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Standardization of Photovoltaic Renewable-Energy Components: A Case Study of Federal Polytechnic Bauchi, Nigeria

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Abstract

The widespread of photovoltaic (PV) renewable-energy systems in h institutions has created a need for systematic standardization of PV components, installation practices, performance verification, safety requirements, and maintenance procedures. Effective PV-system performance depends not only on the quality of PV modules but also on the compatibility, conformity, and proper integration of inverters, batteries, cables, connectors, protection devices, mounting structures, earthing and lightning-protection systems, monitoring equipment, and other balance-of-system components. Consequently, a comprehensive standardization approach is required to ensure that PV components and associated installation practices meet appropriate technical, safety, reliability, and operational requirements. This study focuses on the standardization of PV renewable-energy components at Federal Polytechnic Bauchi, Nigeria, with emphasis on conformity with applicable international technical requirements and their suitability for the institution's environmental and operational conditions. A descriptive evaluative research design was employed, combining component inventory, document review, physical inspection, technical measurements, and structured assessment against relevant standards. Four objectives guided the investigation: identify the PV renewable-energy components requiring standardization; determine their level of conformity with applicable standards; assess the technical, safety, reliability, and operational implications of identified conformity gaps; and develop an institution-specific PV component standardization framework. Data

were analyzed using descriptive statistics, conformity indices, weighted compliance scores, gap analysis, and risk-priority assessment. The results identified 12 major PV component categories and established 100% standards-mapping coverage. The overall conformity index was 79.12%, with PV modules recording the highest conformity of 90.0% and earthing/lightning protection the lowest at 66.7%. The risk assessment identified inadequate earthing/bonding as the highest-priority risk, with an RPN of 420, followed by lightning protection at 350 and circuit protection at 300. Overall, 66.7% of the identified risk areas were classified as high or very high priority. A six-stage institutional standardization framework covering specification, procurement, installation, commissioning, monitoring, and maintenance/requalification was subsequently developed. The study concludes that PV standardization should be implemented as a continuous, risk-based life-cycle process rather than as a one-time equipment procurement activity.

Keywords: Photovoltaic system; Component standardization; Conformity assessment; Renewable energy; PV reliability; Risk assessment.

Introduction

The transition towards renewable-energy technologies has accelerated the deployment of photovoltaic systems in institutions seeking to improve electricity availability, reduce dependence on conventional electricity sources, and strengthen energy sustainability (Achakpo ***et al***., 2026a; Jordan ***et al***., 2020). PV technology is particularly attractive for institutional applications because solar resources can be converted directly into electricity without fuel consumption during operation (Achakpo ***et al***., 2026b; Spertino ***et al***., 2021). However, the long-term effectiveness of a PV installation depends on the quality of the complete system rather than on the photovoltaic modules alone.

A PV system comprises interconnected generation, conversion, storage, protection, transmission, structural and monitoring components whose performance must be coordinated. PV modules, inverters, batteries, charge controllers, cables, connectors, circuit-protection devices, surge-protection devices, mounting structures, earthing systems and monitoring equipment therefore constitute an integrated technical system. IEC 62548-1:2023 specifically addresses PV-array design requirements including DC wiring, electrical protection, switching and earthing, demonstrating that these elements are integral to PV-system safety and design.

The importance of component quality and installation practice is reinforced by large-scale field evidence. Jordan, Marion, Deline, Barnes, and Bolinger (2020) analyzed approximately 100,000 PV systems and reported that installation quality, connectors, wiring, breakers and fuses could influence performance and safety, while proactive monitoring and maintenance reduced the impact of failures.

Inverters are also important determinants of PV-system availability because failures in power-conversion equipment can cause system downtime and energy losses. Spertino ***et al***., (2021), in a reliability analysis of 132 large-scale inverters, demonstrated the importance of inverter component reliability and maintenance in determining PV-system availability and associated energy losses.

PV module standardization is similarly essential because modules must be qualified for long-term operation under outdoor environmental conditions. IEC 61215-1:2021 establishes design-qualification and type-approval test requirements

for terrestrial PV modules, while the IEC 61730 series address PV-module safety qualification.

System-level standardization must, however, extend beyond component certification. IEC 62446-1 establishes requirements for PV-system documentation, commissioning tests, inspection and verification of safe installation and correct operation.

Performance monitoring is another essential component of PV-system management because it enables deviations from expected performance to be detected and evaluated. IEC 61724-1:2021 provides terminology, equipment requirements and methods for monitoring and analyzing PV-system performance.

For an educational institution such as Federal Polytechnic Bauchi, standardization is particularly important because PV systems may serve academic buildings, workshops, laboratories, administrative facilities and other critical loads. Variations in component specifications, installation quality, protection arrangements, documentation and maintenance practices can therefore affect system safety, availability and economic performance.

Despite the availability of international PV standards, institutional adoption of a comprehensive component-standardization framework remains necessary because standards must be translated into procurement specifications, installation requirements, commissioning procedures, monitoring protocols and maintenance practices appropriate to the institution. This study therefore investigates the standardization of PV renewable-energy components at Federal Polytechnic Bauchi and develops an institution-specific framework for improving conformity, safety, reliability and operational performance.

Statement of the Problem

The increasing adoption of PV renewable-energy systems has created a growing requirement for reliable and technically compliant components and installation practices. However, the absence of a unified institutional standardization procedure can result in variations in component specifications, procurement decisions, installation practices, protection arrangements, commissioning documentation and maintenance procedures.

The problem is not necessarily the absence of international standards but the potential dis-connect between those standards and their systematic application at institutional level. A PV module may satisfy its applicable qualification requirements while the complete installation may still contain deficiencies in cabling, connectors, protection, earthing, monitoring, commissioning or component compatibility.

Such deficiencies can increase the likelihood of equipment failure, electrical hazards, energy losses, system downtime and increased maintenance requirements. Large-scale PV field evidence has demonstrated that installation-related problems involving connectors, wiring, breakers and fuses can affect both performance and safety, while improved monitoring and maintenance can reduce production losses.

The absence of an institution-specific framework also makes it difficult to establish consistent criteria for procurement, acceptance testing, commissioning, performance monitoring and replacement of PV components. Consequently, there is a need to assess the existing level of component standardization and develop a systematic framework appropriate for Federal Polytechnic Bauchi.

Aim of the Study

The aim of this study is to assess the standardization of photovoltaic renewable-energy components at Federal Polytechnic Bauchi, Nigeria, and develop an institution-specific framework for improving their conformity, safety, reliability and operational management.

Specific Objectives

The study seeks to:

1. Identify and classify the major PV renewable-energy components requiring standardization at Federal Polytechnic Bauchi.
2. Determine the level of conformity of the identified PV components and associated installation practices with applicable technical standards.
3. Assess the technical, safety, reliability and operational implications of identified PV component standardization and conformity gaps.
4. Develop an institution-specific framework for the standardization, procurement, installation, commissioning, monitoring and maintenance of PV renewable-energy components.

Research Questions

1. What major PV renewable-energy components require standardization at Federal Polytechnic Bauchi?
2. What is the level of conformity of the identified PV components and associated installation practices with applicable technical standards?
3. What are the technical, safety, reliability and operational implications of the identified standardization and conformity gaps?
4. What institution-specific framework can be developed for standardizing PV renewable-energy components at Federal Polytechnic Bauchi?

Significance of the Study

The study is significant because it provides a systematic basis for improving the technical quality and management of institutional PV renewable-energy systems. The findings provide a basis for developing standardized procurement specifications, component acceptance criteria, installation procedures, commissioning requirements and maintenance protocols in Federal Polytechnic Bauchi. The study also provides evidence for the management to prioritize investment in safety-critical components and technical quality assurance. The study therefore provides the procurement personnel, a structured approach for evaluating PV components beyond purchase price and nominal capacity. For engineering and maintenance personnel, the framework provides criteria for inspection, testing, monitoring, fault identification and preventive maintenance. While for researchers and other tertiary institutions, the proposed framework provides a model that can be adapted to similar institutional PV installations.

PV-System Components and Standardization

PV systems consist of interconnected electrical and mechanical components. Standardization is therefore required to ensure that individual components are technically appropriate and mutually compatible.

PV modules constitute the primary energy-generation component, while inverters provide DC-to-AC conversion in systems supplying conventional AC loads. Batteries may provide energy storage, while charge controllers regulate battery charging in systems incorporating storage. Cables, connectors, circuit protection, surge protection, mounting structures and earthing systems provide essential supporting functions.

IEC 61215-1:2021 establishes requirements for design qualification and type approval of terrestrial PV modules suitable for long-term outdoor operation.

IEC 62548-1:2023 extends system-level requirements to PV-array wiring, electrical protection, switching and earthing.

PV-System Reliability

PV-system reliability is determined by the performance of multiple components and by the quality of installation and maintenance. Jordan et al. (2020) found from analysis of approximately 100,000 PV systems that inverters were among the components most frequently reported to fail and that installation quality affected performance and safety.

Spertino et al. (2021) similarly demonstrated that inverter component failures can contribute to downtime and energy losses in large-scale PV systems.

These findings indicate that standardization must encompass both generation components and balance-of-system components.

Testing, Documentation and Commissioning

A PV system cannot be considered adequately standardized merely because individual components meet their respective product requirements. System-level testing and documentation are necessary to establish that the components have been installed correctly and operate safely.

IEC 62446-1 specifies information and documentation to be provided following installation and describes commissioning tests and inspection criteria for verifying safe installation and correct operation.

This supports the inclusion of commissioning and acceptance testing as mandatory elements of an institutional PV standardization framework.

PV Performance Monitoring

Monitoring provides information necessary for evaluating energy yield, availability, degradation and abnormal system behaviour. IEC 61724-1:2021 defines terminology, equipment and methods for PV-system performance monitoring and analysis.

Consequently, monitoring should be incorporated into institutional standardization rather than regarded as an optional operational feature.

Research Gap

Existing PV standards provide extensive technical requirements for components, design, testing and monitoring. However, a standards-based institutional framework that integrates component identification, conformity assessment, risk prioritization and life-cycle management remains necessary for institutional applications.

The gap addressed by this study is therefore the development of an integrated, institution-specific approach that translates technical PV standards into measurable procurement, inspection, commissioning, monitoring and maintenance requirements for Federal Polytechnic Bauchi.

Research Design

A descriptive evaluative research design was adopted. The design was considered appropriate because the study evaluates existing PV components and practices against defined technical requirements and subsequently develops a standardization framework based on the identified conformity and risk gaps.

Study Area

The study was conducted at Federal Polytechnic Bauchi, Bauchi State, Nigeria. The institution was selected because of its growing application and interest in renewable-energy technologies and the need to ensure consistent technical standards for PV installations serving institutional facilities.

Population and Unit of Analysis

The unit of analysis comprised PV renewable-energy components and associated installation, commissioning, monitoring and maintenance practices within the institutional PV systems considered in the study.

Data Collection

Data were obtained through PV component inventory, technical-document review, physical inspection, component specification verification, installation inspection, available technical measurements, commissioning documentation review, and structured conformity-assessment checklists.

The assessment considered the principal technical requirements applicable to PV modules, array design, electrical protection, testing, documentation and monitoring.

Data analysis mapped to objective 1

Objective 1 was analyzed using component inventory, classification and standards mapping.

The component coverage ratio was calculated as shown in Equation 1:

$$CCR = \frac{N_c}{N_i} \times 100 \quad \ldots (1)$$

where:

CCR= component coverage ratio

N_c = number of component categories mapped to applicable requirements;

N_i = total component categories identified.

Data analysis mapped to objective 2

Objective 2 was analyzed using weighted conformity scores.

The conformity score was calculated as seen in Equation 2:

$$CS_i = \frac{\sum W_j C_j}{\sum W_j} \times 100 \quad \ldots (2)$$

where:

CS = Conformity score

W_j = assigned weight of requirement (j);

C_j = conformity status of requirement (j).

The overall conformity index was calculated from the aggregated component conformity scores.

Data analysis mapped to objective 3

Objective 3 was analyzed using gap analysis and Failure Mode and Effects Analysis.

The conformity gap was calculated as indicated in Equation 3:

$$G = 100 - C \quad \ldots (3)$$

Where, G is conformity gap and C is the conformity percentage.
The Risk Priority Number was calculated as shown in Equation 4:

$$RPN = S \times O \times D \quad \ldots (4)$$

Where:

RPN, S, O and D represent Risk Priority Number, severity, occurrence and detectability respectively.

Data analysis mapped to objective 4

Objective 4 was analyzed through synthesis of the findings from Objectives 1–3. Components with significant conformity gaps and high risk-priority scores were used to establish the priority requirements of the proposed institutional standardization framework.

Identification and Classification of PV Components

Objective 1 identified 12 major component categories requiring standardization as presented in Table 1. The categorized components are PV modules, inverters, batteries, charge controllers, DC cables, AC cables, connectors/junction boxes, circuit protection, surge protection, mounting structures, earthing/lightening protection, and monitoring devise (or metering). The standards-mapping exercise achieved 100% coverage, indicating that each identified category could be assigned appropriate technical requirements.

Table 1: Identified PV Component Categories

S/N	Component category
1	PV modules
2	Inverters
3	Batteries
4	Charge controllers
5	DC cables
6	AC cables
7	Connectors/junction boxes
8	Circuit protection
9	Surge protection
10	Mounting structures
11	Earthing/lightning protection
12	Monitoring/metering

The finding confirms that PV standardization must extend beyond PV modules to encompass the complete balance of system. This is consistent with IEC 62548-1, which explicitly addresses wiring, protection, switching and earthing requirements in PV arrays.

Conformity Assessment

The conformity assessment produced an Overall Conformity Index of 79.12%.

Table 2: Component Conformity Results

S/N	Component	Conformity (%)	Gap (%)
1	PV modules	90.0	10.0
2	Inverters	83.3	16.7
3	DC cables	83.3	16.7
4	AC cables	83.3	16.7
5	Charge controllers	80.0	20.0
6	Connectors/junction boxes	80.0	20.0
7	Mounting structures	80.0	20.0
8	Batteries	77.8	22.2
9	Circuit protection	73.3	26.7
10	Monitoring/metering	73.3	26.7
11	Surge protection	75.0	25.0
12	Earthing/lightning protection	66.7	33.3
	Overall	**79.12**	**20.88**

PV modules recorded the highest conformity of 90.0%, while earthing/lightning protection recorded the lowest conformity of 66.7%.

The result suggests that product-level standardization was comparatively stronger than system-level safety and operational requirements. This distinction is important because IEC 61215-1:2021 establishes PV-module qualification requirements, whereas IEC 62548-1 addresses system-level wiring, protection and earthing.

Technical, Safety, Reliability and Operational Implications

Table 3 shows the risk-priority assessment, where Eight of the twelve risk areas, representing 66.7%, were classified as high or very high priority. The earthing/ bonding and the lightening protection were classified as very high, while those classified as high were circuit protection, commission document, monitoring, surge protection, battery compatibility, and connectors. The remaining risk areas such as charge controller, mounting structure, cable selection, and inverter compatibility were classified as moderate.

Table 3: Risk-Priority Assessment

S/N	Risk area	Severity	Occurrence	Detectability	RPN	Risk
1	Earthing/bonding	10	6	7	420	Very high
2	Lightning protection	10	5	7	350	Very high
3	Circuit protection	10	5	6	300	High
4	Commissioning documentation	8	6	6	288	High
5	Monitoring	8	6	6	288	High
6	Surge protection	9	5	6	270	High
7	Battery compatibility	8	5	6	240	High
8	Connectors	9	4	6	216	High

S/N	Risk area	Severity	Occurrence	Detectability	RPN	Risk
9	Charge controller	8	4	6	192	Moderate
10	Mounting structure	8	4	5	160	Moderate
11	Cable selection	8	4	5	160	Moderate
12	Inverter compatibility	8	3	5	120	Moderate
	Risk area	Severity	Occurrence	Detectability	RPN	Risk

The highest RPN of 420 was associated with inadequate earthing/bonding. This finding highlights the importance of PV-array electrical protection and earthing, which are explicitly covered by IEC 62548-1.

Lightning protection recorded an RPN of 350, while circuit protection recorded 300. These findings demonstrate that deficiencies in protective systems can present more serious consequences than relatively minor product-specification deficiencies.

Monitoring and commissioning each recorded an RPN of 288. This finding supports the incorporation of systematic commissioning and monitoring into the institutional framework. IEC 62446-1 addresses commissioning tests and documentation, while IEC 61724-1 establishes a framework for PV performance monitoring.

The findings also support the evidence of Jordan et al. (2020), who reported that installation quality involving connectors, wiring, breakers and fuses can influence PV-system performance and safety.

Proposed Institutional Standardization Framework

Based on the findings, a six-stage framework was developed as revealed in ***Figure*** 1.

Specification → Procurement → Installation → Commissioning → Monitoring → Maintenance/Requalification

Figure 1: The proposed institutional standardization framework

Table 4 presents the principal requirement for each stage of the institutional standardization framework being proposed. The framework incorporates the major deficiencies identified in Objectives 1–3.

Table 4: Proposed Framework

S/N	Stage	Principal requirement
1	Specification	Define technical requirements for every PV component
2	Procurement	Verify supplier qualification and component conformity
3	Installation	Verify component compatibility and installation quality
4	Commissioning	Conduct inspection, testing and documentation
5	Monitoring	Track energy production, availability, faults and performance
6	Maintenance/ requalification	Conduct preventive maintenance and periodic conformity reassessment

In the specification stage, the technical requirements for every PV component were defined. Next is the procurement stage, the supplier qualification and component conformity for instance the manufacturer datasheets, applicable conformity evidence, warranties and compatibility information needs to be verified. In the installation stage, the component compatibility and installation quality such as the cable sizing, connector compatibility, protection, mounting, earthing and labelling should be verified. In the monitoring stage, the energy production, availability, faults and performance need to tracked. This stage should incorporate appropriate performance indicators. For example, IEC 61724-1:2021 provides

requirements and methods for PV performance monitoring and analysis. During commissioning, there is need to conduct inspection, testing and documentation to establish a baseline. The IEC 62446-1 requires system documentation and commissioning tests for verifying safe installation and correct operation. At the final stage called the maintenance or requalification, preventive maintenance and periodic conformity reassessment should be conducted. The stage should incorporate periodic inspection, corrective action and requalification following major modifications or component replacement.

Discussion of Findings

The findings demonstrate that PV component standardization at Federal Polytechnic Bauchi should be treated as an integrated engineering-management activity rather than a simple procurement requirement. The identification of 12 major component categories demonstrates that PV-system quality depends on the interaction of generation, conversion, storage, protection, cabling, structural and monitoring components. This finding is consistent with the scope of IEC 62548-1, which incorporates PV-array wiring, electrical protection, switching and earthing into PV-array design requirements.

The 79.12% overall conformity index indicates relatively high but incomplete conformity. The higher conformity of PV modules compared with earthing/lightning protection suggests that product-level requirements may be more readily controlled than system-level installation and safety requirements.

This finding is important because PV module qualification does not establish complete system conformity. IEC 61215-1:2021 addresses module design qualification and type approval, while IEC 62446-1 addresses system documentation, commissioning and inspection.

The risk analysis further demonstrates that conformity percentage alone is inadequate for prioritizing intervention. Earthing/bonding recorded the highest RPN of 420, demonstrating that a conformity gap affecting a safety-critical requirement may be more important than a larger gap involving a low-consequence requirement.

The finding that monitoring and commissioning were high-priority risks also demonstrates the importance of operational management. PV-system standardization should therefore continue after installation through documented commissioning, performance monitoring, preventive maintenance and periodic reassessment.

The results are consistent with Jordan et al. (2020), whose analysis of approximately 100,000 PV systems showed the importance of installation quality, component failures, monitoring and proactive maintenance. Spertino ***et al***. (2021) likewise demonstrated the influence of inverter reliability and maintenance on PV-system availability and energy losses.

The proposed six-stage framework therefore provides a logical response to the identified gaps by linking technical specification, procurement, installation, commissioning, monitoring and maintenance.

Summary of Findings

The study produced four principal findings corresponding to its four objectives. In line with objective 1, twelve major PV component categories were identified and all 12 were mapped to applicable technical requirements, producing 100% standards-mapping coverage. From objective 2, the overall conformity index was 79.12%. PV modules recorded the highest conformity of 90.0%, while earthing/lightning protection recorded the lowest at 66.7%. In objective 3, earthing/bonding was the highest-risk area with an RPN of 420, followed by lightning protection (350) and circuit protection (300). Eight of the twelve risk areas (66.7%) were classified as high or very high priority. In conformity

with objective 4, a six-stage institutional PV standardization framework was developed covering specification, procurement, installation, commissioning, monitoring and maintenance/requalification.

Conclusions

In line with objective 1, the study concludes that effective PV standardization requires comprehensive coverage of the complete PV balance of system rather than PV modules alone. The identification of 12 component categories demonstrates the need for a formal institutional component standards register.

From objective 2, the study concludes that the assessed PV components exhibited relatively high but incomplete conformity, with an overall conformity index of 79.12%. Particular attention is required for earthing/lightning protection, circuit protection, monitoring and surge protection.

According to objective 3, the study concludes that PV conformity gaps can have important technical, safety, reliability and operational consequences. Earthing/bonding, lightning protection and circuit protection require the greatest attention because of their high risk-priority scores.

In agreement with objective 4, the study concludes that Federal Polytechnic Bauchi requires an institution-specific, life-cycle PV standardization framework. Standardization should extend from technical specification and procurement through installation, commissioning, monitoring, maintenance and eventual component replacement.

Overall, PV standardization should be treated as a continuous risk-based quality-assurance process rather than a one-time procurement activity.

Recommendations

In line with objective 1, Federal Polytechnic Bauchi should establish an institutional PV Component Standards Register covering all major PV components. Furthermore, procurement specifications should cover the complete balance of system rather than PV modules alone. Also, the component compatibility should be a mandatory technical requirement.

With respect to objective 2, all PV components should undergo documented conformity assessment before acceptance; where particular attention should be given to earthing, lightning protection, circuit protection, surge protection and monitoring; and then the manufacturer certification should be supplemented by physical inspection and installation-level verification.

Relating to objective 3, a risk-based conformity system should be adopted, by giving priority to safety-critical deficiencies. Equally, earthing and bonding should receive immediate technical attention because of the highest RPN; while the lightning and surge protection should be inspected and verified periodically; and the commissioning and monitoring records should be mandatory for every institutional PV installation. Preventive maintenance should replace reliance on purely corrective maintenance.

Concerning objective 4, the Polytechnic should formally adopt the proposed six-stage PV standardization framework; and a multidisciplinary PV technical standards and compliance team should oversee implementation. It should be noted that every PV installation should maintain a permanent technical file containing specifications, certificates, drawings, commissioning results, monitoring records and maintenance history. Also, periodic conformity and risk audits should be undertaken, particularly following major system modifications or component replacement; and the technical personnel responsible for procurement, installation, operation and maintenance should receive periodic PV standards and safety training.

Contributions to Knowledge

The study contributes a 12-category PV component standardization taxonomy that extends standardization beyond PV modules to include conversion, storage, cabling, protection, structural, earthing and monitoring components, which is conformity with objective 1.

The study contributes a quantitative conformity-assessment approach using an Overall Conformity Index. The calculated 79.12% OCI provides a measurable basis for evaluating institutional PV component standardization in accordance with objective 2.

The study contributes an integrated conformity-gap and FMEA-based risk assessment approach. This demonstrates that the size of a conformity gap should not be the sole basis for determining intervention priority with respect to objective 3.

The principal practical contribution is the development of an institution-specific PV Renewable-Energy Component Standardization Framework integrating specification, procurement, installation, commissioning, monitoring and maintenance/requalification which is in line with objective 4.

The study therefore contributes an integrated model as:

Component Identification → Standards Mapping → Conformity Assessment → Risk Assessment → Life-Cycle Standardization.

This model provides a basis for institutional PV quality assurance and may be adapted by other tertiary institutions seeking to improve the safety, reliability and operational performance of renewable-energy installations.

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