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Comprehensive Energy Analysis and Performance Evaluation of Lithium-Ion Battery Integration in Photovoltaic Systems: A Comparative Study on Reliability and Environmental Impact

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Abstract: The ongoing advancement of lithium-ion batteries and their distinctive technical attributes lay the groundwork for the exploration undertaken herein. The diversity of loads applied within electric storage battery systems (ESBS) plays a pivotal role in determining the overall efficiency of the battery. In this research endeavor, a comprehensive battery model has been meticulously employed to conduct an in-depth analysis of energy consumption patterns and the efficacy of lithium-ion batteries within solar photovoltaic (PV) systems. Utilizing a specialized tool known as the maximum power point tracker (MPPT), crucial insights into the effectiveness, power output, and capacity of the battery were gleaned by employing an observation and perturbation approach. Over a period spanning six months, the performance of lithium-ion batteries has been meticulously scrutinized across various operational paradigms, leveraging data on load profiles and PV generation. Notably, the lithium-ion battery bank exhibited maximum mean energy efficiencies of 32.76%, 38.3%, 43.33%, 45.03%, 52.64%, and 56.87%, respectively, over the timeframe as mentioned earlier, while boasting an energy capacity of 685Ah. Maintaining a maximum voltage of 14.4V owing to the series connection of batteries, this study offers a condensed yet comprehensive framework for the analysis of energy utilization and the effectiveness of lithium-ion batteries within battery storage systems (BSS).

Keywords: Photovoltaic System; Lithium-ion Battery; Power Output; Energy Efficiency; Electric Storage Battery Systems; Maximum Power Point Tracker; Battery Storage Systems; Energy Consumption Patterns.

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1. Introduction

Energy storage systems are currently viewed as a significant component of electrical power networks, including traditional and renewable energy sources, serving as distributed energy resources (DERs), including on-grid and off-grid power generation [1]-[4]. Energy from renewable sources (RS) is now being used to minimize the high cost of the electrical grid and CO2 generation from diesel generators, which leads to environmental degradation, global warming, and ozone layer depletion [5]. Approximately 29% of the world's electricity as of 2021 is produced by renewable energy [6]. Geothermal, solar (like photovoltaic systems), bioenergy, wind, and water (hydroelectric) energy sources are the five basic types of renewable energy. Being a renewable energy source, photovoltaic (PV) systems have become one of the most widely used ways to produce electricity. Since the early 1800s, photovoltaics (PVs) have undergone advancements, including an improvement in efficiency, fabrication of low-cost solar panels (cells), and increased versatility.

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Recently, PV systems store photovoltaic energy as chemical energy in batteries. These batteries come in a variety of designs, including flooded lead acid, absorbent glass mat (AGM), gel cell, and lithium-ion. Due to their superior gravimetric properties, high power efficiency, and volumetric energy densities, lithium-ion batteries are currently the most popular power source for portable electronics. Due to their maturity and ease of design and installation as compared to other storage systems, battery systems are among the most promising storage systems for stationary applications [7]–[10]. An overview of the fundamental concepts and knowledge of lithium-ion battery energy flow in solar systems is provided in this study.

The improvement of public understanding, information, and purchasing decisions will be greatly aided by raising public awareness of lithium-ion batteries in PV systems. This work is entirely focused on lithium-ion batteries in PV systems and provides a fundamental understanding of renewable battery sources and their evolution in the 21st century. The goal of this study is to analyze energy flow in lithium-ion battery-based photovoltaic systems. Procedures for predicting the performance of batteries in PV systems using experimental data have been presented in this investigation. A method for assessing battery system conversion and overall efficiency that took into account the air conditioning system, battery temperature fluctuations, and inverter losses was proposed by Rydh and Sandén[3].

For sensitivity analysis, constant values with parameter changes were employed, resulting in a maximum total efficiency of 80% for lithium-ion battery systems. In another study, Gatta et al. accessed the overall efficiency of sodium-sulfur (NaS) and lithium-ion (Li-ion) batteries employing auxiliary loads based on the load and photovoltaic generating data collected over 8 months [11]. The commissioning, conditioning, impedance measurement, high current and high-power testing, quick charge tests, and BESS tests to improve lithium-ion batteries for battery energy storage systems (BESS) were used in [12] by measuring the impedance at 3 frequencies, which introduced a method that can choose attributes in a database to construct fuzzy logic models for both available capacity and state of charge estimation [13].

Lee et al. used soft computing techniques to estimate the state of charge of individual batteries in a battery string, which led to the application of the Kalman filter-based state of charge estimation approach [14]. The usefulness of the Kalman filter in an online application has been validated by experimental data generated by Yatsui and Bai [15]. The method for estimating monthly average array efficiency and monthly average electrical energy output from a PV system was developed by Siegel et al. using the estimated monthly average excess electrical energy that must be dissipated, fed back into a utility grid, or possibly stored in a storage battery [16]. Patsios et al. investigated a storage system simulation in a local grid application using a single-particle cell model. The result of the study showed that a higher time-averaged state of charge resulted in battery degradation, and a lower level of charge resulted in lower energy efficiency [17].

A power electronics simulation model for an open-source residential small-scale solar battery storage system and the dynamics of the controller and converter were derived from the dynamics of the household PV battery system. The losses in power electronics and batteries are estimated using data from comprehensive system characterization studies [18]; [19]. Indexes for measuring performance took into account inverter sizing, less-than-ideal power flow control, and the energy management system, as well as energy loss mechanisms from conversion and system standby power usage. Overall system performance and power flow to achieve optimal operation were the primary foci of the investigation [20]. Using weather data from several climate zones and actual thermal factors, Neubauer studied the thermal behaviour of stationary battery systems. The battery's thermal capacity and the system's total thermal mass are combined in the thermal system model. In sunny, warm climates, Neubauer found that solar influences can hasten the breakdown of batteries [21].

From the reviewed literature, the fundamental concepts and knowledge of lithium-ion battery energy flow in solar systems are provided in this study. The study has shown that there exists a fear of buying substandard batteries that prevents consumers from investing in the best PV systems. Although regarded as a renewable energy source, not much is known about its battery life, energy density, power efficiency, or usefulness. The goal of this present study is to improve public understanding, information, and purchasing decisions, which will be greatly aided by raising public awareness of lithium-ion batteries in PV systems. This investigation achieves this by developing a Li-ion battery and providing its inherent technical specifications.

2. Methodology

2.1. Battery Energy Efficiency

The ratio of charged energy to discharged energy is used to calculate energy efficiency.

$$\text{Battery energy efficiency} = \frac{\boldsymbol{P_{ob}}}{\boldsymbol{P_{ib}}} * 100\% \tag{1}$$

where, P_{ob} = power output from the battery

P_{ib}= power input to the battery

2.2. State of Charge and Depth of Discharge

The level of charge in an electric battery relative to its capacity is referred to as its state of charge (SoC). SoC is measured in percentage points (0% = empty; 100% = full). The depth of discharge (DoD), the inverse of SOC (100% = empty; 0% = full), is an alternate indicator of the battery's lifetime after repeated use. SoC is mathematically expressed as follows**:**

$$SoC\ (t)\ = \frac{I_{(t)}}{I_{(n)}} \tag{2}$$

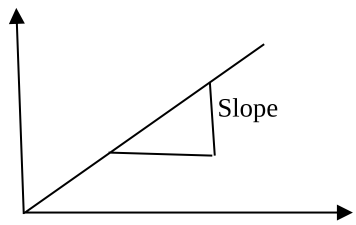
$$DoD = Full\ charge\ (100\%) - SOC\ (t) \tag{3}$$

where, $I_{(t)}$ = current capacity with respect to time
$I_{(n)}$= normal current capacity

2.3. Power Output

The power output of the solar panel and battery bank, which is the input of the energy charged in and the capacity from the battery, is calculated as follows;

$$P = I^2 \times R_L = I\ \times V \tag{4a}$$



$$Output\ \ power,\ P_{p\ or\ c}\ (kW) = \frac{I_p \times\ V_p}{1000} = \ \frac{I_c \times V_{(max)}}{1000} \tag{4b}$$

where, I_p = peak input current
V_p = peak input voltage } from Solar
I_c = current consumed } from Battery

2.4. Battery Capacity

Battery Capacity, B_c is measured in Amp- hour (Ah), which is usually found in a deep cycle battery and theoretically is calculated as a discharge as follows:

$$B_c = \ I_B\ x\ \ t_b \tag{5}$$

where, I_B = current from Battery (Ampere)
t_b = backup time (hour)

2.5. Energy Storage Capacity

Energy Storage Capacity, E_s of battery is measured in kilowatt-hours (kWh) as the product of storage battery capacity and maximum voltage.

$$E_s\ \ = \frac{B_s\ \times\ V_{max}}{1000} = \ P_{max}\ \times t_b \tag{6}$$

where, B_s= Battery charge capacity (Ampere-hour)
V_{max} = Battery voltage before usage (Volt)

P_{max} = maximum power

2.6. Energy Density

Energy Density, E_d of battery is the quantity of energy stored per unit mass in gravimetric units or per volume in volumetric units.

$$E_d = \frac{Energy\ (Wh)}{mass\ (kg)}\ or\ \frac{Energy\ (Wh)}{volume\ (m^3)} \tag{7}$$

2.7. Energy Consumption from the Battery

Energy Consumption from the Battery, E_c is the storage energy capacity of the battery with respect to backup time for the solar system.

$$E_{\boldsymbol{c}} = E_s \times t_b = I_{Ah} \times V_{(\max)} \tag{8}$$

where, E_s= energy storage capacity
t_b = backup time
I_{Ah} = battery capacity (Ampere hour)

2.8. Total Load Consumption

Total Load Consumption, L_T is the ratio of the product of battery voltage and current in ampere-hours to backup time.

$$L_T = \frac{V_{(b)} * I_{(Ah)}}{t_b} \tag{9}$$

where, $V_{(b)}$= battery voltage
$I_{(Ah)}$ = battery current with respect to time

2.9. Total Mean Power Efficiency

Total Mean Power Efficiency Consumed, $\eta_{T_{mp}}$ is the ratio of total power efficiency to the total number of days in a month.

$$\eta_{T_{mp}} = \frac{\eta_p}{n} * 100 \tag{10}$$

where, η_p = total power efficiency
n = number of days

3. Experimental Results

Table 1: Resident appliance energy consumption

Appliance	Rated power (W)	Time used (hr)	η_c	Energy consumption (kWh)	Months					
					Nov.	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**
Solar refrigerator	150	8	37.82		21.32	28.18	29.98	31.59	35.67	45.53
Solar bulbs	36	8	9.08		5.12	6.76	7.20	7.58	8.56	10.93
Solar Television	30	5	4.73		2.67	3.52	3.75	3.95	4.46	5.69
Solar fan	70	8	17.65		9.95	13.15	13.99	14.74	16.64	21.25
Charger mobile	45	5	7.09		4.00	5.28	5.62	5.92	6.69	8.54
Laptop charger	70	5	11.03		6.22	8.22	8.75	9.21	10.40	13.28
Extra load	80	5	12.61		7.11	9.39	9.99	10.53	11.89	15.18

The analysis in Table 1 is done based on 6 months with the home appliance related to energy consumption. Graphs were plotted using data from the solar system for 6 months, as evident in Figures 1 and 2.

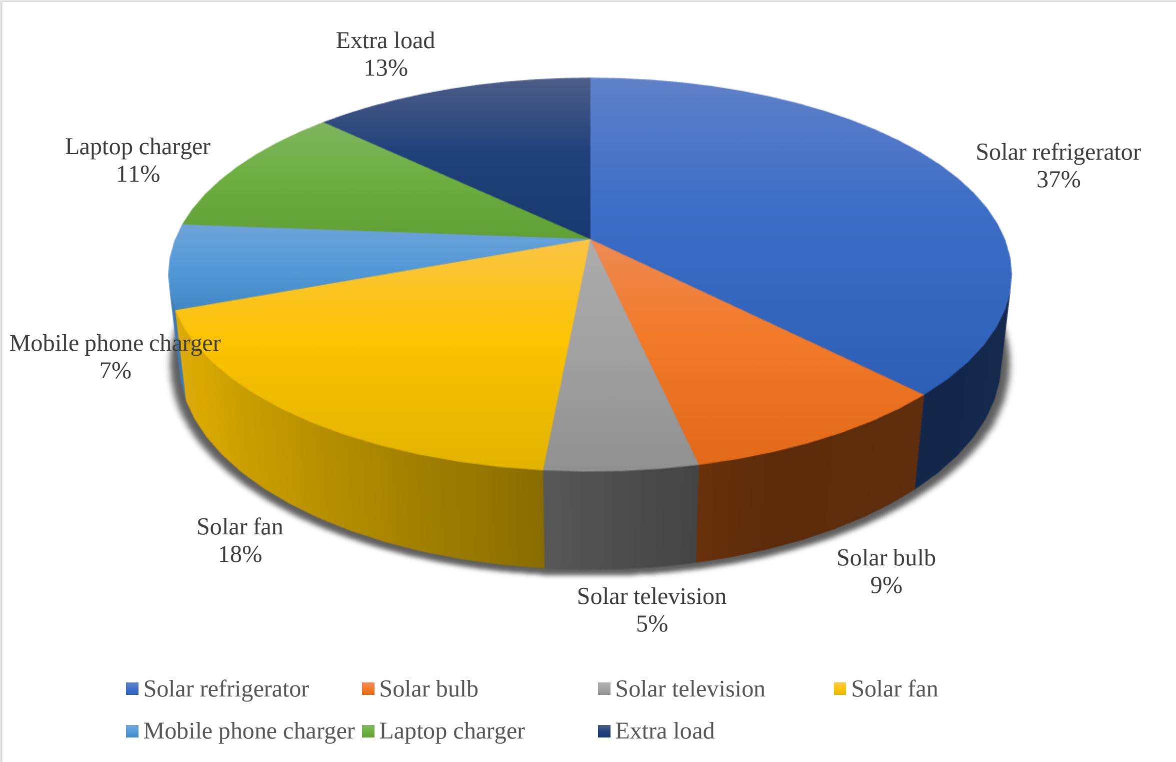


Figure 1: Chart of the percentage of energy used by appliances.

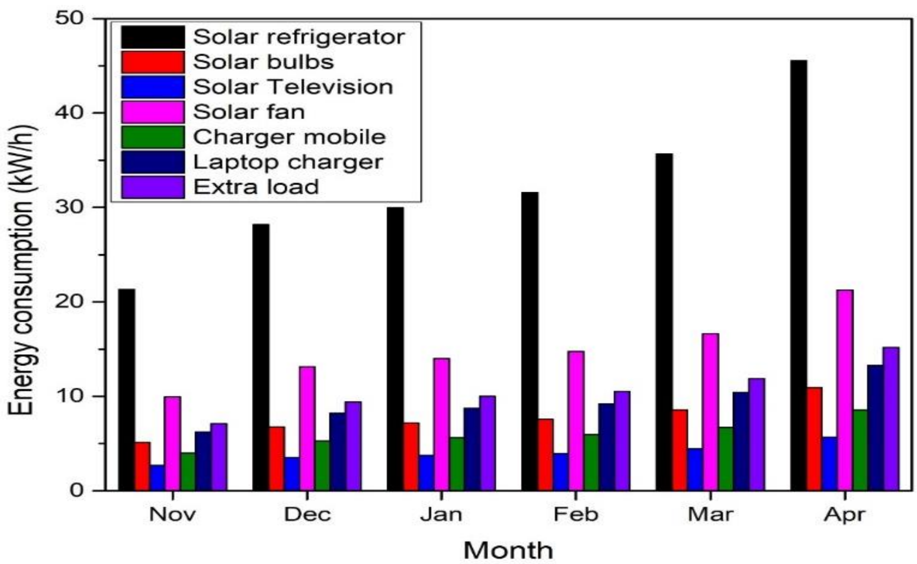


Figure 2: Energy consumption for the 6-month study period by selected appliances

Figure 2 depicts a 6-month energy consumption chart for several appliances. The solar refrigerator consumed 38% more electrical energy or power than the other devices (laptop load, mobile phone load, solar fan load, solar TV load, and solar bulb load, respectively). It can also be noticed that, due to the lack of electricity, energy consumption continues to rise and appliances are being used more frequently than usual.

Figure 3 shows the energy used, which fluctuates from month to month, with the biggest energy use occurring in April. Since then, the construction of the Third Mainland Bridge (which connects the Southwestern part of Nigeria to the southeast) in the study location resulted in power disruptions that affected some areas in Southeast Nigeria. Although the battery usage arithmetic backup time was 8 hours, the gadget was utilized for significantly longer than that.

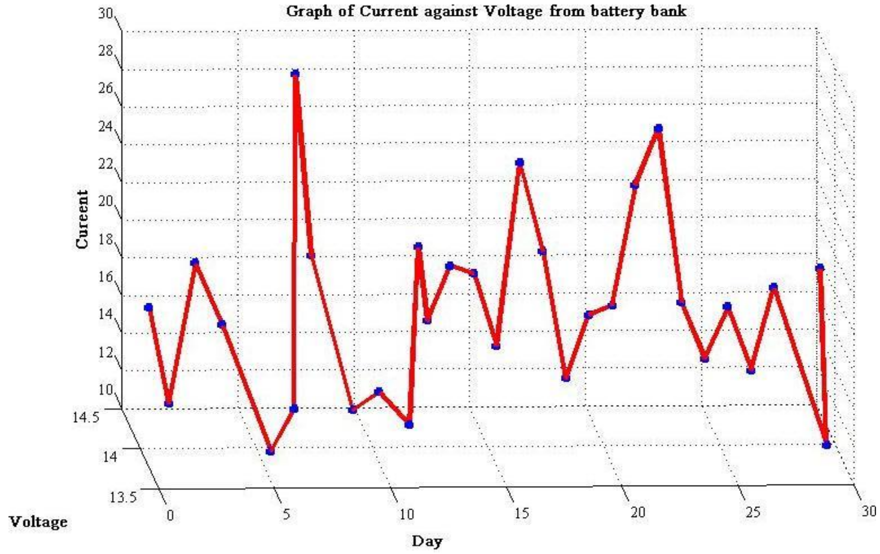


Figure 3: Maximum current - voltage from the battery bank in November 2021

The maximum current voltage from the battery bank that is provided to the house daily is shown in Figure 3, with minimum and maximum values of 0.11kW and 0.41kW, respectively. The graph depicts a total mean power efficiency for the entire month of November of 32.76% with a total load usage of 6.99kW. It was found that the maximum voltage keeps the battery rating's average charge range constant.

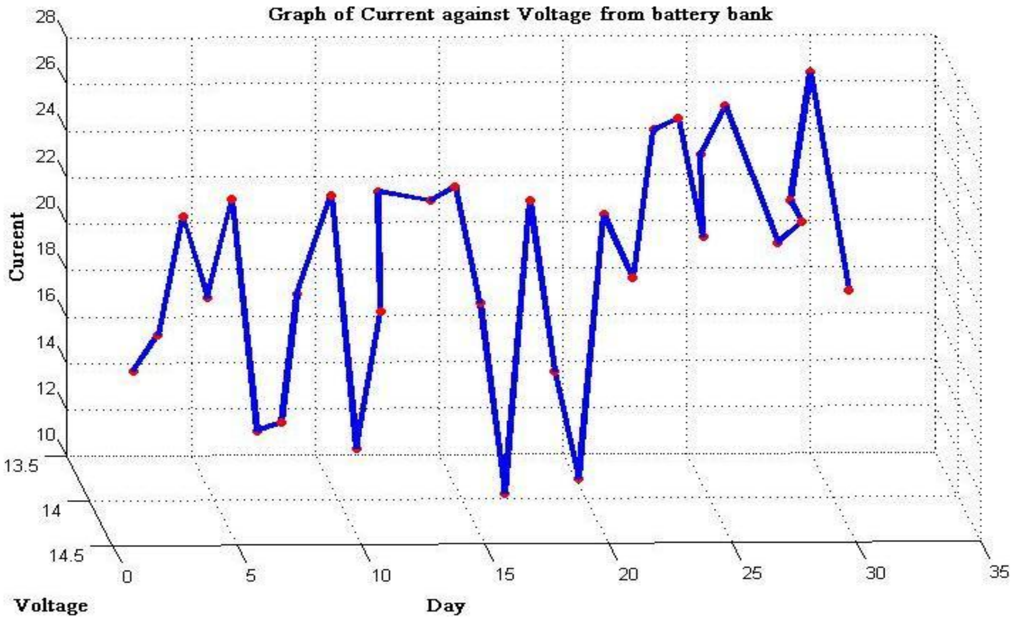


Figure 4: Maximum current - voltage from the battery bank in December 2021

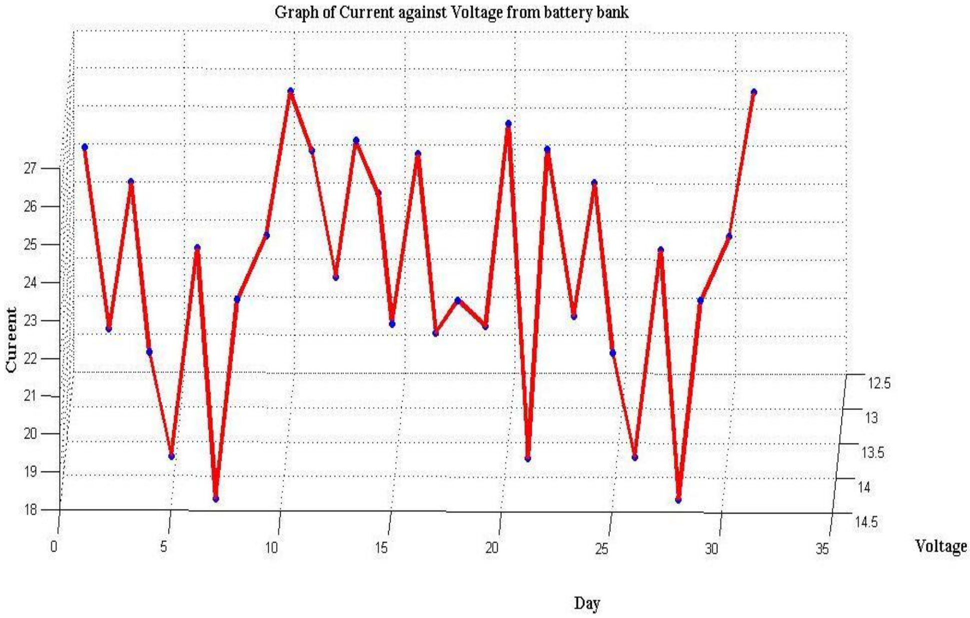


Figure 5: Maximum current – voltage from the battery bank in January 2022

Figure 4 shows a nearly constant maximum battery charge voltage of 14.4V, with the lowest and highest values in December being a current of 27.88A and 11.75A, respectively. The rising and falling of electricity from the battery bank was brought about by a significant variation that occurred during this time; with a total load consumption of 9.30 kW, it was found that the overall mean power efficiency increased to 38.30%, 5.54% more than the previous month's value.

Due to the weather, the maximum voltage in Figure 5 shows fluctuations between 12.9V and 14.4V. The current ascent degree is 27A, with the lowest value being 18.13A, thereby increasing the overall mean power efficiency to 43.33% and the total load consumption to 9.93kW in January. The efficiency increased by 5.03% over the previous month, demonstrating increasing battery capacity with increasing load.

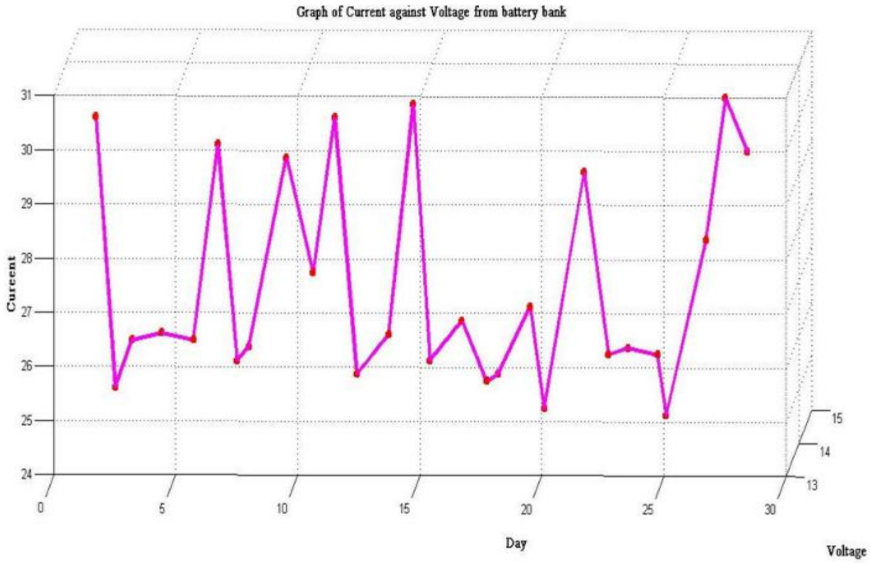


Figure 6: Maximum current – voltage from the battery bank in February 2022

The maximum voltage, as shown in Figure 6, ranges from 13.2V to 14.4V, while the current values of 24.88A are the lowest and 30.38A are the highest. Figure 7 also indicates that the battery expended more energy in February than in January. As a result, the capacity of the battery improved, causing a rise of 45.03% in the total mean power and a 10.56kW increase in the total load consumed.

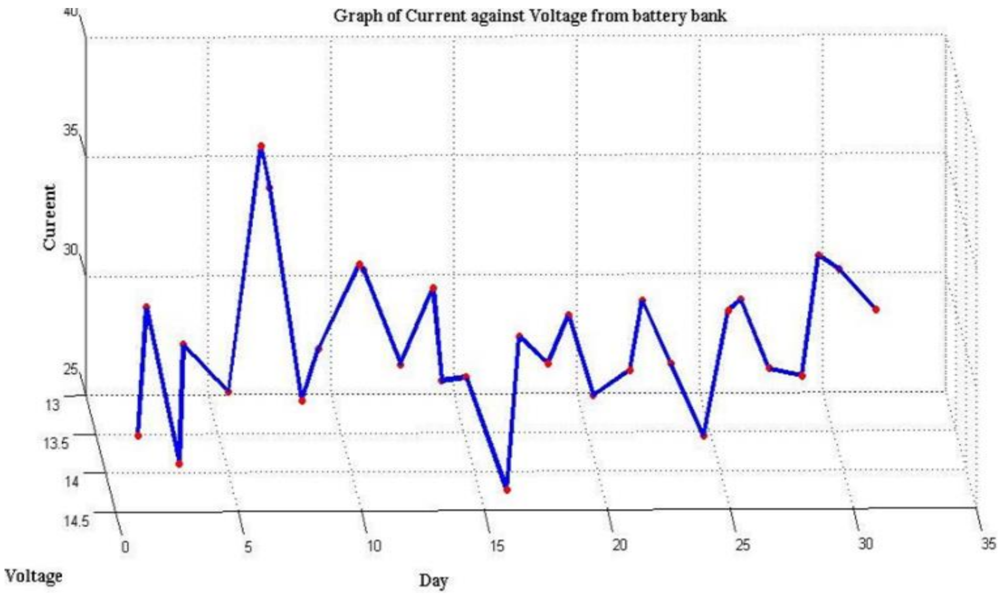


Figure 7: Maximum current – voltage from the battery bank in March 2022

The maximum current-voltage output of the battery bank of the PV system is depicted in Figure 7. The result of the corresponding analysis indicates a total load consumption of 13.19 kW; the generated energy has a mean efficiency of 52.64%. The highest voltage in March ranged from 13.4V to 14.4V, and more energy was used than in earlier months.

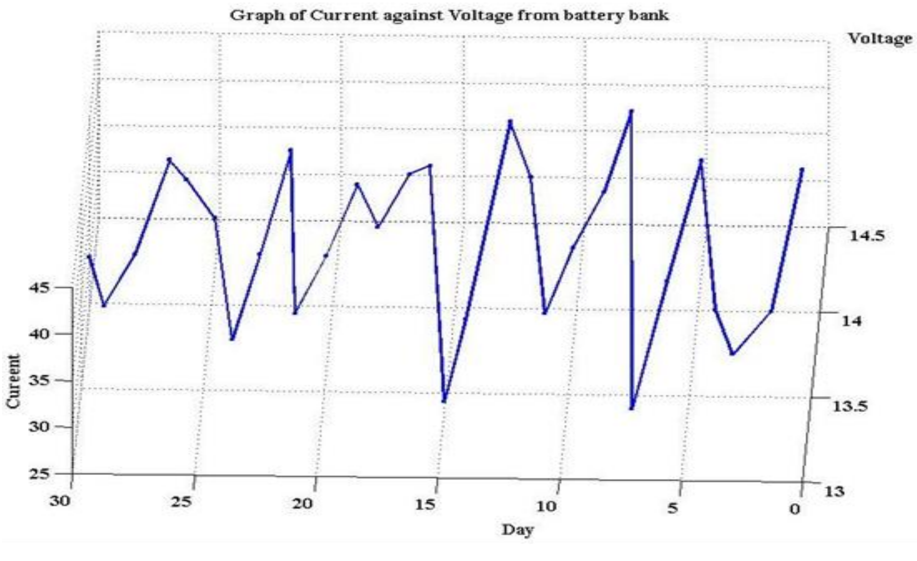


Figure 8: Maximum current – voltage from the battery bank in April 2022

The variation in battery capacity (current) due to backup time and maximum voltage as a function of the battery's daily usage in April 2022 is shown in Figure 8. The results show a battery capacity that ranges from 25A to 40.25A. The total load consumed and total mean efficiency were 14.27kW and 56.87%, respectively, while the maximum voltage ranges from 13 to 14.4V.

Generally, the graphs show that the rise and fall of power production can be fairly uniform on some days but can also be distinguished by very significant variations on other days. The Figures also indicate that the battery bank's maximum voltage output is 14.4 volts, with a slight variation to 14.5 volts in November. The graph shows that the battery supply becomes more efficient the more energy is used and that the capacity is not constant but varies daily within a given month.

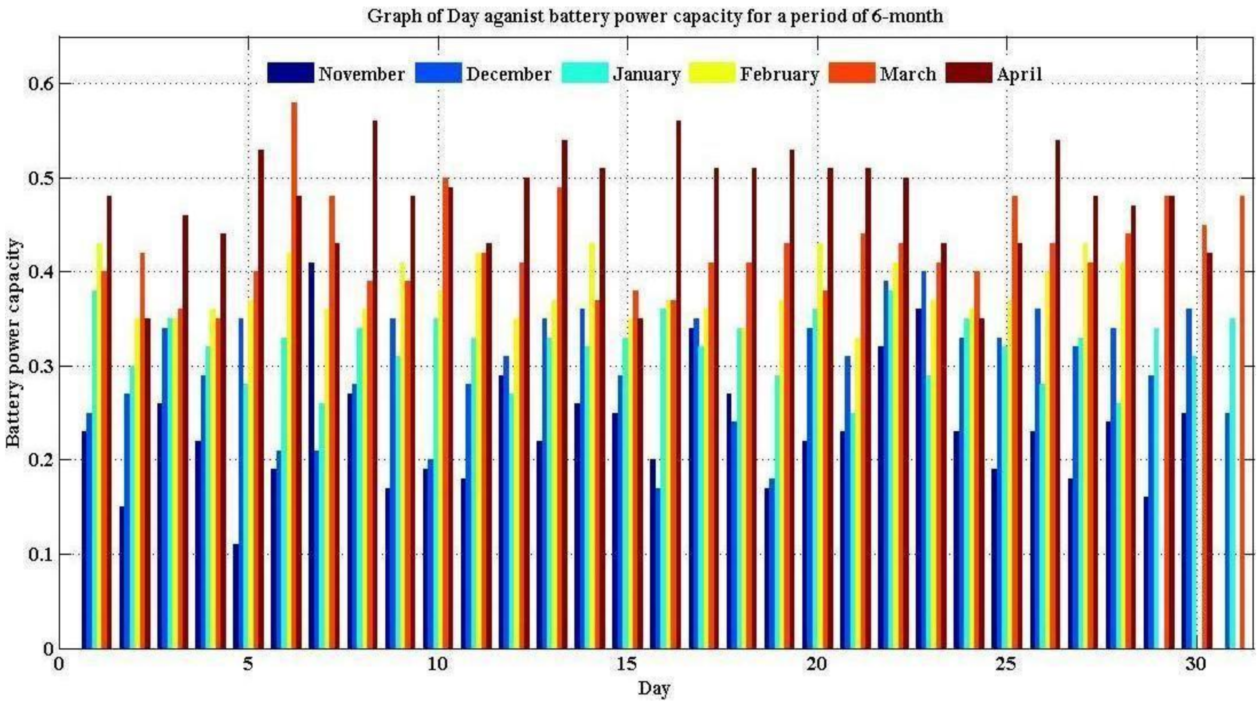


Figure 9: Battery power capacity for the 6 months

Monthly battery capacity usage showing daily utilization is summarised in Figure 9. Battery power reading, as shown in Figure 9, is usually at its lowest and highest during the day due to capacity variation. The largest and lowest values of current from the battery bank were 322 Amp-hours and 82 Amp-hours, which occurred on April 16th, 2022, and November 2nd, 2021, respectively. These values are based on the amount of electricity used within these periods of the lowest. In addition to the fluctuation in battery capacity daily, Figure 9 also shows that the maximum voltage (voltage of the battery) varies daily. The battery's efficiency and power output both increase with the utilization of the battery. As the battery is utilized more frequently, its power increases by way of discharge and charging.

4. Conclusion

In this study, extensive experimental energy assessments of lithium-ion batteries in recently installed PV systems were performed. A study has been conducted to look into how well lithium-ion batteries work. To determine the amount of energy used and its efficiency, the experimental data were collected and evaluated by precise measurement utilizing Amperemeter and Voltmeter readings from November 2021 to April 2022. The energy analysis of lithium-ion batteries in solar systems has led to the following conclusions:

- The results showed that the lithium-ion batteries used had a low energy efficiency (η_e=20%) and total mean power efficiency ($\boldsymbol{\eta}_{\boldsymbol{T}_{\boldsymbol{mp}}}$= 32.76%) consumed during the 6 months.
- The values of high energy efficiency and total mean power efficiency are found to be (η_e=75%) and ($\boldsymbol{\eta}_{\boldsymbol{T}_{\boldsymbol{mp}}}$= 56.87%), respectively.
- The energy efficiencies of the lithium-ion battery increase due to an increase in consumption during the specified period.

The battery's voltage maintains a maximum voltage of 14.4V but varies in current due to batteries being connected in series.

Abbreviation

AGM	Absorbent glass mat
AC	Alternating current

BESS	Battery energy storage systems
BSS	`Battery storage system
DC	Direct current
DERs	Distributed energy resources
DoD	Depth of discharge
EBSS	Energy battery storage system
ESBS	Electric storage battery system
E_C	Energy consumed by the battery
E_d	Energy density
I_{BC}	Battery capacity or accumulation in ampere-hour
I_C	Current consumed from the battery
I_P	Peak input current from the panel
LIBs	Lithium-ion batteries
LIRBs	Lithium-ion rechargeable batteries
L_T	Total load consumption
MPPT	Maximum power point tracker
P_C	Battery output power or consumed power from the battery
PCU	Power conditioning unit
P_P	Peak output power from the panel or peak input power to the battery
PSE	Photovoltaic system energy
PV	Photovoltaic
RS	Renewable source
SoC	State of charge
V_{max}	Maximum battery voltage obtained
V_{min}	Minimum battery voltage obtained
V_P	Peak input voltage from the panel
η_e	Energy efficiency consumed
$\eta_{T_{mp}}$	Total mean power efficiency from battery

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Ethics and Consent Statement: All data collection was conducted after receiving approval from an institutional review board and the agreement of all participants.

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