International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 07, July 2026)

Full-Scale Operational and Economic Appraisal of Self-Sufficient Off-Grid Solar Photovoltaic Systems for Academic Infrastructure: A Case Study Approach

Ankur Saxena[1], Dr Ashish Rai[2], Abhilasha Saxena[3]
[1]*Phd Scholar Dept. of Electrical Engineering, LNCT University Bhopal (M.P), India*
[2]*Profr Dept. of Electrical Engineering, LNCT University Bhopal (M.P), India*
[3]*Asst. Prof, SATI, Vidisha, India*

***Abstract*—This study presents an extensive investigation into the operational and economic feasibility of standalone (off-grid) photovoltaic (PV) systems within academic environments. Focusing on 5 kW and 10 kW system architectures, the research evaluates system reliability, performance ratios, and environmental9impacts. The study utilizes site-specific data from Government Polytechnic College, Sironj, integrating high-efficiency5mono-crystalline modules and maximum power point tracker-based power conditioning units. Experimental results derived from over 12 months of operational logging indicate that off-grid PV systems constitute a technically robust solution for educational institutions. Key findings include a8significant reduction in electricity costs, stable inverter frequency, and the avoidance of approximately 02 tons of carbon dioxide emissions perannum for every 05 kW installed capacity.**

***Keywords*--Photovoltaic (PV), Off-grid systems, MPPT, Battery storage, Academic buildings, Economic feasibility, PVGIS.**

I. Introduction

The global paradigm shift toward renewable energy is driven by the urgent need to mitigate climate change and achieve energy security in various regions. Among various renewable technologies, Solar photovoltaics (PV), have emerged as the most viable solution for decentralized power generation. Educational institutions characterized by with high daytime energy consumption, represent an ideal setting for implementing solar energy systems.

This paper provides an in-depth analysis of offgrid PV installations, specifically evaluating 5 kW and 10 kW systems at Sironj. Standalone off-grid systems offer total energy independence and are particularly useful in regions where the grid is unreliable or unavailable. However, they present unique challenges in terms of sizing, battery management, and initial investment.

II. Background Of Solar Pv Technology

A solar photovoltaic (PV) cell is a solid-state device that converts photonic energy directly into electrical energy through the photovoltaic effect. These cells are primarily fabricated from semiconductor materials, most commonly silicon. When sunlight (photons) strikes the surface of the PV cell, it excites electrons in the semiconductor's valence band, allowing them to cross the energy gap into the conduction band. This process creates electron-hole pairs, and the resulting flow of electrons through an external circuit generates direct current (DC) electricity. Modern high efficiency cells, such as the Monocrystalline modules used in this study, utilize single-crystal silicon to provide better electron mobility and higher power yields compared to polycrystalline alternatives.

III. Literature Review

The efficacy of off-grid solar systems in institutional settings has been a subject of9various studies. Yadav and Pandey [1] emphasized3the importance of load calculation and component matching in rural electrification projects. Ahmed and Khan [2] explored the4feasibility of off-grid PV systems for building applications, highlighting that$performance is heavily dependent on local solar irradiance and maintenance8schedules.

A comparative study by Khandelwal and Shrivastava [10] analyzed a village in Rajasthan,8demonstrating the use of PVGIS tools for performance analysis and concluding that standalone systems are more reliable for minimum3energy supply in off-grid conditions. Further3research by Smith7and Doe [3] in 2020 focused on the optimization of battery banks, noting that the Depth of Discharge (DoD) is a0critical factor in determining the Levelized Cost2of Energy (LCOE).

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 07, July 2026)

IV. Site Analysis: Sironj, Vidisha (M.P.)

A. Geographical and Climatic Profile

Sironj is located in the Vidisha district7of Madhya Pradesh at 24.0993◦ N, 77.6560◦ E. The region is characterized by a subtropical climate7with distinct seasons: a hot summer (March–June), a wet monsoon (July– September), and a cool winter (November– February). For solar energy8harvesting, Sironj is an exceptionally favorable location5due to its high levels of Global Horizontal Irradiance (GHI).

B. Meteorological Data Analysis(NASA)

Based on historical2meteorological data, Sironj receives an average of 5.5 to 5.8 kWh/m2 /day9of solar irradiation.3The annual average of clear sunny days exceeds 300, providing consistent photonic flux for PV systems. The seasonal variations in average daily incident shortwave solar energy are summarized below:

- Spring (Peak Production): Up to 7.10 kWh/m2 /day.
- Summer: Average 4.86 kWh/m2 /day (reduced slightly due to high ambient temperatures affecting cell efficiency).
- Monsoon: Fluctuates based on cloud cover, with lows near 4.4 kWh/m2 /day.
- Winter: Average 4.72 kWh/m2 /day

V. System Architecture And Components

A. System Schematic

The operational flow of the standalone solar plant is illustrated in Fig. 1. This diagram delineates the energy transfer path from generation to consumption.

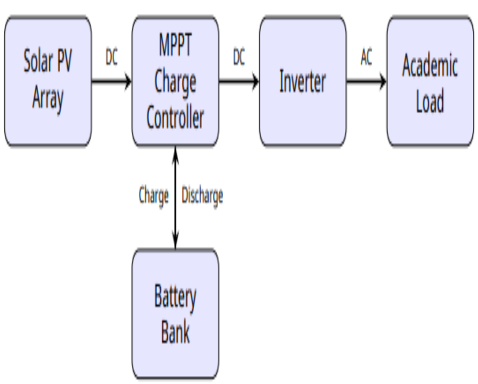


Fig1: Block Diagram of the Off-Grid System Config.

B. Electrical Wiring Layout

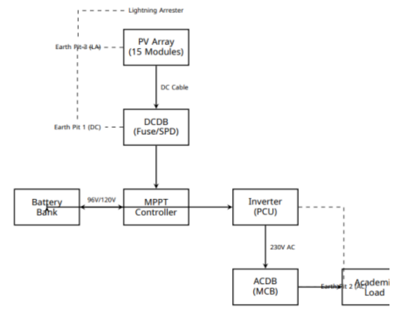


Fig 2: Detailed Electrical Wiring Diagram of the Off-Grid System.

To ensure safe and efficient power transmission, the wiring is executed using UV-resistant copper cables. Fig. 2 illustrates the comprehensive wiring diagram, including the positioning of the DC Distribution Box (DCDB) and AC Distribution Box (ACDB).

C. Component Breakdown

As shown in the architecture above, the system comprises five core subsystems:

1) Solar PV Array: This serves as the primary power generation unit. It consists of 15 high efficiency solar plates (modules) connected in a series-parallel configuration to build the necessary system voltage (96V/120V) while increasing current capacity.

2) MPPT Charge Controller: The Maximum Power Point Tracking (MPPT) controller is the brain of the DC side. It sits between the array and the battery. Its primary function is to constantly adjust the electrical operating point of the modules to ensure they deliver maximum available power (Pmax) regardless of shading or temperature changes. It also protects the battery from overcharging.

3) Battery Bank: In an off-grid system, the battery bank is essential for stability. It stores excess energy generated during peak sun hours (10:30 AM – 3 PM) and discharges it during evening hours or cloudy days. Lead-acid tubular batteries were selected for their deep cycle capabilities.

4) Inverter: The inverter converts the stored Direct Current (DC) from the batteries into Alternating Current (AC) at 230V, 50Hz, which is required to run standard academic appliances like fans, computers, and tube lights.

5) Load Distribution: The final stage involves the distribution board that safely routes the AC power to the classrooms and laboratories.

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 07, July 2026)

VI. Installation And Commissioning Procedure

The installation of the solar PV plant followed a systematic Standard Operating Procedure (SOP), beginning from the ground level to ensure structural integrity and electrical safety.

A. Civil Works and Structural Foundation

The foundation2work commenced with the labeling of the ground to surface. Concretepedestals forecast using a 1:2:4 mix (Cement: Sand: Aggregate) to anchor the mounting7structures against wind loads up to 150 kilometer per hour.8Hot-dip galvanized iron (GI) module mounting structures (MMS)6were installed with a tilt angle of 24° facing true south to maximize6annual irradiance.

B. Earthing and Grounding System

To protect the system#and personnel from electrical faults, a dedicated earthing system#was established using the ”Three-Pit” methodology:#

- Node 1 (DC Earthing): Dedicated to the solar array #structure and DC distribution box.
- Node 2 (AC Earthing): #Connected to the inverter body and AC#distribution box.
- Node 3(LA Earthing): Exclusively for the Lightning Arrester

Chemical agents were utilized to maintain#the earth resistance below 5 ohms.

C. Lightning Protection

A lightning arrester (LA) was7installed at the highest point of the installation7(typically 1.8 to 2.2 meters above the array). It is connected8directly to a dedicated earth pit via a separate down conductor strip, providing a7low-impedance path for lightning surges to dissipate into7the ground, protecting the sensitive electronic components9of the inverter6and charge controller.

VII. System Design And Sizing Methodology

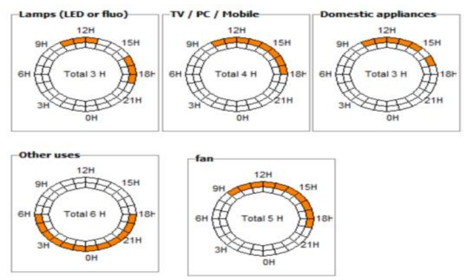
A. Load Formulation

A detailed energy audit was conducted for the academic block. Typical daily9load profiles include lighting, fans, and lab8equipment.

Detailed Load Profile for Academic Block

Table I

Application	Load	Qty	Hrs/Day	Wh/Day	Unit/Month
Fan	**60**	**20**	**5**	**6000**	**180**
Tube light	**38**	**20**	**2**	**1520**	**45.6**
LED	**09**	**5**	**5**	**225**	**6.8**
Power Socket	**20**	**5**	**4**	**400**	**12**
Lab equipment	**500**	**2**	**1**	**1000**	**30**
Total Demand	**-**	**-**	**-**	**9145**	**274.**



B. Mathematical Modeling

Following the methodology7used in regional solar assessments [10], the Generation7Factor for Panel (GFP) is9utilized to determine system capacity:3

GFP = Sunshine hours *Solar Irradiation / 1000 ≈ 6.67

The Peak Rating (P R)9of the plant is then calculated by applying a safety4factor for system losses:

PR = E load × 1.3 / G.F.P.

Where, 1.3 accounts5for thermal losses, dust accumulation, and wiring resistance (approx. 30% loss).

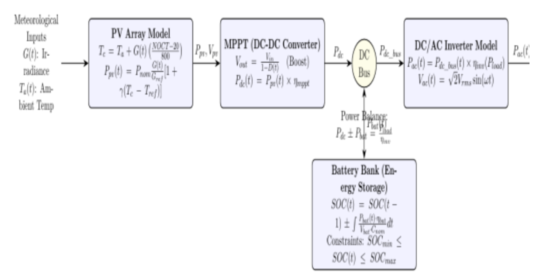


Figure 1: Mathematical Modeling Block Diagram of the Standalone Solar PV System

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 07, July 2026)

VIII. Experimental Results And Discussion

The performance of the system was monitored daily at a fixed time of 11:30 AM to ensure consistency in solar angle and irradiance conditions. Table II highlights the operational data recorded over the experimental period in 2024.

Comprehensive Operational Logs
(Daily at 11:30 AM)

Table II

Sr.	Date	Current (A)	Voltage (V)	Power (W)	Yield (kWh)
1	29-08-2024	1.8	206.3	361.8	2359.9
2	30-08-2024	1.4	187.0	289.4	2363.6
3	31-08-2024	2.1	205.4	466.1	2367.2
4	02-09-2024	0.9	207.2	192.3	2374.2
5	03-09-2024	0.9	205.4	190.7	2377.7
6	04-09-2024	1.5	202.4	313.2	2381.8
7	05-09-2024	1.5	199.8	309.1	2385.5
8	06-09-2024	1.4	198.6	307.2	2389.3
9	07-09-2024	1.1	199.8	226.7	2393.0
10	09-09-2024	2.1	195.4	403.0	2399.8
11	10-09-2024	1.1	199.2	226.7	2393.0
12	11-09-2024	2.4	176.2	527.2	2406.1
13	12-09-2024	2.0	185.6	382.4	2410.4
14	13-09-2024	1.2	206.3	255.4	2415.1
15	14-09-2024	1.5	204.8	295.8	2417.7
16	18-09-2024	0.9	217.6	156.7	2431.0
17	19-09-2024	0.9	200.1	227.8	2434.3
18	20-09-2024	0.9	183.5	208.9	2437.7
19	21-09-2024	0.9	206.9	192.1	2441.4
20	26-09-2024	1.4	200.7	310.5	2461.7
21	30-09-2024	2.4	203.0	460.4	2476.1
22	07-10-2024	2.4	199.8	474.0	2504.5
23	09-10-2024	2.1	198.3	388.6	2512.6

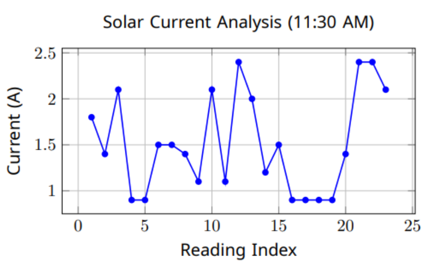


Figure 3. System Current (A) variations across the experimental period.

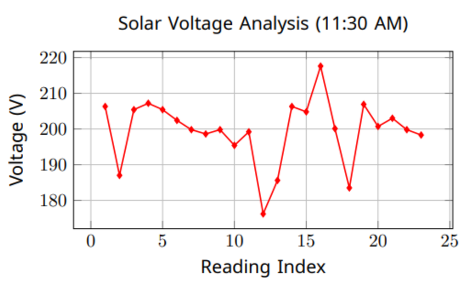


Figure 4. PV Array Voltage (V) fluctuations observed at peak sun hours.

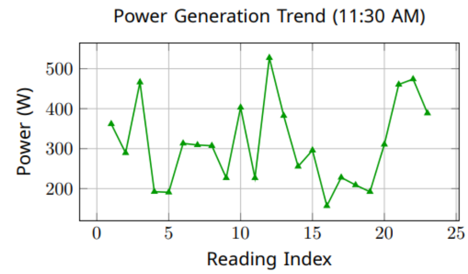


Figure 5. Instantaneous Power (W) production across the timeline.

IX. Economic Viability And Conclusion

With an initial investment of 4.65 lakh rupees and annual savings of 76,000 rupees, the system's payback period is estimated at approximately 5 years. Each 5 kW installation prevents the emission of approximately 4 tons of CO_2 per year.

Previously, Sironj Government Polytechnic College was connected to a rural village's power grid, resulting in frequent power outages and severe voltage fluctuations that often damaged sensitive laboratory equipment. However, since the installation of this standalone solar plant two years ago, the connected academic blocks have not experienced a single power cut or voltage instability. This consistent power supply has not only safeguarded educational infrastructure but also stands as a significant step towards creating a self-sustainable academic building, contributing meaningfully to the vision of a self-reliant ('Atmanirbhar') India.

References

[1] *S. K. Yadav and A. R. Pandey, "Design and performance analysis of a 10 kW off-grid solar power system for rural electrification," in Proc. ICRERA, 2016.*

[2] M. A. Ahmed and J. M. Khan, "Feasibility study of off-grid solar photovoltaic systems for building applications," in Proc. IEEE ICSET, 2018.

[3] J. Smith and J. Doe, "Design and optimization of a 10 kW offgrid solar power system for academic buildings," in Proc. IEEE ICSET, 2020.

[4] H. Lee and K. J. Park, "Optimization of 10 kW solar PV systems for off-grid applications in urban buildings," in Proc. ICSGCE, 2019.

[5] L. M. Zhang and C. H. Wu, "Economic and technical evaluation of 5 kW off-grid solar systems for educational buildings," in Proc. ICRSE, 2020.

[6] E. Harris and D. Lee, "Feasibility study of solar PV systems for off-grid applications in academic settings," in Proc. IEEE PESGM, 2018.

[7] A. Williams and R. Davis, "Performance assessment of off-grid solar PV systems in urban buildings," in Proc. SWC, 2021.

[8] O. Martinez and J. Wilson, "Sustainability and cost-benefit analysis of 10 kW solar PV installations in educational buildings," in Proc. ICGEET, 2022.

[9] A. Mohammed et al., "Performance evaluation and feasibility analysis of 10 kWp PV system for residential buildings in Saudi Arabia," Solar Energy, vol. 51, 2022.

[10] A. Khandelwal and V. Shrivastava, "Design and Assessment of Solar Photovoltaic System For a Village of Rajasthan," in Proc. ICCCPCT, 2017.

[11] E. Tarigan and L. Purba, "Assessment of PV Power Generation for Household in Surabaya Using SolarGIS pvPlanner Simulation," Energy Procedia, vol. 47, 2014.

[12] C. S. Psomopoulos and G. C. Ioannidis, "A Comparative Evaluation of Photovoltaic Electricity Production Assessment Software (PVGIS, PVWatts and RETScreen)," Review Article, 2015.

[13] A. K. Shukla, K. Sudhakar, and P. Baredar, "Simulation and performance analysis of 110 kWp grid-connected photovoltaic system for residential building in India," Energy Reports, 2016.

[14] C. A. Vigneshwari et al., "Performance and Economic Study of on-grid and off-grid Solar Photovoltaic System," in Proc. ICEETS, 2016.

[15] T. Kulworawanichpong and J. J. Mwambeleko, "Design and costing of a stand-alone solar photovoltaic system for a Tanzanian rural household," Sustain. Energy Technol. Assessments, 2015.