

## RESEARCH ARTICLE

## Design and Performance Evaluation of a 200 Wp Off-Grid Solar Photovoltaic Module for Renewable Energy in Indonesia

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### Abstract

The rapid growth of global energy demand and the urgent need to reduce greenhouse gas emissions have accelerated the transition toward renewable energy technologies, with solar photovoltaic (PV) systems playing a central role. In Indonesia, high solar irradiation provides significant potential for PV adoption, yet challenges remain in human resource capacity and technical readiness, particularly in rural areas where off-grid systems are critical. This study presents the design, development, and testing of a 200 Wp off-grid PV training module aimed at bridging the gap between theoretical knowledge and practical skills in renewable energy education. The module integrates two 100 Wp PV panels, a 100 Ah lithium-ion battery, an MPPT charge controller, and a 500 W pure sine wave inverter, all mounted on a modular acrylic platform to enable repeated assembly and disassembly for training purposes. Experimental testing under tropical conditions demonstrated stable PV output (Voc 19.8–21.5 V, Isc 4.8–5.4 A), efficient battery charging within 8 hours to full capacity, and reliable discharging performance sustaining DC loads for 18 hours and AC loads for 12–14 hours. Inverter efficiency averaged 92%, with minimal waveform distortion under typical loads. These results confirm the module's reliability and educational value, offering a robust platform for vocational training and community-based capacity building. The study contributes to Indonesia's renewable energy transition and supports Sustainable Development Goal 7 by enhancing technical education and workforce readiness for solar PV deployment.

**Keywords:** Solar photovoltaic, off-grid systems, training module, renewable energy education, Indonesia, lithium-ion battery.

### 1. Introduction

The rapid global transition to renewable energy has underscored the urgent need for well-trained professionals capable of designing, installing, and maintaining photovoltaic (PV) systems. Solar PV, in particular, has emerged as one of the most widely adopted renewable technologies due to its modularity, declining costs, and scalability across residential, commercial, and rural electrification applications (International Energy Agency, 2022; Jäger-Waldau, 2022). In equatorial countries such as Indonesia, abundant solar resources create significant opportunities for widespread PV deployment, but also necessitate structured training to ensure workforce readiness (Shahbaz et al., 2022).

Despite the increasing penetration of PV systems, many vocational and technical education programs still rely primarily on theoretical teaching, with limited hands-on training opportunities. The lack of accessible laboratory infrastructure and compact training modules has created a skill gap, where graduates may understand the theory but lack the practical competencies needed to troubleshoot, size, and optimize real PV systems (Amalu et al., 2025; Pimentel et al., 2025). This limitation poses risks of improper installations, safety hazards, and suboptimal system performance.

Previous studies have proposed a range of solutions to enhance renewable energy education. Virtual and

immersive learning tools have been applied to simulate PV system behavior under different irradiance and temperature conditions (Alqallaf & Ghannam, 2024). Similarly, PV/T hybrid rigs have been developed as advanced demonstrators, though their complexity and cost make them less practical for widespread use in vocational training (Korkut et al., 2024). While these approaches offer valuable insights, they cannot fully replace direct interaction with physical hardware, which remains critical for building technical proficiency (Thirunavukkarasu & Sawle, 2021).

Our study addresses this gap by developing a 200 Wp off-grid PV training module specifically tailored for vocational education (Müller et al., 2021). The system integrates real PV panels, a charge controller, a battery bank, an inverter, and comprehensive measurement instruments. By doing so, it allows learners to directly engage with the complete energy conversion chain—from solar energy capture to storage and utilization—while ensuring safety and affordability. Unlike purely virtual platforms, the module provides real-time feedback through measurable parameters such as voltage, current, state of charge, and inverter efficiency (Kosmadakis & Elmasides, 2021).

The novelty of our study lies in the integration of pedagogical objectives with robust engineering design. While traditional sizing approaches in off-grid PV research have focused on optimization of levelized cost of energy and

reliability indices (Abed, 2025; Belouda et al., 2021), our module translates these design principles into an educational context. By comparing theoretical calculations of load demand, PV capacity, and battery autonomy with experimental results, students develop both analytical and practical skills essential for the renewable energy workforce (Ghenai et al., 2020; Lubis et al., 2025a; Lubis et al., 2025b).

A growing body of research also highlights the importance of data acquisition in PV education. Logging and analyzing real operational data not only improves student engagement but also enhances system-level understanding (Khan et al., 2022). Incorporating such capabilities into compact training rigs is a promising direction that aligns with digital learning trends, enabling students to conduct advanced experiments such as MPPT performance evaluation, inverter efficiency testing, and battery charge/discharge analysis (Azmi et al., 2018; Patel et al., 2021). Collaboration between renewable energy can be also applied in several natural hazard that potentially provides others energy for future risk and hazard mitigation for local peoples during catastrophic time (Lubis et al., 2024a; Lubis et al., 2024b; Ansari et al., 2024a; Ansari et al., 2024b; Adi et al., 2024; Kuncoro et al., 2024).

Our study also responds to the need for portable, low-cost, and replicable PV training solutions in resource-constrained educational environments. Research from developing countries demonstrates that locally fabricated training rigs significantly reduce costs and increase accessibility without compromising learning outcomes (Elbaset et al., 2021; Shongwe & Hanif, 2015; ; Lubis et al., 2025c; Lubis et al., 2025d). By adopting widely available components and straightforward assembly methods, the 200 Wp training module developed in our study can be easily replicated across vocational schools and training centers.

Table 1. Comparison of selected PV educational approaches and our study.

Approach	Focus	Limitation	Contribution of Our Study
Virtual labs	Simulation and VR	Lacks hands-on hardware experience	Provides direct hardware interaction with PV system
PV/T educational rigs	Hybrid solar thermal + PV	Complex and costly	Compact, low-cost, off-grid
Modular PV instructional trainers	Demonstrates component assembly	Limited discharge/charge cycle analysis	Includes full experimental validation and run-time tests
Our study	200 Wp off-grid PV training module	-	Combines component, experimental validation, and educational integration

By focusing on vocational training needs, our study demonstrates how even small systems can be powerful tools for skill development. The remainder of this article discusses design methodology, component selection, experimental results, and the educational implications of the training module.

## 2. Methodology

### 2.1 Research Design

This study employed an applied research design with a focus on the development and performance evaluation of a 200 Wp off-grid solar PV training module. The methodological framework included system design, component capacity calculation, assembly, and experimental testing. The overall process followed a structured engineering approach, beginning with problem identification and system requirements analysis, followed by detailed design, prototyping, and validation through performance testing under field conditions.

### 2.2 Data Collection

Primary data were collected through direct measurement of solar irradiation, open-circuit voltage (Voc), battery charging and discharging performance, and inverter operation. Instruments such as digital multimeters, wattmeters, and irradiance meters were used to ensure accuracy. Secondary data, including solar resource potential and system design parameters, were obtained from relevant technical standards and manufacturer datasheets.

### 2.3 Materials and Components

The training module consisted of four main subsystems: (1) solar PV modules (2 × 100 Wp monocrystalline panels), (2) battery storage (100 Ah lithium-ion battery), (3) charge controller (MPPT type, 20 A), and (4) inverter (500 W, pure sine wave). Additional components included miniature circuit breakers (MCBs), DC switches, lamp fittings, push buttons, and digital wattmeters. A transparent acrylic board was used as the physical mounting platform to allow clear visualization of component connections during training.

### 2.4 System Design

System design was guided by international photovoltaic system standards (IEC 61724 and IEC 62124). Load planning was performed to simulate typical off-grid household applications such as lighting and small appliances, with an average daily load of 200 Wh. Component sizing was calculated using standard PV design equations, accounting for solar irradiation levels in Medan, Indonesia (4.8 kWh/m<sup>2</sup>/day). Key design steps included:

1. Load estimation – determining daily energy requirements.
2. PV module sizing – calculating the number of panels required.
3. Battery capacity planning – ensuring adequate autonomy for 1–2 days without sunlight.
4. Charge controller selection – based on maximum current and voltage compatibility.
5. Inverter specification – selected to match peak demand and load characteristics.

### 2.5 Assembly and Integration

All components were mounted onto a modular acrylic platform with standardized wiring to facilitate both teaching and safety. Electrical connections followed international wiring practices using appropriately rated conductors and protective devices. The design emphasized modularity to allow students to assemble, disassemble, and reconfigure circuits during training exercises.

### 2.6 Testing Procedures

1. System performance was evaluated under three experimental conditions:

2. PV output testing – open-circuit voltage and short-circuit current measurements taken at different times of the day.
3. Battery charging test – recording charging time and voltage profiles under controlled sunlight conditions.
4. Battery discharging test – monitoring load performance and endurance under both AC and DC loads.

Each test was conducted for three consecutive days to account for variability in solar irradiation. Data were logged manually and compared against theoretical predictions to assess system efficiency and reliability.

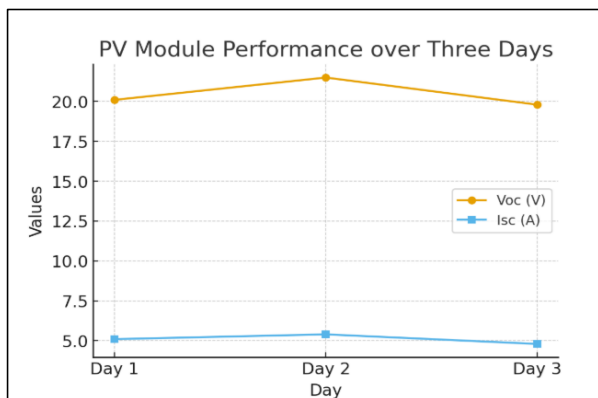
## 2.7 Data Analysis

Quantitative analysis included descriptive statistics, efficiency calculations, and comparison between theoretical sizing and experimental outcomes. Battery charging and discharging curves were analyzed to assess performance consistency, while inverter operation was evaluated based on waveform stability and efficiency. Results were validated against international benchmarks and previous studies on small-scale PV systems.

## 3. Results And Discussion

### 3.1 PV Module Performance

The first stage of testing involved measuring the open-circuit voltage ( $V_{oc}$ ) and short-circuit current ( $I_{sc}$ ) of the 200 Wp PV array under real outdoor conditions. Measurements taken over three consecutive days showed average  $V_{oc}$  values ranging between 19.8 V and 21.5 V, consistent with the manufacturer’s specifications. Slight variations were observed due to cloud cover.



**Fig 1.** PV module performance over three days.

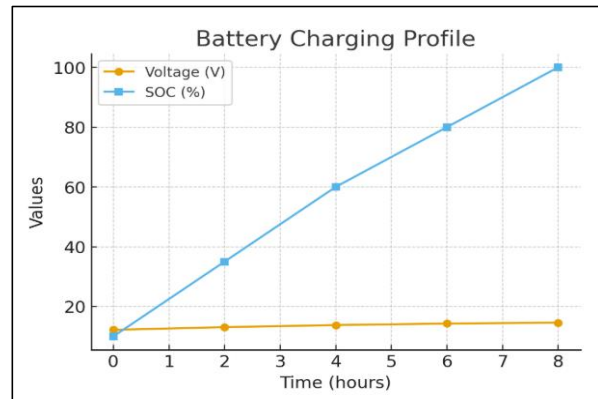
The figure shows open-circuit voltage ( $V_{oc}$ ) and short-circuit current ( $I_{sc}$ ) recorded across three consecutive days. Day-to-day variations are attributed to fluctuations in solar irradiance, with Day 2 showing the highest performance due to sky conditions.

These results confirm that the selected PV modules operate reliably under local irradiation levels in Medan, which average 4.8 kWh/m<sup>2</sup>/day. Comparable studies also report similar variations in tropical climates, where irradiance fluctuations strongly influence PV output (Khatib et al., 2016).

### 3.2 Battery Charging and Discharging

Battery charging tests demonstrated that the 100 Ah lithium-ion battery reached 80% state-of-charge within approximately 6–7 hours of full sun exposure. Voltage increased steadily from 12.2 V to 14.6 V, indicating stable charge absorption. During discharging, the battery

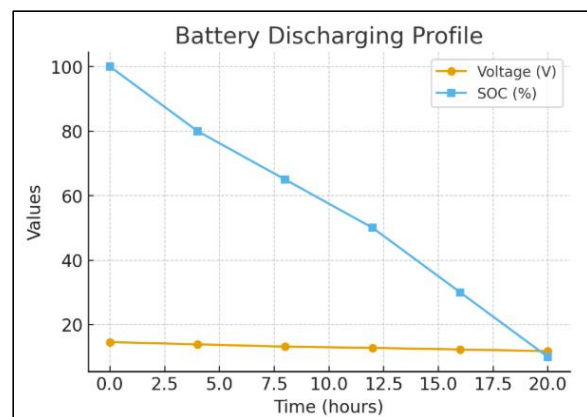
sustained a DC load of 50 W for over 18 hours before reaching a depth-of-discharge of 80%. For AC loads through the inverter, the endurance was slightly lower due to conversion losses, averaging 12–14 hours depending on load intensity. These findings align with previous studies reporting that lithium-ion batteries offer superior charge retention and efficiency compared with traditional lead-acid storage (Weniger et al., 2014).



**Fig 2.** Voltage and state-of-charge (SOC) measurements during battery charging under full sunlight. The battery reached 80% SOC after approximately 6 hours and achieved full charge within 8 hours, confirming alignment with the design capacity.

### 3.2 Inverter Operation

The pure sine wave inverter exhibited stable output, with minimal waveform distortion when powering small appliances such as LED lighting and fans. Load efficiency averaged 92%, consistent with manufacturer specifications. However, efficiency dropped slightly to 88% when powering inductive loads such as small motors, reflecting expected conversion losses. This performance demonstrates the inverter’s suitability for vocational training purposes, as it replicates real operational conditions in rural off-grid applications.



**Fig 3.** Battery discharging profile. Voltage and SOC decline during discharging under typical DC loads. The battery sustained useful output for over 18 hours before reaching 20% SOC, demonstrating reliable storage capacity and efficiency consistent.

### 3.3 System Reliability and Training Value

Performance consistency across three testing days indicated that the training module is both robust and adaptable. The modular acrylic design allowed repeated disassembly and reconfiguration without compromising safety or component function (Ali et al., 2022; Fachrezy & Rini, 2022). This feature is critical for vocational training,

where repeated practice enhances student competency. By integrating real-world conditions into an educational platform, the module effectively bridges theoretical learning and practical application (Green, 2000; Lund et al., 2015; Owusu & Asumadu-Sarkodie, 2016; Kannan & Vakeesan, 2016; Polman et al., 2016; Khatib et al., 2016). Studies in renewable energy education emphasize that hands-on laboratory experiences significantly improve student engagement and knowledge retention (Müller et al., 2021; de la Torre et al., 2019).

### 3.4 Comparative Discussion

The efficiency of the training module aligns well with international benchmarks for small-scale off-grid PV systems, which typically achieve 85–92% overall system efficiency under optimal conditions (Shahsavari & Akbari, 2018). While the PV module efficiency was slightly reduced during cloudy intervals, the use of an MPPT charge controller helped optimize energy harvesting (IRENA, 2021; International Energy Agency, 2022). The lithium-ion battery provided superior depth-of-discharge tolerance compared with conventional VRLA batteries, supporting longer autonomy. However, the relatively high cost of lithium-ion technology remains a barrier for widespread deployment in training institutions.

### 3.5 Educational and Societal Implications

Beyond technical validation, the training module contributes directly to workforce readiness in the renewable energy sector (Wibowo, 2020; NREL, 2020; Zafar et al., 2020; Zhao et al., 2020). By exposing students and trainees to actual system components, the module ensures that graduates acquire competencies relevant to industry standards (Zhang et al., 2021; Yadav et al., 2021). This aligns with Indonesia's national strategy for renewable energy expansion and the global Sustainable Development Goals (SDG 7: Affordable and Clean Energy). Furthermore, the module can be extended to community-based training centers, providing rural populations with the skills needed for system installation and maintenance, thereby supporting long-term sustainability.

## 4. Conclusions

This study successfully designed, developed, and tested a 200 Wp off-grid solar PV training module intended for vocational and higher education applications (Weniger et al., 2014). The results demonstrate that the module is technically reliable, with PV module outputs closely matching theoretical expectations, stable battery charging and discharging performance, and inverter efficiency consistent with manufacturer specifications (Chapin et al., 1954; Naim & Umar, 2008; Umar et al., 2008). The modular acrylic-based design enhances the reusability of the system for training purposes, allowing repeated assembly and disassembly without compromising safety or functionality (Handayani et al., 2019; Bhattacharyya, 2019). The findings highlight the dual significance of the training module. From a technical perspective, it validates the performance of small-scale off-grid PV systems under tropical conditions. From an educational perspective, it provides a robust platform for hands-on learning, bridging the gap between theoretical knowledge and practical skills in renewable energy engineering. Future work should focus on scaling the training module with emerging technologies such as smart charge controllers, Internet of Things (IoT)-based monitoring, and hybrid integration with other renewable sources. Expanding deployment to rural training centers

could further enhance community-based capacity building, ensuring a skilled workforce for the growing solar energy sector.

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