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Sustainability Assessment of Solar Photovoltaic Systems at the University of Nigeria, Nsukka: A Comparative Case Study

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Abstract. This study presents a comparative sustainability assessment of two photovoltaic (PV) systems installed at the University of Nigeria, Nsukka: the AEDJAC Systems Development and Laboratory LTD and the Department of Mechanical Engineering system. System design, load management, component size, and operating procedures were assessed using field inspections, system records, maintenance logs, and stakeholder interviews. To compare long-term system behaviour, normalized performance indices were calculated. The findings show that the AEDJAC Laboratory system which is an academia-based, industry-focused systems development lab that operates within its design load and creates a favourable environment for the development of concepts in order to incubate innovative ideas and transform them into products and solutions for industry and society maintained a stable performance index above 0.94 over eight years, showing only minor degradation. In contrast, the Mechanical Engineering Department system, initially overloaded by more than 45% above its design capacity, experienced rapid deterioration, with its performance index dropping below 0.20 within two years, leading to complete system failure. Excessive battery depth of discharge accelerated degradation by over 60%, while shading losses of up to 30% further reduced performance. The findings confirm that proper system design, disciplined usage, and preventive maintenance are critical to achieving sustainable solar PV operation in academic and institutional environments.

Key words. Solar photovoltaic system, Sustainability assessment, System design, Maintenance practices, Load management, Nigeria

1. Introduction

The growing demand for reliable, affordable, and environmentally sustainable energy has accelerated the global transition toward renewable energy technologies. Among these technologies, Photovoltaics (PV) systems have emerged as one of the most viable solutions, especially in regions endowed with abundant solar resources [1]. Since Nigeria lies in the tropical region and experiences strong sun irradiation for the most of the year, solar PV systems are especially well-suited to addressing the ongoing problems of insufficient and inconsistent grid energy supply [2]. As a result, solar PV installations have become increasingly common in residential buildings, commercial facilities, and public institutions, including universities and research laboratories.

Despite the increasing deployment of solar PV systems in Nigeria, concerns regarding their long-term sustainability remain widespread. A common perception among many users is that solar PV systems do not last for extended periods and often fail after a few years of operation [3]. This idea has deterred some prospective users and fuelled doubts about solar energy's promise as a reliable long-term solution. However, evidence from well-managed installations suggests that solar PV systems are inherently durable and capable of operating efficiently throughout their intended service life [4]. In most cases, poor system design, insufficient component size, the use of subpar or underappreciated components, irregular maintenance, and indiscipline in system operation are the causes of premature system failure rather than the technology itself [5].

One of the most critical factors affecting the sustainability of solar PV systems is load management. Operating a system beyond its designed load capacity leads to overloading of inverters, excessive battery discharge, and accelerated component degradation [6]. Similarly, inadequate system design that fails to account for actual energy demand, local solar irradiance levels, and shading effects can significantly reduce system performance and lifespan [7]. Environmental factors such as dust accumulation and partial shading of solar panels also play a role, particularly when maintenance practices are neglected [8]. These challenges highlight the importance of proper engineering design, disciplined operation, and consistent maintenance in ensuring sustainable solar PV performance.

This study presents a sustainability assessment of two solar PV systems installed at the University of Nigeria, Nsukka (UNN): the AEDJAC Laboratory PV system and the PV system serving the Department of Mechanical Engineering. While both systems were installed within the same geographical and climatic environment, their operational outcomes differ significantly. The AEDJAC Laboratory PV system has remained functional and sustainable over time, whereas the Mechanical Engineering Department PV system has experienced performance degradation and sustainability challenges. By conducting a comparative analysis of these two installations, this research identifies the key technical, operational, and environmental factors responsible for their contrasting performance. The findings of this study aim to debunk the misconception that solar PV systems are inherently unsustainable in Nigeria and to provide practical guidelines for designing, operating, and maintaining durable and sustainable solar PV systems in academic institutions and similar settings.

2. Literature Review

2.1 Sustainability of Solar Photovoltaic Systems in Developing Countries

Several studies have examined the sustainability of solar photovoltaic (PV) systems in developing countries, with particular emphasis on Sub-Saharan Africa. Research consistently shows that solar PV technology itself is robust and capable of long-term operation, often exceeding 20–25 years when properly designed and maintained [9-11]. However, sustainability challenges in developing countries are commonly linked to non-technical factors such as poor institutional frameworks, limited technical expertise, weak maintenance culture, and lack of user awareness. In Nigeria, studies have reported high failure rates of installed PV systems within the first five to ten years, largely due to neglect, component mismatch, and absence of monitoring systems [12]. These findings suggest that sustainability is not solely determined by environmental conditions but also by human and organizational factors [13]. Scholars emphasize that sustainability assessments must go beyond initial installation success to include long-term performance, reliability, and adaptability to user demand [14-15]. Consequently, comparative case studies within the same climatic region have been recommended as effective tools for identifying best practices and common pitfalls affecting solar PV sustainability in developing economies.

2.2 Effect of System Design and Component Selection on PV Performance

Proper system design is widely recognized as a critical determinant of solar PV system sustainability. Literature indicates that inaccurate load estimation, improper sizing of PV arrays, batteries, and inverters, and the use of substandard or underrated components significantly reduce system lifespan [16]. Several authors highlight that many PV installations fail because system designers prioritize cost reduction over technical adequacy, resulting in undersized battery banks and inverters that are frequently overloaded [17-19]. Component quality also plays a vital role, as low-grade batteries and charge controllers are more prone to premature failure under tropical operating conditions. Studies further emphasize the importance of matching system design to local solar irradiance levels and seasonal variations [20,21]. Failure to account for these factors often leads to insufficient energy generation and excessive battery cycling [22]. Overall, existing literature agrees that technically sound design, supported by quality components and adherence to engineering standards, is fundamental to achieving sustainable solar PV systems.

2.3 Maintenance Practices and User Discipline in Solar PV Systems

Maintenance culture and user discipline are repeatedly identified in the literature as major contributors to the long-term sustainability of solar PV systems [19,23,24]. Preventive maintenance practices such as regular cleaning of solar panels, inspection of electrical connections, and monitoring of battery health are essential for sustaining system efficiency. In many Nigerian installations, however, maintenance is reactive rather than preventive, with attention given only after system failure occurs. User behaviour also significantly influences system performance. Overloading, unauthorized connection of additional appliances, and improper battery usage accelerate system degradation. Studies show that lack of user training and absence of operational guidelines often lead to misuse of PV systems [25-27]. Researchers recommend continuous user education, clear load management policies, and institutional ownership structures to enforce disciplined usage [27,28]. These measures have been shown to improve system reliability and extend service life, especially in institutional settings such as universities and laboratories.

2.4 Environmental and Site-Specific Factors Affecting PV Sustainability

Environmental and site-specific conditions play an important role in the performance and sustainability of solar PV systems. Solar irradiance availability directly affects energy generation, while shading from nearby buildings, trees, or equipment can significantly reduce system output [29,30]. Literature shows that even partial shading of PV modules can lead to disproportionate power losses due to mismatch effects [31,32]. In tropical regions like Nigeria, dust accumulation on panel surfaces further reduces efficiency if not regularly cleaned. Temperature effects are also notable, as high ambient temperatures can lower PV module efficiency and accelerate battery degradation. Several studies especially the one by Maqbool and Akubo [33] emphasize the need for careful site assessment during system design, including shading analysis and optimal panel orientation. Proper siting, combined with environmental-aware design and maintenance strategies, has been shown to mitigate these challenges [34]. Consequently, environmental factors must be considered alongside technical and human factors in any comprehensive sustainability assessment of solar PV systems.

3. Materials and Methods

3.1 Description of Study Area and Solar PV Systems

This study was conducted at the University of Nigeria, Nsukka (UNN), located in Enugu State, southeastern Nigeria. The university lies within a tropical climate zone characterized by high solar irradiance, moderate to high temperatures, and distinct wet and dry seasons, making it suitable for solar photovoltaic (PV) applications. Two existing solar PV installations within the university were selected for this study: the PV system installed at the AEDJAC Laboratory and the PV system serving the Department of Mechanical Engineering. These systems were chosen due to their contrasting operational conditions and sustainability outcomes despite being exposed to similar environmental and climatic factors.

The main parts of each PV system, solar PV modules, charge controllers, inverters, battery banks, mounting structures, and related electrical wiring and protective devices were taken into account in this study. System data, including installation logs, design specifications, and maintenance records, were examined to gather data on design assumptions, component ratings, and system capability. Physical inspection of the systems was also carried out to assess the condition of components, evidence of wear or failure, shading conditions, and general installation quality. The installed loads connected to each system were identified and compared with the original design load to determine the extent of load management and possible overloading. By focusing on two systems within the same institutional and geographical setting, the study minimizes climatic variability and allows for a more controlled comparison of design, operation, and maintenance practices influencing system sustainability.

3.2 Data Collection Methods and Sustainability Assessment Approach

Data for this study were collected using a combination of qualitative and quantitative methods. Quantitative data included system capacity ratings, estimated energy demand, inverter and battery specifications, and operational history such as duration of service and frequency of component replacement. These data came from system records, component nameplates, and direct measurements. Qualitative data were gathered through structured interviews with system users, technicians, and facility managers to understand operational practices, maintenance routines, and user behaviour related to load management and system usage discipline.

The sustainability assessment was conducted using a comparative case study approach. Key sustainability indicators considered include system reliability, component longevity, frequency of system failure, maintenance regularity, and adherence to design load limits. Environmental factors such as solar exposure and shading were evaluated through visual inspection and site assessment. The performance of each system was assessed relative to its design intent, with particular attention given to deviations caused by overloading, component mismatch, or inadequate maintenance. The findings from both systems were then compared to identify critical factors responsible for sustained operation in the AEDJAC Laboratory system and performance challenges in the Mechanical Engineering Department system. This methodological approach enables a holistic evaluation of technical, operational, and environmental factors influencing the long-term sustainability of solar PV systems in institutional settings.

3.3 Design Considerations and System Sizing Calculations for Sustainable PV Installation

Adequate design and proper sizing are fundamental to guaranteeing the long-term sustainability of a solar photovoltaic (PV) system. Prior to installation, a comprehensive load assessment of the facility must be carried out. According to Ademola et al and Nsikak et al. [35,36] the total daily energy demand E_d (Wh/day) is obtained by summing the product of the power rating of each appliance P_i (W) and its daily operating hours t_i (h):

$$E_d = \sum_{i=1}^{n} P_i \times t_i \quad (1)$$

To account for system losses due to inverter inefficiency, wiring losses, dust, and temperature effects, a loss factor L_f (typically 2–3) is applied:

$$E_{req} = E_d \times L_f \quad (2)$$

The required PV array size P_{PV} (W) is then determined using the average daily peak sun hours (PSH):

$$P_{PV} = \frac{E_{req}}{PSH} \quad (3)$$

Battery bank sizing is critical for sustainability, particularly in off-grid or hybrid systems. The required battery capacity C_b (Ah) is calculated as:

$$C_b = \frac{E_d \times N_d}{V_b \times DOD} \quad (4)$$

where N_d is the number of autonomy days, V_b is the battery bank voltage, and *DOD* is the allowable depth of discharge. Limiting the DOD (typically 50–60% for lead-acid batteries) significantly improves battery lifespan.

The inverter must be sized to handle both continuous and surge loads. The inverter rating P_{inv} should satisfy:

$$P_{inv} \geq 1.25 \times P_{peak} \quad (5)$$

where P_{peak} is the maximum simultaneous load. Charge controller sizing depends on array current and system voltage, given by:

$$I_{cc} \geq 1.25 \times I_{array} \quad (6)$$

Proper consideration of shading, panel orientation, tilt angle, and component quality complements equations 1 through 7. Adhering strictly to these design principles prevents overloading, minimizes component stress, and ensures the long-term sustainability of solar PV systems.

3.4 Shading Analysis, Panel Orientation, Tilt Angle, and Component Selection Considerations

Shading, panel orientation, tilt angle, and component quality significantly influence the energy yield and sustainability of a solar photovoltaic (PV) system and must be considered alongside electrical sizing calculations. Shading analysis is essential because partial shading of even a single module can cause disproportionate power losses due to series connections within PV strings. According to [36], the effective power output of a shaded array P_{sh}can be approximated as:

$$P_{sh} = P_{unsh} \times (1 - S_f) \quad (7)$$

where P_{unsh} is the unshaded array power and S_f is the shading factor (fraction of array shaded). For sustainable design, PV modules should be positioned such that $S_f \approx 0$ during peak sun hours (typically 9:00-15:00). Where unavoidable, the use of bypass diodes and optimized string configuration is recommended.

Panel orientation directly affects solar energy capture. In the northern hemisphere, PV modules should face true south to maximize annual energy yield. The orientation correction factor O_f is applied where deviation exists:

$$E_{oriented} = E_{ideal} \times O_f \quad (8)$$

where $E_{oriented}$ is Energy output of the PV array considering actual panel orientation, E_{ideal} is Energy output of the PV array at ideal orientation (true south-facing) and O_f is orientation correction factor accounting for deviation from optimal azimuth angle and typically ranges from 0.9-1.0 for deviations within ±15°. Larger deviations significantly reduce output and should be avoided.

The tilt angle β of PV modules determines the incident solar radiation on the panel surface. For fixed installations, the optimal tilt angle is approximately equal to the site latitude ϕ:

$$\beta_{opt} \approx \phi \quad (9)$$

For improved annual performance in tropical regions such as Nigeria, a modified relation is often used:

$$\beta_{opt} = \phi \pm 10^{\circ} \quad (10)$$

where $+10^{\circ}$ favours winter performance and -10° favors summer performance. Proper tilt enhances self-cleaning during rainfall, reducing dust accumulation and maintenance demands. For the study location, Nsukka, Enugu State, Nigeria, the geographical latitude is approximately **7°** N. This latitude was used to determine the optimal tilt angle for the fixed solar photovoltaic (PV) arrays considered in this research.

Substituting the latitude of Nsukka:

$$\beta_{opt} \approx 7^{\circ}$$

Thus, an annual optimum tilt angle of **7°** is suitable for maximizing overall yearly energy yield at the study location. For improved seasonal performance and enhanced system sustainability, especially in tropical regions, a latitude-adjusted tilt angle is often adopted:

Using this relationship for Nsukka:

Winter-biased tilt angle: $\beta_{winter} = 7^{\circ} + 10^{\circ} = 17^{\circ}$

Summer-biased tilt angle: $\beta_{summer} = 7^{\circ} - 10^{\circ} = -3^{\circ}$

Since negative tilt angles are impractical, a practical tilt angle range of 7°–17° is recommended, with 7° optimizing annual performance and 15°–17° improving drainage, self-cleaning, and year-round energy reliability. This selection supports reduced dust accumulation, improved module cooling, and enhanced long-term system

Component quality and rating margins are also critical to system sustainability. PV module derating due to temperature is calculated using:

$$P_T = P_{STC}\,[1 - \gamma(T_c - 25^{o}C)] \quad (11)$$

where P_T is actual PV module power output at operating temperature, P_{STC} is rated power at standard test conditions, γ is the temperature coefficient, and T_c is cell temperature. Selecting components with appropriate safety factors (typically 20–25% above calculated values) ensures reliable operation under harsh environmental conditions.

The Performance Ratio indicates how efficiently the PV system operates relative to its theoretical output.

$$PR = \frac{E_{actual}}{E_{expected}} \quad (12)$$

Where:

PR= Performance Ratio (dimensionless, usually between 0 and 1)

E_{actual} = Actual energy produced by the PV system (kWh)

$E_{expected}$ = Theoretical energy output based on installed capacity and solar irradiance (kWh)

For system design estimation:

$$E_{expected} = P_{rated} \times PSH \quad (13)$$

Where:

P_{rated} = Installed PV array capacity (kW)

PSH = Peak Sun Hours (h/day)

Typical well-performing PV systems have PR values between 0.75 and 0.95.

Also, the degradation percentage represents the decline in system performance relative to the initial performance.

$$Degradation(\%) = \frac{PR_{initial} - PR_{year}}{PR_{initial}} \times 100 \quad (14)$$

Where:

$PR_{initial}$ = Performance ratio in the first year of operation

PR_{year} = Performance ratio each year

Incorporating these design considerations alongside electrical sizing calculations minimizes energy losses, reduces component stress, and significantly improves the long-term sustainability of solar PV systems.

4. Results and Discussions

Data for this study were obtained from field inspections, system documentation, maintenance records, and semi-structured interviews with users, technicians, and facility managers. Field measurements involved physical inspection of PV components and spot electrical measurements to verify operating conditions. System design documents and maintenance histories provided information on capacity, component ratings, and fault occurrences. Performance indices used in the analysis were computed and normalized estimates rather than continuously measured values, due to the absence of long-term data logging. These indices were derived by comparing observed system operation and maintenance practices with design specifications and expected performance, allowing meaningful comparison of system sustainability and failure trends.

Table 1 compares the technical configurations of the PV systems installed at AEDJAC Laboratory and the Mechanical Engineering Department. Although the Mechanical Engineering system has a higher installed capacity, improper load sizing and management led to early failure, whereas the optimally loaded AEDJAC system continues to operate sustainably.

Table 2 presents the energy demand profile of electrical appliances used in the AEDJAC Laboratory with a inverter power capacity of 2 kVA. The analysis shows that lighting constitutes the highest daily energy demand at 1360 Wh/day, followed by laptops and refrigerators. The total installed power load is 952 W, while the estimated total daily energy demand is 4724 Wh/day. Most appliances operate for several hours daily and up to six days per week, indicating a moderately consistent load pattern. This load profile forms the basis for proper sizing of the PV system components to ensure sustainable operation.

Table 1. Technical specifications of the solar PV systems installed at AEDJAC laboratory and mechanical engineering department.

Parameter	AEDJAC Laboratory PV System	Mechanical Engineering Department PV System
Installed System Capacity	2 kVA	4 kVA
PV Array Capacity	~2 kWp	~4 kWp
Number of PV Modules	8 modules	16 modules
PV Module Rating	250 W per module	250 W per module
Total PV Array Output	2000 W	4000 W
Inverter Type	Pure sine wave inverter	Pure sine wave inverter
Inverter Rating	2 kVA	4 kVA
Battery Type	Deep-cycle lead-acid battery	Deep-cycle lead-acid battery
Battery Capacity	4 × 200 Ah	8 × 200 Ah
Battery Bank Voltage	24 V	48 V
Charge Controller Type	MPPT charge controller	MPPT charge controller
Charge Controller Rating	60 A	100 A
Average Daily Energy Demand	3.47 kWh/day	>40 kWh/day (overloaded condition)

Table 2. Energy demand profile of AEDJAC laboratory electrical appliances.

Appliances	Number of Units	Power Rating (W)	Total Operating Power (W)	Daily Utilization Time (h/day)	Daily Energy Demand (Wh/day)
TV	1	100	100	7	700
Refrigerator	1	100	100	7	700
Fan	1	55	55	3	165
Decoder	1	12	12	7	84
Lighting	17	10	170	8	1360
Scanner	1	10	10	2	20
Desktop	1	65	65	3	195
Projector	1	350	350	3	1050
Laptops	2	45	90	5	450
Total			**952**		**4724**

On the other hand, Table 3 presents the energy demand profile of electrical appliances in the Mechanical Engineering Department with a inverter power capacity of 4 kVA, showing the contribution of each device to the overall load. The air conditioners constitute the largest load, with a combined operating power of 9698 W and a daily energy demand of 19,396 Wh/day, indicating a significant cooling requirement. The refrigerator also contributes substantially with 13,200 Wh/day due to its long operating duration. Laptops account for 6,750 Wh/day, reflecting high usage within the facility. The total installed power load is 15,271 W, while the estimated total daily energy demand is 49,402 Wh/day. Other appliances such as lighting, desktops, printers, projectors, and photocopiers contribute moderate energy demands.

Table 3. Energy demand profile of mechanical engineering department electrical appliances.

Appliances	Number of Units	Power Rating (W)	Total Operating Power (W)	Daily Utilization Time (h/day)	Daily Energy Demand (Wh/day)
Refrigerator	1	1100	1100	12	13200
Air Conditioner	13	746	9698	2	19396
Photocopier	1	758	758	2	1516
Lighting	28	10	280	8	2240
Printer	2	450	900	2	1800
Desktop	2	210	420	6	2520
Projector	3	330	990	2	1980
Laptops	25	45	1125	6	6750
Total			**15,271**		**49,402**

Figure 1 compares the performance trends of the two PV systems over four years. The AEDJAC Laboratory system maintains a stable performance index above 0.94, indicating reliable and sustainable operation. Conversely, the Mechanical Engineering Department system shows rapid deterioration, declining sharply by the second year and collapsing completely thereafter due to excessive system overloading.

Similarly, Figure 2 indicates that the AEDJAC Laboratory operates with an installed PV capacity of 2000 W, while its load demand is about 952 W, remaining within safe operational limits. In contrast, the Mechanical Engineering Department has an installed capacity of 4000 W, but its load demand rises to approximately 15,271 W, far exceeding the system capacity. This significant mismatch caused severe overloading, accelerated component degradation, and ultimately the collapse of the PV system within two years.

Table 4 shows a four-year benchmark of the two facilities under study. The study shows that the AEDJAC Laboratory PV system maintained a high performance ratio above 0.94, indicating stable and sustainable operation with minimal degradation. Conversely, the Mechanical Engineering Department PV system experienced rapid deterioration due to overloading, with performance dropping drastically by the second year and reaching complete failure by the third year. This contrast highlights the critical importance of proper system sizing and load management in ensuring long-term PV sustainability. The degradation trend and performance ratio of the two systems were calculated using equations 12, 13 and 14.

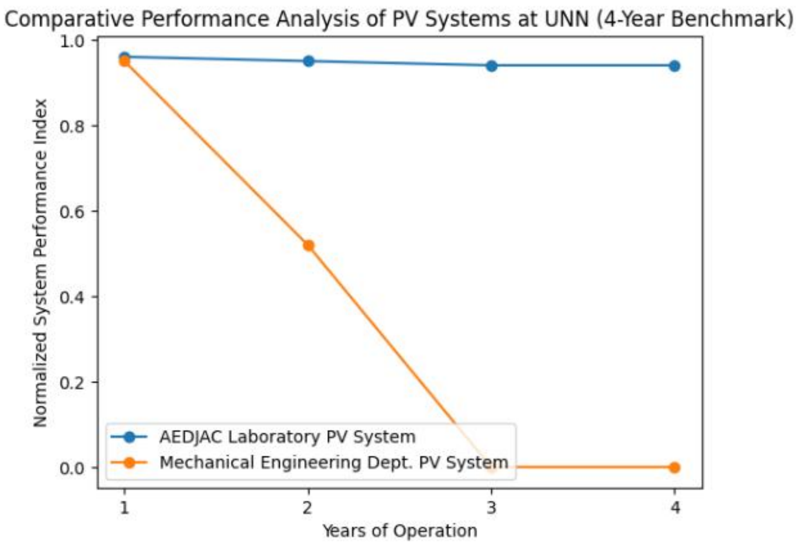

Figure 1. Comparative performance analysis of tested PV systems at UNN.

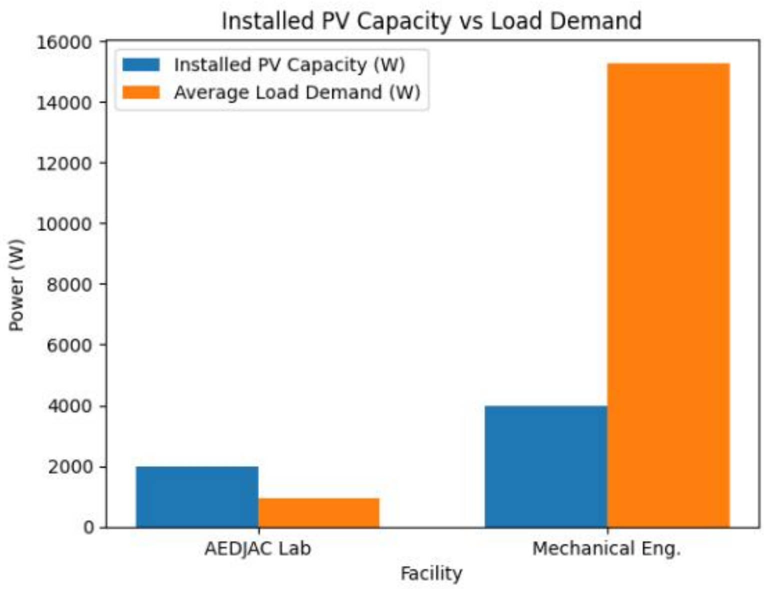

Figure 2. Installed PV capacity vs load demand.

Table 4. Four-year benchmark of system performance ratio and degradation trend.

Year of Operation	AEDJAC Lab Performance Ratio (PR)	AEDJAC Degradation (%)	Mechanical Eng. PR	Mechanical Eng. Degradation (%)
1	0.96	0.0	0.95	0.0
2	0.95	1.0	0.52	45.3
3	0.94	2.1	0.00	100
4	0.94	2.1	0.00	100

5. Conclusion

This study demonstrates that the long-term sustainability of solar photovoltaic (PV) systems in institutional settings depends primarily on proper system sizing, disciplined load management, and consistent maintenance practices, rather than environmental limitations or installed capacity alone. The comparative assessment of the two PV systems revealed that the AEDJAC Laboratory system, though smaller in capacity, remained reliable due to appropriate load matching and operational discipline, while the larger Mechanical Engineering system failed prematurely as a result of persistent overloading and inadequate management. These findings provide practical evidence that technical and managerial factors are the dominant determinants of PV system performance and longevity in developing regions.

From a policy perspective, the results underscore the need for institutions and government agencies to adopt standardized guidelines for PV system design, installation, and operation, including mandatory load audits, routine maintenance schedules, and user training programs. Regulatory bodies and energy planners should also encourage the integration of monitoring and evaluation frameworks to ensure accountability and long-term system reliability in publicly funded renewable energy projects.

Future research should focus on long-term performance monitoring using automated data logging systems, lifecycle cost and reliability analysis of institutional PV installations, and the development of predictive maintenance models. Such studies will further support evidence-based planning and sustainable expansion of solar energy systems in educational and public-sector facilities.

6. Recommendations and Practical Guidelines

As a product of this research, practical guidelines are proposed to support the design, installation, operation, and management of reliable and sustainable solar photovoltaic (PV) systems in academic and institutional settings. These guidelines are derived from the comparative assessment of the AEDJAC Laboratory and Mechanical Engineering Department PV systems and reflect best practices necessary to ensure long-term system performance.

First and foremost, a comprehensive load assessment should be conducted prior to system design. All electrical appliances, their power ratings, and operating durations must be accurately documented, with allowances made for future load expansion. This ensures proper sizing of PV arrays, battery banks, inverters, and charge controllers, thereby preventing system overloading and premature component failure.

Secondly, PV system components should be properly sized and selected using standard design calculations and adequate safety margins. High-quality, appropriately rated modules, batteries, and power electronics should be prioritized to withstand tropical operating conditions. Panel orientation toward true south and tilt angle selection based on site latitude, with adjustments for seasonal performance, are essential for maximizing energy yield.

Furthermore, shading should be minimized through careful site selection and layout planning, while routine preventive maintenance such as panel cleaning, battery inspection, and electrical checks should be institutionalized. Finally, user discipline must be enforced through operational guidelines, load management policies, and continuous user education. Adherence to these practices will significantly enhance the reliability, efficiency, and long-term sustainability of solar PV systems in institutional environments.

Generative AI Statement

The authors declare that no generative artificial intelligence technologies were used when preparing this manuscript.

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