

# Design and Performance Evaluation of a 3.5 kVA Solar Photovoltaic System: An Implementation Study

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## Abstract:

This study presents the design, installation, and performance evaluation of a 3.5 kVA solar photovoltaic system integrated with a 3kWh (24V) lithium battery at the Directorate of Research and Development, Kaduna Polytechnic. Developed using systematic load assessment and proper component sizing, the system comprises a 2kW PV array, hybrid inverter with MPPT, and battery storage, providing stable voltage output (220–230 V), efficient energy conversion, and reliable backup during grid outages. The lithium battery exhibited high charging efficiency (~90%) and long cycle life (>6000 cycles), ensuring operational sustainability. Implementation significantly reduced reliance on the unstable grid, minimized downtime for critical research equipment, and enabled uninterrupted power supply through effective solar–battery–grid integration. The results demonstrate that medium-scale solar PV systems are technically feasible, reliable, and economically viable for institutional applications, offering a scalable framework for renewable energy deployment in tertiary institutions.

**Keywords** — Energy reliability, Hybrid inverter, Lithium battery, Renewable energy, Solar photovoltaic.

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## I. INTRODUCTION

Reliable electricity supply remains a major challenge in Nigeria, where frequent grid failures and voltage instability disrupt economic, academic, and research activities. Tertiary institutions are particularly affected because their operations depend heavily on uninterrupted electricity for computing systems, internet services, laboratory equipment, and administrative functions. At Kaduna Polytechnic, the Directorate of Research and Development (DRD) experiences recurrent power outages that significantly affect productivity and delay research outputs. Nigeria's electricity access and reliability challenges have been widely documented in the literature [1], [2].

Solar photovoltaic (PV) technology has emerged as one of the most viable renewable energy solutions for decentralized power generation. PV systems

convert solar radiation directly into electrical energy through the photovoltaic effect [3]. The electricity generated is in direct current (DC) form and can be stored in batteries or converted to alternating current (AC) using inverters for powering conventional loads [4]. Advances in solar cell technologies and system integration have further improved the efficiency and reliability of PV installations [5].

Energy storage is essential in standalone solar systems due to the intermittent nature of solar radiation. Lithium-ion batteries have gained preference over conventional lead-acid batteries because of their higher depth of discharge (DoD), longer cycle life, higher energy density, and lower maintenance requirements [6]. Furthermore, the use of Maximum Power Point Tracking (MPPT) charge controllers enhances system performance by continuously optimizing the operating point of PV

modules to extract maximum available power under varying environmental conditions [7], [8].

Nigeria’s geographical location provides high solar irradiation levels, particularly in the northern region, with average daily solar insolation ranging between 5–7 kWh/m<sup>2</sup>/day [2]. This makes solar PV systems technically feasible and economically justifiable for institutional applications. Implementing a properly sized standalone solar power system can reduce dependence on unreliable grid electricity, minimize generator usage, and contribute to environmental sustainability by lowering greenhouse gas emissions.

This study presents the design and implementation of a 3.5kVA standalone solar photovoltaic system integrated with a 3kWh lithium battery for the Directorate of Research and Development at Kaduna Polytechnic. The system was developed through detailed load analysis, component sizing, installation, and performance evaluation. The objective is to provide a reliable, efficient, and sustainable alternative power solution tailored to the energy demands of the DRD while serving as a scalable model for renewable energy adoption in tertiary institutions.

## II. METHODOLOGY

This section presents the systematic procedure adopted for the design, sizing, installation, and evaluation of the 3.5 kVA solar photovoltaic (PV) system with 3 kWh lithium battery storage installed at the Directorate of Research and Development, Kaduna Polytechnic.

### A. Load Assessment and Energy Demand Calculation

The first step involved detailed load analysis of all electrical appliances within the DRD. Each appliance was itemized according to:

- Power rating (W)
- Quantity
- Average daily operating hours

The daily energy consumption was calculated using:

$$E_{load} = \sum (P_i \times H_i)$$

where:

$P_i$  = Power rating of appliance (W)

$H_i$  = Daily operating hours (h)

To account for system losses such as inverter inefficiency, temperature losses, cable losses, and battery inefficiencies, a correction factor of 1.3 was applied [2]:

$$E_{corrected} = E_{load} \times 1.3$$

Thus, the corrected daily energy demand  $\approx$  14.43 kWh/day. This ensures proper sizing and prevents under-dimensioning of system components.

### B. PV Array Sizing

The required peak power of the PV array was determined as:

$$P_{PV} = \frac{E_{corrected}}{H_{sun}}$$

where:

$H_{sun}$  = Average peak sun hours

Eight (8) monocrystalline PV panels rated at 250W each were selected:

$$Total\ PV\ Capacity = 8 \times 250W = 2000W(2kW)$$

The panels were configured in a series-parallel arrangement to meet the DC input voltage requirement of the 3.5kVA hybrid inverter. Series connection increased voltage, while parallel configuration increased current to match inverter input specifications.

TABLE I  
PV Module Specification

Parameter	Value
Rated Power	250 W
Type	Monocrystalline
Open Circuit Voltage (Voc)	37 V (typical)
Short Circuit Current (Isc)	8–9 A
Total Panels	8
Total Capacity	2 kW

### C. Battery Bank Sizing

Energy storage is essential for maintaining supply during nighttime and grid outages. Battery capacity was determined using:

$$\text{Battery Capacity(Ah)} = \frac{E_{corrected} \times \text{Days of Autonomy}}{V_{system} \times \text{DoD} \times \eta}$$

Assuming:

- Days of autonomy = 1 day
- Depth of Discharge (DoD) = 0.85 (85%)
- Battery efficiency ( $\eta$ ) = 0.9

$$\text{Battery Required} \approx \frac{14,430}{0.85 \times 0.9}$$

However, considering cost optimization and prioritization of essential loads, a 3kWh lithium-ion battery (24V system) was adopted. The system is configured to support critical loads during outage periods while allowing grid assistance when necessary.

Table II  
Updated Battery Specification

Parameter	Value
Battery Type	Lithium-ion (LiFePO <sub>4</sub> )
Capacity	3 kWh
Nominal Voltage	24 V
Depth of Discharge	80–90%
Cycle Life	> 6000 cycles
Efficiency	~90%

The selected lithium battery offers significantly improved lifecycle performance compared to conventional lead-acid batteries, which typically range between 500–1500 cycles. The extended cycle life (>6000 cycles) ensures long-term reliability and reduced replacement costs, making it suitable for institutional deployment.

For a 24 V system, the equivalent ampere-hour capacity of the 3 kWh battery is:

$$\text{Capacity(Ah)} = \frac{3000Wh}{24V} = 125Ah$$

Thus, the installed battery is approximately 24V, 125Ah lithium-ion storage.

#### D. Inverter Selection

The inverter is a critical component of the solar photovoltaic system as it converts direct current (DC) from the PV array and 24 V lithium battery bank into alternating current (AC) suitable for powering conventional electrical appliances. Proper inverter sizing ensures system reliability, operational efficiency, and safe handling of surge loads. For the Directorate of Research and Development at Kaduna Polytechnic, a 3.5kVA smart hybrid inverter (24V DC input) was selected based on calculated peak load demand, surge requirements, and future expansion considerations.

Inverter sizing followed the standard design criterion below:

$$P_{inverter} \geq 1.25 \times P_{peak\ load}$$

The 25% safety margin accounts for transient surge currents from equipment such as printers and inductive loads, inverter efficiency losses, and possible load growth. Based on the estimated peak connected load of approximately 2.8 kW, the required inverter rating becomes:

$$1.25 \times 2.8kW = 3.5kW$$

Thus, a 3.5 kVA inverter was selected to ensure stable performance under peak and surge conditions.

A hybrid inverter configuration was chosen due to its integrated functionality, which combines DC–AC conversion, MPPT solar charge control, battery management, and automatic grid transfer within a single unit. This reduces system complexity, improves operational flexibility, and enhances overall efficiency. The integrated Maximum Power Point Tracking (MPPT) controller continuously optimizes the operating voltage of the PV array to maximize energy harvesting under varying irradiance and temperature conditions, typically improving efficiency by 20–30% compared to conventional PWM controllers.

The selected inverter produces a pure sine wave output, ensuring compatibility with sensitive electronic equipment such as computers, networking devices, and research instrumentation used in the DRD.

Table III  
Inverter Technical Specification

Parameter	Value
Rated Power	3.5 kVA
Output Power Factor	1.0
Output Voltage	220–230 V AC
Battery Input Voltage	24 V DC
Solar Charger Type	MPPT (Integrated)
Maximum PV Input Power	~2000 W
Waveform	Pure Sine Wave
Transfer Time	< 10 ms

The inverter operates in multiple modes including solar priority mode, battery mode, grid support mode, and automatic switching mode. The seamless transfer time (<10 ms) ensures uninterrupted supply during grid failure, thereby maintaining operational continuity within the Directorate.

### E. Cable Sizing

Cable sizing was performed to ensure adequate current carrying capacity, acceptable voltage drop, and safe operation in accordance with standard electrical installation principles. The sizing process considered inverter rating (3.5kVA), system voltage (24V DC), operational current, cable length, and protection coordination.

The maximum DC current drawn from the 24 V battery by the inverter was determined using:

$$I = \frac{P}{V \times \eta}$$

Where:

$P = 3500\text{W}$ ,

$V = 24\text{V}$ ,

$\eta = 0.9$  (inverter efficiency).

$$I = \frac{3500}{24 \times 0.9} \approx 162\text{A}$$

Although theoretical surge current may approach 160–200 A when safety factors are applied, the system is configured such that the battery does not continuously supply full inverter capacity. PV contribution and grid support reduce sustained DC loading. Furthermore, the battery-to-inverter cable length is short ( $\leq 1.5$  m), which minimizes voltage drop and resistive losses.

Voltage drop was evaluated using:

$$V_{drop} = \frac{2 \times L \times I \times \rho}{A}$$

Where:

$L$  = cable length (m),

$I$  = current (A),

$\rho$  = resistivity of copper,

$A$  = cross-sectional area ( $\text{mm}^2$ ).

The permissible voltage drop limits adopted were:

- $\leq 2\%$  for DC circuits
- $\leq 5\%$  for AC circuits

Based on calculated currents, installation conditions, and operational load management, the following cable sizes were implemented:

Table IV  
Selected Cable Sizes

Circuit Section	Estimated Current	Cable Type	Selected Size
PV Array to Inverter	15–20 A	DC Solar Cable (Copper, UV-rated)	6 $\text{mm}^2$
Battery to Inverter (24 V DC)	Up to 120 A (operational)	Flexible Copper Cable	10 $\text{mm}^2$
Inverter to Distribution Board (AC)	16 A	PVC Insulated Copper	4 $\text{mm}^2$
Earthing Conductor	—	Copper Earth Wire	6 $\text{mm}^2$

The 10 $\text{mm}^2$  flexible copper cable used between the battery and inverter provides adequate current handling capacity under the controlled operational load of the system and short installation distance. Properly crimped lugs, DC-rated breakers, and battery fuse protection were installed to enhance safety and minimize contact resistance.

### F. Installation Procedure

The installation of the 3.5kVA solar photovoltaic system with a 3kWh (24V) lithium battery was carried out as follows:

1. Site Preparation: Selection of a shade-free rooftop location and structural assessment.

2. Mounting Structure Installation: Fabrication and anchoring of galvanized steel frames at 12–15° tilt angle.
3. PV Module Installation: Mounting and series-parallel connection of eight (8) 250W panels using 6 mm<sup>2</sup> DC solar cables.
4. Battery Installation: Placement of 3kWh (24V) lithium battery in ventilated space and connection using 10mm<sup>2</sup> copper cable with DC fuse protection.
5. Inverter Installation: Wall mounting of 3.5kVA hybrid inverter and configuration to solar-priority mode.
6. AC Wiring and Protection: Connection to distribution board using 4mm<sup>2</sup> cable; installation of MCBs and surge protection devices.
7. Testing and Commissioning: Verification of wiring, voltage levels, and system performance under load (220–230V AC output).

This structured procedure ensured safe installation and reliable operation of the system.

### III. RESULTS AND DISCUSSION

The system was tested under varying load and weather conditions to evaluate operational stability, energy performance, and reliability.

System testing was conducted during peak sunshine hours and during grid outage periods to assess both charging and discharging performance.

#### A. PV Array Performance

The PV array (2 kW total capacity) was monitored during clear-sky conditions.

Table V  
Array Performance Results

Parameter	Measured Value	Expected Range
Open Circuit Voltage (Voc)	Within design limit	Acceptable
Operating Voltage	Within MPPT range	Acceptable
Peak Power Output	1.6 – 1.9 kW	~2 kW (rated)
Average Daily Energy Yield	7 – 9 kWh	Dependent on irradiance

The system achieved up to approximately 90–95% of rated output during optimal sunlight conditions, demonstrating effective MPPT operation.

#### B. Battery Performance

The 3 kWh (24 V) lithium battery was evaluated for charging efficiency, discharge duration, and voltage stability.

Table VI  
Battery Performance Results

Parameter	Observed Value
Nominal Voltage	24 V
Charging Efficiency	~90%
Depth of Discharge (Operational)	≤ 85%
Backup Duration (Critical Load)	3 – 5 hours
Voltage Stability	Stable within safe limits

The battery maintained stable discharge characteristics and supported essential loads during grid outage periods. No significant voltage sag was observed under controlled loading conditions.

#### C. Inverter Output Performance

The 3.5 kVA hybrid inverter was tested for voltage regulation, waveform quality, and load response.

Table VII  
Inverter Performance Results

Parameter	Measured Value	Standard Requirement
AC Output Voltage	220 – 230 V	220 V ±10%
Output Frequency	50 Hz	50 Hz
Transfer Time	< 10 ms	< 20 ms
Waveform Type	Pure Sine Wave	Required

The inverter maintained stable voltage output under varying load conditions. The seamless transfer time ensured uninterrupted operation of computers and networking equipment within the Directorate.

### IV. CONCLUSIONS

The design and implementation of the 3.5 kVA solar photovoltaic system with a 3 kWh lithium battery at Kaduna Polytechnic successfully demonstrated the technical viability and operational reliability of medium-scale solar energy for institutional applications. The system provided stable voltage, efficient energy conversion, and dependable backup during grid interruptions, while the lithium battery ensured long-term sustainability with high efficiency and extended cycle life. By

reducing dependence on the unreliable grid and minimizing downtime for critical research equipment, the hybrid solar–battery–grid configuration proved effective in maintaining uninterrupted power supply. These findings highlight the potential of replicating such systems across other departments and tertiary institutions in Nigeria, offering a practical and economically justified approach to enhancing energy security and promoting renewable energy adoption at the institutional level.

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