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Development and Performance Evaluation of a Demonstration Board for Basic Solar Photovoltaic System Installation

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ABSTRACT

The growing global imperative for sustainable energy solutions has intensified the need for effective educational tools in renewable energy technologies. This work details the design and construction of a functional demonstration board for a basic solar photovoltaic (PV) system, intended as a practical pedagogical instrument. The system integrates an 80-watt PV panel, a 10Ah 12/24V charge controller, a 40Ah battery, a 300W 120/230V inverter, a 15A socket outlet, and various loads including a fan, a 100-watt AC bulb, and a 7-watt DC bulb, all interconnected with standard 1.5mm copper wiring. The construction process and wiring schematics are outlined to provide a replicable model for educational laboratories. Performance testing was conducted to verify load operation, power consumption, and the system's ability to charge the battery effectively. The board successfully functions as a robust teaching aid, allowing students to visualize system components, understand safety protocols, and grasp the operational sequence of a solar installation, thereby bridging the gap between theoretical knowledge and practical application.

Keywords: Solar System, Installation, Demonstration Board, Performance Evaluation

INTRODUCTION

The pursuit of sustainable and clean energy sources has become a defining challenge of the 21st century, driven by the escalating environmental consequences of fossil fuel dependence. Solar energy, a thermal power generated by fusion reactions on the sun's surface, presents a compelling and inexhaustible alternative. The urgency to transition towards this renewable resource has intensified over the last two decades, largely due to the profound drawbacks associated with non-renewable energy resources. Chief among these disadvantages is the substantial emission of hazardous gases including sulphur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO) which significantly elevate air pollution levels, thereby contributing to climate change and global warming (Satharasinghe et al., 2020; Hughes et al., 2020; Dias et al., 2020). Hydropower, bioenergy, and geothermal, solar photovoltaic (PV) technology has proven exceptionally versatile, suitable for both expansive utility-scale plants and decentralized small-scale installations in urban and rural settings. Furthermore, the integration of renewable energy with broader electrification efforts yields considerable benefits, enabling clean and efficient power for heating and transportation (Armaroli et al., 2011; Nicola et al., 2011; Balzani et al., 2011; Vincenzo et al., 2011).

For a nation like Nigeria, the adoption of solar energy is not merely advantageous but appears inevitable, as it aligns with the critical need to deploy alternative energy technologies that complement government initiatives for providing sustainable and reliable power to its citizens. Nigeria is endowed with abundant solar radiation throughout the year, with estimates indicating approximately 3,000 hours of annual sunshine, creating a vast and largely untapped potential for solar power generation (Augustine et al., 2010; Nnabuchi et al., 2010).

A fundamental component of any solar energy system is the photovoltaic (PV) cell. This photoelectric device operates by altering its electrical characteristicssuch as current, voltage, or resistance upon exposure to light. Individual solar cells are the foundational building blocks of photovoltaic modules, more commonly referred to as "solar panels." The global market is overwhelmingly dominated by crystalline silicon PV cells, which account for approximately 95% of commercial production, with the remainder largely comprised of cadmium telluride thin-film solar cells (International Energy Agency et al., 2022).

Given the growing significance of solar technology, effective education and training are paramount. The objective of this work is to design and construct a functional demonstration board for a basic solar system installation. Such a board serves as an indispensable pedagogical resource, providing students with tangible, hands-on experience. It enables learners to visualize the core concepts of solar energy, interact with its essential components, and understand the operational principles of a complete system. By bridging theoretical knowledge with practical application, this tool significantly enhances learning outcomes and deepens technical comprehension. The efficacy of the constructed board was rigorously evaluated by both students and lecturers to confirm its operational integrity, safety, and functionality as intended.

Solar energy is derived directly from harnessing solar radiation that strikes the Earth's surface (West et al., 1993). This radiation, which encompasses ultraviolet, visible, and infrared spectra, varies considerably depending on geographic location, time of day, season, landscape, and local weather conditions (Rajput et al., 2017). A key advantage of solar energy is its direct conversion into electricity through photovoltaic (PV) cells, eliminating the need for intermediate heat engines. PV cells are remarkably scalable, capable of generating outputs ranging from microwatts to megawatts, making them suitable for a diverse array of applications from standalone consumer devices such as calculators, watches, and remote controls, to water pumping systems, building-integrated photovoltaic's, communication satellites, space vehicles, and large-scale megawatt power plants (Goswani et al., 2015).

The construction of a solar system demonstration board holds significant relevance to technical education, primarily because it offers students a tangible platform to bridge theoretical knowledge with practical skills. Solar PV systems inherently integrate multiple electrical and electronic concepts, including voltage, current, electrical power, energy conversion, battery storage, charge regulation, and the critical conversion of direct current (DC) to alternating current (AC). While these concepts are traditionally introduced through classroom lectures and mathematical derivations, practical laboratory activities are indispensable. They enable students to observe, interact with, and troubleshoot an actual photovoltaic system, thereby reinforcing theoretical understanding through experiential learning (Alqahtani et al., 2018).

Concept of Solar Energy

The historical trajectory of solar energy utilization spans centuries, with early applications dating back to the seventh century, when mirrors were employed to harness solar power for heating purposes. A pivotal milestone occurred in 1893 with the discovery of the photovoltaic (PV) effect, which subsequently laid the scientific foundation for decades of research and technological development aimed at electricity generation (Fraas et al., 2014). Through sustained global innovation, solar energy technology has evolved into two primary application domains: solar thermal systems, which capture heat for direct use or power generation, and solar photovoltaic (PV) systems, which convert sunlight directly into electricity. Solar PV systems, in particular, have experienced remarkable growth and cost reduction, positioning them as the most economical option for new electricity generation in numerous global regions. This widespread adoption is evidenced by a 77% decline in the cost of solar PV electricity generation between 2010 and 2018. Concurrently, global installed PV capacity expanded by a factor of 100 between 2005 and 2018, underscoring the technology's rapid scalability and market penetration. Consequently, solar PV has emerged as an indispensable pillar of the low-carbon sustainable energy infrastructure necessary to provide affordable, reliable, and universal electricity access. Its continued deployment is instrumental in fulfilling the commitments of the Paris Climate Agreement and achieving the United Nations 2030 Sustainable Development Goals (SDGs) (Gahrens et al., 2021; Alessandra et al., 2021; Steinfatt et al., 2021).

MATERIALS AND METHODS

System Components and Specifications

A solar photovoltaic (PV) energy system comprises multiple interconnected components, each fulfilling a distinct and essential function. The specific configuration of components is determined by the system type and its intended application. For the construction of the demonstration board for a basic solar system installation, the following materials were utilized: an 80-watt photovoltaic panel, a 10Ah 12/24V charge controller, a 40Ah deep-cycle battery, a 300W 120/230V inverter, 1.5mm² copper wiring, a 15A socket outlet, a cooling fan, a 100-watt AC bulb, a 7-watt DC bulb, and single-gang switches. The complete bill of quantities, along with the functional description of each component, is presented in Table 1.

Table 1: Bill of Quantities and Component Specifications

S/N	Component	Quantity	Description
1	Charge Controller	1	Regulates battery charging parameters to prevent overcharging and deep discharge
2	Photovoltaic (PV) Cell	1	Converts incident sunlight directly into direct current (DC) electricity
3	Inverter	1	Converts DC power from the battery into alternating current (AC) for standard loads
4	Battery	1	Stores electrical energy for later use, ensuring power availability during periods of low sunlight
5	Single Gang Switch	3	Provides manual control for circuit isolation and load switching
6	Fan	1	Generates airflow for cooling and ventilation applications
7	AC Bulb	2	Operates on alternating current, serving as a representative AC load
8	DC Bulb	1	Operates on direct current, serving as a representative DC load
9	Socket Outlet	1	Provides a receptacle for connecting external electrical devices to the system

Wiring System Procedure

The wiring procedure was executed systematically to ensure safety, functionality, and adherence to standard electrical practices. The step-by-step process is outlined below:

Component Positioning

All system components were securely positioned on the demonstration board according to the predetermined layout to facilitate accessible connections and clear visual representation.

PV Panel to Charge Controller Connection

A DC breaker was installed between the solar panel and the charge controller for over current protection. The live terminal of the solar panel was connected to the breaker input, while the neutral terminal was connected to the corresponding neutral input. The output terminals of the breaker were then connected to the solar input terminals of the charge controller, observing the designated positive (+) and negative (-) polarity markings.

Battery Connection

The battery terminals were connected to the charge controller's battery input terminals, strictly observing the positive (+) and negative (-) polarity as indicated on the controller's wiring diagram.

DC Load Circuit Wiring

The live (L) wire from the last load terminal of the charge controller was connected to the input of a single-pole switch designated for the DC circuit section. The neutral (N) wire was drawn from the negative (-) terminal of the controller directly to the DC bulb. Finally, the live wire from the output terminal of the single-pole switch was connected to the DC bulb, completing the DC load circuit.

Inverter Sub-circuit Connection

The positive input terminal of the inverter was connected to the positive terminal of the battery, enabling the inverter to draw DC voltage directly from the battery for conversion to AC.

AC Load Circuit Wiring
With the inverter output terminals accessible, the neutral wire was routed through the AC bulbs in parallel configuration. The live wire was drawn to all switches to provide independent control of each AC bulb in the circuit.

Socket Outlet Integration
The 15A socket outlet was connected to the inverter output at a junction point, with both live and neutral wires securely terminated to provide a standard AC receptacle for external devices.

Final Integration
The output supply from the inverter was connected to the junction box of the AC sub-circuit, thereby completing the entire system wiring and enabling full system operation.

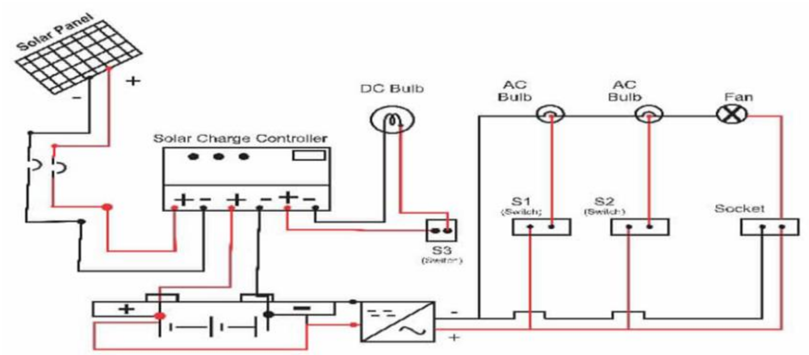

Figure 1: Circuit diagram of a demonstration board for basic solar system installation

RESULTS AND DISCUSSION
Based on the performance evaluation summarized in Table 1, the solar PV demonstration board operated successfully across all tested parameters. Each measured value fell within the expected range, confirming the system's functionality and reliability. Key outcomes include the PV panel generating an open-circuit voltage of 21.0 V and a short-circuit current of 3.59 A under full sun conditions, the charge controller maintaining proper output voltage (12.5 V), and the battery charging from a discharged state (10.5 V) to a fully charged level (13.0 V) after six hours. Additionally, both DC and AC loads operated as intended, the inverter delivered a stable 220 V AC output, and system grounding continuity was verified at 0.02 Ω, well below the acceptable limit. These results collectively validate the system's design and its suitability for practical applications (see Table 1).

Table 1: Performance Test Results of the Solar PV Demonstration Board

S/N	Test Parameter	Condition	Measured Value	Expected Value	Status
1	PV Panel Open-Circuit Voltage Source (Voc)PM	Full Sun (12:00PM)	21.0V	21-22V	✓Pass
2	PV Panel Short-Circuit Current Source (Isc)	Full Sun (12:00)	31.59A	3.59-3.97A	✓ Pass
3	Charge Controller Output voltage	Battery Connected	12.5V	12.0-24.0V	✓Pass
4	Battery Voltage (Discharged)	Before Charging	10.5V	<12.0V	✓Pass
5	Battery Voltage (Charged)	After 6hours	13.0V	12.5-14.0V	✓Pass
6	DC Load (7W Bulb) Operation	Switch ON	7.2W	6.5-7.5W	✓Pass
7	AC Load (100W Bulb) Operation	Switch ON	102.0W	100-120W	✓Pass
8	Fan Operation	Switch ON	11.9V DC	12V DC	✓Pass
9	Inverter Output Voltage	Load Connected	220V AC	220-240V AC	✓Pass
10	Socket Outlet Voltage	No Load	220V AC	220-240V AC	✓Pass
11	Battery Charging Rate	0-6 Hours	0.23A	0.2-0.3A	✓Pass
12	System Grounding Continuity	All Components	0.02Ω	<0.1Ω	✓Pass

Limitations

i. Educational Scale and Capacity: The system is designed for demonstration purposes with limited power output (80W PV panel, 40Ah battery), restricting its applicability to real-world power supply scenarios beyond basic load testing.
ii. Standalone Configuration and Monitoring: The system operates off-grid without grid-tie capability or integrated performance monitoring, limiting its scope for demonstrating advanced solar applications and data analysis.
iii. Site-Specific Performance: System evaluation was conducted under local weather conditions and may not accurately reflect performance across diverse climatic regions or seasonal variations.

Discussion
This work details the design and performance evaluation of a demonstration board for a basic solar photovoltaic (PV) system installation, intended as a practical pedagogical instrument. The bill of quantities in Table 1 is provided along with a functional description of each component. The result is consistent with (International Energy Agency et al., 2022), which identified that the fundamental component of a solar energy system is the photoelectric device operates by altering its electrical characteristics, such as current, voltage, or

resistance, upon exposure to light. Similarly, (Goswani et al., 2015) reported that PV cells are remarkably scalable, capable of generating outputs ranging from microwatts to megawatts, making them suitable for a diverse array of applications from standalone consumer devices such as calculators, watches, and remote controls, to water pumping systems, building-integrated photovoltaic's, communication satellites, space vehicles, and large-scale megawatt power plants.

The findings revealed that the developed demonstration board for basic solar system installation serves as an educational tool for renewable energy education. These findings are consistent with (Alqhatani et al., 2018), who highlighted that the demonstration board holds significant relevance to technical education, primarily because it offers students a tangible platform to bridge theoretical knowledge with practical skills.

The results indicate that the demonstration board can improve practical learning in the installation of solar PV systems by giving students the opportunity for practical experience. It can help bridge the gap between the theoretical teaching and practical application and, at the same time, assist in the development of technical skills relevant to renewable energy technologies. As a result, the board has the potential to serve as a valuable teaching aid in the field of electrical/electronic technology education, especially in organizations where access to working solar PV training facilities is limited.

CONCLUSION

This work successfully achieved the design and construction of a functional demonstration board for a basic solar photovoltaic (PV) system installation, intended to serve as an effective pedagogical tool for renewable energy education. The system integrates essential solar PV components, including a photovoltaic cell for direct sunlight-to-electricity conversion, a rechargeable battery for energy storage, an inverter for DC-to-AC conversion, a charge controller for regulating power flow between the battery and connected loads, a fan for cooling applications, and both AC and DC lighting loads, all interconnected via appropriately rated switches and wiring.

The completed demonstration board was subjected to comprehensive performance testing to validate its operational integrity. Tests were conducted to verify load operation and power consumption, confirm the security of all electrical connections, and assess the system's capability to effectively charge the battery under varying conditions. The results confirmed satisfactory performance across all parameters, demonstrating the system's reliability and functionality.

The demonstration board has proven to be a valuable educational resource, providing students and trainees with a tangible platform to visualize and comprehend the complete operational sequence of a solar PV system. Furthermore, it facilitates the understanding of critical safety guidelines, component interrelationships, and the technical requirements necessary for practical solar system installation. By bridging the gap between theoretical knowledge and hands-on application, this work contributes meaningfully to the advancement of technical education in renewable energy and supports the development of skilled manpower for the growing solar energy sector.

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