1)

$$P = V \times I \tag{1}$$

While the power generated by a single cell is small, multiple cells can be combined into a solar panel to produce sufficient electricity. A typical solar PV system comprises solar panels, charge controllers, inverters, and batteries, each with a designated function. Solar panels convert sunlight to direct current (DC), charge controllers regulate voltage and prevent battery overcharging, inverters transform DC to alternating current (AC) for household or grid use, and batteries store excess energy for use during low sunlight [5]. The power output of the panel is calculated using equation (2)

$$P = A \times \eta \times G \tag{2}$$

Where: P is the power output of the panel (W), A is the area of the solar panel (m^2), η is the efficiency of the PV module, and G is the solar irradiance (W/m^2).

These systems are especially valuable for rural electrification in developing regions lacking grid access, providing a sustainable solution for critical services like lighting, healthcare, and communication, as highlighted by recent research [8,9]. This study explores key parameters in maintainability and reliability for solar PV systems, providing insights into fault diagnostics, maintenance protocols, and lifespan optimization techniques. By focusing on these aspects, we aim to enhance the economic viability and environmental impact of solar energy systems, contributing to more resilient and sustainable energy solutions.

2. Methodology

This study aims to examine the sustainability, reliability, and maintainability of solar PV systems in Uganda's Lango region using a narrative review methodology. A comprehensive literature search, critical appraisal, and synthesis of findings were conducted to address the environmental, technical, community, policy, and technological challenges impacting PV system performance.

2.1 Literature Search Strategy

A literature search was performed using databases such as Scopus, Web of Science, IEEE Xplore, SpringerLink, and Google Scholar. Keywords including "solar PV reliability," "maintenance of solar PV systems," "rural energy access," "Uganda solar energy," and "predictive maintenance" were used in various combinations to identify relevant peer-reviewed articles and technical reports published between 2010 and 2024. From this search, 70 articles were selected and analyzed based on inclusion criteria such as their focus on solar PV systems in resource-limited settings, empirical data relevance, and discussion of maintenance and reliability.

2.2 Data Collection and Thematic Categorization

The data extraction process involved categorizing key findings into five thematic areas: environmental impacts on PV reliability, component quality and maintenance practices, community and technical capacity challenges, policy and institutional support, and technological innovations for enhanced maintainability. Critical appraisal of the articles was conducted to evaluate methodological rigor, relevance to Uganda's Lango region, and applicability of findings.

2.3 Findings and Thematic Synthesis

The synthesized findings were interpreted in the context of the thematic areas, revealing significant insights into the challenges and opportunities for improving solar PV systems. Environmental factors such as high temperatures, humidity, and dust were identified as major stressors that accelerate system degradation. Preventive and predictive maintenance practices, along with community-based training programs, emerged as key strategies for enhancing system reliability.

3. Solar Energy Landscape in Uganda

The solar energy landscape in Uganda has seen significant growth over the past two decades, propelled by government policies, international aid, and the increasing need to address energy access gaps, particularly in rural areas [10]. Uganda is endowed with abundant solar resources, with an average solar irradiance of about 5.2 kWh/m²/day, which is favourable for solar PV technology [11]. However, the country faces challenges related to grid access, especially in rural regions, which limits electricity availability and drives interest in decentralized energy solutions like solar PV. Uganda’s energy policies have increasingly supported solar energy as a primary component of the country’s renewable energy strategy. The National Development Plan (NDP), Uganda’s Vision 2040, and the Renewable Energy Policy 2007 underscore the importance of renewables for sustainable development, emphasizing energy diversification and rural electrification through renewable sources [12]. The government’s Vision 2040 outlines a goal of achieving 5,000 MW of solar capacity, showing strong national support for renewable energy. The Renewable Energy Policy, in particular, has set ambitious targets, aiming to increase the contribution of renewable energy in the energy mix. Solar PV technology is key to these policies, providing a scalable, sustainable energy solution that aligns with Uganda’s commitment to environmental goals and economic development. Government programs like the Rural Electrification Strategy and Plan (RESP), overseen by the Rural Electrification Agency (REA), focus on extending electricity access through solar mini-grids and off-grid solar home systems in remote areas. Under this framework, private sector engagement has been encouraged, leading to partnerships with non-governmental organizations (NGOs) and private companies to distribute and maintain solar PV systems, particularly in underserved rural communities. These initiatives aim to achieve 100% rural electrification by 2040 [12].

The adoption rates of solar PV systems in Uganda have shown steady growth, with considerable uptake in rural areas. According to recent data, over 1.8 million households in Uganda rely on solar for their primary or supplementary energy needs. This adoption is driven by various factors, including the affordability and modularity of solar PV systems, declining system costs, and the availability of innovative financing options such as pay-as-you-go (PAYG) solar solutions [13]. PAYG models, in particular, have reduced upfront costs, making solar PV more accessible for low-income households and promoting its adoption in off-grid areas. Despite these advancements, challenges remain, including financial barriers, limited technical expertise, and maintenance issues that hinder the long-term sustainability of solar PV installations. Access to financing continues to be a major constraint, as many rural communities cannot afford even the subsidized costs of solar PV systems without external financial support. Additionally, the lack of a skilled workforce and adequate infrastructure for ongoing maintenance and repairs poses reliability risks for solar PV users, particularly in isolated rural settings. In Lango, a rural region with limited grid connectivity, solar PV systems offer a viable solution to bridging the energy access gap. Despite various government and NGO initiatives, such as the installation of solar PV in healthcare facilities under the USAID-funded RHITES-N program, challenges remain due to insufficient maintenance infrastructure and technical capacity [14].

Uganda’s solar energy landscape reflects both promising progress and ongoing challenges. National policies and programs have created a supportive environment for solar energy expansion, leading to increased adoption rates, especially in rural areas where grid extension is financially and logistically challenging. However, for Uganda to fully realize the benefits of solar PV technology, additional efforts are needed to address the financial, technical, and maintenance challenges that affect the reliability and sustainability of these systems. Future developments in policy, public-private partnerships, and capacity-building initiatives will be crucial in ensuring that solar PV remains a viable and enduring solution for Uganda’s energy needs [15,16].

3.1 Solar PV Systems in the Lango Sub-region

The Lango sub-region, situated in northern Uganda, comprises eight districts and has a largely rural population, with a high dependence on agriculture. This area faces unique geographical, climatic, and socio-economic conditions that impact the adoption and operation of solar PV systems. Understanding these regional characteristics is essential for assessing the maintainability and reliability of solar PV technology in Lango, as well as for devising solutions tailored to the area's energy needs.

3.1.1 Climate and Geography

Lango's climate is characterized by two main seasons: a wet season from April to November and a dry season from December to March. The region experiences average annual sunshine of approximately 4.5-5 kWh/m²/day, which is conducive to solar energy generation, particularly during the dry season. However, the variability in sunshine due to seasonal changes affects the consistency of solar energy output, posing challenges for households and institutions that rely on solar PV as their primary energy source. This seasonal variability necessitates reliable storage systems, such as batteries, to ensure energy availability throughout the year, especially during periods of low solar irradiance. Geographically, Lango's terrain is mostly flat with scattered wetlands and rivers, which influences both the placement of solar PV systems and the infrastructure needed to maintain them. The predominantly rural setting and low population density pose logistical challenges for the distribution and maintenance of solar PV systems. Additionally, the area's remoteness from major urban centres makes it difficult to access technical support, spare parts, and other resources essential for maintaining the reliability of solar installations [17]. Figure 2 illustrates the energy generation of each energy source in Uganda, showing that renewable sources are gradually penetrating into the country.

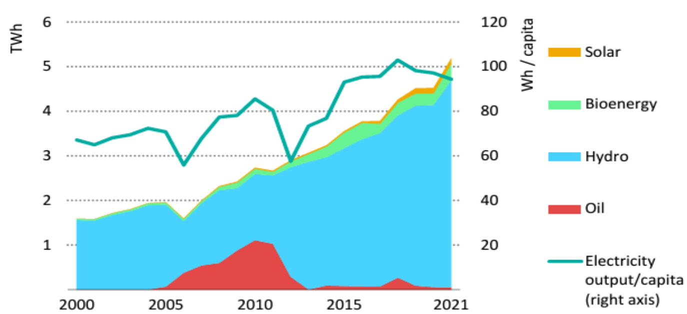

Figure 2: Electricity generation in Uganda, 2000-2021 [16]

3.1.2 Energy Demand and Access

1. In the Lango region, as in much of rural Uganda, access to modern energy remains a significant challenge. Most households rely heavily on traditional biomass fuels, such as wood and charcoal, for cooking and lighting, contributing to severe environmental degradation and adverse health outcomes. The national electricity grid has limited reach in rural areas, and the high cost of extending grid infrastructure to remote locations has made solar PV systems an increasingly viable alternative for electrification. Consequently, the adoption of off-grid and mini-grid solar PV systems has surged, particularly among households, schools, health centers, and small businesses seeking affordable and reliable energy solutions. Energy requirements in the Lango region vary significantly across user categories. Households primarily use solar PV systems for essential applications such as lighting, mobile phone charging, and operating small appliances. In contrast, institutions like schools and health centers require higher-capacity systems to support energy-intensive applications, including lighting, refrigeration, and powering medical devices. These variations in energy demand directly influence the design, capacity, and operational complexity of solar PV systems deployed in the region. Larger, more sophisticated systems necessitate advanced maintenance protocols and enhanced reliability measures to ensure sustained performance and longevity [18]. The energy demand profiles of Ugandans are illustrated in Figure 3.

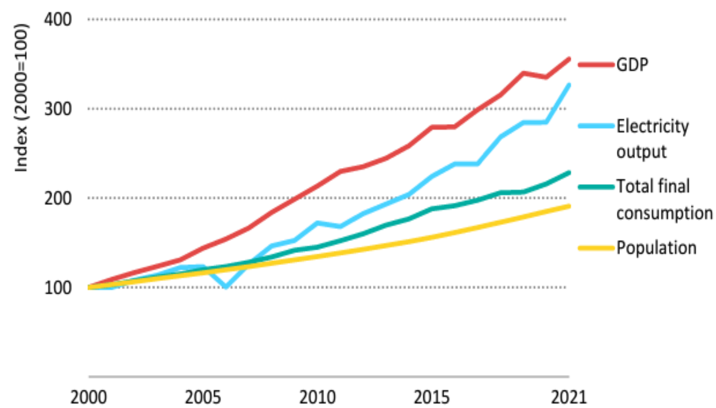

Figure 3: Uganda Energy Demand and Drives [12]

3.1.3 Adoption of Solar PV Systems

In recent years, the adoption of solar PV systems in Lango has increased, driven by government initiatives, NGO projects, and private sector engagement. Programs like the RESP have promoted the distribution of solar systems in underserved areas, providing subsidies and incentives to improve affordability. Additionally, the prevalence of financing options such as PAYG models has facilitated access to solar PV for low-income households, allowing them to make gradual payments and thereby reducing the financial burden of solar technology [19,20]. Despite these positive trends, several challenges affect the uptake and sustainability of solar PV systems in Lango. One of the major barriers is the limited technical expertise available in the region. While the presence of solar systems has grown, the availability of qualified technicians for installation, troubleshooting, and maintenance remains low. This skills gap affects the reliability of solar PV installations, as inadequate maintenance and improper handling often lead to system breakdowns and reduced performance over time. Furthermore, the region's socio-economic conditions present financial constraints that can limit the adoption and long-term sustainability of solar PV technology. Although PAYG models have improved accessibility, many households still struggle with the ongoing costs of maintenance and battery replacements, which are essential for reliable solar power. These financial challenges underscore the need for continued support from government and development agencies to subsidize maintenance costs and provide training for local technicians.

Therefore, the adoption of solar PV systems in the Lango sub-region is a critical development in addressing energy access challenges, particularly in off-grid rural communities. Lango's favorable solar irradiance levels, combined with increasing energy demand from households and institutions, highlight the potential for solar PV to bridge the energy gap. However, the unique climatic, geographic, and socio-economic conditions in Lango pose distinct challenges to the reliability and maintainability of these systems. Addressing the region's technical expertise shortage, ensuring the affordability of maintenance services, and enhancing community awareness about solar system operation and care are essential steps in sustaining solar energy solutions in Lango. By aligning energy solutions with local needs and capacities, stakeholders can better support the long-term viability and impact of solar PV systems in this region.

3.2. Factors Influencing Reliability of Solar PV Systems

The reliability of solar PV systems in Lango, Uganda, is influenced by a range of factors unique to the region's environmental, technical, and operational conditions. Reliable solar PV systems are essential for ensuring consistent energy access in rural areas, where grid connectivity is limited or unavailable [21]. Key factors affecting system reliability include environmental conditions such as high temperatures, humidity, and dust, which can degrade system components and reduce efficiency. Additionally, the quality and design of PV system components are often influenced by local availability and cost constraints play a critical role in performance and durability. Operational practices, including user knowledge, maintenance habits, and technical support accessibility, further impact system reliability. Addressing these factors is vital to enhance the resilience and longevity of solar PV systems, ensuring they meet the energy needs of communities in Lango sustainably [22].

1. Environmental Factors: The reliability of solar PV systems is heavily influenced by the environmental conditions in which they operate, and in Lango, specific climatic factors play a considerable role. The region's climate is characterized by high temperatures, variable humidity levels, and frequent dust, all of which impact the performance and longevity of solar PV components [22].

2. Temperature Effects: High temperatures, especially during the dry season, can reduce the efficiency of solar PV panels and accelerate degradation. Solar cells typically perform best within a specific temperature range, and excessive heat can lead to thermal stress, reducing their output and lifespan. This is because the performance of photovoltaic cells generally decreases as temperature increases, resulting in lower power output. In Lango, where daytime temperatures can often exceed 30°C, this thermal impact is a significant concern for solar PV systems, particularly for lower-cost systems that may lack thermal management features [23].

3 Humidity and Moisture Exposure: During the rainy season, humidity levels in Lango can become high, exposing solar PV systems to increased risks of moisture-related damage. Moisture can infiltrate solar panels, inverters, and other electrical components, leading to corrosion and short-circuiting. This is especially problematic for systems with lower-quality sealing and protection standards. High humidity also contributes to condensation, which can affect the reliability of electrical contacts and other sensitive components. In areas where humidity is consistently high, frequent maintenance checks are often needed to prevent moisture-related failures, but this can be a logistical challenge in Lango's rural setting [23].

4 Dust and Soiling: Lango's dry season is marked by dusty conditions, which result in dust accumulation on solar panels. Dust and soiling can substantially reduce the efficiency of solar PV systems by blocking sunlight from reaching the photovoltaic cells, thereby reducing energy generation [24]. Studies have shown that soiling can cause up to a 30% reduction in output if panels are not regularly cleaned, which is a frequent issue in arid and semi-arid regions. For rural areas like Lango, where regular cleaning and maintenance may not be feasible, dust accumulation presents a serious challenge to PV system reliability. Therefore, dust-resistant coatings or easy-to-clean panel designs could improve system performance under these conditions. Dust accumulation on PV modules, for example, can reduce power output by 20–30%, impacting overall performance [25]. Dust can also cause hot spots on solar panels, leading to cell degradation and increased failure rates over time [26]. Figure 4 shows solar PV panels with different ranges of dust accumulation.

Figure 4: Dust accumulation in a Solar PV panel [27]

5. Component Quality and System Design: The quality and design of solar PV system components are fundamental determinants of reliability and long-term performance. In Lango, where access to high-quality components and certified installation services is often limited, the selection and design of PV systems significantly influence their functionality and durability. The reliability of solar PV systems in this region hinges on the robustness of critical components, including PV panels, inverters, batteries, and charge controllers. High-quality PV panels are engineered to withstand environmental stressors such as ultraviolet (UV) radiation, temperature fluctuations, and exposure to dust and rain. However, in rural areas like Lango, many households and institutions rely on lower-cost systems that fail to meet rigorous quality standards, leading to frequent malfunctions and reduced lifespans. Batteries, which are essential for energy storage, are particularly prone to degradation under extreme temperatures, a common challenge in Lango. Inferior batteries often have a limited number of charge-discharge cycles, compromising their ability to store and deliver energy reliably [28].

A well-designed PV system incorporates redundancy, efficient energy management, and components tailored to local environmental conditions. However, in Lango, system design is frequently constrained by financial limitations and insufficient technical expertise. These constraints can result in suboptimal system configurations that are less resilient to environmental stress. For instance, systems lacking protection against overloading or without adequate thermal management are prone to premature failure. Similarly, inverters and charge controllers that are not equipped with surge protection are highly susceptible to damage during power fluctuations caused by variable sunlight exposure. Seasonal variations in sunlight and temperature further exacerbate these challenges. Systems that do not account for these variations in their design often underperform, reducing reliability and user satisfaction with solar technology [29]. The availability of counterfeit or substandard components, such as inverters, batteries, and connectors, also undermines the reliability of PV systems in rural areas. Counterfeit components frequently lack the durability to endure operational stresses, leading to failures and necessitating frequent replacements.

Establishing reliable supply chains and ensuring access to certified, high-quality components are critical steps toward improving solar PV system reliability in Lango. Additionally, educating users and installers on the importance of component selection and system design can help mitigate these challenges. Designing systems to withstand the region's specific environmental conditions, including temperature extremes, dust accumulation, and variable sunlight, is essential for ensuring sustainable and reliable energy delivery. Addressing these issues through coordinated efforts between policymakers, suppliers, and technical experts can enhance the resilience and performance of solar PV systems in Lango, fostering greater adoption and satisfaction among users.

3.3 Operational Challenges and User Practices

User practices and the operational challenges encountered in the use of solar PV systems in Lango also significantly impact system reliability. Proper handling, routine maintenance, and user knowledge are essential for maximizing the lifespan and efficiency of solar systems.

1. User Knowledge and Training: In rural areas like Lango, users may lack the technical knowledge needed to operate and maintain solar PV systems correctly. Improper handling of system components, such as overcharging batteries, neglecting inverter settings, or failing to clean panels, can lead to reduced efficiency and premature failure. Training users on basic maintenance practices, such as regularly checking battery charge levels and cleaning panels, can improve the system's reliability. Moreover, providing users with simple troubleshooting skills helps them address minor issues independently, reducing the need for costly repairs or replacements [22].

2. Maintenance Practices and Accessibility of Technical Support: Routine maintenance is essential for the longevity of solar PV systems, but in Lango, access to trained technicians is limited, and maintenance services can be costly or unavailable. This lack of accessibility often leads to deferred maintenance, which can exacerbate wear and tear on the system. For example, unmaintained batteries may degrade faster, reducing the system's storage capacity, while unchecked wiring and connections may lead to shorts or power losses. Increasing the number of trained local technicians and promoting periodic maintenance could help address these operational challenges and enhance system reliability. Developing regions often lack skilled personnel for system installation, maintenance, and repair. This shortage can lead to improper installations and inadequate maintenance, further reducing system lifespan and performance. Proper training in handling and troubleshooting PV systems is essential to maintain optimal system operation [30].

3. System Misuse and Load Management: In some cases, users may inadvertently overload the system by connecting devices that exceed the system's designed load capacity. This misuse can strain components, particularly batteries and inverters, leading to frequent malfunctions. For instance, if a solar PV system is designed for basic lighting and phone charging, connecting additional appliances like TVs or refrigerators can quickly drain the battery and reduce its lifespan. Educating users about load management and the importance of respecting system limits is critical for maintaining reliability.

4 Community Awareness and Ownership: Promoting a sense of ownership and responsibility among community members regarding their solar PV systems can also improve operational reliability. When users view their solar systems as valuable investments, they are more likely to adopt practices that enhance system performance and longevity. Community-based initiatives that encourage cooperative maintenance practices, such as group cleanings or shared maintenance checkups, could foster a collective approach to system care, improving reliability on a broader scale [31].

3.4. Maintainability and Reliability of Solar PV Systems

In solar PV systems, maintainability and reliability are critical metrics that define the system's operational effectiveness and sustainability over time. Maintainability refers to the ease, speed, and cost-effectiveness with which a solar PV system can be serviced, repaired, or updated to ensure optimal functioning [5]. For solar PV systems, maintainability involves regular inspections, preventive maintenance, and repairs of components like PV panels, batteries, inverters, and wiring. High maintainability allows for reduced system downtime, ensuring that users receive consistent and uninterrupted energy access, a critical need in off-grid regions. Reliability, on the other hand, describes a solar PV system's ability to consistently deliver power under various operational conditions without failure. Reliability is influenced by the quality of components, environmental factors, design robustness, and proper installation [32]. In solar PV systems, reliability is often measured by metrics like mean time between failures (MTBF), availability, and energy yield consistency over the system's lifecycle. In developing regions where electricity access is limited or absent, reliability is essential to ensure that solar PV systems provide a dependable source of energy that communities can rely on for daily activities, health services, and economic productivity. Reliability can be mathematically represented as shown in equation (3).

$$R(t) = e^{-\lambda t} \qquad (3)$$

Where: λ is the failure rate, and t represents time in operation. This formula assumes a constant failure rate, which is common for electronic components within solar PV systems but may vary due to external environmental stressors [33].

Both maintainability and reliability are crucial for the long-term success of solar PV systems, particularly in resource-constrained areas. In regions with limited access to technical support and spare parts, as is often the case in rural settings, high maintainability and reliability reduce the dependence on external technical expertise, minimize operational disruptions, and lower overall lifecycle costs. In this way, a focus on maintainability and reliability aligns solar PV systems with the sustainable development goals of providing affordable and clean energy, reducing reliance on fossil fuels, and promoting energy independence in developing areas.

3.4.1. Current Maintenance Strategies and Approaches for Solar PV Systems

As solar PV systems continue to expand globally, their efficient operation and longevity have become critical to ensuring optimal energy production and cost-effectiveness. Maintenance strategies for solar PV systems are essential in preventing energy loss, reducing downtime, and prolonging the system's operational life. Current approaches to solar PV maintenance include predictive, preventive, and corrective maintenance strategies. Predictive maintenance uses data-driven insights from monitoring systems to anticipate and address issues before failures occur, whereas preventive maintenance involves regular inspections and cleaning to reduce wear and tear. Corrective maintenance focuses on fixing faults after they have occurred. With the advent of advanced technologies such as drones, thermal imaging, and machine learning, these maintenance approaches are evolving to provide more precise and proactive solutions for solar PV system upkeep [34].

3.4.1.1 Maintenance Strategies for Solar PV Systems

Maintenance strategies in solar PV systems are categorized primarily into three types: preventive, predictive, and corrective maintenance, each targeting system reliability and performance sustainability.

1. Preventive Maintenance (PM): Preventive maintenance involves regular inspection and servicing of PV components to prevent unexpected failures or regularly scheduled activities that help prevent system degradation. In solar PV systems, this involves cleaning panels to prevent dust buildup, inspecting connections for signs of corrosion or wear, and monitoring battery health. Dust accumulation, particularly during Lango's dry season, can greatly reduce panel efficiency if not regularly removed. In many cases, panel cleaning is conducted manually and requires consistent scheduling, as soiling can cause a 10-30% reduction in energy generation. Ensuring that connections and wiring remain secure and free from damage is also essential, as electrical faults can lead to energy loss or even pose safety risks. Battery maintenance is crucial, as degraded batteries can compromise the entire system's reliability. In Lango, regular inspection and water topping (for flooded batteries) are typical battery maintenance tasks. However, the frequency and consistency of such practices can vary due to resource limitations and user awareness [35]. The preventive Maintenance Cost Estimation model can be represented in equation (4).

$$CPM = C_{inspection} + C_{cleaning} + C_{repair} \quad (4)$$

Where: C_{PM} = Total preventive maintenance cost, $C_{inspection}$ = Cost of component inspection

$C_{cleaning}$ = Cost of cleaning (if applicable), C_{repair} = Cost of minor repairs detected during routine checks

(2). Predictive Maintenance (PdM): Predictive maintenance uses real-time data from monitoring devices to predict potential component failures before they occur. Sensors can track temperature, voltage, and current across PV components, allowing early detection of anomalies. Predictive algorithms and statistical methods, such as the Weibull distribution, and model time-to-failure (TTF) for components, improve system uptime by scheduling maintenance activities based on actual conditions rather than scheduled checks [36]. The failure Prediction model can be determined using the Weibull Distribution as represented in equation (5).

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (5)$$

Where: $R(t)$ = Reliability at time t, η = Characteristic life (scale parameter) and β = Shape parameter (describes the failure rate trend)

3. Corrective Maintenance (CM): Corrective maintenance refers to actions taken to restore a system to operational status after a fault or failure occurs. Common corrective tasks in solar PV systems include inverter repairs, battery replacements, and rewiring. In Lango, corrective maintenance is often reactive due to limited access to technical resources and spare parts. This approach can be problematic, as delayed repairs can result in prolonged downtime, reducing users' energy reliability and satisfaction with solar PV systems. When a component like an inverter or charge controller fails, it may take considerable time to source a replacement, particularly in remote areas where logistical support is limited. As a result, corrective maintenance in Lango tends to be ad-hoc and heavily dependent on the availability of skilled technicians and parts [37]. Corrective maintenance is typically less favourable in remote and low-resource settings due to logistical challenges and the availability of skilled technicians.

3.4.2. Methods Used in Maintainability and Reliability Analysis

Several analytical methods assess the maintainability and reliability of PV systems, each offering insights into system performance and potential failure points. The Reliability Block Diagram (RBD), Failure Modes and Effects Analysis (FMEA), and Fault Tree Analysis (FTA) are commonly applied approaches.

Reliability Block Diagram (RBD): RBDs visually represent the operational flow of PV system components, showing how component reliability affects overall system reliability. Each PV system component (e.g., modules, inverter, batteries) is represented as a "block," with parallel and series arrangements indicating redundancy and dependency. The reliability (R) of a series system is given by equation (6).

$$R = \prod_{i=1}^{n} Ri \quad (6)$$

Where: R_i represents the reliability of each component in the series. This model emphasizes weak points in system reliability and highlights where preventive or predictive maintenance could increase uptime [38].

Failure Modes and Effects Analysis (FMEA): FMEA identifies potential failure modes within each component, assigning a Risk Priority Number (RPN) based on severity, occurrence, and detection ratings. This proactive approach allows maintenance teams to prioritize components for preventive maintenance, especially in rural settings where resource limitations make full system checks challenging [39]. RPN can be calculated using equation (7)

$$RPN = S \times O \times D \quad (7)$$

Where; S = Severity of failure, O = Likelihood of occurrence and D = Detectability of failure

Fault Tree Analysis (FTA): FTA is a top-down approach to analysing the root causes of failures in PV systems. Starting with an undesired top event (e.g., system blackout), FTA traces potential fault combinations that lead to the event, making it particularly useful in identifying critical failure paths in complex PV setups. FTA helps quantify risk in multi-component systems, essential for designing robust maintenance strategies [39].

3.4.3 Reliability Metrics in Solar PV Systems

Reliability metrics are vital for quantifying the expected performance and failure rates of PV components over time. Key metrics in reliability analysis include Mean Time to Failure (MTTF), Failure Rate (λ), and the Reliability Function R(t).

Mean Time to Failure (MTTF): MTTF is the average time a component is expected to operate before failure. For non-repairable components, MTTF is calculated as in equation (8)

$$MTTF = \frac{1}{\lambda} \tag{8}$$

Where; λ represents the component's constant failure rate, applicable under the assumption of an exponential failure distribution. MTTF is particularly useful for assessing components like batteries and inverters, where end-of-life is a critical reliability indicator [30].

Failure Rate (λ): The failure rate indicates the likelihood of a component failing within a specified time. In solar PV systems, components such as PV modules and inverters are susceptible to failures influenced by environmental conditions, manufacturing quality, and operational stress. The failure is calculated using equation (9)

$$\boldsymbol{\lambda} = \frac{N_{Fail}}{N*T} \tag{9}$$

Where; N_{fail} = Number of failures observed, N = Total number of components under observation and T = Total operational time.

Reliability Function R(t): The reliability function represents the probability that a component will perform without failure over a specified time t. For exponentially distributed lifetimes, the reliability function is expressed as in equation (10)

$$R(t) = e^{-\boldsymbol{\lambda}\mathbf{t}} \tag{10}$$

Where: λ is the constant failure rate. This function is useful for modelling the probability of continuous operation for components with known failure rates, such as inverters or batteries subjected to regular charge-discharge cycles [40].

Weibull Analysis: For components with varying failure rates over time, Weibull distribution provides a more accurate model of reliability. The reliability function R(t) for a Weibull distribution is given by the equation (11)

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}} \tag{11}$$

Where: η = Scale parameter, representing characteristic life and β = Shape parameter, indicating failure behaviour over time [4]. Weibull analysis is particularly valuable for PV modules and batteries with "wear-out" failures, allowing adjustments to maintenance schedules based on evolving failure patterns.

In summary, critical components like PV modules, inverters, batteries, and charge controllers play key roles in the operational reliability of solar PV systems. Using reliability metrics such as MTTF, Failure Rate, and the Reliability Function, along with analytical methods like RBDs, FMEA, and Weibull analysis, provides a robust framework for assessing and enhancing solar PV reliability. Addressing these aspects, especially under the specific environmental and operational conditions in Lango, Uganda, will inform the development of an effective, region-specific maintenance strategy.

3.4.4. Maintainability of Solar PV Systems: Practices and Challenges in Lango

The maintainability of solar PV systems is essential to ensuring consistent performance, reliability, and long-term sustainability, particularly in regions with limited infrastructure. In Lango, Uganda, solar PV systems are increasingly deployed to meet rural electrification needs, but unique challenges such as harsh environmental conditions, limited technical expertise, and constrained access to replacement parts impact system maintenance. Effective practices in preventive, predictive, and corrective maintenance are necessary to address these issues, but they require adaptation to the local context [41]. This paper explores the current maintenance practices for solar PV systems in Lango, the challenges encountered, and potential strategies to enhance system longevity and efficiency.

1. Availability of Skilled Personnel and Resources

The maintainability of solar PV systems in Lango is also shaped by the availability of skilled technicians and access to necessary resources, including replacement parts and support infrastructure. The availability of trained personnel who understand PV systems is critical, as proper installation and maintenance require specific technical knowledge and skill.

2. Training and Capacity of Local Technicians

There is a significant shortage of skilled solar PV technicians in Lango, partly due to limited training programs and technical education opportunities in rural Uganda. While some training initiatives have been introduced by NGOs and private organizations, the technical skills needed for effective solar PV maintenance are still in short supply. Local technicians often lack advanced training in troubleshooting PV-specific issues, leading to suboptimal repair practices and reliance on external support. This skills gap can result in maintenance delays and increased system downtime, as less experienced technicians may struggle with diagnosing and fixing problems accurately [42].

3. Access to Spare Parts and Resources

The availability of replacement parts such as inverters, batteries, and connectors is another critical issue affecting solar PV system maintainability in Lango. Rural areas often face supply chain challenges, as spare parts may not be readily available locally and must be sourced from urban centers or imported. This dependency on external suppliers introduces delays and increases costs, especially when specialized parts are required. In some cases, the use of counterfeit or low-quality components due to cost constraints can further undermine system reliability and performance. To address this issue, establishing reliable local supply chains and partnerships with reputable distributors could help improve access to high-quality parts, reducing system downtime and maintenance costs [43].

4. Support Infrastructure and Technical Assistance

In addition to technician training and parts availability, support infrastructure such as service centers and diagnostic tools are necessary to maintain PV systems effectively. In Lango, formal service centers for PV systems are scarce, limiting access to professional assistance and diagnostic services. Users and technicians in rural areas may lack basic testing equipment, such as multimeters, to carry out diagnostics, relying instead on visual inspections that may miss underlying issues. Strengthening the support infrastructure by establishing local service centers and providing technicians with adequate tools and resources could significantly improve maintenance outcomes in Lango. Overall, the limited availability of skilled technicians, spare parts, and support infrastructure poses substantial challenges to the maintainability of solar PV systems in Lango. Addressing these issues through technician training, local supply chain development, and infrastructure investments is essential for creating a reliable and sustainable maintenance ecosystem [30,43].

3.4.5 Cost Implications of Maintenance

Maintenance costs are a significant consideration for households, communities, and organizations using solar PV systems in Lango. These costs include not only the direct expenses associated with repairs and replacements but also the economic impact of system downtime and reliance on external services.

1. Direct Maintenance Costs

Direct costs include expenses for parts, labor, and equipment needed for routine and corrective maintenance. In rural settings, maintenance costs are often higher due to logistical challenges, as parts and technicians may need to travel long distances. Replacement batteries, inverters, and other essential components can be particularly costly, and their expenses may be beyond the budget of low-income households. Additionally, frequent failures of low-quality or counterfeit parts can lead to increased maintenance expenses over time, reducing the cost-effectiveness of the solar PV system. For many households in Lango, these direct costs are a barrier to consistent maintenance, resulting in deferred repairs and a higher risk of system failures [44].

2. Economic Impact on Households and Organizations

Solar PV systems provide essential energy access for households, schools, health centers, and small businesses in Lango. When these systems are offline due to maintenance needs, users face both economic and productivity losses. For example, small businesses may be unable to operate without power, impacting income generation, while schools and health centers may struggle to provide basic services in the absence of reliable energy. For low-income households, the economic burden of maintenance costs can discourage investment in PV technology altogether, which poses a risk to the long-term viability of solar adoption in the region. The high upfront costs of solar PV systems and components like batteries and inverters can be prohibitive. Additionally, the prevalence of low-quality or counterfeit products can lead to early system failures, which drive up maintenance costs [44]. Counterfeit batteries and panels, for instance, are prone to faster degradation, leading to frequent replacements that can double the operational costs over the system's lifespan

3. Long-term Cost Benefits of Effective Maintenance

While the upfront and ongoing costs of maintaining solar PV systems can be high, effective maintenance practices can reduce long-term expenses by preventing system failures and extending component lifespans. Regular battery maintenance, panel cleaning, and inspection of connections can prevent more costly repairs and replacements in the future. For communities in Lango, investing in effective maintenance is therefore a cost-effective strategy that supports system reliability and sustainability. Some regions have explored community-based maintenance programs, where costs are shared and systems are maintained collectively, reducing the individual financial burden on households [44].

In conclusion, maintenance costs are a critical factor influencing the adoption and sustainability of solar PV systems in Lango. Addressing these costs through support programs, cost-sharing initiatives, and training local technicians can help mitigate the economic impact of maintenance, making solar energy a more viable and affordable solution for rural electrification in the region.

3.5 Importance of Maintenance Strategies in Improving System Performance and Extending Lifespan

Proper maintenance strategies are crucial in enhancing the lifespan and performance of solar PV systems. Solar panels, inverters, batteries, and charge controllers all experience performance degradation over time, primarily due to environmental factors such as dust, humidity, and temperature variations. Maintenance strategies designed to mitigate these effects can significantly reduce downtime and failure rates, thus improving the system's overall reliability [4].

Preventive Maintenance (PM) and Predictive Maintenance (PdM) are two critical strategies used in solar PV systems. Preventive maintenance focuses on scheduled actions, such as periodic inspections and cleaning, which prevent common issues like dust accumulation and thermal stress. Predictive maintenance, on the other hand, relies on data analytics and real-time monitoring to forecast potential failures. For example, using temperature sensors and current-voltage (I-V) measurements can help detect early signs of inverter failure or panel degradation [45].

3.6. Technological Advancements and Innovation in PV System Maintainability and Reliability

Technological advancements have been pivotal in enhancing the maintainability and reliability of solar PV systems, particularly for rural applications. This section explores key innovations in monitoring, diagnostic tools, and component durability that address common challenges in off-grid and remote settings. These innovations not only improve system longevity but also offer more efficient maintenance solutions, reducing downtime and maintenance costs for PV installations in rural and harsh environments.

3.6.1. Improvements in Component Durability

Advances in PV panel and battery technology have been instrumental in improving the durability and longevity of solar PV systems, particularly in harsh or remote environments. Enhanced component durability reduces the frequency of maintenance interventions, extends system lifespans, and lowers the total cost of ownership, making solar PV solutions more viable for rural applications.

1. Advancements in PV Panel Technology: PV panel technology has evolved significantly, with recent innovations focusing on materials that enhance durability and efficiency. Newer PV panels incorporate materials that are more resistant to environmental stressors, such as extreme temperatures, high humidity, and UV exposure. For instance, bifacial PV panels, which can capture sunlight from both sides, offer not only improved energy yield but also greater resilience to temperature fluctuations. Anti-reflective and hydrophobic coatings further enhance these panels' ability to resist dust, dirt, and water accumulation, which are common issues in rural and arid areas. These advancements contribute to reduced cleaning and maintenance needs, as the panels can self-clean to a certain extent, thereby retaining efficiency over longer periods without manual intervention [46,47].

2. Innovations in Battery Technology: Battery technology has also made substantial strides, especially with the development of lithium-ion, lithium iron phosphate ($LiFePO_4$), and solid-state batteries that offer higher energy density, longer cycle life, and enhanced safety profiles. Lithium iron phosphate batteries, for example, are known for their stability and longer cycle life, making them well-suited for off-grid solar PV applications. Unlike traditional lead-acid batteries, these newer batteries have a lower risk of thermal runaway and require less frequent replacement, thereby reducing maintenance frequency and costs. For PV systems in rural settings, where battery degradation often leads to frequent downtimes, these innovations are transformative, providing more reliable and durable energy storage solutions. Additionally, advancements in battery management systems (BMS) enhance the reliability of battery storage by continuously monitoring cell voltage, temperature, and state of charge. BMS algorithms optimize charging and discharging cycles, ensuring batteries operate within safe parameters, which extends their lifespan and prevents premature failures. With rural systems increasingly dependent on battery storage for consistent power, these innovations offer a substantial improvement in overall system resilience [48,49,50].

3. Protective Inverter and Charge Controller Designs: Inverters and charge controllers are crucial components in PV systems that have also benefited from innovations aimed at improving reliability. High-quality inverters now incorporate advanced cooling mechanisms and protective casings that minimize wear from environmental stress. For rural PV systems, ruggedized inverters that can withstand dust, moisture, and voltage fluctuations offer more stable and long-lasting performance. Meanwhile, intelligent charge controllers equipped with maximum power point tracking (MPPT) optimize power conversion efficiency, even under varying solar conditions, ensuring that batteries are charged effectively and system performance remains consistent [7,51].

Overall, these advancements in PV panels, batteries, inverters, and charge controllers significantly bolster the durability and reliability of solar PV systems, especially in challenging environments. By reducing the need for frequent maintenance and enhancing system resilience, these technological improvements contribute to more sustainable and cost-effective solar PV solutions for rural communities. As technology continues to advance, the potential for even greater reliability in off-grid solar applications will expand, enabling broader energy access in remote areas worldwide.

3.7 Case Studies and Empirical Evidence

This section presents case studies and empirical findings to highlight practical outcomes, challenges, and lessons in deploying and maintaining solar PV systems within the Lango region of Uganda. Comparative analysis further extends the discussion by situating these findings within a broader East African context, examining how similar regions address the reliability and maintainability of solar PV installations.

3.7 1 Case Studies from the Lango Region

The Lango sub-region in Northern Uganda has witnessed numerous solar PV system installations aimed at enhancing energy access in both residential and institutional settings. A series of project reports and case studies provide insights into the operational reliability and maintenance practices observed within this locale. These studies often underscore the critical role of environmental factors, local capacity for maintenance, and community engagement in determining system effectiveness and longevity. For instance, a Case Study by [52] evaluated solar isodose lines: Mercatorian and spatial guides for mapping solar installation areas, highlighting the systems' initial success in providing reliable lighting and powering educational devices. However, it was noted that within two years, system degradation due to dust accumulation and lack of routine cleaning led to a decrease in efficiency by approximately 15–20%. The study attributed this decline not only to environmental conditions but also to limited technical training for local technicians, who struggled with system upkeep and troubleshooting. A key finding from this case was that while donor agencies subsidized initial installation costs, ongoing maintenance expenses were not considered, leading to system downtimes that affected educational outcomes [30,53].

Another example, Case Study in Ghana and Uganda health centres, documented the deployment of solar PV systems in rural health centres, which proved vital for cold chain management and emergency lighting. Here, reliability challenges primarily arose from inadequate storage capacity in the batteries, particularly during periods of high demand and low solar insolation. Battery failures were frequent, pointing to a need for improved battery technologies or hybrid systems that could incorporate other energy sources. Interviews with health centre staff revealed that frequent system downtimes hampered service delivery, especially in maternal and child healthcare services. This case underlined the importance of tailored design and reliable storage solutions for critical service-oriented facilities Javadi et al, 2020. Through these case studies, it becomes evident that while solar PV installations in the Lango region offer significant benefits, sustainability issues such as maintenance training, spare parts availability, and tailored

3.7.2. Comparative Analysis of Case Studies and Findings from Similar Regions

When compared to solar PV deployments in other regions of Uganda, such as Karamoja and Western Uganda, as well as similar installations in neighbouring East African countries like Kenya and Tanzania, notable differences in maintainability and reliability challenges emerge. This comparative analysis highlights the regional specificity of these challenges and identifies broader lessons applicable to the Lango region.

Sub-Saharan Africa: The importance of reliability and maintenance is underscored by several studies conducted in sub-Saharan Africa, where solar PV systems are widely used for rural electrification. In these regions, the harsh environmental conditions and limited access to technical expertise pose significant challenges to system reliability [54].

East Africa: The impact of dust and temperature in a study focusing on East Africa, the researcher in [4] found that dust accumulation reduced PV efficiency by approximately 20% over three months without cleaning. High temperatures further exacerbated this reduction, affecting the efficiency of PV modules, particularly in arid areas. They noted that thermal management and routine cleaning improved performance reliability by over 15%, showing the effectiveness of basic preventive maintenance strategies in such climates.

West Africa: the battery maintenance and reliability challenges in West Africa, a study by [30] highlighted that maintenance of batteries, a critical component in PV systems, is often neglected due to a lack of technical expertise. This oversight results in frequent battery failures, which severely affect system reliability. The authors found that implementing charge controllers with MPPT technology helped optimize battery health and increased battery lifespan by up to 30%.

In the Karamoja region, for example, solar PV projects have encountered similar issues with environmental factors, including dust and limited technician availability. However, Karamoja has benefited from a more extensive NGO presence focusing on community-based maintenance training programs, which has positively impacted system reliability. By contrast, the Lango region's reliance on external contractors for periodic maintenance has limited the local community's ability to sustain system performance independently. This observation suggests that community-based approaches, as seen in Karamoja, may enhance system longevity by empowering local technicians and increasing community ownership.

3.8. Policy and Institutional Support for Solar PV System Maintenance in Uganda

Policy and institutional support play a crucial role in promoting the sustainability and resilience of solar PV systems, especially in rural areas where challenges in maintenance and technical expertise are common. This section reviews the efforts by government agencies, non-governmental organizations (NGOs), and funding mechanisms aimed at enhancing the maintainability and reliability of solar PV installations across Uganda. By examining initiatives, subsidies, and incentive structures, we gain insights into the ways policy frameworks and financial support can bolster solar PV system longevity and improve energy access in underserved communities [55]. Table 1 is the Selected targets from Uganda's National Energy Policy 2023.

Table 1: Selected targets from Uganda's National Energy Policy 2023 [12]

Indicator
Households with at least one source of clean and modern energy on- or off-grid
Rate of electricity access (grid-connected)
Electricity generation capacity (MW)
Electricity consumption (kWh per capita)
Population using clean cooking fuels and technologies
Energy consumption from renewable sources
Increased energy diversification (energy resources in the energy mix)
Energy intensity (MJ per 2017 USD GDP)
CO_2 emissions from energy activities (Mt CO_2-eq)

Notes: MW = megawatt; kWh = kilowatt hour; MJ = megajoule; USD product; Mt CO2-eq = million tonnes carbon dioxide equivalent.
Source: MEMD (2023a).

2.8.1. Government and NGO Initiatives

Government and NGO-led initiatives have been central to expanding solar PV adoption in Uganda, particularly through programs and policies that address common challenges in system maintenance and reliability. In rural regions, where the logistical and financial barriers to maintaining PV systems are particularly high, these initiatives provide critical support that enhances the sustainability of solar energy solutions.

1. Government Policy and Subsidies: The Ugandan government, through its RESP, has actively promoted renewable energy to address the energy access gap in rural areas. Key policies, such as tax exemptions on solar equipment and components, have made PV systems more affordable for low-income households and institutions. These policies lower initial costs, facilitating wider deployment; however, they often do not extend to maintenance support. Recognizing this gap, the government introduced the Uganda Energy Credit Capitalisation Company (UECCC), which facilitates credit for off-grid energy systems, including provisions that support maintenance financing. UECCC's programs are designed to encourage private investment in off-grid solar, thereby creating a market for service providers that offer maintenance packages to rural clients. Additionally, the Ministry of Energy and Mineral Development (MEMD) has developed training and certification programs aimed at building a skilled local workforce for PV installation and maintenance. The Solar Technician Certification Program, for example, equips technicians with the necessary skills to install and maintain solar PV systems. This initiative addresses the issue of limited technical capacity in rural areas, ensuring that there is a pool of certified technicians who can sustain PV system operations over the long term [56,57].

2. NGO Programs and Partnerships: Numerous NGOs in Uganda, such as the Global Village Energy Partnership (GVEP) and Barefoot Power Uganda, have been instrumental in providing support for solar PV systems beyond the installation phase. These organizations often work directly with communities, focusing on capacity building, maintenance training, and providing technical support to ensure the reliable operation of solar installations. For instance, GVEP runs a program that trains local entrepreneurs in solar PV maintenance and repair, creating a network of solar service providers within rural communities. By empowering local technicians and entrepreneurs, these programs foster greater community ownership and reduce dependence on external technical support. Another significant NGO effort is the partnership between NGOs and community-based organizations (CBOs) to offer maintenance subsidies and create spare parts distribution networks in remote areas. The Solar Sister Initiative, which empowers women as solar product entrepreneurs, not only promotes clean energy access but also establishes a local base for maintenance and repair services. These initiatives improve the accessibility of maintenance services and replacement parts, helping to ensure the continuity of solar PV systems in rural settings where logistical challenges can lead to extended downtimes [31,56].

3.8.2. Funding and Incentive Structures

Effective funding mechanisms and incentive structures are essential for sustaining solar PV systems, particularly in rural regions where the cost of maintenance and technical support can be prohibitive. This section reviews the funding approaches and financial incentives available to improve PV system reliability, focusing on mechanisms that support maintenance, training, and capacity-building efforts to extend system longevity [58].

1. Funding Mechanisms for Maintenance: Uganda's funding landscape for renewable energy maintenance has evolved to include various programs that address the financial barriers associated with PV system upkeep. The UECCC provides soft loans and credit guarantees to microfinance institutions (MFIs), which in turn offer low-interest loans to rural households and small businesses for solar PV purchases, including funds earmarked for maintenance. These loans make it easier for users to cover maintenance costs without compromising system reliability due to financial constraints. Additionally, donor-funded initiatives, such as the World Bank's Energy for Rural Transformation (ERT) program, provide grants and funding for capacity-building in PV maintenance, enabling community members and technicians to access training at reduced costs [58, 59].

Another notable funding structure is the PAYG model, widely adopted by solar providers such as M-KOPA and SolarNow. This model, while primarily designed to facilitate affordable ownership of solar PV systems, incorporates periodic maintenance as part of the payment plan. PAYG systems allow users to make small, incremental payments, with a portion allocated to maintenance services, ensuring ongoing system reliability. The PAYG model has proven particularly effective in Uganda, where limited disposable income often constrains access to energy services. By embedding maintenance support into the financing model, PAYG addresses the sustainability challenge, providing households with reliable solar energy over the system's lifetime [59].

2. Incentive Structures for Training and Personnel Development: To address the shortage of trained personnel capable of installing and maintaining solar PV systems, several programs offer incentives for technical training and certification. The Ugandan government, in collaboration with international partners like Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), has developed scholarships and grants for solar technician training programs, particularly targeting young people in rural areas [60]. These programs aim to build a robust, decentralized workforce of solar technicians, making it feasible to support PV systems in remote regions where access to trained personnel has historically been limited. Additionally, private sector companies involved in solar PV installations, such as Fenix International, have begun offering performance-based incentives to local technicians who demonstrate high service quality in system maintenance and customer satisfaction. These incentives encourage technicians to actively monitor and maintain systems within their communities, improving overall service quality and ensuring system longevity. By creating a network of incentivized, skilled technicians, these programs contribute to the sustainability of solar PV systems across Uganda [18,16].

3. Subsidies for Spare Parts and Components: Recognizing the importance of spare parts availability in maintaining system reliability, certain NGOs and government programs offer subsidies or vouchers for the purchase of replacement components. For instance, the Ugandan government, through its partnerships with solar product suppliers, provides tax exemptions on replacement parts such as inverters, charge controllers, and batteries. These exemptions reduce the cost burden on users and maintenance providers, facilitating timely repairs and reducing system downtimes. Furthermore, some NGOs partner with local vendors to create "spare parts banks" in rural areas, where commonly needed components are stocked and sold at subsidized rates. These initiatives enhance the accessibility and affordability of maintenance parts, supporting the longevity of solar PV installations in regions where logistical challenges often impede timely repairs [18,16,60].

In summary, funding mechanisms and incentives in Uganda play a pivotal role in supporting solar PV system maintenance. By facilitating access to maintenance financing, incentivizing technician training, and reducing the cost of spare parts, these structures address key barriers to system reliability. Together with supportive policies and NGO initiatives, they contribute to a sustainable framework that strengthens Uganda's rural energy infrastructure, empowering communities to maintain their PV systems and ensuring reliable energy access for years to come.

3.9. Future Prospects for Enhancing PV System Reliability and Maintainability in Lango

As solar PV systems continue to expand across the Lango sub-region, ensuring long-term reliability and maintainability remains a key priority. Addressing challenges related to system resilience, technical expertise, and policy support will be crucial to achieving sustainable energy access in rural communities. This section presents targeted interventions and capacity-building strategies designed to enhance PV system performance, with a focus on improving component quality, environmental resilience, and the availability of technical skills for sustainable maintenance.

3.9.1. Training and Capacity Building for Sustainable Maintenance

Ensuring sustainable maintenance of PV systems in Lango requires developing local expertise among technicians and users, supported by policy adjustments to promote continuous learning and resource access. This subsection outlines capacity-building strategies and policy recommendations to address the maintenance needs of solar PV systems, emphasizing the importance of skilled personnel and accessible maintenance resources for long-term sustainability [61-65].

1. Capacity Building for Local Technicians: A major challenge in rural areas is the lack of trained technicians capable of maintaining and troubleshooting PV systems. Establishing regional training centers or mobile training programs that offer practical, hands-on experience with PV installation and repair can bridge this gap. These training initiatives could be designed in collaboration with technical institutions and funded by government or NGO programs, offering certifications that boost the credibility and employability of local technicians. One recommendation is to incorporate specific modules on PV system diagnostics, component replacement, and preventive maintenance into training curricula. Emphasis on diagnostics and troubleshooting would empower technicians to identify potential issues early, preventing costly downtimes. Moreover, partnerships with technology providers could enable training centers to access the latest diagnostic tools, ensuring that technicians remain current with emerging maintenance technologies. In addition, creating a mentorship program that pairs experienced technicians with trainees in Lango could facilitate knowledge transfer and foster a network of skilled professionals who can support each other. This approach would not only improve maintenance quality but also create local employment opportunities, strengthening the community's capacity for self-sustained PV system maintenance.

3. User Training and Community Engagement: Beyond technical training, engaging PV system users through basic maintenance training is crucial. Educating users on simple tasks, such as cleaning panels, inspecting components, and monitoring system performance, can help prevent issues that arise from neglect or misuse. Community workshops organized by NGOs, local authorities, or system providers could cover these basic maintenance practices, empowering users to take an active role in preserving their systems. User guides in local languages and pictorial instruction manuals can further support user understanding and engagement. Community-based maintenance networks, where trained users or technicians provide services to nearby households, can also enhance system sustainability. These networks could be organized as cooperatives, offering affordable maintenance services, sharing tools, and stocking spare parts. Such community-driven models have shown success in other regions, and they could help address Lango's specific challenges by fostering a culture of shared responsibility for system upkeep.

4. Policy Recommendations for Supporting Sustainable Maintenance: Policy adjustments at both local and national levels could provide additional support for sustainable PV maintenance. First, a subsidy program targeting ongoing maintenance costs, rather than solely system installation, could alleviate the financial burden on users. Such subsidies could be administered through a voucher system, allowing users to access certified maintenance services as needed. Second, establishing a standardized certification framework for solar technicians, recognized by both public and private sectors, would create a skilled labor force dedicated to renewable energy maintenance. This framework could include ongoing education requirements, ensuring that certified technicians remain updated on industry standards and advancements. Additionally, policies promoting the establishment of local spare parts suppliers could reduce downtime by improving access to necessary components, especially in remote areas where logistics are challenging [56,31].

Finally, integrating PV maintenance into broader energy policy frameworks, such as Uganda's Renewable Energy Policy and Rural Electrification Strategy, would ensure that system maintenance is prioritized at a national level. By embedding maintenance support into these frameworks, the government can drive sustained funding and programmatic attention toward ensuring the long-term success of PV systems in Lango and other rural areas.

In conclusion, building technical capacity, empowering users, and implementing supportive policies are essential steps for enhancing the sustainability of solar PV systems in Lango. Through targeted interventions and a collaborative approach to capacity building, the region can foster a resilient energy infrastructure that empowers communities and supports long-term energy access. These recommendations serve as a foundation for achieving reliable and maintainable solar PV solutions, supporting Lango's socio-economic development and contributing to Uganda's renewable energy goals.

3.10 Gaps in Current Literature

Existing literature offers valuable insights into solar PV systems and their performance; however, several critical gaps persist, particularly concerning the Lango region of Uganda. The key gaps identified are as follows:

2.10.1. Gaps In the Current State of Solar PV Systems in Lango

Although there have been initiatives to deploy solar PV systems in Lango, comprehensive data on their maintainability and reliability is limited. Most studies focus on installation and early performance, lacking detailed, long-term assessments of operational challenges and reliability issues in the post-installation phase.

2.10.2. Gaps in Factors Affecting Performance and Sustainability

Although technical, environmental, and socio-economic factors affecting solar PV performance are recognized, the literature often lacks a focused, integrated analysis for Lango. Common issues like dust, shading, and product quality are frequently discussed in general terms, without direct links to system performance in Lango. Additionally, there is limited localized analysis of socio-economic factors, such as education, awareness, and financial mechanisms, which play crucial roles in the region's solar PV adoption and sustainability.

2.10.3. Gaps in Developing a Tailored Maintenance Strategy

Existing literature presents general maintenance strategies for solar PV systems but does not account for the unique challenges of Lango. The absence of a tailored maintenance framework that integrates local conditions, environmental factors, and available resources underscores the need for a region-specific strategy.

2.10.4. Gaps in Implementing Maintenance Strategies

Literature often lacks detailed, actionable guidelines for implementing maintenance strategies in regions like Lango. There is a need for comprehensive guidelines that address technical, financial, and community engagement aspects, as well as capacity building and policy support specific to the region.

2.10.5. Summary of the Literature Review

The existing literature provides useful insights into solar PV systems but lacks the depth needed to address maintainability and reliability issues in Lango. The identified gaps highlight the need for research focused on developing and implementing tailored maintenance strategies for the region. This study aims to bridge these gaps, offering practical solutions to enhance the reliability and sustainability of solar PV systems in off-grid areas like Lango and the related research summarized as in Table 2.

Table 2: Summary of the related review

Author(s)	Research Focus	Literature Gap
Tillmans & Schweizer-Ries (2011) [62]	Knowledge gaps in installation and maintenance practices of solar PV systems among technicians and users.	Limited detailed analysis of the region-specific training and education requirements needed for sustainable solar PV operations in Lango, Uganda.
Osmani, et al., (2020) [4]	Comparison of corrective, urgent, predictive, and preventive maintenance strategies for solar PV systems.	Absence of localized and adaptive maintenance strategies tailored to the specific environmental and socio-economic conditions of regions like Lango, Uganda.
Mustafa, et al., (2020) [25]	Effects of environmental factors (dust, shading, bird droppings) on solar PV system efficiency.	Insufficient research on the long-term impacts of environmental conditions specific to Uganda’s regions like Lango, including strategies to mitigate these challenges.
Wassie & Adaramola (2021) [26]	The impact of poor quality and counterfeit solar products on the performance and reliability of solar PV systems.	Lack of focus on localized solutions for regions like Lango, Uganda, where counterfeit products severely undermine solar system sustainability.
Aboagye, et al., (2022) [30]	Influence of preventive maintenance strategies on solar PV system degradation rates and efficiency.	Lack of region-specific data and tailored maintenance strategies for off-grid areas like Lango, focusing on degradation due to environmental and operational challenges.
Alinaitwe, G. (2023) [44]	Challenges in solar PV system maintenance, including lack of after-sales services and socio-economic drivers.	Absence of specific case studies for remote areas like Lango where economic drivers such as income levels and education directly affect solar PV adoption and sustainability.
Pimpalkar, et al., (2023) [63]	Failure modes and effects analysis (FMEA) for solar PV systems in arid and urban environments.	Limited focus on field-based analyses for rural and off-grid systems, particularly in understanding failure modes specific to Lango’s geographical and climatic conditions.

4. Findings

I. Environmental Impacts on PV Reliability: Uganda’s climate, characterized by high temperatures, variable humidity, and dust, imposes significant stress on PV system components, leading to rapid degradation if not properly managed. High temperatures reduce the efficiency of PV panels, while humidity and dust increase the likelihood of corrosion and soiling, resulting in lower energy generation.

II. Component Quality and Maintenance Practices: Limited access to high-quality PV components in rural areas like Lango affects overall system reliability and longevity. Low-cost systems with substandard components often fail prematurely.

Furthermore, limited maintenance resources and technical expertise lead to prolonged downtimes, reducing system effectiveness. Preventive and predictive maintenance strategies, such as regular inspections and monitoring using sensors, have been shown to improve system performance significantly by preventing or quickly addressing component failures.

III. Community and Technical Capacity Challenges: Training for local technicians and community members is essential for effective maintenance, yet such training is often scarce. In regions like Lango, where technical support is limited, reliance on external contractors for maintenance reduces system sustainability. Initiatives focused on training local users in basic maintenance and troubleshooting skills can mitigate this issue.

IV. Policy and Institutional Support: Uganda's energy policies, while supportive of PV adoption, require enhancement to address long-term maintenance and reliability challenges. Current subsidies and tax exemptions primarily target system installation rather than ongoing maintenance, leaving a gap in support for system upkeep. Partnerships with NGOs and private-sector companies have proven effective in promoting community-based maintenance training, but these efforts need scaling to reach wider regions.

V. Technological Innovations for Enhanced Maintainability and Reliability: Technological advancements, including MPPT-equipped charge controllers and ruggedized inverters, improve PV system reliability by adapting to harsh environmental conditions. In particular, monitoring and diagnostic tools that leverage predictive maintenance algorithms enable early fault detection, thereby extending system lifespans and optimizing energy output.

5. Conclusions

Enhancing the maintainability and reliability of solar PV systems in rural Uganda requires a comprehensive approach that combines technical, policy, and community-driven strategies. By addressing environmental challenges through appropriate maintenance protocols and ensuring access to certified components, PV systems can achieve greater operational longevity and efficiency. Policy recommendations include expanding maintenance-focused subsidies, establishing standardized certification for solar technicians, and supporting local supply chains for replacement parts. These measures, alongside community education on basic maintenance practices, will strengthen Uganda's capacity to maintain sustainable, reliable energy infrastructure in rural regions. Emphasizing policy and institutional support, Uganda can foster a resilient PV energy landscape that not only enhances rural electrification but also contributes to broader renewable energy goals.

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