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Simulation based design and technoeconomic analysis of a stand alone solar PV system with battery storage in government hostel building

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Abstract

India's growing energy demand and the persistent challenge of rural electrification highlight the urgent need for decentralized, sustainable power solutions. Stand-alone solar photovoltaic (SAPV) systems with battery storage offer a viable alternative for ensuring reliable electricity supply in off-grid and partial electrification regions. The novelty of the proposed methodology lies in the integrated, site-specific assessment of a stand-alone PV-battery system for a rural institutional building, combining technical performance, battery behaviour, energy balance, techno-economic feasibility, and environmental benefits, with comparative evaluation against grid electricity and diesel-based generation. This study presents the design and performance analysis of an SAPV system for the boys' hostel of Government Degree College, Fatehpur, India, using PVsyst simulation. The proposed system consists of eleven crystalline PV modules (550 Wp each), an off-grid inverter, and a lead-acid battery storage system to ensure energy autonomy. Results indicate an annual performance ratio of 73.1% and a solar fraction 91.2%, which shows the system's ability to effectively meet hostel electricity demand throughout the year despite seasonal variations. The annual electricity generation of 7286.1 kWh was used for the economic assessment with a levelized cost of energy (LCOE) of USD 0.094/kWh. Using a net present value-based approach, the discounted payback period is estimated as 11.14 years when evaluated against grid electricity tariffs, while a significantly shorter payback period of 2.16 years is achieved under diesel displacement conditions. Environmental analysis indicates substantial CO₂ emission mitigation over the system lifetime, along with additional economic benefits through carbon credit generation. Overall, the study demonstrates that well-designed SAPV systems with battery storage are technically feasible, economically viable, and environmentally beneficial solutions for promoting sustainable energy access in rural institutional applications.

Keywords Stand-alone PV (SAPV) System, Battery storage, Performance ratio, Solar fraction, Rural electrification



1 Introduction

Despite rapid economic growth and significant advancements in the power sector in India, large sections of rural and semi-urban areas continue to face unreliable or insufficient electricity supply [1]. This energy gap not only hinders nation development but also perpetuates dependence on conventional fossil fuel-based solutions, which are costly, environmentally unsustainable, and inadequate to meet the growing demand. In this context, solar photovoltaic (SPV) systems have emerged as a reliable, clean, and decentralized energy source capable of addressing power needs while contributing to national renewable energy targets [2]. The initiatives taken by Government of India to the adoption of SPV technologies has increased the deployment of SPV systems. The National Solar Mission aims to increase the country's solar power capacity and improve access to clean and reliable energy, particularly in geographically remote and energy-scarce regions [3]. Despite these favourable government policies promoting SPV technologies, challenges remain in ensuring equitable access to reliable electricity, particularly in rural and remote regions [4]. The adoption of stand-alone PV systems with battery storage enhances energy equity, supports environmental sustainability in rural areas. Therefore, the implementation and evaluation of such systems hold not only technical but also strategic significance within the broader global agenda for sustainable development.

Numerous studies have explored stand-alone PV (SAPV) systems using the different methods and designing process. In a study, researchers used daily utilization and load demand to size the PV array, solar charge controller, backup battery storage, DC/AC inverter, and connecting cables [5]. A study determines the sizing of a standalone PV system for a remote health clinic. A 3.2 kW stand-alone PV system was developed in MATLAB/Simulink using the perturb and observe (P&O) MPPT algorithm, demonstrating efficient maximum power extraction under varying irradiance and temperature conditions [6]. Li et al. [7] used real-world data to optimize PV systems with battery energy storage systems (BESS) particularly PV panel size, BESS capacity, and BESS charging/discharging schedule to minimize the long-term cost of utility bills using mixed integer nonlinear programming (MINLP). They applied the newly developed algorithms to San Francisco business user data which shows that the system breaks even at the 66th month and reduces system cost by 29.3%. In another study, Wang et al. [8] evaluated photovoltaic–battery energy storage for building power supply, showing that combining solar generation, battery storage, and the grid can reliably meet energy demand under varying conditions. Results demonstrate technical feasibility and practical benefits, though frequent battery cycling may raise long-term costs. Overall, the approach enhances sustainability and provides useful guidance for efficient building energy management. Behmann et al. [9] analysed various designs for integration of the battery into the micro-photovoltaic system. Thus, battery and photovoltaic modules have a parallel electrical link in a passive hybrid structure. Resulting PV/battery/inverter systems with 300 Wp PV and 555 Wh battery were tested in continuous operation over three days under real solar irradiance conditions. The experimental results demonstrated that both active and passive coupled architectures were feasible for the integration of photovoltaic modules with battery storage systems.

Recent studies have demonstrated the growing application of photovoltaic systems for institutional and educational buildings. Balal et al. [10] designed and simulated a rooftop PV system for a university building, highlighting the usefulness of simulation tools

in evaluating system performance before installation. Aktas and Ozenc [11] performed a comprehensive techno-economic and environmental assessment of a grid-connected solar plant for Siirt, Turkey, using PVsyst, PV*SOL, and HOMER Pro. It projects 762 MWh/year, with IRR 19.55%, NPV USD346,085, LCOE USD0.1892/kWh, and a 17.4-year payback, alongside economic and environmental assessments. Similarly, Zukowski and Sobolewski [12] presented a technical and economic evaluation of a 210 kWp photovoltaic system at Bialystok University of Technology, using DesignBuilder simulations and regression analysis. Five panel arrangements were compared via NPV and IRR. The optimal design features three vertical rows at 37° tilt, producing 166,392 kWh/year. Eiva et al. [13] investigated the design and techno-economic performance of a 135-kW grid-tied PV system for a university's remote building. To evaluate the system's optimal size, technical specifications, and electrical power output, they used SketchUp for shadow analysis tools and PVsyst for PV on-grid design. Recent researches used different simulation tools to design and analysis of SAPV system. Nkuriyingoma et al. [14] conducted a techno-economic analysis of solar PV–battery system for 100 households in Rwanda using PV*SOL. They found that 57.33 kWp PV with 89.2 kWh storage can meet demand efficiently, achieving strong performance and economic viability, with a 9.14% return on assets and a payback period under ten years.

Hassan et al. [15] analyzed and designed a stand-alone solar-powered irrigation system using PVsyst for optimization. The system comprises 14 PV modules, a 4-kW inverter with MPPT, and an AC submersible pump matched to irrigation demand. Simulations show a 5.3 kW peak output and a 57.2% annual performance ratio. They applied water tanks as storage, allowing the system to align solar availability with water demand. Researchers modeled a stand-alone PV system on the roof of the College of Engineering parking structure at Al-Nahrain University to power the garage and engineering labs using PVsyst. The Park garage roof area was selected as the key design factor. They discovered that the best tilt angle for solar panels in the event of shadows is 19° to the south, and the PV system using CdTe panels has the lowest kWh unit price (USD 0.236/kWh) when compared to the other three varieties [16]. Another study used PVsyst to design and analysis of a solar PV system integrated with battery energy storage system (BESS) at composite climate of Indian village. They found that the designed SPV system has a capacity of 1.785 Wp and has a battery storage of 560 Ah. The results revealed that the system produces 2149.28 kWh of energy per year, with a performance ratio (PR) of 72.75% and a solar fraction (SF) of 98.31% [17]. Although numerous studies have investigated the design and techno-economic performance of photovoltaic systems, most have focused on grid-connected configurations or general system optimization. Limited attention has been given to the simulation-based evaluation of stand-alone PV systems with battery storage for government educational institutions under composite climatic conditions. Moreover, comparative assessments of grid electricity and diesel generator displacement, together with their environmental benefits, remain limited. To address these research gaps, the present study develops and evaluates a stand-alone photovoltaic system with battery storage for a government hostel building using PVsyst. Unlike previous PVsyst-based studies that primarily focus on system sizing, energy yield, or techno-economic assessment, the present work provides an integrated, site-specific evaluation under the composite climatic conditions of Fatehpur, India. The distinctive contribution of this study lies in simultaneously assessing monthly energy balance, battery behaviour,

performance ratio, solar fraction, system losses, life-cycle cost, and discounted payback under both grid-electricity and diesel-displacement scenarios, together with life-cycle CO₂ mitigation and carbon-credit potential.

To address these research gaps, the present study develops and evaluates a stand-alone photovoltaic system with battery storage for a government hostel building using PVsyst. The proposed system is comprehensively assessed in terms of technical performance, economic feasibility, and environmental benefits under the composite climatic conditions of Fatehpur, India. The novelty of this study lies in its comprehensive assessment of the proposed system through technical, economic, and environmental analyses, including energy balance, system losses, battery behaviour, performance ratio, solar fraction, life-cycle cost, payback period, and carbon emission mitigation using site-specific simulation data. In addition, the study seeks to evaluate how the deployment of such a system contributes to the broader goals of United Nations Sustainable Development Goals (SDG 7: Affordable and Clean Energy, SDG 11: Sustainable Cities and Communities, and SDG 13: Climate Action). This tailored approach offers valuable insights for rural educational institutions where reliable electricity access is essential for academic and residential activities.

2 Materials and methods

2.1 Description of the site

This study aims to design a stand-alone solar PV system integrated with battery storage for the boys' hostel of Sadanand Degree College in Chheolaha, Fatehpur analyse its performance using simulation data, and assess its economic and environmental benefits. The geographical coordinates of the sites are 25°55'51'' N and 81°03'55'' E. The region experiences a composite climate with hot summers, a humid monsoon season, and relatively cold winters which receives an average solar irradiation of 5.5 kWh/m²/day. The overview of the selected site is represented in Fig. 1. The total available roof area was calculated as 731.71 m², which is significantly larger than the area required to accommodate the estimated photovoltaic array. With each 550 Wp module occupying approximately 2.6 m², the total array of 11 modules (Fig. 2) arranged in a single string requires 28.7 m², leaving ample roof space for future expansion or additional installations. The surplus roof area also ensures flexibility in maintaining optimal tilt and azimuth without spatial constraints, thereby supporting the long-term operational efficiency and scalability of the system.

2.2 Load estimation

The daily energy demand of the hostel was estimated by considering the electrical appliances used by students and staff during the day. Table 1 represents the total load includes lighting, ceiling fans, refrigerators, televisions, mobile charging units, and other essential appliances. In addition to the active loads, a standby consumption of 0.024 kWh/day was included in the load profile to represent the continuous low-power demand of electrical appliances and electronic devices in standby mode. Considering standby consumption in the load estimation provides a more realistic representation of actual electricity demand and is recommended for accurate sizing and performance simulation of stand-alone photovoltaic systems [18]. As Table 1 suggests the total daily electrical energy demand of the hostel was estimated to be approximately 21.90 kWh/day, which was used as the

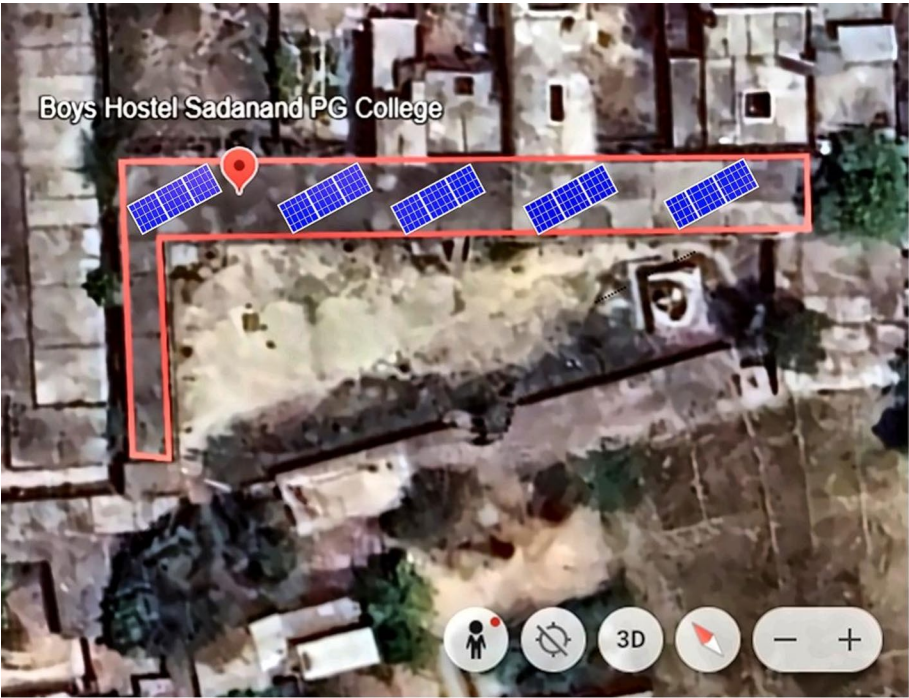


Fig. 1 Satellite view of the hostel roof with selected installation area. Figure is created by using Google Earth (<https://earth.google.com/web>)

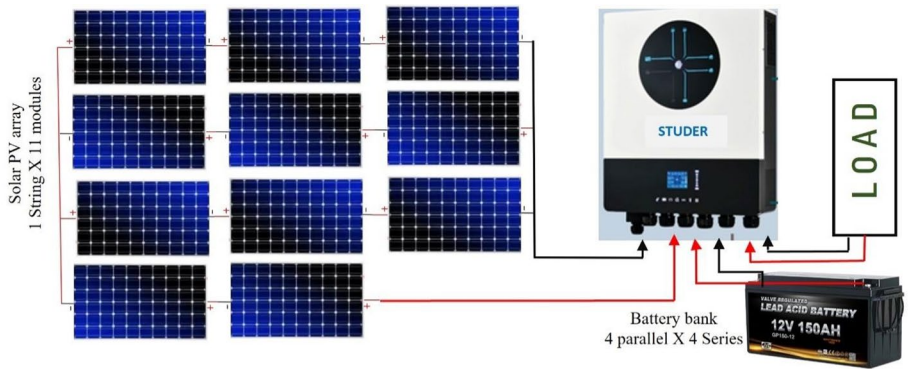


Fig. 2 Proposed stand-alone solar PV system to supply power for hostel demand

Table 1 Daily consumption of the hostel

S. No.	Appliances	Power (watt)	Quantity	Consumption (hours/day)	Energy (kWh/day)
1.	LED lamp	20	18	12	4.320
2.	Television	60	1	3	0.180
3.	Fridge	100–150*	1	24	2.501
4.	Fan	60	15	12	10.800
5.	Mobile charger	10	15	0.5	0.075
6.	Iron	1000	2	2	4.000
7.	Standby Consumption	1		24	0.024
Total energy consumption					21.900

*The refrigerator operates intermittently due to thermostat-controlled compressor cycling; hence, its average energy consumption is lower than its rated power. Therefore, the PVsyst model uses the estimated daily energy consumption for load estimation

design load for the PVsyst simulation. The estimated demand indicates a representative annual average daily load profile, with the hostel electricity consumption assumed to remain nearly constant throughout the year. Energy consumption was assumed to remain nearly constant across the year to simplify system design.

2.3 Selection of PVsyst simulation software

PVsyst was selected for designing SAPV system, because it is one of the most widely accepted and validated software packages for the design, simulation, and performance evaluation of SPV systems [19]. It provides comprehensive modelling of PV modules, battery storage, charge controllers, inverters, and load profiles while incorporating site-specific meteorological data such as solar irradiance, ambient temperature, and geographical location. For stand-alone PV systems, PVsyst offers advanced battery management algorithms, energy balance analysis, detailed loss assessment, and reliability evaluation under varying climatic conditions. These features enable accurate prediction of annual energy production, battery state of charge, performance ratio, solar fraction, and system losses [20]. PVsyst was selected because the present study focuses on the detailed design and performance assessment of a stand-alone PV–battery system. It provides an integrated framework for modelling the PV array, battery, inverter, load, site-specific meteorological conditions, energy balance, system losses, performance ratio, solar fraction, and system yields. Compared with HOMER Pro and MATLAB/Simulink, which are primarily suited to hybrid-system optimization and detailed dynamic modelling, respectively, PVsyst directly supports the photovoltaic-specific performance and loss analysis required in this study [21–23].

2.4 Simulation procedure

Figure 3 presents the overall methodology adopted in this study. The workflow begins with site assessment and load estimation, followed by the sizing of the PV array and battery bank. The PVsyst model incorporated local meteorological data such as solar irradiance, ambient temperature, and seasonal variations [24]. The software generated detailed monthly outputs including available energy, array output, final user energy, performance ratio, solar fraction, system losses, yields, battery state of charge, and current profiles. The photovoltaic array, inverter and battery bank were then selected for simulation whose detailed characteristics given in Tables 2, 3 and 4. Considering the system capacity, we selected a 550-Watt crystalline Trina Solar PV module (TSM-DE19-550Wp), a 6.0 kW UTL off-grid solar inverter and a Brawn Solar battery chosen to design the system. The battery bank and inverter capacities were selected based on the estimated load demand and the PV system configuration. The battery bank was sized to provide adequate energy storage during periods of low solar irradiance, while the 6.0 kW off-grid inverter was selected to satisfy the peak load demand and ensure compatibility with the 6.05 kWp PV array for reliable system operation. The PV modules were installed at a tilt angle of 23° with 0° Azimuth. The PV modules were installed at a tilt angle of 23° with an azimuth of 0° (south-facing orientation). The tilt angle was calculated using the widely adopted empirical relation ($\text{Tilt} = \text{Latitude} \times 0.9$) given by Dang and Sharma, confirmed that, for year-round operation, the maximum solar energy is collected when the tilt is 0.9 times the latitude angle [25]. For the installation site at Fatehpur, located at a latitude

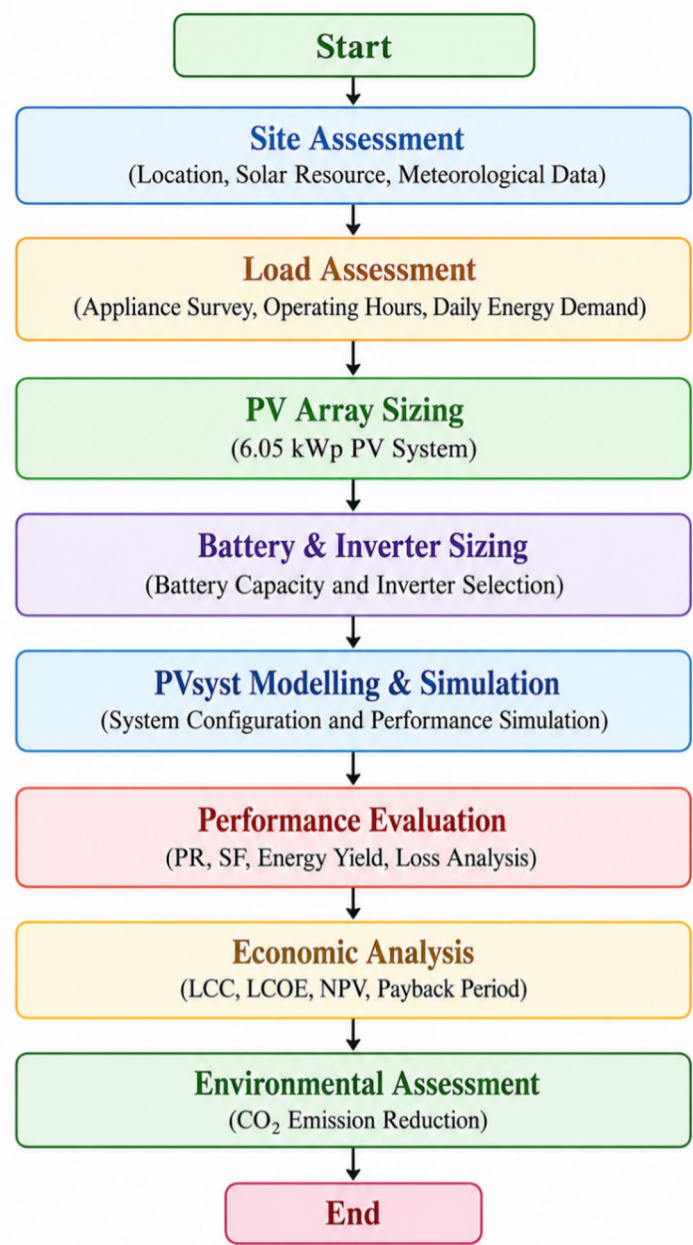


Fig. 3 Methodological framework for the design and evaluation of the proposed SAPV system

Table 2 Specification of the solar PV module

Description	Value
Maximum power (Pmp)	550 Wp
Open circuit voltage (Voc)	37.90 V
Short circuit current (Isc)	18.52 A
Maximum power voltage (Vmp)	31.60 V
Maximum power current (Imp)	17.40 A
Efficiency	21.05%
Temperature coefficient of Voc	−0.28%/°C
Temperature coefficient of Isc	0.040%/°C
Temperature coefficient of Pmax	−0.34%/°C

Table 3 Specification of the proposed battery

Parameters of battery	
Technology	Lead-acid, VRLA
Nominal voltage	12.0 V
Capacity at C10	100 Ah
AH efficiency	>90 (%)
Operating temperature range	− 10° to 50 °C

Table 4 Inverter specifications

Description	Values
DC Input	125–500 Vdc
MPPT	150–425 V
Maximum input voltage	500 Vdc
Nominal output voltage	48 V
Maximum power output	6.0 kW
Maximum efficiency	97.6%
Euro efficiency	96.5%

of 25.9° N, this formula gives an optimal tilt of approximately 23°, which was therefore selected for the system.

2.5 Performance parameters

Key performance parameters such as performance ratio (PR), and different yields were used to quantify the effectiveness of the system [26]. In addition, loss analysis (array capture losses, system losses, unused energy, and battery-related losses) was performed to understand the main contributors to performance variability. Battery performance was assessed using voltage, state of charge (SOC), and charging/discharging current profiles, providing insights into storage efficiency and reliability. We can estimate the performance of the same PV system under different climatic conditions [27].

2.5.1 Yields

The mathematical expressions for estimating the different yield components of the PV plant are outlined below:

$$Y_A = \frac{E_{A, DC}}{P_o} \quad \text{kWh/kWp/day} \quad (1)$$

$$Y_F = \frac{E_{AC}}{P_o} \quad \text{kWh/kWp/day} \quad (2)$$

$$Y_R = \frac{H_T}{G_o} \quad \text{kWh/kWp/day} \quad (3)$$

In this context, Y_A , Y_P and Y_R represent the array yield, final yield, and reference yield, respectively. $E_{A, DC}$ (kWh) denotes the DC energy output from the PV array, while P_o (kW) corresponds to the array's rated output power. E_{AC} (kWh) refers to the total AC energy generated per day, G_o (W/m²) indicates the reference irradiance, and H_T (kWh/m²/day) represents the average daily in-plane solar insolation.

2.5.2 Performance ratio (PR)

The PR reflects the actual operational efficiency of a solar PV system under real-field conditions. It is defined as the ratio between the final yield and the reference yield.

$$PR(\%) = \frac{Y_F}{Y_R} \times 100 \quad (4)$$

PR analysis serves as a key indicator for evaluating how effectively the installed system performs relative to its rated capacity, accounting for environmental and technical losses. The performance ratio value of a PV system usually varies between 0.60 and 0.80.

2.5.3 Solar fraction (SF)

It is expressed as the proportion of the total energy demand of a load that is met by the solar PV system, either directly from the array or indirectly through the battery storage. It reflects the system's capability to satisfy user demand without requiring auxiliary or backup sources. it can be expressed as:

$$SF(\%) = \frac{E_{user}}{E_{load}} \times 100 \quad (5)$$

A solar fraction of 100% indicates that the PV system alone meets the entire load, while lower values signify partial dependence on alternative sources.

2.5.4 Various losses

In the performance analysis of any system, an accurate estimation of system losses is very important. The losses considered in our work are.

2.5.4.1 System losses (L_S) System losses occur during the conversion of the DC electric energy into AC electric energy. These losses are caused by inverter, conduction, and losses of passive circuit components.

$$L_S = Y_A - Y_F \quad \text{kWh/kWp/day} \quad (6)$$

2.5.4.2 Array capture losses (L_C) Array capture losses occur due to array operation, which can represent as:

$$L_C = Y_U - Y_A \quad \text{kWh/kWp/day} \quad (7)$$

Here Y_U is the normalized potential PV production.

2.5.4.3 Unused (Full battery) losses (L_U) Unused or full battery losses represent the portion of generated solar energy that cannot be utilized because the battery bank is already fully charged and the load demand at that time is lower than the available PV output.

$$L_U = Y_R - Y_U \quad \text{kWh/kWp/day} \quad (8)$$

2.6 Economic performance

It is a method for determining the current and future costs of a system over its lifetime. In the present study, life cycle cost (LCC) of stand-alone solar PV system has been calculated taking 25 years of lifetime [28].

2.6.1 Levelized cost of energy (LCOE)

The LCOE is defined as the ratio of the total life cycle cost to the total generated electricity over its lifetime by the PV system. It represents the average cost of producing one unit of electricity and is widely used to evaluate the economic feasibility of solar PV systems [29, 30]. The LCOE of the SAPV system is formulated as:

$$\text{Levelized Cost of Energy (LCOE)} = \frac{\text{LCC}}{\text{Lifetime generated electricity}} \quad (9)$$

$$\text{Lifetime generated electricity} = \sum_{t=0}^n \frac{E_{AC} \times (1-d)^t}{(1+i)^t} \quad (10)$$

In India, LCOE is measured as in USD/kWh. Here E_{AC} is the yearly generated electricity by the PV system, ' t ' denotes the year of operation (1, 2, ..., n) over the project lifetime, ' n ' the life of the system, ' i ' is the interest rate, and ' d ' is the PV modules degradation rate.

LCC represents the total present value of all costs incurred during the lifetime of the system and is given by:

$$\text{LCC} = C_0 + C_{MR} + C_R - C_s \quad (11)$$

where C_0 is the initial capital cost, C_{MR} is the maintenance and repair cost of the system that occurs during its working period. M represents as the annual average maintenance and repair cost of the SPV system. C_{MR} in terms of present value is calculated as:

$$C_{MR} = M \times \left[\frac{(i+1)^n - 1}{i(i+1)^n} \right] \quad (12)$$

The replacement cost (C_R) accounts for the periodic replacement of major components such as batteries and inverter which is significantly higher in stand-alone PV systems with battery storage compared to grid-connected systems. The total C_R in present value terms is expressed as:

$$C_R = R_5 \times \left[\frac{1}{(i+1)^5} \right] + R_{10} \times \left[\frac{1}{(i+1)^{10}} \right] + R_{15} \times \left[\frac{1}{(i+1)^{15}} \right] + R_{20} \times \left[\frac{1}{(i+1)^{20}} \right] + R_{inv,15} \times \left[\frac{1}{(i+1)^{15}} \right] \quad (13)$$

where R_5 , R_{10} , R_{15} , R_{20} represent the battery replacement costs at 5, 10, 15, and 20 years, respectively, and $R_{inv,15}$ is the inverter replacement cost after 15 years of operation.

C_s is the salvage cost. It incurred during the post-life treatment of the system components [30]. If post-life treatment cost of the system is S_{PV} , then its salvage cost in terms of present value is:

$$C_s = S_{PV} \times \left[\frac{1}{(i+1)^n} \right] + S_5 \times \left[\frac{1}{(i+1)^5} \right] + S_{10} \times \left[\frac{1}{(i+1)^{10}} \right] + S_{15} \times \left[\frac{1}{(i+1)^{15}} \right] + S_{20} \times \left[\frac{1}{(i+1)^{20}} \right] + S_{inv,15} \times \left[\frac{1}{(i+1)^{15}} \right] \quad (14)$$

where S_{PV} represents the salvage value of the PV system at the end of its service life. S_5 , S_{10} , S_{15} , S_{20} denote the salvage values of batteries at the respective years and $S_{inv,15}$ is the salvage value of the inverter at the end of 15 years.

2.6.2 Payback period (PBP)

It is an important economic assessment indicator used to estimate the time required for a SAPV system to recover its initial capital investment. It is widely applied to evaluate the economic feasibility of solar PV systems. In the study, payback period of the solar PV system has been calculated using net present value (NPV) method [31]. The payback period corresponds to the time at which the cumulative NPV of the system becomes zero, which is formulated as:

$$NPV = \sum_{t=0}^n \frac{CF_t}{(1+i)^t} - C_0 \quad (15)$$

where ' n ' is the lifetime of the PV system (years), ' t ' is the year of operation, ' i ' is the annual interest rate, and C_0 is the initial capital investment of SAPV system. CF_t is the annual cash flow, which is determined from the monetary savings from the produced electricity by the PV system and calculated as:

$$CF_t = E_{AC}(1-d)^t \times C_E \quad (16)$$

where E_{AC} (kWh/year) is the electricity generated by the PV system in the first year, ' d ' is the annual degradation rate of the PV modules, and C_E (USD/kWh) is the unit cost of grid electricity.

The payback period of the present SAPV system was also evaluated against diesel-based electricity generation, which is commonly used in off-grid and remote locations. The annual cash flow of diesel-based electricity generation and is given by:

$$CF_t = E_{AC}(1-d)^t \times C_D \quad (17)$$

where C_D (USD/kWh) is the unit cost of grid electricity generated by a diesel generator which is estimated using the specific fuel consumption (S_{fc}) of the diesel generator and the prevailing diesel price as:

$$C_D = S_{fc} \times P_d \quad (18)$$

where S_{fc} is the specific fuel consumption (L/kWh) and P_d is the diesel price (USD/L).

2.7 Environmental performance

Solar rooftop PV systems offer a clean alternative to coal-based electricity generation, which is a significant source of the greenhouse gas carbon dioxide (CO_2). By generating power from sunlight, they help mitigate climate change by avoiding CO_2 emissions.

2.7.1 CO_2 Emission

This indicator represents the cumulative CO_2 emissions associated with the construction of PV systems, including emissions arising from the manufacturing of all system components. The life-cycle carbon dioxide emission factor for crystalline solar PV modules is taken as 0.053 kg/kWh [31], yearly CO_2 emission ($CO_{2,yr}$) is calculated as:

$$\text{CO}_{2,\text{yr}} = E_{AC} \times 0.053 \text{ in kg} \quad (19)$$

Lifecycle CO_2 emission ($\text{CO}_{2,\text{LC}}$) is calculated as:

$$\text{CO}_{2,\text{LC}} = \sum_{t=1}^n E_{AC} \times (1 - d)^t \times 0.053 \text{ in kg} \quad (20)$$

2.7.2 CO_2 mitigation

CO_2 mitigation refers to the reduction in carbon dioxide emissions achieved by generating electrical energy from the PV system, thereby offsetting the CO_2 emissions that would otherwise be released by coal-based thermal power plants to produce an equivalent amount of electricity. In India, although the average CO_2 emission factor for thermal power generation is approximately 0.98 kg CO_2/kWh , transmission and distribution losses increase the effective emission factor to 1.58 kg CO_2/kWh [32]. Annual CO_2 mitigation ($\text{CO}_{2,\text{mit}}$) is calculated as follows:

$$\text{CO}_{2,\text{mit}} = E_{AC} \times 1.58 \text{ in kg} \quad (21)$$

Annual CO_2 mitigation by replacing diesel-based electricity generation is calculated as follows:

$$\text{CO}_{2,D,\text{mit}} = E_{AC} \times \varepsilon_f \text{ in kg} \quad (22)$$

Emission factor (ε_f) of diesel is calculated from the equation as follows:

$$\varepsilon_f = S_{fc} \times E_d \quad (23)$$

where E_d is the CO_2 emission value produced on burning one litre of diesel, which is taken as 2.68 kg/l [33].

The net reduction in CO_2 ($\text{CO}_{2,\text{net}}$) for the SAPV system is determined by subtracting life-cycle CO_2 emissions associated with PV module manufacturing from the total CO_2 mitigation achieved due to electricity generation.

$$\text{CO}_{2,\text{net}} = [1.58 - 0.053] \times \sum_{t=1}^n E_{AC} \times (1 - d)^t \quad (24)$$

The net reduction in CO_2 replacing diesel-based electricity is calculated as follows:

$$\text{CO}_{2,D,\text{net}} = [0.868 - 0.053] \times \sum_{t=1}^n E_{AC} \times (1 - d)^t \quad (25)$$

2.7.3 Carbon credits earned

Carbon credits represent a market-based mechanism used to assign a quantifiable value to reductions in greenhouse gas emissions. One carbon credit corresponds to the verified reduction of one tonne of carbon dioxide equivalent (tCO_2e) and can be traded in international carbon markets, which is estimated as following:

$$\text{Earned Carbon Credits (ECC)} = \text{CO}_{2,\text{net}} \times C_{\text{CO}_2} \quad (26)$$

For replacing diesel-based electricity:

$$\text{Earned Carbon Credits (ECC}_D) = \text{CO}_{2,D,\text{net}} \times C_{\text{CO}_2} \quad (27)$$

where C_{CO_2} denotes the market price of one carbon credit. For carbon credit revenue estimation, a benchmark compliance carbon price of USD 74.07 per tonne CO_2 equivalent (tCO_2e) (EU ETS average 2024) is assumed [34].

3 Results and discussions

The optimized simulated solar PV system designed for the hostel has 1 parallel strings, and each string has 11 series-connected PV modules. The energy storage system consists of 16 batteries with a nominal capacity of 100 Ah. Figure 4 illustrates how the performance of the PV module varies with changes in cell temperature as 10 °C, 25 °C, 40 °C, 55 °C, and 70 °C and incident solar irradiance from 0 to 1000 W/m^2 . The figure demonstrates that as irradiance increases, the short-circuit current rises almost proportionally. Conversely, the open-circuit voltage decreases as temperature increases, due to the negative temperature coefficient of the module, which leads to reduced maximum power output at elevated operating temperatures [35]. At standard test conditions the module achieves its rated efficiency of around 21.05%, producing maximum power near 550 W.

Figure 5 illustrates the relationship between SOC and charge–discharge behaviour of the battery under different current conditions at a reference temperature of 20 °C. The battery is charged and discharged at varying current levels i.e., 112 A, 28 A, and 6 A for charging, and 112 A, 28 A, and 5.6 A for discharging, showing how current intensity influences the charging duration, SOC stability, and depth of discharge. The charge cut-off voltage is set at 52.5 V, while the discharge cut-off voltage is fixed at 43.5 V, ensuring that the battery operates within a safe range to avoid overcharging or deep discharging, both of which can significantly reduce its lifespan. The figure highlights that higher charging currents at 112 A accelerate charging but increase the risk of heat generation and efficiency losses, whereas lower charging currents at 6 A and 28 A ensure smoother charging, better SOC stabilization, and reduced thermal stress on the battery. Similarly, in discharging, high currents lead to faster depletion of stored energy, reducing effective

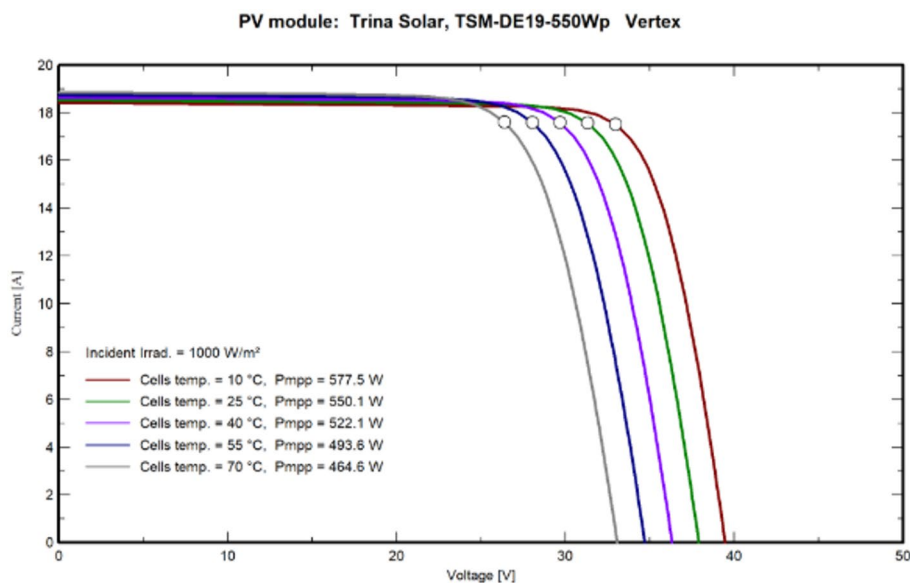


Fig. 4 I-V curve for selected crystalline PV module

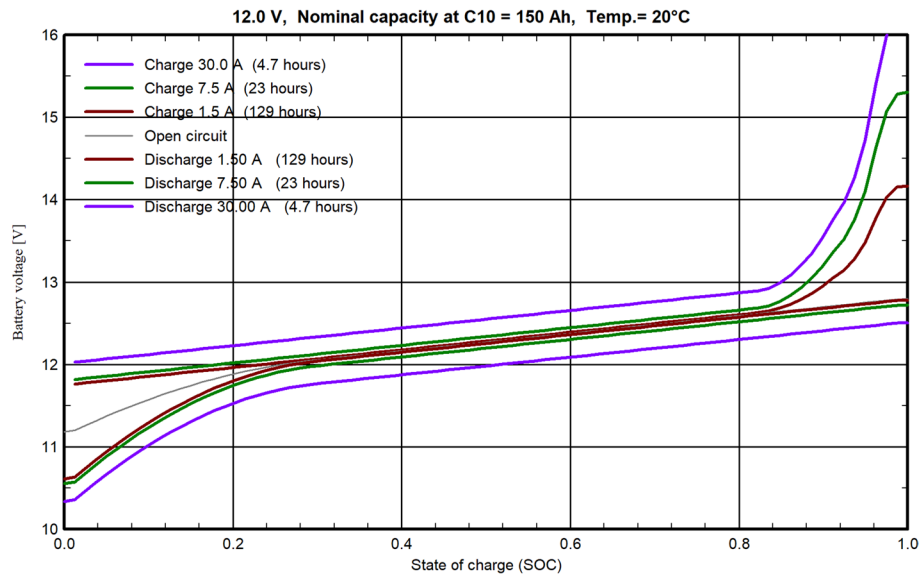


Fig. 5 Characteristics of the charge and discharge profiles vs. SOC for BESS

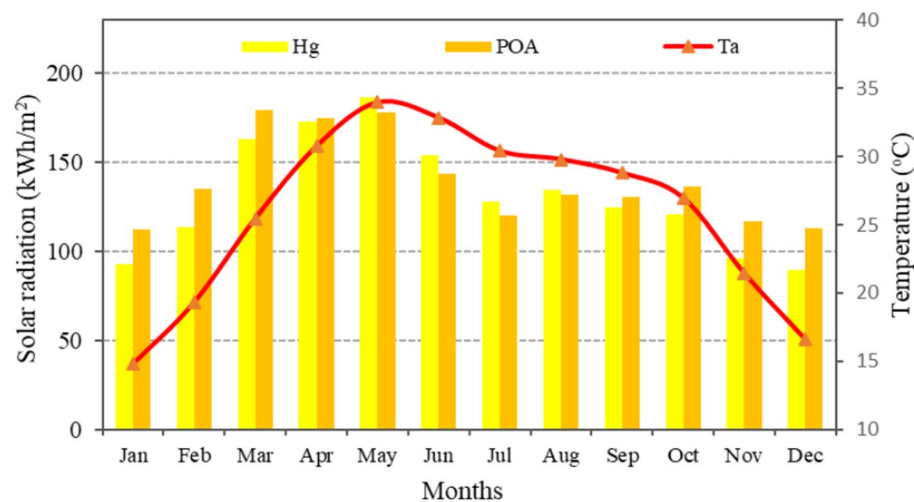


Fig. 6 Variation of solar irradiation and ambient temperature throughout the year

capacity due to internal resistance, while moderate discharging currents provide more stable energy delivery to the load [36].

The Fig. 6 represents the variation of radiation and temperature throughout the year. The highest radiation on horizontal surface (H_g) predicted in May of 186.6 kWh/m², indicating optimal solar exposure during these months. In contrast, the lowest values occur in December 89.9 kWh/m² reflecting reduced solar potential in the winter months. The highest plane-of-array (POA) radiation value of 179.6 kWh/m² observed in March, signifying optimal conditions for energy generation due to panel orientation and sun angles. Conversely, the lowest POA values occur in January of 112.5 kWh/m². The peak ambient temperatures are seen in May at 33.96 °C, which could influence the yield of solar panels due to higher operating temperatures. The lowest ambient temperature predicted in January of 14.79 °C, correlating with the lower solar irradiation in winter.

Figure 7 presents the electricity supplied to the hostel by SAPV system closely follows the seasonal variation in solar irradiance, with the highest generation occurring during March and May as 678.9 kWh due to higher solar availability. A noticeable reduction is observed during the monsoon months of July to September, because of increased cloud cover and lower incident solar radiation. Electricity generation improves again in October as 634.5 kWh under favourable post-monsoon weather conditions, while relatively lower values are recorded during the winter months owing to shorter daylight hours and reduced solar irradiance. These results demonstrate the influence of changes in solar irradiance, cloud cover, and ambient temperature under the composite climatic conditions of the study area. Higher energy generation during the summer months is attributed to increased solar availability, whereas the reduction during the monsoon season results from frequent cloud cover and lower solar insolation.

The Fig. 8 shows the monthly energy profile of the present SAPV systems. The monthly energy balance between available energy (E_{avail}), array output (E_{array}), and load demand (E_{load}) highlights the operational characteristics of the SAPV system. The available energy and array output generally follow the seasonal trend of solar irradiation, with higher generation during summer and lower values in winter, though actual user energy depends strongly on storage dynamics and load matching. In months such as March to June and October, the system consistently delivers the full hostel demand, indicating adequate solar resource and efficient utilization of both array and storage capacity. During the peak summer months, however, the available energy often exceeds the hostel demand, leading to unused energy when the batteries are full. In March, high solar resource allowed 903.8 kWh of available energy and 752.2 kWh array output, comfortably meeting the load of 678.9 kWh, with the full amount supplied to the user. April and May follow this pattern, where available and array energy (861.2 kWh and 722.7 kWh in April; 869.3 kWh and 740.8 kWh in May) exceeded the load (657.0–678.9 kWh), ensuring that user demand was fully satisfied. June shows similar adequacy, with 703.0 kWh available and 689.9 kWh array output covering the load of 657.0 kWh. Conversely, during monsoon months like in July, 590.0 kWh available and 580.0 kWh from the array

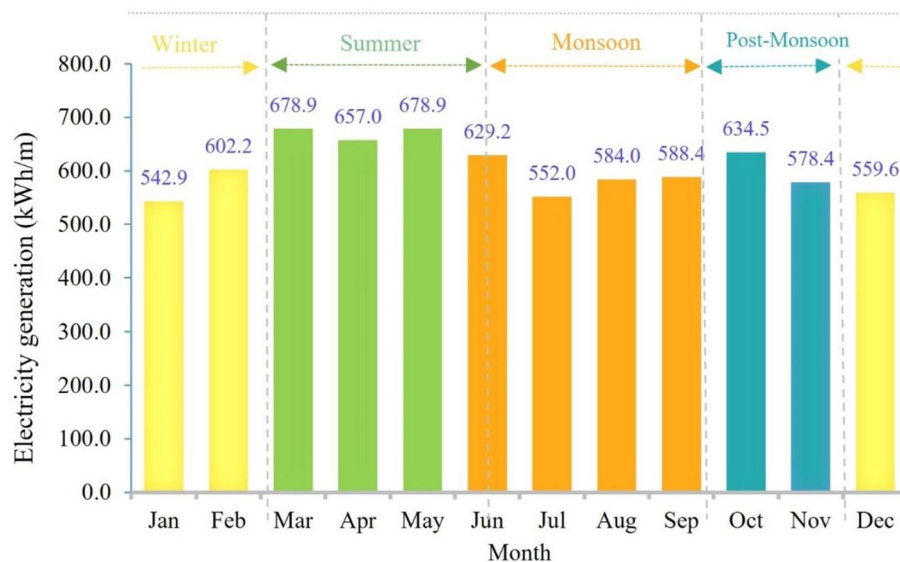


Fig. 7 Monthly electricity supplied to the hostel predicted by the PVsyst simulation

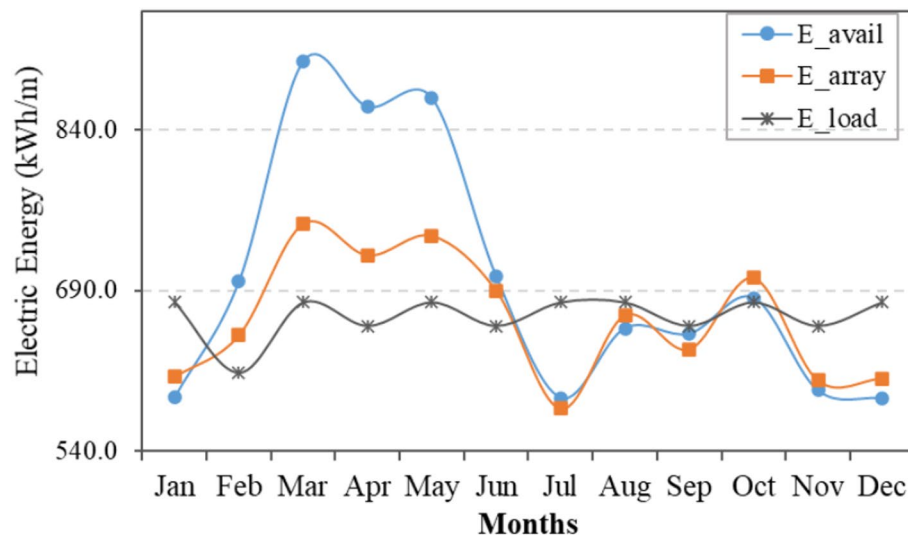


Fig. 8 Energy profile of the standalone SPV system

could not meet the load of 678.9 kWh, resulting in only 552.0 kWh supplied, while in August, although 654.9 kWh was available and 666.9 kWh produced, only 584.0 kWh reached the user due to storage and conversion losses.

In the winter season of November, reduced irradiation caused the available and array energy to fall to 596.9 kWh and 606.5 kWh, against a load of 657 kWh, with only 578.4 kWh delivered to the user. December marks another shortfall month, with 589.4 kWh available and 608.2 kWh from the array, yet the load of 678.9 kWh was only partially met with 559.6 kWh supplied. This shortfall in winter is also due to cloud cover, and shorter daylight hours, as well as higher dependency on stored energy that undergoes conversion losses. Overall, the monthly energy distribution demonstrates that while the system is capable of meeting the annual energy requirement with a high degree of reliability, seasonal climatic conditions and storage-related inefficiencies play a decisive role in shaping the annual performance and directly influence the effective energy delivered to the hostel.

The Fig. 9 represents monthly yields for a SAPV system over a year. These correspond to different performance parameters such as Y_R , Y_A , and Y_P . The Y_R , which represents the ideal system output under standard test conditions and local irradiance, is consistently higher than the Y_A , which accounts for module temperature effects, soiling, mismatch, and wiring losses. The highest value of Y_R is in April at 5.83 and the lowest in January at 3.63 kWh/kWp/day while the maximum Y_A recorded in March of 4.01 kWh/kWp/day which gradually decreases, reaching its lowest in December at 3.24 kWh/kWp/day. The difference between these two values is most evident in the summer months of March to May, where high solar irradiation pushes the reference yield above five units per kilowatt per day, yet the array yield falls to just above four due to significant temperature-induced losses and dust accumulation in the pre-monsoon period. The Y_P , which indicates the usable energy supplied to the load after inverter conversion and battery storage losses. The maximum value of Y_P is in March at 3.62 kWh/kWp/day and the minimum in December at 2.98 kWh/kWp/day. During favourable conditions, such as February, March, and October, the final yield remains at its maximum level, reflecting a balance between high solar availability and efficient energy conversion. Conversely,

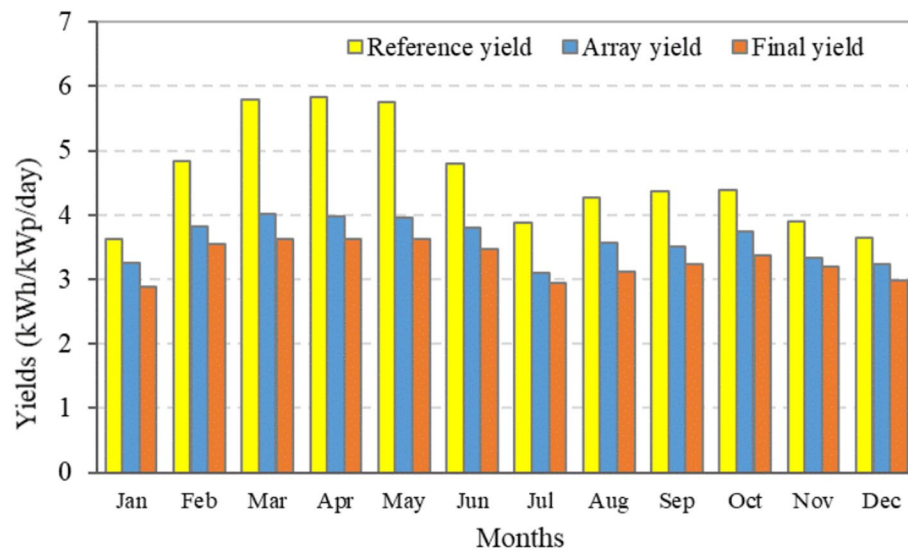


Fig. 9 Variation of different yields throughout the year

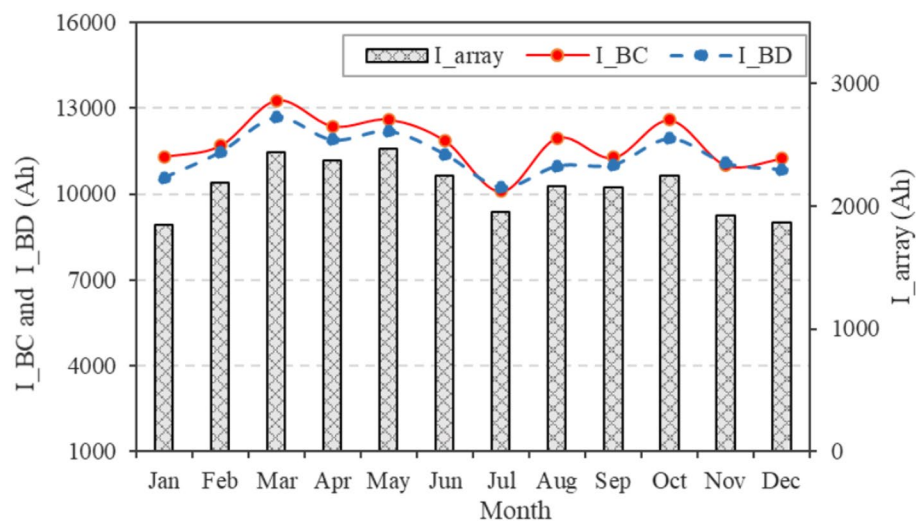


Fig. 10 Current profile of the SAPV system throughout the year

during the monsoon months of July and August, reduced irradiance leads to both lower reference yields and final yields around three units, aligning with earlier observations of dips in solar fraction and user-supplied energy. In the winter months of November and December, shorter days and reduced insolation cause the final yield to drop below three units, highlighting the seasonal dependency of the system.

Figure 10 depicts the monthly variation of solar PV array current (I_{array}), battery charging current (I_{BC}), and battery discharging current (I_{BD}) of the SAPV system and its ability to reliably meet the energy requirements of the hostel. The array current follows the seasonal pattern of solar irradiance, reaching peak values during March to May when insolation is highest and falling during the monsoon (July–August) and winter months (November–December), consistent with the solar radiation pattern of the site. The battery charging current is consistently higher than the array current across most months, reflecting the effect of charge controller regulation and efficiency factors

[37]. This indicates that during surplus energy months, particularly February to May, the system effectively stores excess solar energy to maintain a high SOC from March to May. The battery discharging current closely follows the hostel's load demand and becomes particularly significant during low irradiance months such as July, August, and December, when discharging currents remain relatively high despite reduced array output. This observation matches findings from previous SAPV studies that emphasize the buffering role of batteries during monsoon and winter seasons when generation is insufficient [38]. Annually, the total array current of 25,317.6 Ah, charging current of 14,128.7 Ah, and discharging current of 13,621.8 Ah demonstrate a balanced operation, where slightly higher charging than discharging prevents deep discharge and ensures long-term battery health.

Figure 11 displays the PR and SF, two key indicators for assessing the effectiveness of the stand-alone PV system, and their variation over the year reflects both system efficiency and its ability to meet the hostel's energy demand. The PR, which measures the conversion efficiency of incident solar energy into usable electricity after accounting for system losses, ranges from 62 to 82%, with higher values in the cooler months (October–March) and lower values in peak summer (April–May) due to elevated module temperatures that reduce efficiency [39]. In contrast, the SF, which indicates the share of load met by the PV system, remains close to 100% for most months, highlighting the adequacy of system sizing and storage capacity to meet demand, even when PR is relatively lower. Seasonal dips in SF during the monsoon months (July–August) and winter (November–December) are mainly attributed to reduced solar irradiance and shorter sunshine hours, which limit generation despite good system efficiency. The interrelation between the two indicates that while PR determines how efficiently the system converts the available solar energy, SF ensures that the actual load demand is met, achieving a solar fraction of 91.2%. The system achieves an annual PR of 73.1%, which is comparable to the performance reported in previous studies on stand-alone photovoltaic systems.

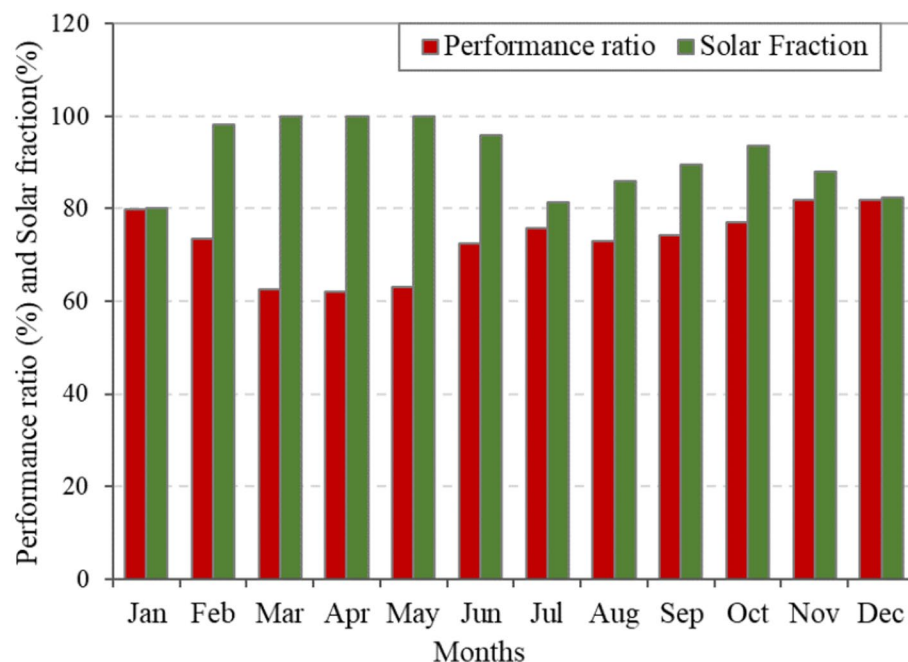


Fig. 11 Variation of performance ratio and solar fraction of the hybrid SPV throughout the year

For example, Kumar et al. reported an annual performance ratio of 72.8% for a PVsyst-based stand-alone PV system in the composite climatic conditions of India [40]. Slouma et al. [41] designed SAPV system using PVsyst and determined that the proposed system, which is technically suitable for the area, has a performance ratio of 58.3% and a high specific efficiency generation, alongside a solar fraction of about 92.5%. Similar studies by Elsaadawi et al. [42], Spea and Khattab [43], and Mashaly et al. [44] also demonstrated that PVsyst provides reliable predictions for the technical and economic evaluation of stand-alone solar photovoltaic systems. A standalone PV system designed for an engineering college computer centre achieved a SF of 1.00, indicating complete fulfilment of the annual energy demand through solar power. The corresponding PR was 0.51, demonstrating the system's overall conversion performance relative to the available solar resource [45].

Figure 12 shows the variation of battery voltage and state of charge and provides important evidence of how effectively the SAPV system balances generation, storage, and demand. During the high-irradiance months of March through May, the battery voltage reaches its maximum level above 50.4 volts, and the SOC stabilizes close to 0.77, reflecting surplus solar generation, full charging of the storage system, and efficient coverage of the hostel's load. In June, with good solar availability but slightly higher system demand, the SOC remains strong at around 0.64, indicating a well-charged battery bank. However, during the monsoon season from July to September, the reduced solar input due to heavy cloud cover and rains lowers both battery voltage and SOC, with SOC values ranging between 0.47 and 0.55, highlighting partial charging and greater reliance on stored energy to meet the load. August in particular shows one of the lowest SOC values of 0.47, matching the earlier observation of reduced user-supplied energy during this month. In the winter months of November and December, shorter days and lower irradiation further reduce the SOC to its annual minimum of about 0.44, accompanied by reduced battery voltages. Annually, the average battery voltage of 49.59 volts and SOC of 0.59 indicate that the storage system generally operates in a healthy mid-range state, balancing charging during high-resource periods with discharging during deficit months.

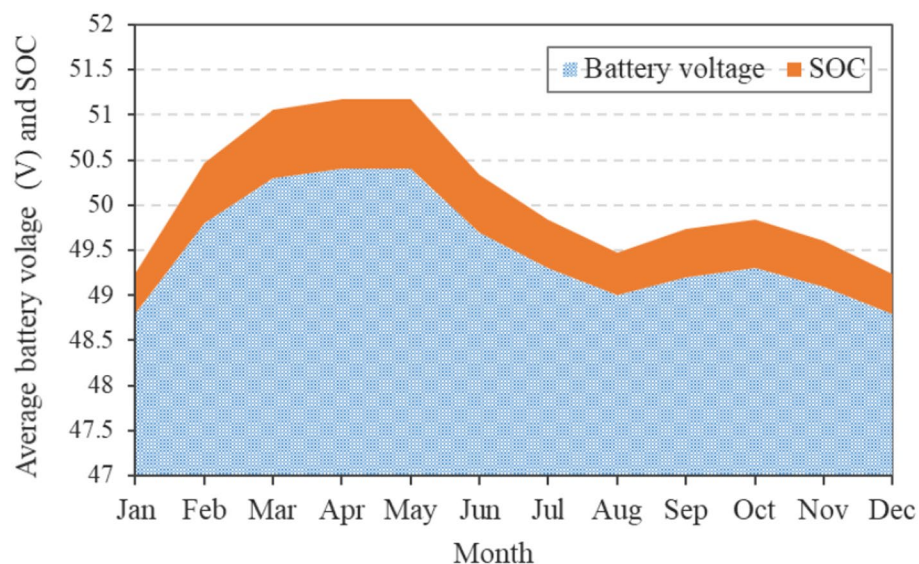


Fig. 12 Variation of average battery voltage and state of charge throughout the year

The monthly variation of different losses provides valuable insight into the technical performance of the stand-alone PV system and reflects the influence of both climatic parameters and system operating conditions. The unused losses, which occur when the system generates electricity beyond the immediate storage or demand capacity, are almost negligible throughout the year except for March to June varying from 0.92 kWh/kWp/day to 0.80 kWh/kWp/day (Fig. 13), when high solar irradiance combined with longer daylight hours results in surplus generation that exceeds battery charging or load requirements. Array capture losses, which include effects of module temperature, soiling, mismatch, and irradiance variability, are highest during March–May (1.78–1.80 kWh/kWp/day) due to elevated ambient temperatures and dust accumulation in the pre-monsoon dry season, both of which reduce module efficiency. In contrast, array capture losses are lower in the winter months, 0.41 kWh/kWp/day in December and 0.38 kWh/kWp/day in January, when temperature and irradiance conditions are more favorable. Similarly, PVsyst predicts the average monthly capture losses ranges from 0.34 to 1.14 h/day of a solar PV system in the composite climate of Northern India, [46]. The annual averages array capture losses of the SAPV are predicted as 0.98 kWh/kWp/day comparable to the real operating PV system losses as 0.98 kWh/kWp/day operating under same climate [46].

System losses, comprising wiring, inverter, and storage inefficiencies, remain fairly stable from 0.15 to 0.44 kWh/kWp/day but show slight peaks in February and August, reflecting the combined effect of fluctuating weather conditions and higher charge–discharge cycles of the battery bank during periods of variable solar availability. The annual averages system losses are predicted as 0.31 kWh/kWp/day comparable with the previous studies [47, 48]. Results demonstrate that while the system is generally efficient, climatic factors such as high summer temperatures, dust deposition, and monsoon cloud cover play a crucial role in influencing monthly variations.

Figure 14 shows the various losses of the SAPV system which are categorized into PV array capture losses, power conditioning losses, and battery operation losses, all of which directly influence the net annual energy generation used in the techno-economic analysis. Among the PV array capture losses, the dominant factor that is temperature

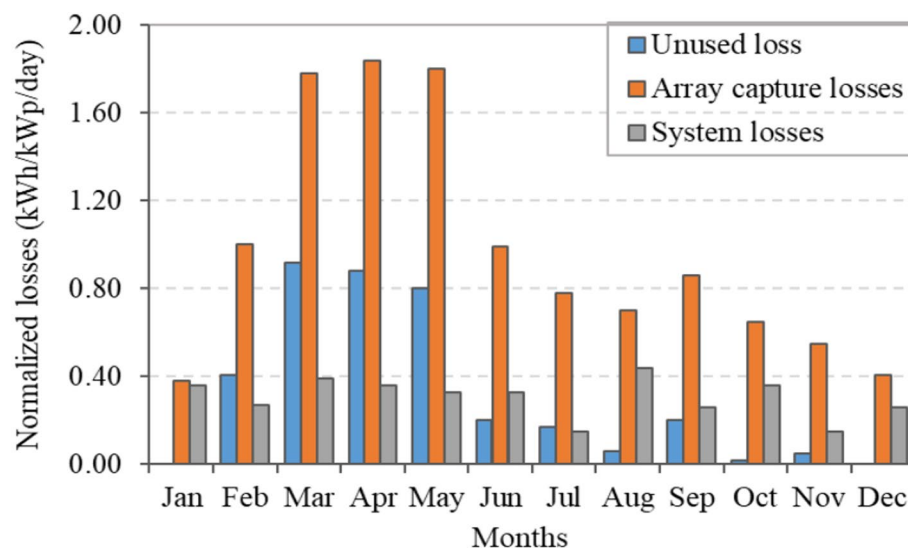


Fig. 13 Normalized unused, array capture and system losses of the stand-alone PV system

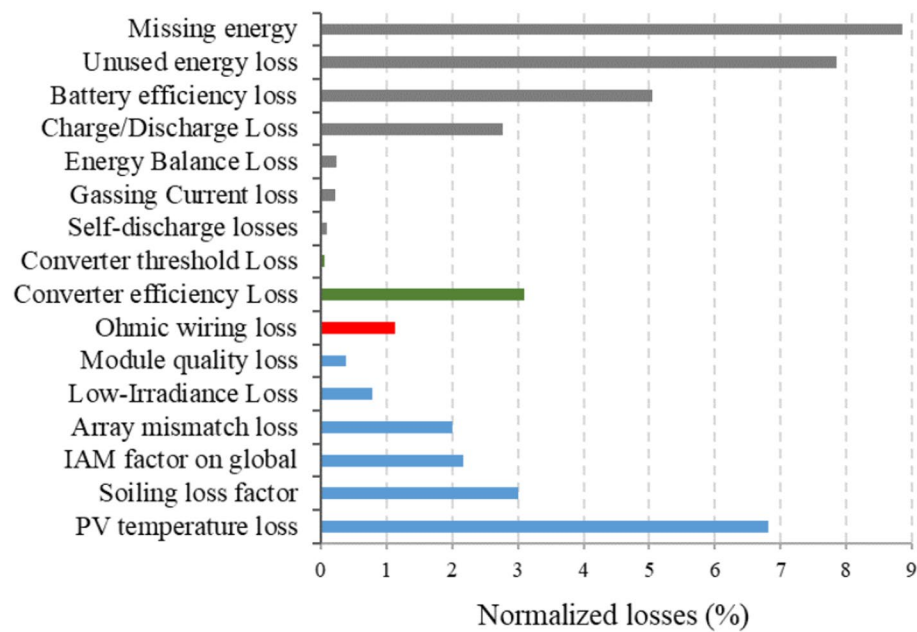


Fig. 14 Loss diagram of the stand-alone PV system throughout the year

Table 5 Cost breakup of stand-alone solar PV system

Component	Units	Unit cost (USD)	Total cost (USD)
PV modules	11	106.97	1176.06
Battery bank	16	136.20	2179.10
Off-grid inverter	1	701.43	701.43
Mounting structure	1	336.68	336.68
Wiring & protection	–	360.07	360.07
Installation cost	–	270.05	270.05
Total cost			5023.97

loss represents as 6.81%, reflecting the elevated operating temperatures typical of the tropical Indian climate. Soiling contributes 3.0% loss, caused by dust accumulation on module surfaces, also contributes significantly to performance degradation. Additional array-level losses include the incidence angle modifier (IAM) loss (2.16%), array mismatch loss (2.0%), and low-irradiance loss (0.79%), which collectively account for non-uniform irradiance conditions and electrical mismatches. Minor losses arise from module quality (0.38%) and ohmic wiring resistance (1.13%). Losses associated with the power electronics include converter efficiency loss (3.09%) and converter threshold loss (0.06%), indicating energy losses during DC to AC energy conversion. Battery-related losses, inherent to stand-alone systems, are significant and include charge–discharge loss (2.76%), battery efficiency loss (5.04%), self-discharge (0.09%), and gassing current loss (0.22%). Finally, unused energy loss (7.85%) and missing energy (8.85%) highlight the mismatch between energy generation and load demand.

3.1 Cost breakup of the SAPV system

The cost of each system component was determined based on prevailing local market prices at the present time. Table 5 presents the detailed breakup of initial investment of the proposed SAPV system obtained from quotations available through commercial

suppliers (IndiaMART and local vendors). The total cost of the system is estimated USD 5023.97. The PV modules constitute the primary cost component, with 11 modules accounting for USD 1176.06 representing approximately 23.4% of the total investment (Fig. 15). This represents the major cost component of the SAPV system. The battery bank, consisting of 16 batteries, accounts for USD 2179.10 which is the largest cost share about 43.4%, highlighting the significant contribution of energy storage to SAPV system economics. This high battery cost strongly influences the replacement cost and, consequently, the LCOE of the system.

The off-grid inverter costs USD 701.4 represents about 14.0% of the total capital cost and is responsible for power conditioning of generated electricity. The mounting structure ensures mechanical stability and appropriate module orientation contribute 7% of the investment, while wiring and protection components include DC/AC cabling, junction boxes, and safety devices an overall contribution of about 7%. The installation cost, which is USD 270.05 covers labor and commissioning expenses.

3.2 Levelized cost of energy (LCOE) of SAPV system

The capital investment reported in Table 5 is used as the initial investment (C_0) in the life cycle cost assessment. The LCOE analysis of the present SAPV system was conducted assuming 25 years of PV modules, corresponding to the expected service life of crystalline silicon PV modules [49, 50]. The off-grid inverter and batteries, on the other hand, would need to be replaced more often during the project's duration. The capital cost of the off-grid PV system has been estimated as USD 5023.97, excluding land cost, as the system is installed on an existing building rooftop. The battery bank and PV modules are the two components that make up the majority of the total capital cost, as shown in Table 5. This cost distribution is typical for off-grid PV systems, where energy storage

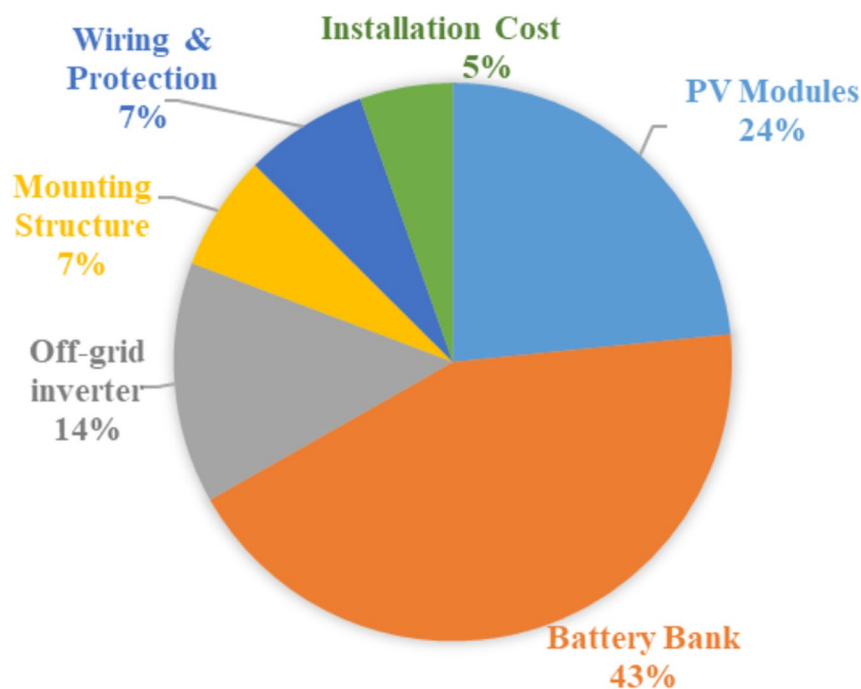


Fig. 15 Capital cost distribution of the stand-alone solar PV system

is essential to ensure an uninterrupted power supply during the unavailability of solar radiation. The off-grid inverter, mounting structure, wiring and protection components, and installation costs collectively contribute to the remaining capital expenditure.

The assumptions used in the economic assessment of are presented in Table 6. A discount rate of 5% was adopted for the economic calculations [51, 52]. The operation and maintenance (M) cost was taken as 1% of the initial capital cost per year, while the battery bank and off-grid inverter were assumed to be replaced after their respective service lives [55], and its present value over the system life has been calculated using the discounted cash flow approach. Replacement costs, primarily associated with the battery bank and inverter, have been incorporated into the LCC assessment by applying the appropriate discount factors. Batteries are assumed to be replaced at regular intervals, while the inverter is replaced once during the system lifetime. Furthermore, the salvage value of the PV system, batteries, and inverter at the end of their respective service lives was estimated according to their remaining useful life at the end of the project period [52, 57]. The proposed SAPV system's life-cycle cost has been found in present value terms by adding up the initial capital cost, the discounted C_{MR} cost, and the replacement cost and taking away the salvage value. The LCOE of the system has then been calculated as USD 0.094 by dividing the total life-cycle cost by the lifetime electricity generation. The predicted LCOE is in close agreement with the value reported by Mashaly et al. (2025), who estimated an LCOE of USD 0.082/kWh [44]. A life-cycle assessment of a 3.4 kWp rooftop SAPV system in Bhubaneswar, India reported an LCOE of INR 5.40/kWh, an IRR of 2.02%, and an energy payback time of 4.61 years [58].

3.3 Payback period

The payback period of the present SAPV system is calculated through the NPV method, which accounts for the time value of money and annual degradation in energy generation. An annual PV degradation rate of 0.5% was assumed according to manufacturer warranty specifications and published literature [53, 54]. The initial capital investment of the proposed SAPV system is considered as USD 5023.97. The annual electricity generation of 7286.1 kWh, obtained from the PVsyst simulation, was used to estimate the annual cash flow after accounting for the annual degradation of the PV modules. Uttar Pradesh power cooperation limited (UPPCL) has announced the current tariff

Table 6 Assumptions used in the economic assessment

Parameter	Value	Basis/Justification	Reference
Project lifetime	25 years	Typical service life of crystalline silicon PV modules	Manufacturer warranty/[49, 50]
Discount rate	5%	Assumed real discount rate commonly used in PV techno-economic studies	[51, 52]
PV degradation rate	0.5% /year	Manufacturer warranty and published literature	[53, 54]
Battery replacement interval	5 years	Expected service life of the selected batteries	Manufacturer datasheet/[55]
Inverter replacement interval	15 years	Typical operational lifetime of off-grid inverters	Manufacturer warranty
Annual maintenance cost	1% of initial capital cost	Common assumption for stand-alone PV systems	[50, 55]
Grid electricity tariff	USD 0.080/kWh	UPPCL non-residential tariff	[56]

for non-residential consumers, which corresponds to the unit cost of grid electricity for the estimation of annual savings at USD 0.080/kWh [56]. Based on the cumulative discounted cash flow analysis, the payback period of the proposed solar PV system is approximately 11.14 years.

For a diesel generator with a specific fuel consumption of 0.324 L/kWh [59] and a diesel price of USD 1.029/L, the average retail market price during the study period. The cost of diesel-generated electricity is computed using Eq. (13). Using this cost as the basis for annual monetary savings, and applying to calculate payback using NPV methodology. The discounted payback period for the present SAPV system is calculated as 2.16 years (Fig. 16). This short payback reflects the large annual savings obtained by displacing relatively expensive diesel generation with solar energy with an annual first-year saving of USD 2428.59. The higher unit cost of diesel-based electricity compared to the grid tariff that replaces diesel generates much larger annual cash flows and, as a result, faster recovery of the initial CAPEX.

These findings are consistent with previously performed studies on SAPV systems like a study estimates the system's payback period to be 13.19 years for a designed 8.0 kW SAPV system in India to meet an electricity demand of 31.30 units per day, using 46 PV modules and 16 batteries, with the initial cost of the system to be approximately Rs. 14.0 lakhs [60]. Shukla et al. [61] analyzed the techno-economic performance of a SAPV system installed for a hostel building in India. Based on life-cycle cost analysis and discounted cash flow evaluation, the authors reported a payback period of 8.2 years for the stand-alone PV system, a relatively lower payback period arisen due to higher system capacity. Another study shows a techno-economic analysis of a 5-kWp hybrid rooftop solar PV system installed at Diyala province, reported that payback period ranging from approximately 5.0 to 15.5 years, depending on electricity tariff levels. At lower tariffs, payback approaches the system lifetime, while higher tariffs significantly reduce the payback duration [62].

Future variations in component prices and electricity tariffs may influence the economic feasibility of the proposed SAPV system. A reduction in battery and PV module prices would lower the initial investment and replacement costs, thereby reducing the LCOE and shortening the payback period [28, 29]. Conversely, an increase in battery

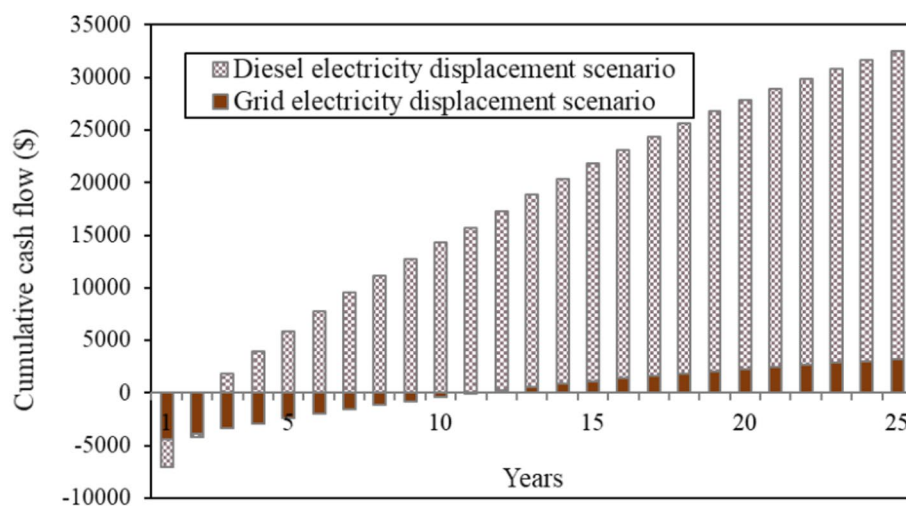


Fig. 16 Cumulative cash flow comparison for grid and diesel electricity displacement scenarios

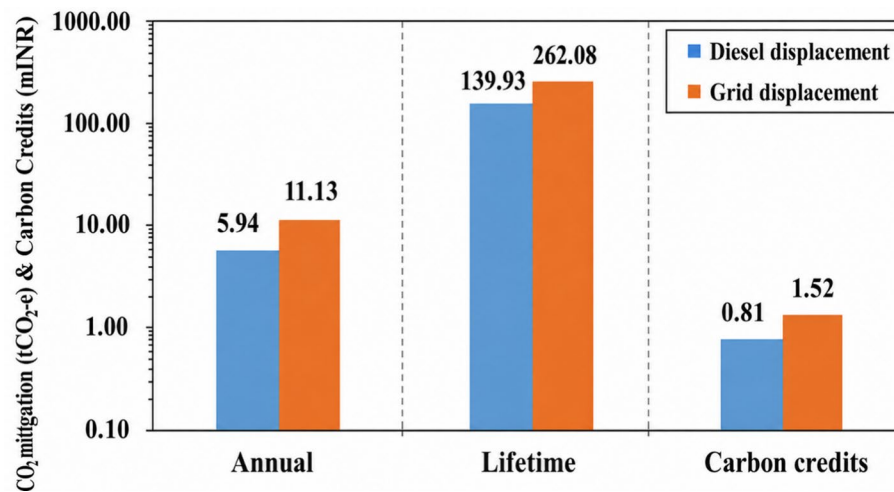


Fig. 17 Comparative representation of CO₂ mitigation and earned carbon credit of SAPV under grid and diesel scenarios

prices could significantly affect the life-cycle cost because battery replacement represents a major recurring expenditure. Similarly, an increase in electricity tariffs would improve the economic attractiveness of the SAPV system by increasing the monetary savings from solar generation, whereas lower tariffs would result in a longer payback period [29].

3.4 Environmental economics

The SAPV system demonstrates a strong relationship between environmental sustainability and economic performance. By harnessing solar energy to generate clean electricity, the proposed system significantly reduces CO₂ emissions and contributes to climate change mitigation. Based on the annual electricity generation of the system and considering module degradation over a 25-year operational lifetime, the annual emission mitigation achieved is approximately 11.13 tCO₂e, while the net lifetime emission mitigation is calculated about 262.08 tCO₂e (Fig. 17) after accounting for the life-cycle CO₂ emissions associated with PV module manufacturing.

The environmental performance of the SAPV is also evaluated under a diesel displacement scenario, which is representative of off-grid and remote applications where diesel generators are mostly used for power supply. In this scenario, the SAPV system achieves an annual CO₂ mitigation of approximately 5.94 tCO₂e, leading to a net lifetime CO₂ mitigation of about 139.93 tCO₂e over its life. Although the cumulative CO₂ mitigation under diesel displacement is lower than that of grid displacement due to differences in baseline emission factors, the results highlight the substantial environmental benefit of replacing diesel-based electricity generation with solar PV, particularly in remote rural areas.

In addition to environmental benefits, the SAPV system provides measurable economic value through the generation of carbon credits, which represent certified reductions in greenhouse gas emissions. Based on the net lifetime CO₂ mitigation and adopting a benchmark international carbon price of USD 74.07 per tCO₂e, the total carbon credit revenue generated by the system over its lifetime is estimated to be approximately USD 19412.3. Under the diesel displacement scenario, the net lifetime CO₂

mitigation of approximately 139.93 tCO₂e, the corresponding carbon credit revenue is estimated to be about USD 10364.9 over the system lifetime. The estimated carbon-credit benefits are subject to uncertainty because carbon credit prices can fluctuate over time. Therefore, the calculated carbon-credit revenue should be considered an indicative estimate, and variations in future carbon credit prices may influence the overall economic benefits of the proposed SAPV system. Such systems can play an important role in supporting the rural energy transition by providing reliable and clean electricity to government educational institutions located in areas with unreliable grid supply. The environmental and economic benefits demonstrated in this study indicate that SAPV systems can contribute to long-term sustainable energy development while supporting national clean energy and greenhouse gas emission reduction targets.

4 Conclusion

This study presented the design and techno-economic analysis of a SAPV system integrated with battery storage for an institutional application in an Indian climate zone. The system was designed and analyzed using site-specific meteorological data and realistic load demand, ensuring that the results reflect practical operating conditions. Performance analysis indicates that the proposed SAPV system is capable of reliably meeting the electrical demand of the facility, with a performance ratio of approximately 73.1% and a solar fraction exceeding 91.2%, demonstrating a high degree of energy autonomy throughout the year. The analysis carried out using a life-cycle cost framework, resulted in a LCOE of USD 0.094/kWh, confirming the economic competitiveness of the system, particularly in off-grid and remote regions. The discounted payback period was found to be 11.14 years when compared with grid electricity tariffs. In contrast, when the SAPV system was assessed as a replacement for diesel-based electricity generation, the payback period was significantly reduced to 2.16 years, clearly demonstrating the economic advantage of SAPV system in diesel-based applications. The SAPV installation achieves substantial net CO₂ emission mitigation over its operational lifetime, contributing to climate change mitigation while also offering the potential for additional economic benefits through carbon credit generation.

The findings demonstrate that SAPV systems with well-sized battery storage are not only technically feasible but also environmentally beneficial. Further research should focus on integrating advanced battery technologies such as lithium-ion or hybrid storage for higher round-trip efficiency, exploring demand-side management strategies to minimize unused energy, and conducting long-term field validation studies to complement simulation-based performance analysis. Practical implementation may, however, face challenges related to battery replacement and maintenance, seasonal variations in solar availability, initial investment requirements, and the availability of reliable technical support in rural institutional settings.

Author contributions

H.S.M, P.K.K, K.Y.S: Investigation, Data curation, Formal analysis, Methodology, Writing – original draft.S.K.Y: Conceptualization, Visualization, Supervision, Review & editing. P.R: Software, Validation, Review and editing.S.M.M.H, P.P, M.Y: Resources, Funding Acquisition, Project Administration, Supervision, Writing – review & editing.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics approval

Not applicable.

Clinical trial number

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Competing interests

The authors declare no competing interests.

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