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RESEARCH ARTICLE

The True Cost of Off-Grid Solar Power: Evaluating Solar Energy in a Dense Tropical Forest

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ABSTRACT

Renewable energy solutions are vital for sustainable development, particularly in Small Island Developing States (SIDS) facing challenges related to fossil fuel dependence. This study examines the design, installation, and performance evaluation of an off-grid solar photovoltaic (PV) system. The system is located in a remote, forested region of Trinidad, providing electricity for wildlife rehabilitation efforts in a facility lacking conventional grid access. The research analyzes empirical data on system performance under humid tropical conditions, addressing practical challenges and highlighting the importance of accurate solar resource assessments for such environments. Financial analysis includes a detailed cost breakdown and calculation of the levelized cost of electricity (LCOE), providing insights into the economic feasibility of off-grid solar solutions. Results indicate significant discrepancies between simulated and actual performance, underscoring factors such as lower-than-anticipated solar irradiance and the impact of a constant nighttime energy load on battery cycling. Recommendations are provided to optimize future off-grid PV installations for similar applications in Trinidad and Tobago and the broader CARICOM region.

Keywords: Off-grid solar, Photovoltaics, Small Island Developing States (SIDS), Trinidad and Tobago.

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1. Introduction

The global context of renewable energy adoption highlights the challenges faced by Small Island Developing States (SIDS) in meeting their energy needs sustainably. Research indicates that SIDS heavily relies on imported fossil fuels, impacting the environment, budgets, and energy security [1]. To address these challenges, the adoption of solar photovoltaic (PV) systems is crucial. Studies emphasize that residential PV systems play a significant role in the sustainable energy transition, with a focus on enhancing the perception of benefits to drive adoption [2]. Furthermore, the role of solar PV systems in advancing energy independence and environmental sustainability in SIDS is underscored. Policies such as carbon taxes and renewable portfolio standards are identified as effective tools for reducing carbon emissions and increasing energy independence in small island states like Jamaica [3].

Trinidad and Tobago's energy landscape showcases a blend of traditional hydrocarbon resources and a growing commitment to renewable energy. The nation aims to reduce emissions by 28.7 $MtCO_{2\text{-}e}$ by 2030, with initiatives like introducing zero-carbon renewable energy sources and exploring Carbon Capture and Storage (CCS) technologies [4]. Additionally, there is a focus on off-grid renewable electricity development supported by legal frameworks [5]. A pre-feasibility study highlights the country's potential for a green hydrogen market, leveraging existing infrastructure and capabilities for sustainable energy production [6]. Efforts towards sustainable energy transition include improving energy efficiency, transitioning to combined-cycle operations, and increasing renewable energy penetration to reduce CO_2 emissions significantly [7]. Trinidad and Tobago's energy landscape reflects a dynamic shift towards cleaner and more efficient energy practices within the CARICOM framework.

Off-grid solar PV systems play a crucial role in providing electricity to remote and rural areas where grid access is limited or non-existent. These systems are essential for electrifying regions far from traditional power sources [8]. They offer a sustainable solution to meet energy demands, especially in low-population areas or rugged terrains, reducing reliance on fossil fuels and mitigating environmental impacts. The optimization of PV systems, including battery storage and efficient design, is vital for ensuring reliable energy supply in off-grid locations. By utilizing renewable energy sources like solar power, these systems not only enhance energy access but also contribute to reducing carbon emissions, making them a cost-effective and environmentally friendly solution for remote electrification [9].

The primary objective of this study was to design, install, and evaluate the performance of an off-grid solar photovoltaic (PV) system tailored for a conservation facility dedicated to the care of wildlife impacted by environmental pollutants in Trinidad's dense forest regions. Recognizing the critical need for reliable power sources in remote locations that are bereft of conventional grid electricity, this research aimed to provide a sustainable and environmentally friendly power solution while addressing the unique challenges posed by the local ecosystem. This study offers empirical data and insights into the operational efficiencies and challenges of solar PV systems in humid tropical climates. This data is invaluable for researchers, engineers, and policymakers aiming to optimize solar energy solutions in similar climatic conditions, not just within Trinidad and Tobago but across the wider CARICOM region, where such climates are prevalent. Financial viability is a critical component of sustainable energy solutions, and this study's detailed cost analysis sheds light on the economic aspects of off-grid solar PV systems. By providing an evaluation of the levelized cost of electricity, this research contributes to a more nuanced understanding of the economic considerations necessary for the adoption of solar PV systems in remote locations.

2. Methodology

The roof-mounted solar PV system is located in a heavily forested area east of Trinidad. The climate in Trinidad is characterized by a humid tropical environment with significant rainfall and consistent temperatures throughout the year [10]. The solar PV system will power equipment and fixtures in an existing structure that is used for the care and rehabilitation of local reptiles and birds, in particular reptiles and birds that are affected by onshore and offshore oil and other chemical spills. The site is remote and not connected to the electrical grid. Diesel-powered generators met the site's electricity needs.

A site visit was conducted, and the slope and orientation of the roof were measured. The tilt and azimuth of the roof were measured as 200 and 0, respectively. The electrical load was calculated by recording the power consumption of the electrical appliances and their usage patterns. The average daily consumption was calculated as 10.1 kWh/day, and the daily average electrical consumption pattern is provided in Fig. 1. The site was unaffected by shading at the time of the site visit.

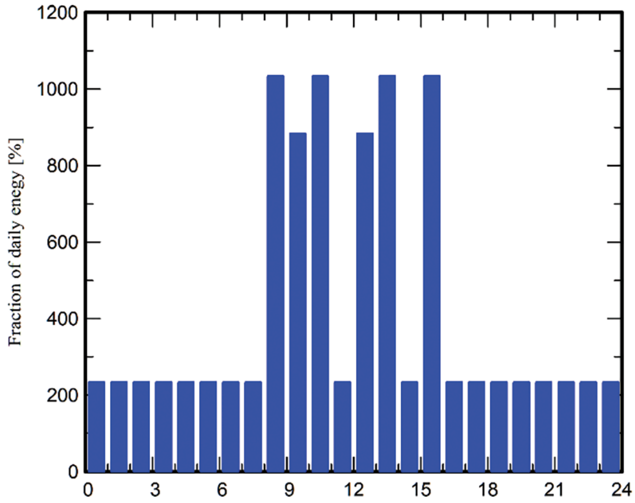

Fig. 1. Daily variation in electrical load.

Using information from the site visit and the National Solar Radiation Database (NSRDB), which provided solar irradiance data for the site, the off-grid roof-top solar PV system was designed using the industry-leading software PVsyst. The solar PV design was then used to inform a request for proposals, which resulted in the purchase of solar PV equipment and the contracting of a solar contractor to install the system. The system was installed to meet National Electric Code (NEC) 2020 standards. The performance data for the solar PV system was logged by the energy management component of the system for every 5-minute interval from September 2023 to March 2024. This data was used in the analysis that follows.

3. Results

The results of the solar PV design and simulation are provided in this section, along with the data logged during the 6 months of operation of the system. The design performance is then compared against the real-life performance of the system. The main components of the system and their rating are provided in Table I.

The single-line diagram of the system is provided in Fig. 2. The system meets NEC 2020 requirements.

TABLE I: Solar PV System Components

Solar system component	Rating or size
Power rating of modules	445 W
Number of modules	12
Battery bank voltage	48 V
Battery bank capacity	480 Ah
Charge controller	100 A, dual channel MPPT
Inverter	5 KVA, input voltage 48 Vdc, output voltage, 230 VAC, 60 HZ

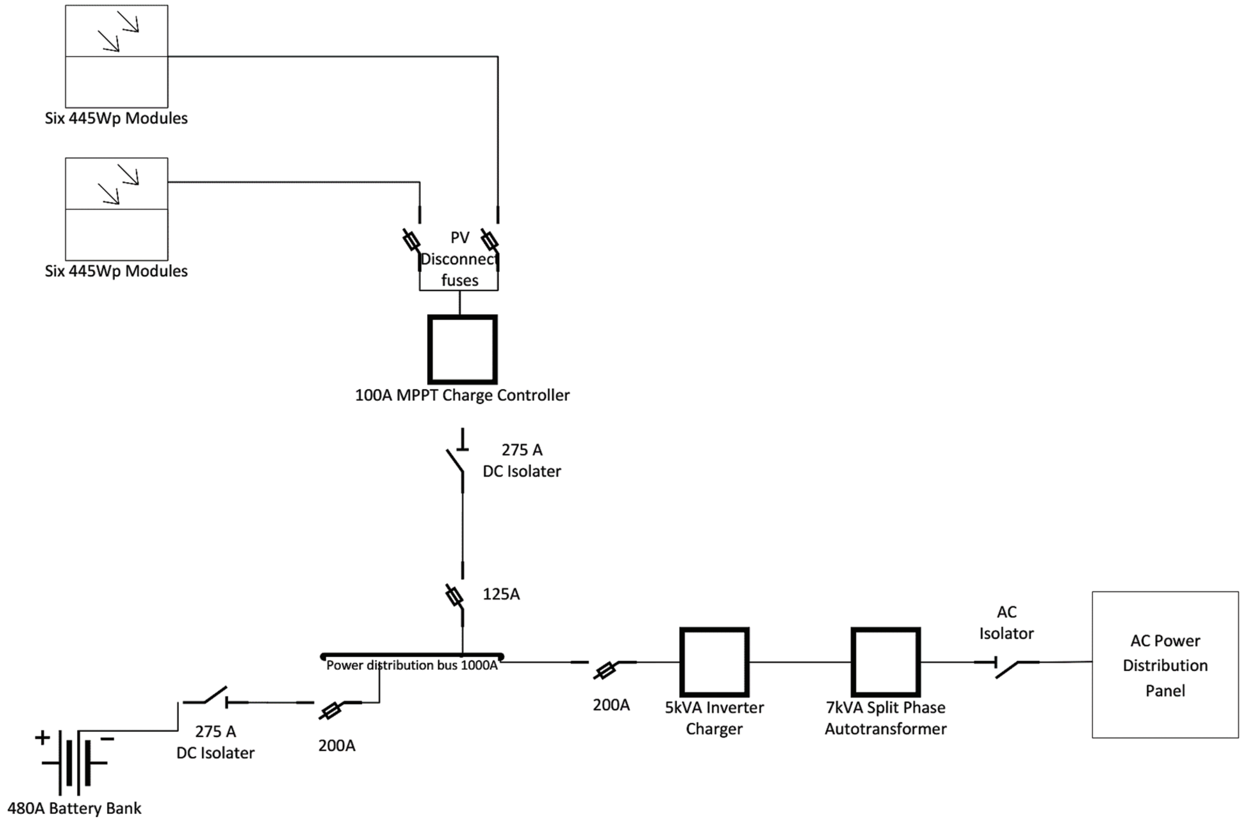

Fig. 2. Single line diagram for the solar PV system.

TABLE II: Summary of the PVsyst Simulation Results

Available energy	8815 kWh/year
Used energy	3692 kWh/year
Excess (unused)	4977 kWh/year
Specific production	1670 kWh/kWp/year
Performance ratio	34.64%
Levelized cost of energy	0.19 USD/kWh
Used energy cost	1.085 USD/kWh

3.1. *Simulation Results*

A summary of the simulation results is presented in Table II and the simulated monthly energy production and losses in Fig. 3.

3.2. *Real World Performance Data*

This section focuses on the presentation and analysis of actual performance data taken from the data logging and energy management system of the solar PV system.

Fig. 4 presents that daily variation of solar irradiance data over the data collection period. It should be noted that during the reporting period, 1000 W/m^2 irradiance levels were never attained. Fig. 5 presents the Cumulative Frequency Distribution (CFD) curve and the calculated median solar irradiance value of 423 W/m^2. The histogram in Fig. 6 illustrates that the highest frequency of solar irradiation observations falls within the 100 to 500 W/m^2 range, suggesting that these are the most common irradiance levels during daylight hours.

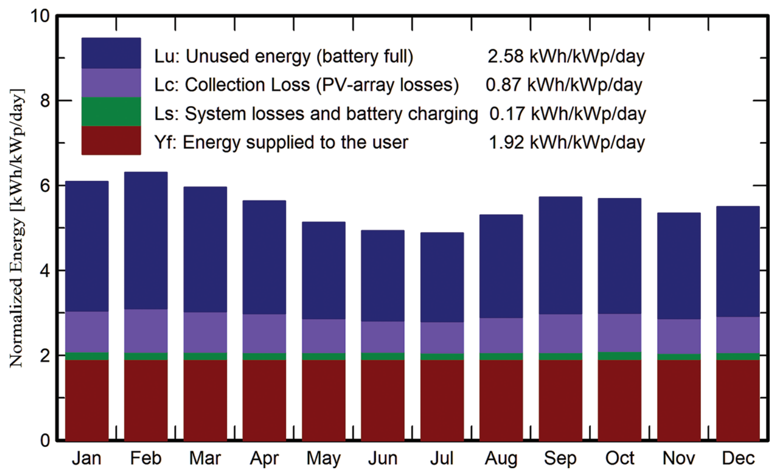

Fig. 3. Simulated results for energy production and losses per month.

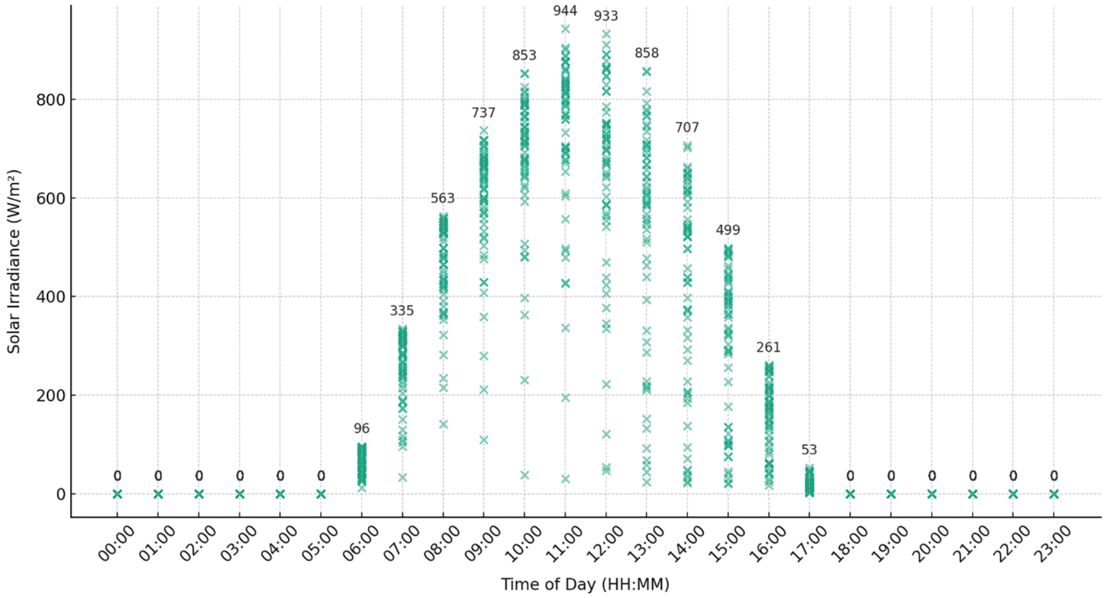

Fig. 4. Daily variation in solar irradiance (W/m^2).

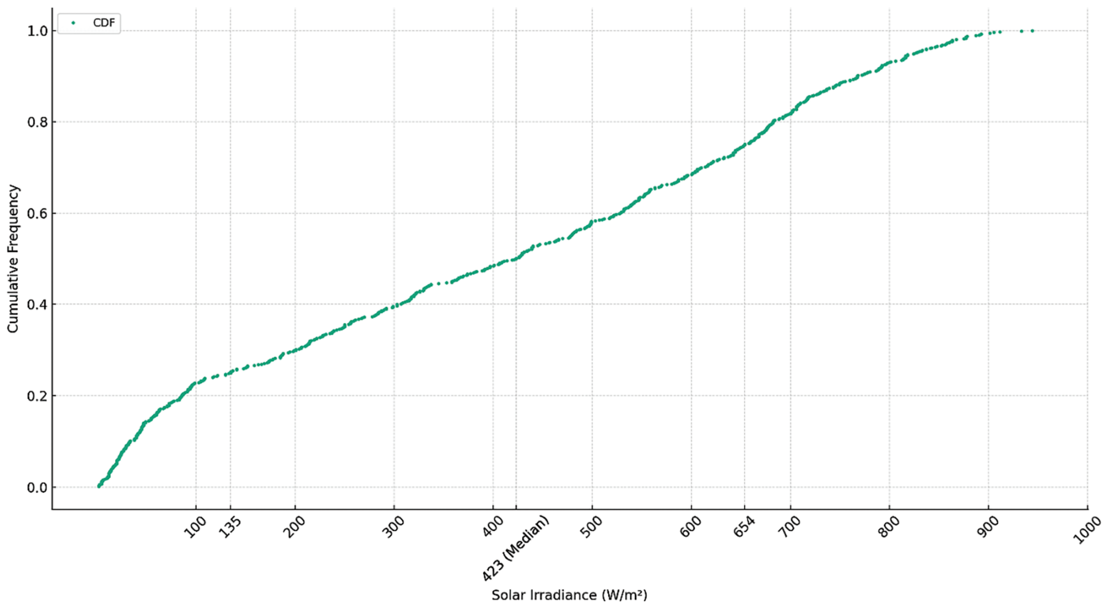

Fig. 5. Cumulative frequency distribution of solar irradiance data.

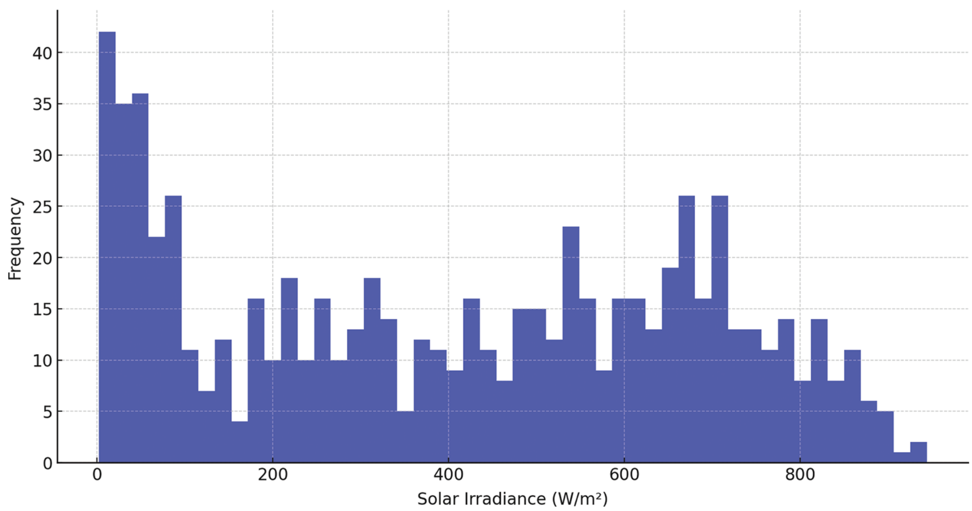

Fig. 6. Histogram of solar irradiance.

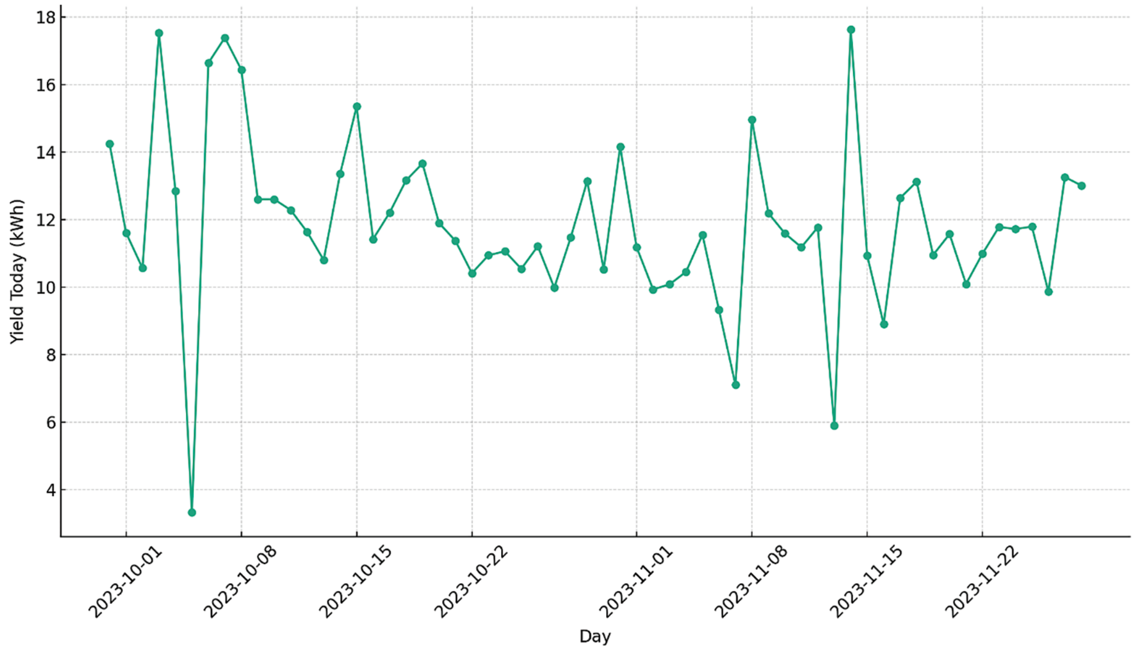

Fig. 7. Daily solar energy yield.

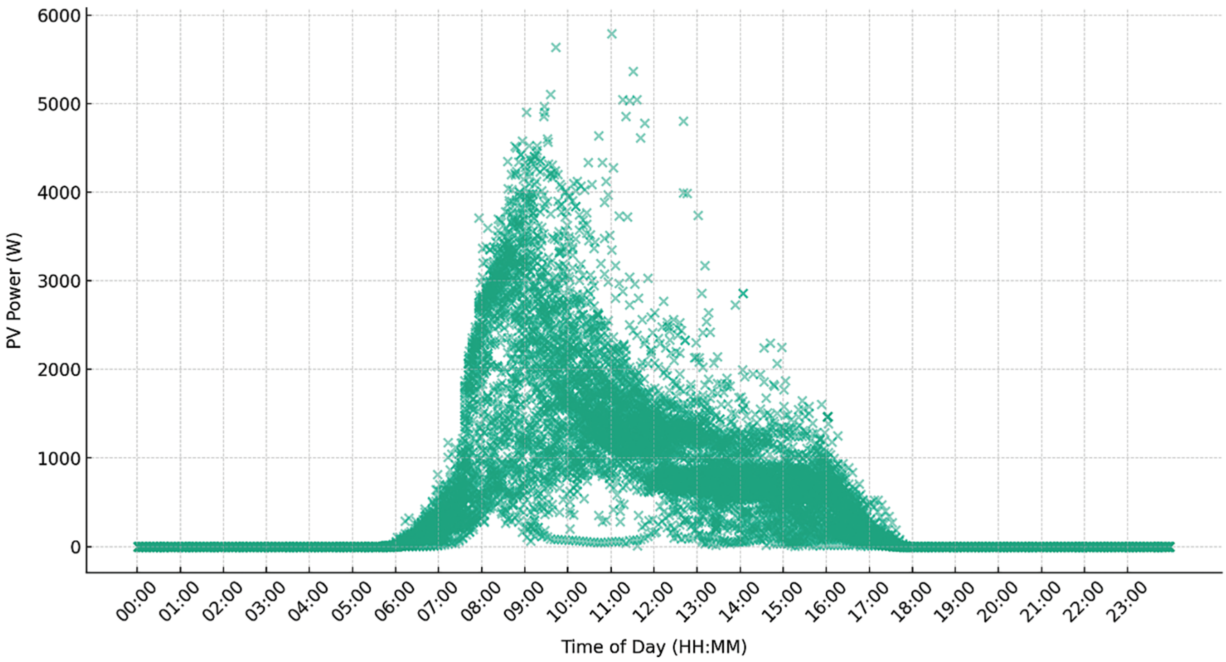

Fig. 8. Daily variation in solar PV production.

The average daily yield (kWh) value from October and November 2023 is presented in Fig. 7. The mean value is approximately 11.86 kWh. This is 49% of the simulated average daily yield value of 24.15 kWh. The daily variation in solar PV power is presented in Fig. 8. During the reporting period, the system rarely reaches or exceeds its installed capacity of 5.34 kW. Fig. 8 also illustrates that PV production peaks between 9 am and 10 am regularly.

The daily variation in electrical demand is presented in Fig. 9, and the corresponding electrical demand histogram in Fig. 10. Fig. 9 illustrates that the electrical demand is fairly consistent throughout the reporting period, and the histogram in Fig. 10 highlights that the highest bin covers the range from 219.8 W to 303.6 W, indicating this is the most frequently observed range of AC power consumption. The second highest bin covers the range from 136.0 W to 219.8 W, showing this as the next most common range of consumption.

The daily charging and discharging of the battery bank are presented in Fig. 11. The battery bank charging pattern does follow the solar PV power production pattern. The discharging of the battery bank, especially at night when there is no solar, matches the electrical load demand profile presented in Fig. 9. The battery bank histogram presented in Fig. 12 shows that the highest bin covers the range from approximately −423.2 W to −220.3 W, and the second highest bin covers the range from approximately −626.2 W

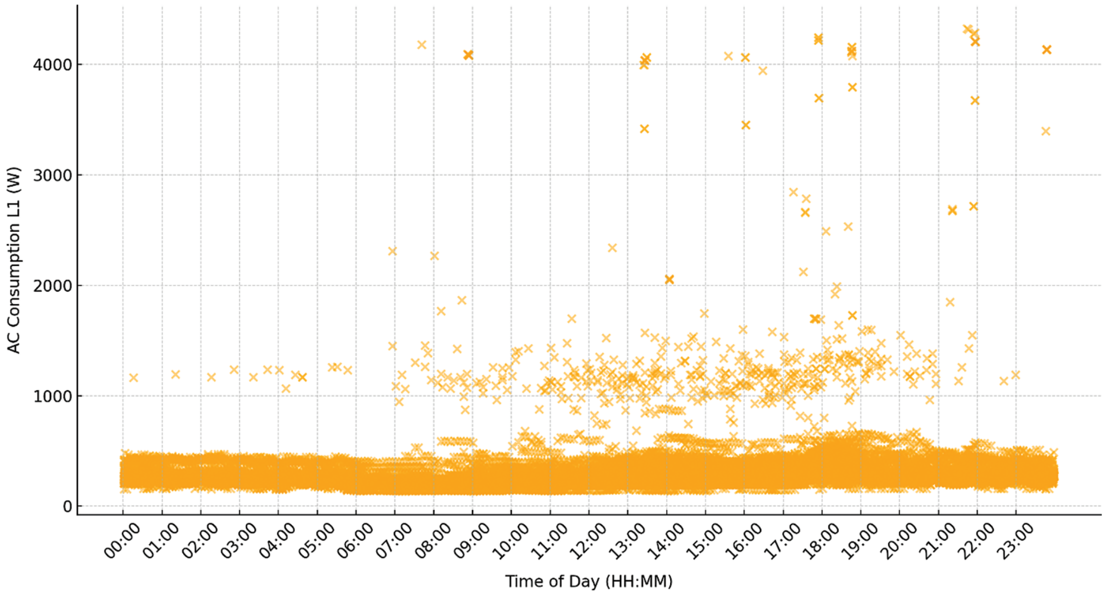

Fig. 9. Daily variation in power consumption.

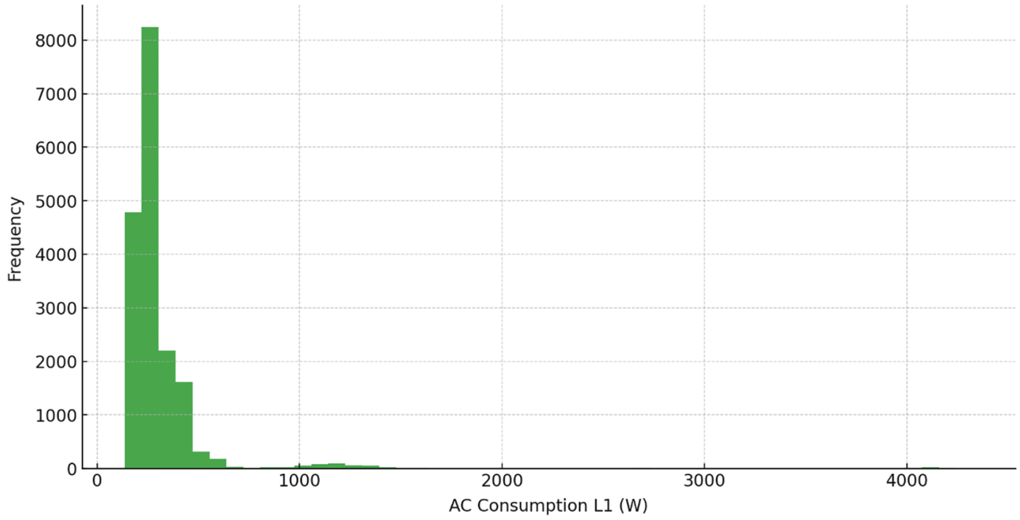

Fig. 10. Histogram showing daily variation in electricity consumption.

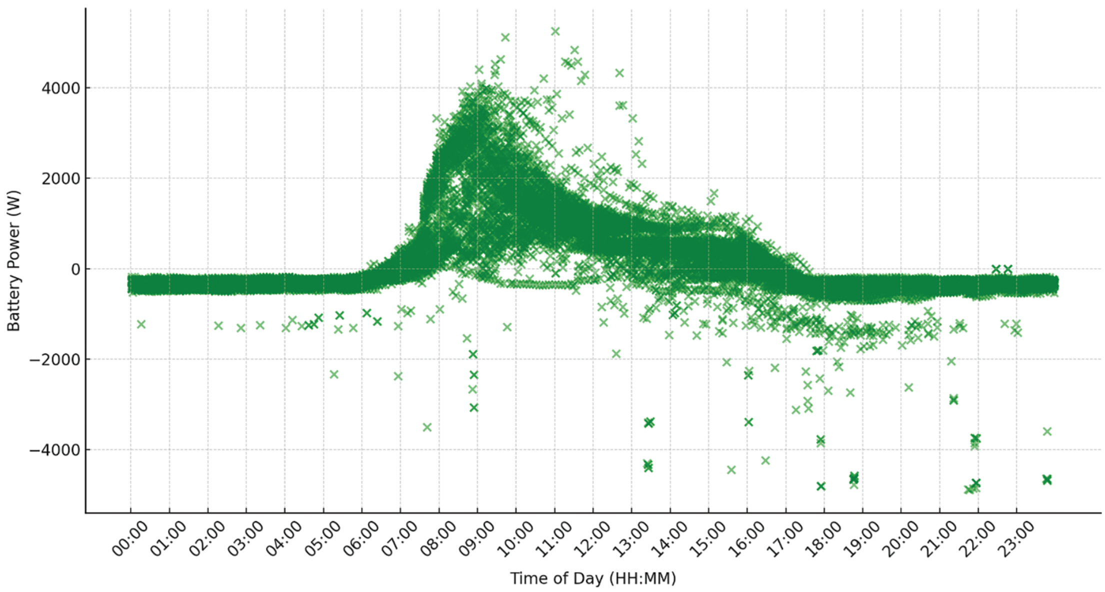

Fig. 11. Daily variation in battery power.

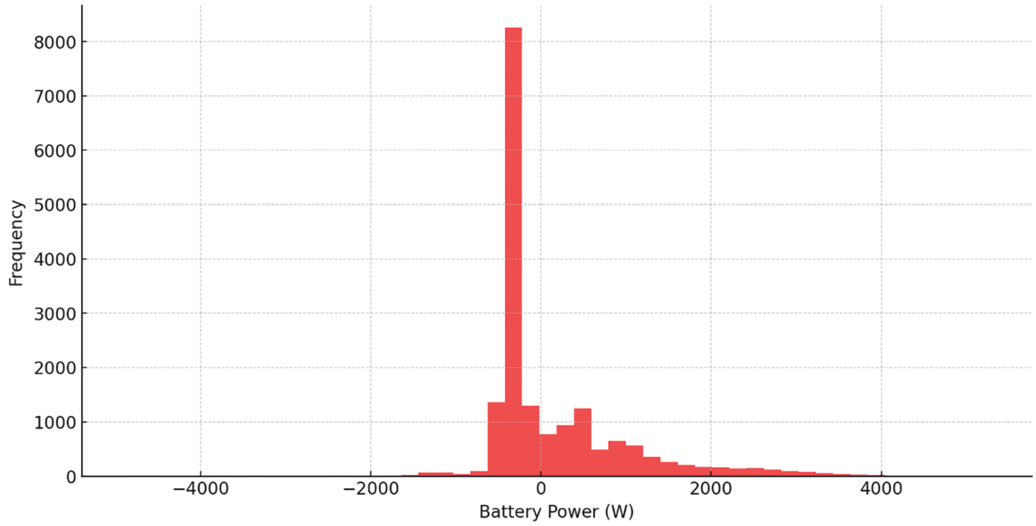

Fig. 12. Histogram of daily variation in battery power.

to −423.2 W. This exceeds the range provided for the electrical power demand in Fig. 10.

The interplay between solar PV power production, battery charging, and discharging, and electrical load consumption is presented in Fig. 13.

Lead carbon batteries specifically for solar PV energy storage were used. Fig. 14 presents the variation in battery voltage for a typical day. Battery voltage is a direct indication of the state-of-charge of the battery bank. The red dashed line in Fig. 14 represents the battery voltage when fully discharged, and the higher two dashed lines represent the voltage range when the battery bank enters the float stage. The battery bank reaches close to fully discharged at around 6 am and spends a short time in the float stage before it is discharged again.

The percentage of power loss during charging and discharging of the batteries is presented in Figs. 15 and 16, respectively. Both figures illustrate that at low load power consumption, there are instances of high losses, exceeding 50%. However, the charging power losses at low load power consumption are regularly less than 20%, and for discharging, it is also regularly less than 20%.

4. Financial Analysis

The breakdown of the equipment cost of the solar PV system is provided in Fig. 17. The equipment was provided by a separate vendor and not the solar installer for this project. The cost of the battery bank is the most significant cost, consuming 37% of the total equipment cost.

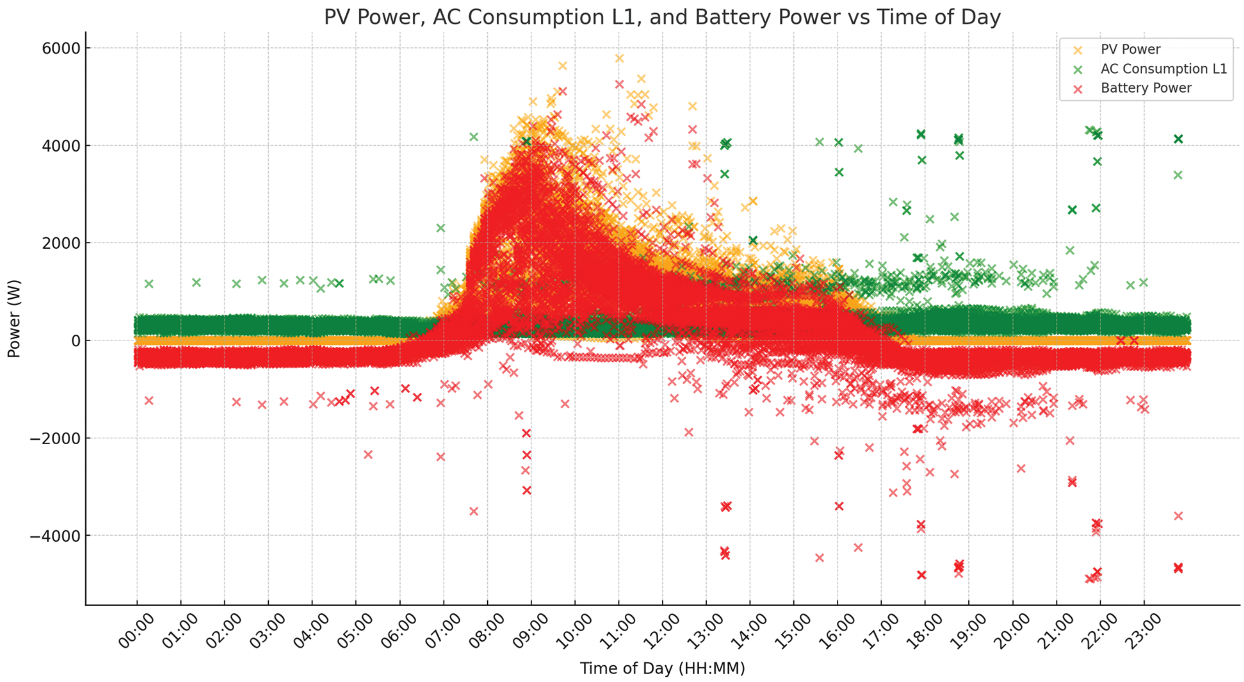

Fig. 13. Daily variation in solar PV power, battery bank power, and load power consumption.

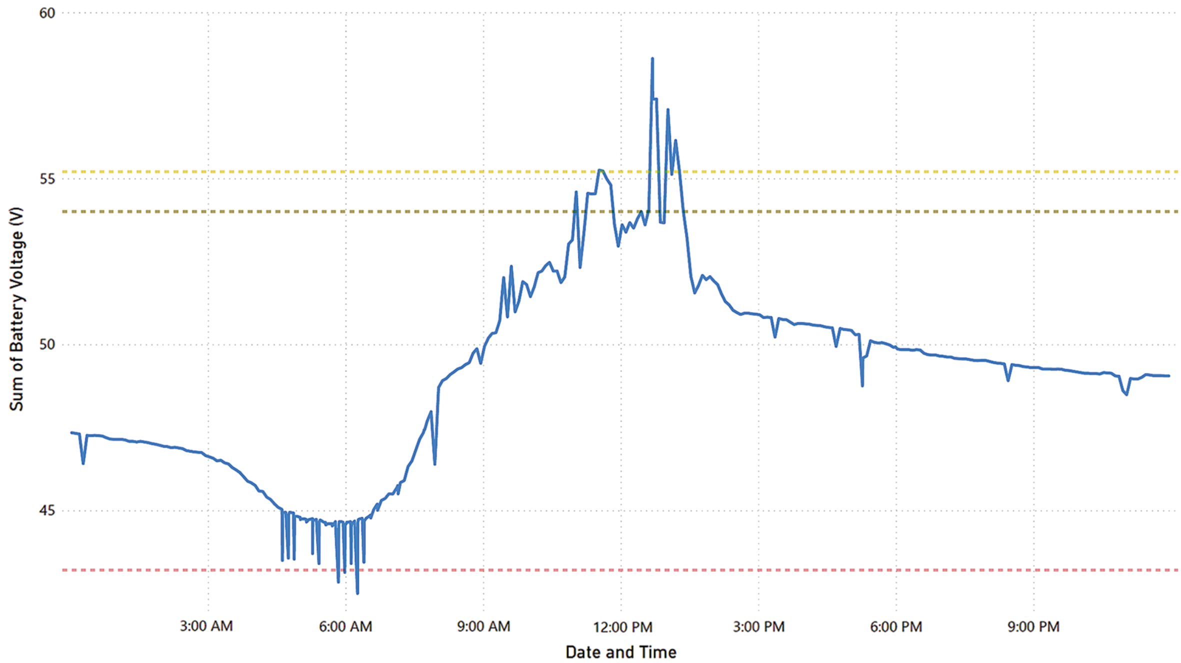

Fig. 14. Battery voltage variation for a typical day.

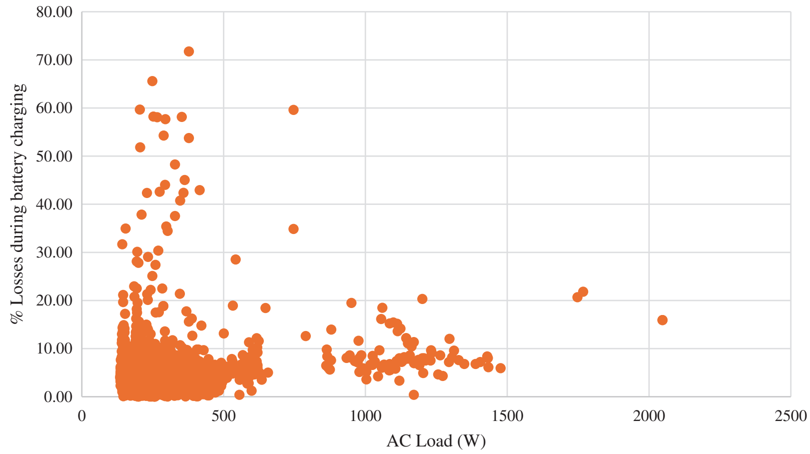

Fig. 15. Losses during the charging of the batteries.

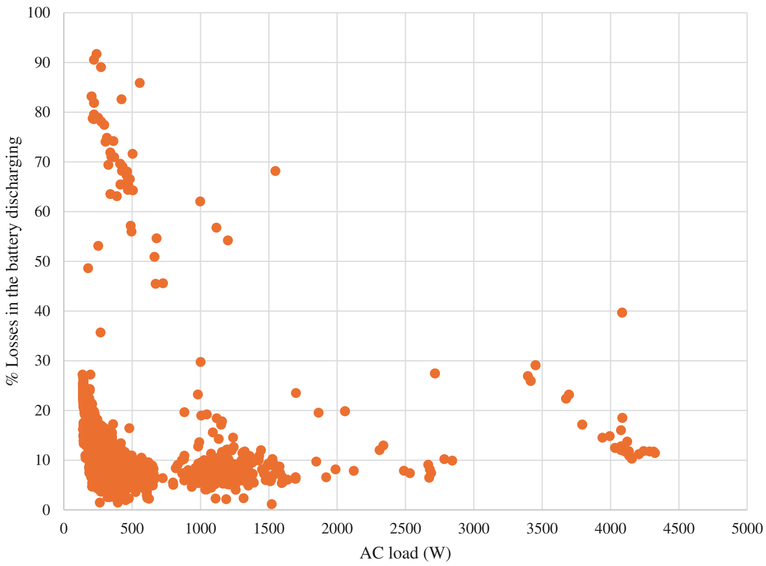

Fig. 16. Losses during the discharging of the batteries.

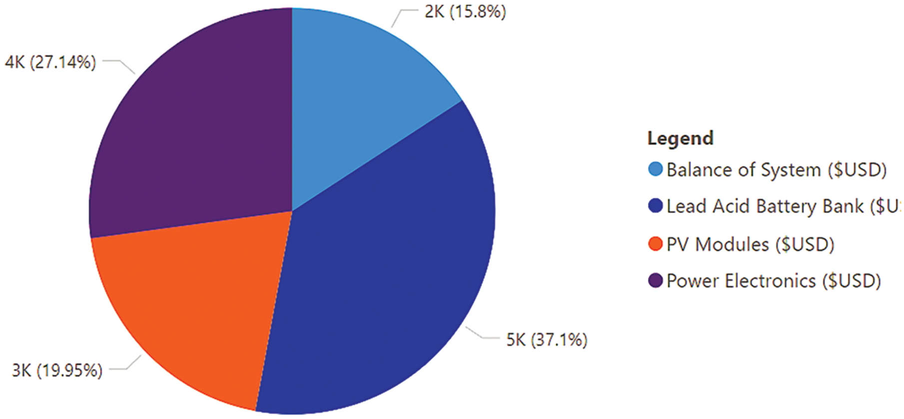

Fig. 17. Breakdown in equipment cost ($USD).

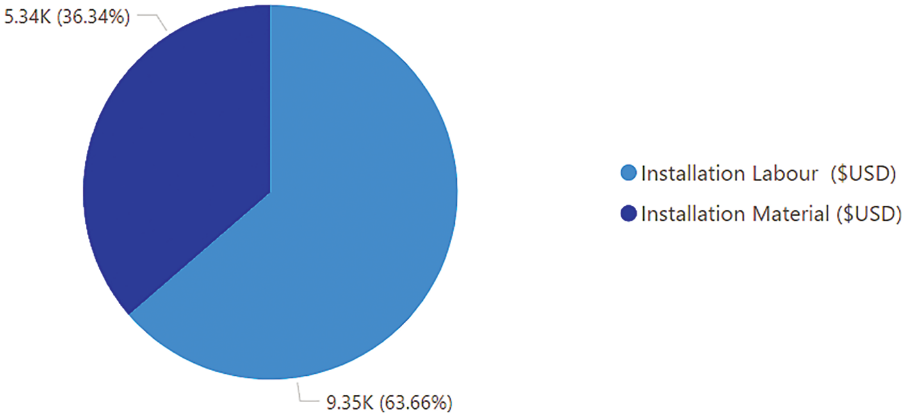

Fig. 18. Breakdown of installation cost.

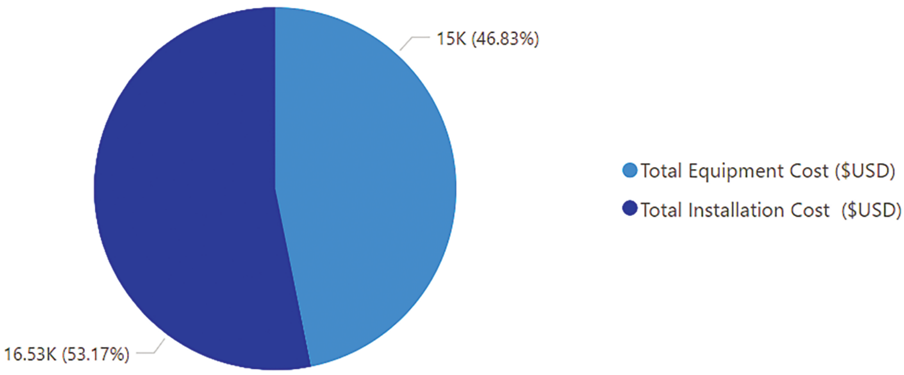

Fig. 19. Equipment cost compared to the installation of the equipment cost.

Fig. 18 shows the installation labour cost to be greater than the installation equipment cost. The installation equipment cost, in this case, is the electrical equipment and materials required to interconnect the solar PV system with the existing electrical infrastructure of the existing building. The total installation cost exceeds the total equipment cost for this project. The total equipment cost refers to the cost of the major solar PV components and the balance of the system required to interconnect the system. The total equipment cost does not include the cost of equipment that interconnects the solar PV system with the existing electrical system. This breakdown in cost is presented in Fig. 19.

4.1. Levelized Cost of Electricity (LCOE)

The parameters used to calculate the Levelized Cost of Electricity (LCOE) using the real-life energy production data and cost are provided in Table III.

The LCOE for your solar installation, before adjusting for the discount rate, is approximately $0.588/kWh. After adjusting for the discount rate on the operation and maintenance (O&M) costs over the system's lifetime, the LCOE is approximately $0.567/kWh.

5. Emissions

The off-grid site used a small diesel generator for electrical power prior to the installation of the solar PV system.

TABLE III: Parameters Used to Calculate the LCOE of the System Using Real-Life Production Data

Parameters	Value
Installed capacity	5.34 kW
Total capital cost	USD $31,081
O&M cost	$100/year
System lifetime	20 yrs
Electricity production in 11 months	2580 kWh
Discount rate	10%

TABLE IV: A Comparison of Key Performance Parameters for Simulated and Actual Results

Parameters	Simulated	Actual	% difference
Annual energy	3692 kWh/year	2815 kWh/year	−23.8%
Performance ratio	34.64%	26.38%	−23.8%
Levelized cost of energy	0.19 USD/kWh	$0.588/kWh	+209%

A small diesel generator, rated at 2 kW that meets the current load requirements of the facility has an emissions factor of 1.22 kg CO_{2e}/kWh [11]. For a year, the solar PV system would have avoided approximately 3,433.7 kg CO_{2e} of emissions. The avoided emissions associated with the small diesel generator are much higher than the emissions associated with electricity produced from the local grid, which is almost completely natural gas based. The avoided emissions from the solar system, had the electricity grid been connected to the site, would be 1,404.4 kg CO_{2e} per year. This is, of course, impractical because of the remote location of the site and the high cost of the installation of the electricity distribution system.

6. Discussion

The rated peak power output of solar PV modules is given at standard testing conditions (STC). The STC conditions are an irradiance of 1000 W/m^2 (watts per square meter), a solar PV cell temperature of 25 °C, and an air mass (AM) of 1.5. The STC conditions do not reflect the nominal temperature and irradiance conditions at the site. For the data collection period, an irradiance of 1000 W/m^2 was not observed, and the average annual temperature in Trinidad and Tobago is between 26.4 °C and 26.9 °C [12]. It is no surprise that solar PV installation rarely produces its simulated rated power output and its daily energy yield. The solar PV design software PVsyst does use ambient temperature and irradiance in its calculations, but these values are based on historical metrological data that have been reanalyzed. This site is around 30 km from the metrological site at the international airport, in a valley location, and in a dense tropical rainforest. These site-specific details were not accounted for in the temperature and irradiance variations. The energy production directly affects the LCOE, with the actual LCOE being more than two times higher than the LCOE derived from simulation results. The LCOE for both the simulated and actual are both high when compared to the average domestic rate for electricity locally. The simulated LCOE is 3.8 times the local electricity rate, and the actual LCOE is 11.8 times the local electricity rate. This high cost is because the local electricity rate is subsidized by a lower than market price for natural gas, and the PV system, being totally off-grid, has a battery system that is 37% of the equipment cost. A summary of the actual and simulated performance parameters is provided in Table IV.

The electricity load of the system is fairly constant, however, there are numerous occasions when there is a sharp spike in electrical demand, as seen in Fig. 9. This sharp spike is due to the use of a water pump, a small air dryer, and an electric heater. The system was not designed to accommodate the surge current required for the operation of a water pump. The water pump was connected by the site user after the installation. The constant load extends throughout the night; this represents a nightly current draw and cycling of the batteries. Fig. 14 expounds on the issue of the constant load draw on the batteries at night. At around 6 am, the batteries are close to depleted and rely on a sunny day or a day with a high average solar irradiance to recharge. If this is not the case, the batteries can be completely depleted during the next night if the electrical load is not decreased. This did not happen during the data collection period. The system was designed with one day of autonomy. However, the lower solar energy output and the extended energy usage at night decreased the buffer provided by the day of autonomy.

The system has a 5 kW inverter installed but rarely operates at this rated power and operates mostly at 1.5 kW output. An inverter typically has lower efficiency when operating at a lower output power. This is illustrated in Fig. 16, where there are mainly losses of around 20% when operating at a power output of 1.5 kW and less.

The cost to install the system exceeded the total cost of the equipment and the cost of the labour component of the installation exceeded the cost of the equipment, and materials to perform the installation. This is illustrated in Figs. 18 and 19. The cost is directly reflective of the remote nature of the site and the unavailability of an electrical connection during the installation of the solar system.

After analyzing the system's performance, the following recommendations are being made: It is uncommon to perform a solar resource assessment for small domestic and light commercial installations; however, for off-grid, remote systems, a one-to three-month long logging of solar irradiance data using a low cost digital pyranometer can greatly benefit the technical design and financial analysis of the solar PV system. The high labor cost for this project, mainly caused by the remote and off-grid nature of the site, would decrease in the short and medium term as the local solar PV market grows, and the global decline in energy storage costs would also benefit off-grid sites [13].

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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