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Reliability Assessment and Failure Analysis of Solar Photovoltaic Systems in the Northern Region of Adamawa State, Nigeria

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ABSTRACT

The deployment of solar photovoltaic (PV) systems in Northern Nigeria is crucial for addressing energy poverty. However, long-term success is often hindered by high failure rates. This study provides a detailed assessment of failures and reliability for solar PV systems installed in the Adamawa Northern Region from 2009 to 2022. Data were collected from 38 solar PV systems, comprising 12 Solar Street Lights (SSLs), 19 Solar Clinic Systems (SCSs), and 7 Solar Home Systems (SHSs), using field inspections, structured interviews, and component reliability analysis. The findings reveal a troubling infant mortality rate, with 52.63% of failures occurring within the first year of operation. The overall system failure rate (λ) was 0.2278 per month, with a Mean Time Between Failures (MTBF) of 3.16 months and an overall system reliability of 76% during the observation period. Major causes of failure included poor installation practices, the use of non-deep-cycle batteries, inadequate system design, and a lack of proper post-installation maintenance. Our reliability models indicate that parallel system configurations can improve system reliability from 76.0% to 94.24%, representing approximately 24% improvement over conventional series configurations. The study concludes by highlighting the importance of establishing improved technical standards, rigorous quality control during procurement and installation, and organized maintenance protocols to extend the lifespan and boost the reliability of solar PV systems in the region.

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INTRODUCTION

Access to reliable and affordable electricity remains a pressing challenge in Northern Nigeria, where grid power is often unreliable and, in many rural and peri-urban communities, completely unavailable. This persistent energy gap continues to slow socio-economic development, restrict access to quality healthcare and education, and weaken the delivery of essential public services (Shaaban and Petinrin, 2014). In this context, solar photovoltaic (PV) technology has become an increasingly attractive solution for decentralized electricity generation, largely due to Nigeria's abundant solar resources, favorable climatic conditions and the steadily declining cost of PV components (Adelaja *et al*., 2021).

Consequently, solar PV systems are now widely deployed across the region to power solar street lights (SSLs), solar home systems (SHSs), and critical healthcare infrastructure such as solar clinic systems (SCSs). In the Northern Region of Adamawa State, as in much of North-Eastern Nigeria, numerous solar PV projects have been implemented since the late 2000s through government programs, international donor support, and non-governmental organizations (Stephen *et al*., 2012). These initiatives were primarily aimed at improving public safety through street lighting, expanding household electrification, and ensuring reliable electricity supply to healthcare facilities (Olayinka and Olaolu, 2019). Despite the technical promise of solar PV systems and the substantial financial investments involved, the operational performance of many installations has consistently fallen short of expectations. Although numerous studies have investigated photovoltaic performance and solar resource availability in Nigeria, very few have quantified component failure rates and long-term reliability under actual field conditions in Northern Adamawa State. Consequently, information on failure mechanisms and reliability indices remains limited, creating uncertainty for future solar electrification projects. This study aims to analyze the failure modes, failure rates, and reliability of solar photovoltaic (PV) systems installed in Northern Adamawa State between 2009 and 2022, and to predict their future performance using reliability assessment techniques. Furthermore, it seeks to recommend practical strategies for improving the reliability, operational efficiency, and long-term sustainability of solar PV projects in the region.

MATERIALS AND METHODS

The Study Area

The study was conducted in the Adamawa Northern Region, comprising five Local Government Areas: Mubi North, Mubi South, Maiha, Michika, and Madagali. The region lies within the northern Guinea Savannah zone, between latitudes 9°30' and 11° N and longitudes 13° and 13°45' E (Adebayo, 2004). It experiences a distinct dry (November-March) and wet (April-October) season, with a mean annual rainfall of 700mm to 1,050mm (Tekwa and Usman, 2006). The area is predominantly agrarian, and the choice of this region is significant due to its relatively high number of solar PV installations and its vulnerability to grid instability

Data Collection and System Classification

A field survey was conducted to identify and map existing solar PV installations. Data were collected through physical inspections and structured interviews with system owners and operators. The systems were classified into three categories:

i. Solar Street Lights (SSL): Used for public lighting.
ii. Solar Home Systems (SHS): Used for residential power.
iii. Solar Clinic Systems (SCS): Used primarily for lighting and vaccine refrigeration in healthcare facilities. The data collected included the installation year, component specifications (PV panels, batteries, inverters, and charge controllers), failure history, and maintenance records from 2009 to 2022

Failure and Reliability Analysis

The following key reliability metrics were calculated based on the field data:

i. Failure Rate (λ): The number of failures per unit time, calculated using the standard formula for a constant failure rate as reported by (Kuitche *et al.*, 2011). $\lambda = \frac{n}{\sum_{=i}^{n} ti}$ (1)
where *n* is the number of failures and t_i is the time to the i-th failure.
ii. Mean Time between Failures (MTBF): The average time elapsed between failure occurrences for repairable systems reported by Meyer and van (2004). $MTBF = \frac{1}{\lambda}$ (2)
iii. Reliability R (t): The probability that a system will perform its intended function for a specified time period (IEC, 2016). For a constant failure rate, the distribution is given by the exponential distribution, as defined by this equation (IEA, 2002).
$R(t) = e^{-\lambda t}$ (3)
iv. System Configuration Analysis: The reliability of series and parallel system configurations was analyzed. For a series system, the overall reliability is the product of the individual component reliabilities. For a parallel (redundant) system, the reliability is given by (Batzelis *et al.*, 2007).
$R_{parallel} = 1 - \prod_{i=1}^{n}(1 - Ri)$ (4)

RESULTS AND DISCUSSION

System Inventory and Component Overview

A total of 38 systems were surveyed. The inventory and component capacities are summarized in Table 1. Solar Clinic Systems (SCS) were the most numerous, underscoring the critical need for reliable power in healthcare facilities for lighting and refrigeration.

Table 1: PV System Components and Capacity Summary

PV System Classification	No. of Systems	PV Panel (W)	Battery (AH)	Inverter (kVA)
Solar Street Light (SSL)	12	3,850	3,700	N/A
Solar Clinic System (SCS)	19	7,540	4,080	10.5
Solar Home System (SHS)	7	2,420	3,000	9.0
Total	38	13,810	10,780	19.5

Failure Mode and Temporal Analysis

The distribution of failures over time is presented in Figure 1. A striking 52.63% (20 out of 38) of all failures occurred within the first year of operation. This pattern aligns with the "infant mortality" region of the classic bathtub curve for equipment failure, as illustrated in Figure 1. The high initial failure rate is attributed to:

i. Poor Installation and Workmanship: Corroded connections due to exposure to rain led to voltage drops and chronic undercharging of batteries.
ii. Component Quality: The use of shallow-cycle batteries instead of deep-cycle batteries, which are unsuitable for the daily charge-discharge cycles of PV systems.
iii. Design Flaws: Improper system sizing and a lack of consideration for the Depth of Discharge (DOD), often exceeding the recommended 60% for lead-acid batteries.
iv. Governance Issues: A lack of stringent supervision during project execution and a focus on project commissioning over long-term sustainability.

After the first year, the failure rate decreased and stabilized, indicating the onset of the "useful life" period, where failures are random and less frequent. Figure 1 illustrates the Failure Characteristics (Bathtub Curve) of the surveyed PV systems, which is shown in a graph as a high initial peak (infant mortality) that quickly declines and stabilizes into a constant failure rate (useful life).

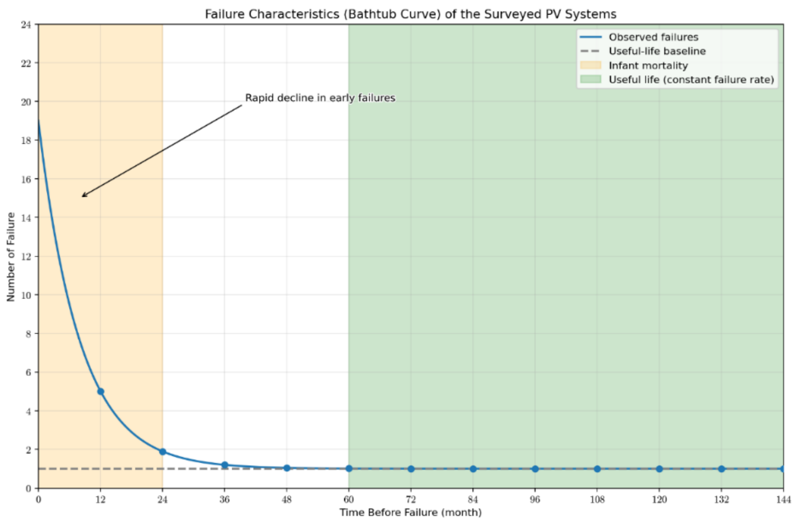

Figure 1: Failure characteristics of the PV systems

Quantitative Reliability Metrics

From the aggregated failure data, the following metrics were calculated:

i. Failure Rate (λ): = 2.278×10^{-1} per month.
ii. Mean Time between Failures (MTBF) =3.16 months.
iii. System Reliability: The probability of survival over the observed period was R(t)=0.76 (76%).

The low MTBF value reflects the prevalence of early-life failures. While the overall reliability of 76% might seem reasonable, it masks the fact that many systems (particularly SSLs) failed and were never repaired.

Component-Level Failure Analysis

Component-specific failure data revealed critical insights:

i. Batteries were the most failure-prone component. Batteries with 100AH capacity recorded the highest number of failures (10), as shown in Table 2, often due to premature degradation from poor charging practices and excessive DOD.
ii. PV Panels**:** Panels with lower capacities (80W and 90W) showed a higher incidence of failure (11 and 10, respectively), as seen in Table 3, potentially linked to their use in lower-budget, less robustly engineered systems.

Table 2: Battery Failures by Capacity

Battery Capacity (AH)	200	120	100
No. of Failures	4	2	10

Table 3: PV Panel Failures by Capacity

Panel Capacity (W)	360	200	120	100	90	80	60
No. of Failures	1	2	6	5	10	11	3

Reliability Prediction and Improvement through Redundancy

Using the exponential model, system reliability was projected over a 35-year lifetime as shown in Figure 2. The results indicate a steady decline, underscoring the need for component replacement and regular maintenance.

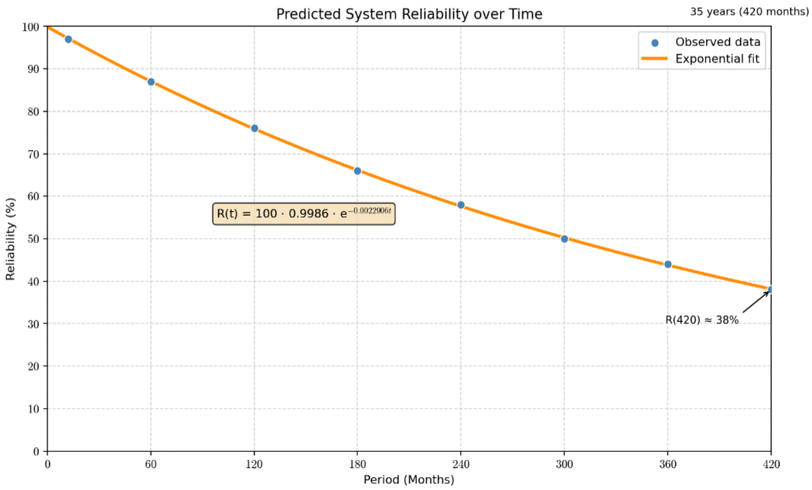

Figure 2: Predicted System Reliability over Time

A key finding of this study is that the architecture of a photovoltaic (PV) system has a significant influence on its overall reliability. In a series configuration, where the reliability of each critical component is R=0.76, the failure of any single component, such as the battery, charge controller, or inverter, results in the failure of the entire system. This explains why many of the surveyed PV installations experienced frequent system outages despite having only one failed component. From a scientific standpoint, series systems have no fault tolerance because all components are interdependent, making the weakest component the limiting factor for overall system performance. In contrast, introducing redundancy through a parallel configuration substantially enhances system reliability. For example, using two batteries in parallel increases the system reliability to $R_{parallel}$=0.9424, compared with 76% for a single battery. This improvement occurs because the system can continue operating even if one battery fails, with the remaining battery maintaining power delivery until maintenance or replacement is carried out. From a reliability engineering perspective, redundancy reduces the probability of complete system failure by providing alternative operational paths, thereby improving fault tolerance, availability, and service continuity. These findings demonstrate that incorporating redundant critical components into PV system design is an effective strategy for increasing the long-term reliability and sustainability of solar energy systems, particularly in remote areas of Northern Adamawa State, where maintenance and replacement of failed components may be delayed.

CONCLUSION

This study demonstrated that solar photovoltaic (PV) systems installed in the Northern Region of Adamawa State experience a high infant mortality rate, with 52.63% (20 out of 38) of the surveyed systems failing within the first year of operation. These early failures were primarily attributed to poor installation practices, the use of substandard or improperly selected components, inadequate system design, and the absence of routine preventive maintenance, rather than the natural ageing of system components. Quantitative reliability analysis further revealed an overall failure rate of 0.2278 month^{-1}, a Mean Time Between Failures (MTBF) of 3.16 months, and an overall system reliability of 76% during the study period, indicating that the existing PV systems are considerably less reliable than expected for long-term operation.

Reliability modeling further showed that incorporating redundancy into critical system components could increase system reliability from 76.0% to 94.24%, representing an approximately 24% improvement over the conventional series configuration. These findings underscore the need for improved engineering design, strict adherence to installation standards, procurement of high-quality PV components, and implementation of structured maintenance programs. Adopting these measures will significantly reduce premature failures, improve system availability, extend service life, and enhance the long-term sustainability of solar PV projects in Northern Adamawa State and other regions with similar environmental and operational conditions.

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