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# Investigating Variability in Power Capacity through Experimental Testing of Lithium-Ion Batteries

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**Abstract:** Lithium-ion batteries have captured the attention of researchers in renewable energy because of their advantages over the other types. This study studied the power capacity variation of a lithium-ion battery when installed with solar panels for home appliances to improve the users' experience. An experiment was conducted for five months (November to March). The study discovered that the lithium-ion battery's power capacity was reasonably stable (or uniform) on some days but was also characterized by very significant variations on others. The theoretical maximum power, $P_{max,th}$. from the battery bank was 10.08kW, but the experimental maximum power, $P_{max,exp}$. was 9.864kW. Also, the maximum theoretical energy, $E_{max,th,}$ from the battery bank was 80.64kWh, and the experimental maximum energy capacity generated from the battery bank, $E_{max,exp}$. was 78.912 kWh. The slight power capacity variation was attributed to the solar panel's usage and efficiency, which is sometimes affected by cloudy or hazy weather.

**Keywords:** Power Capacity; Variation of Lithium-Ion Battery; Energy and Efficiency; Sustainable Energy; Renewable Resources; Hazy Weather; Photovoltaic Systems.

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## 1. Introduction

Sustainable and renewable energy has been a major achievement in developing alternative energy technologies. Harnessing sustainable energy resources has gone a long way to mitigating pollution and climate change while providing cost-effective electrical power generation services [1]. Studies and improvements on batteries are part of the successes recorded by researchers on alternative energy technologies. The main function of a battery is to store energy obtained from renewable energy resources like solar. The measure of energy stored in a battery is known as the power capacity, and it is expressed in Watt-hours (Wh). By extension of the definition, power capacity is the product of the voltage (V) and the current (Amps) that a battery provides for a given time, especially in hours. Energy storage systems are a crucial part of electrical power systems, and with the increasing awareness of renewable energy, the best way to improve energy storage in batteries has always gained researchers'

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attention [2]. Some forms of renewable resources are available everywhere in the world, such as solar radiation, wind, tidal waves, and heat from biomass [3].

Some forms are infinite and virtually limitless, like solar. Apart from being renewable, the popularity of solar energy is also attributed to batteries used in solar energy systems, which function as energy accumulators and are responsible for storing energy harnessed through the solar panel. Without batteries, off-grid solar panels cannot work. One of the batteries widely recommended for solar energy storage is the lithium battery. Lithium-ion batteries are adding much value to the world of renewable- energy [4]. For the last two decades, lithium-ion batteries (LIBs) have become an important power source for electric vehicles (EVs), power grids, and solar energy storage [5]. With better power efficiency attributed to higher energy density, voltage capacity and lower self-discharge, they charge quicker and retain charges more than other batteries. They are many times rechargeable without loss of stability. Among the rechargeable, it has a European conformity (CE) rating of 99%, which is better than lead acid and saltwater batteries with 80-85% efficiency. Lithium-ion batteries are ideal for solar battery units and are expected to last between 5 and 15 years. Therefore, they are preferably used for home energy storage. Intense price competition leads manufacturers to develop new chemistries and improved processes to reduce production costs [6], reducing cost ineffectiveness [7].

Also, Yang et al. [8] noted that though batteries are storage systems for electrical energy, the fact that their use does not produce any immediate emissions; they are considered an integral part of the utilization of energy from renewable sources to remedy the intermittent nature of the power supply, has given part of the public the erroneous impression that they are themselves a source of clean energy. But again, the recyclability of lithium-ion is limited [9]. Despite some of the above worries, Lithium-ion batteries as a power source dominate portable electronics, penetrate the electric vehicle market, and are on the verge of entering the utility market for grid-energy storage [10]. However, there is a need for compromise among the various performance parameters like energy, power, cycle life, cost, safety, and environmental impact, especially on application [11]. Experimental testing of power capacity variation of lithium-ion batteries is intended to enhance users' experience further, especially when installed with solar panels for home appliances.

Even though current lithium-ion batteries are safer and have a longer lifespan, the operating environment and use of batteries in photovoltaic applications continue to be a source of worry. Investigating Power capacity variation in lithium-ion batteries is crucial to improving these batteries' performance, safety, and sustainability across a wide range of applications. This research will benefit industries and consumers and advance our scientific knowledge. The study area was the University of Nigeria, Nsukka, a tropical world region. The objectives of this research are to analyze the energy capacity flow of the battery, examine the energy efficiency of the battery, carry out further analyses of various results obtained using Matlab Software, and ensure the safety and sustainability of battery-powered systems in our modern world.

## 2. Theoretical Background

### 2.1. Basics

Primarily, the function of batteries is to store excess energy generated by photovoltaic (PV) systems, later to be used as an alternative energy source. So, batteries are made to capture surplus energy generated by solar systems, which allows solar energy to be stored as chemical energy for future use. Batteries can discharge rapidly and yield more current than the charging source can produce. Since solar PV panels can last over two decades, the storage battery will likely need replacement in your PV system's lifetime. Installation of a Lithium-ion battery is a perfect representation of a stable, high-quality and reliable battery [12]. At the same time, being a maintenance-free product with a low-pressure venting system makes it perfect for standby applications. Early lithium-ion batteries for consumer electronics had short lifespans and poor safety, both technological difficulties.

However, new battery usage techniques are necessary for optimal performance and a long lifespan. For example, high charge and discharge currents are necessary when employing the battery in a PV system. Charge currents are sometimes comparable to or even exceed discharge currents. Because lithium-ion batteries are typically used in applications that demand higher discharge currents, the cells are commonly built with a higher discharge current capability. High-discharge and high-charge current battery cells are now commercially accessible. Although current lithium-ion batteries are safer and have a longer lifespan, the operating environment and use of batteries in photovoltaic applications continue to be a source of worry. The state of health of lithium-ion batteries has to be monitored through some developed algorithms [13]. To accomplish the goal of long cycle life, Liu et al. [14] suggested that accurate assessment for degradation of lithium-ion batteries is necessary in hybrid energy management.

Ma et al. [15] observed that temperature, as a critical factor, significantly impacts the performance of lithium-ion batteries and limits their application. In related research, Wu et al. [16] demonstrated that capacity and power degradation are more severe under a low discharge rate than the widely accepted high discharge rate. Also, degradation mechanisms affect the operational effects of such capacity or power fade [17]. For example, Lu et al. [18] noted that the relationship between lithium-ion battery performance and operating temperature is significant in designing a battery thermal management system (BTMS). Batteries experience a clear rise in temperature during the overcharge/over-discharge process. Ouyang et al. [19] discovered in a study that temperature rise can worsen and require less time when the battery is overcharged/over-discharged, and with probable risk of explosion when overcharged. Also, Harris et al. [20] suggested that increased efforts to make batteries with more consistent lifetimes should improve battery cost and safety.

### 2.2. Recent trends in lithium-ion batteries and testing

Li et al. [21] provided an overview of the development of lithium-ion batteries over the past three decades, highlighting the advancements in electrode materials, electrolytes, and cell designs, whereas Blomgren [22] discussed recent progress in electrolyte formulations and interfacial phenomena in lithium-ion batteries, emphasizing the challenges and opportunities for improving their performance and safety. Also, Li et al. [23] reviewed developing high-nickel cathode materials, their synthesis methods, and the strategies employed to enhance their electrochemical performance and stability. Furthermore, Zheng et al. [24] conducted another research that reviewed recent advancements in solid-state batteries, including solid electrolytes, interfacial engineering, and all-solid-state battery architectures, discussing the challenges and potential solutions for their practical implementation.

Ikwuagwu et al. [25] researched comprehensive energy analysis and performance evaluation of lithium-ion battery integration in photovoltaic systems over six months, the performance of lithium-ion batteries. They meticulously scrutinized 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 boosting an energy capacity of 685Ah.

Given the preceding, taking into cognizance the various works done by researchers in the field of lithium-ion batteries and aligning critically to the essential phenomenon that underscores this research, it is evident that the novelty of this research lies in its focus on experimental testing of power capacity variation in lithium-ion batteries. This involved conducting experiments to understand how the power capacity of lithium-ion batteries changes under different conditions, such as temperature, charging/discharging rates, and cycling. This research is crucial for improving battery performance and lifespan in applications like electric vehicles and renewable energy storage systems.

## 3. Experimental Procedure

### 3.1. Experimental set-up, data collection and evaluation

The selected study area for this experiment was the University of Nigeria, Nsukka, located in the tropical region of the world. Usually, solar energy varies from the dry season to the rainy season. However, the amount of solar energy generated in the dry season is much more than in the rainy season. The experiment was conducted in the dry season (November to March). The Solar panels and lithium-ion batteries were connected in parallel to power various home appliances. The selected home appliances include solar refrigerators, bulbs, solar televisions, solar fans, mobile chargers, and laptop chargers. Extra loads were also considered. Data was collected for five months (November 2021 – March 2022), and calculations were done with MATLAB Simulink. The solar panel has a voltage and current rating of 18.1V, 8.29A per pair, and 12 pairs of solar panels were installed in parallel. The battery bank has a voltage and current rating of 12V 210Ah per pair, and two pairs of batteries were installed in parallel.

Photovoltaic system performance was carried out to investigate the system's effectiveness using several performance metrics presented in the sub-sections below.

### 3.2. Power rating of the solar panels and battery bank

The power ratings of solar panels and battery banks were evaluated using the voltage and current ratings of the solar panels and battery banks. Power rating is expressed with Eq.1:

$$P = IV \tag{1}$$

Where:
P = power (W)
I = Current (A)

### 3.3. Battery capacity

Battery capacity measured in Amp- hour (Ah) is usually found in a deep cycle battery and was evaluated with Eq.2.

$$B_c = I_B \; x \; t_b \qquad (2)$$

Where:
$B_c$ = Battery capacity (Ah)
$I_B$ = current from Battery (Ampere)
$t_b$ = backup time (hour)

### 3.4. Energy storage capacity

The product of battery charge capacity and maximum voltage of battery measured in kilowatt- hour (kWh) is the energy storage capacity. It was evaluated with Eq.3.

$$E_s = \frac{B_s \times V_{max}}{1000} = P_{max} \times t_b \qquad (3)$$

where, $B_s$= battery charge capacity (Ampere-hour)

$V_{max}$ = battery voltage before usage (Volt)

$P_{max}$ = maximum power

$t_b$ = backup time (hour)

### 3.5. Maximum theoretical power of the solar panel and battery bank

These were measured as the current attends its peak in both the solar panels and battery bank, as expressed in Eq.4

$$P_{max,th} = \text{IpVp} \qquad (4)$$

Where Ip and Vp are peak input current and voltage, respectively.

### 3.6. Maximum theoretical energy of the solar panels and battery bank

This measures the product of maximum theoretical energy and time as expressed in Eq.5

$$E_{max,th} = \text{T} \, (P_{max,th}) \qquad (5)$$

### 3.7. Maximum experimental power of the solar panels and battery bank

Maximum experimental power is the product of the current and voltage measured from the experiment as expressed in Eq.6

$$P_{max,exp} = \text{IpVp} \qquad (6)$$

### 3.8. Maximum experimental energy of the solar panels and the power bank

Maximum experimental energy measures the product of the maximum experimental power and time. Evaluated with Eq. 7

$$E_{max,exp} = \text{T} \, (P_{max,exp}) \qquad (7)$$

Where;

$E_{max,exp}$ = Maximum experimental energy (Wh)

$T$ = time (hr)

$P_{max,exp}$ = maximum experimental power (Wh)

### 3.9. Energy rate of the solar panel and the battery bank

The energy rate is the percentage expression of the Maximum experimental energy to the maximum theoretical energy. The energy rate is measured with Eq.8:

$$\text{ER} = \frac{E_{max,exp}}{E_{max,th}} \times 100 \qquad (8)$$

### 3.10. Energy density of the battery bank

The energy density of the battery bank measures the quantity of energy stored per unit mass in gravimetric units or per volume in volumetric units. It is evaluated with Eq.9

$$E_d = \frac{Energy\ (Wh)}{mass\ (kg)}\ or\ \frac{Energy\ (Wh)}{volume\ (m^3)} \qquad (9)$$

### 3.11. Energy consumption from the battery bank

Energy consumption from the battery is the storage energy capacity of the battery to backup time for the solar system. It is evaluated with equation Eq. 10:

$$E_c = E_s \times t_b \qquad (10)$$

where, $E_s$= energy storage capacity

$t_b$ = backup time (hr)

## 4. Results and Discussion

The maximum power voltage with a current rating is 18.1V 8.29A for one pair of solar panels, which gives 150W. The 12 pairs of solar panels installed in parallel, theoretically, resulted in 1.8 $kW$. Theoretical maximum energy converted, $E_{max,th}$ from the solar panel in 12 hours was 21.6KWh. The current increase from 8.29A to 99.48A was observed because of the parallel connection; hence, the rating was 18.1V 99.48A. But in the experimental measurement, the solar panel gave a mathematical reading of 18V 55A, and the experimental maximum power red 0.99KW, making the experimental maximum energy converted, $E_{max,exp}$, to be 11.88KWh. When the theoretical and experimental maximum energy converted were compared, the energy rate obtained was 55% and 82.5Wh.$kg^{-1}$ as the energy density. The theoretical maximum power and energy conversion evaluated from the solar panel are shown in Table 1.

**Table 1:** Theoretical maximum power and energy conversion from solar panel

| No. of pairs of solar panels | Time (hr) | V (V) | I (Amp) | $I_2$ (Amp) | P (W) | $P_{maxth}$ (KW) | $P_{max.exp}$ (KW) | $E_{maxth}$ (KWh) | $E_{maxaxp}$ (KWh) | Energy Rate (%) | Energy Density $WhKg^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 12 | 18.1 | 8.29 | 99.48 | 150 | 1.8 | 0.99 | 21.6 | 11.88 | 55 | 82.5 |

Figures 1 to 5 show the peak current against the peak voltage from the solar panel for five months. Short circuit current was found to be low during the sunrise or sunset but increases as the sun rises higher. In other words, the short circuit current is proportional to the amount of solar energy that strikes the solar panel.

The lowest and highest output power occurred in November 2021, with values of 0.33kW and 1.05kW. The lower value of the panel's output power indicates cloudy or hazy weather, and as a result, some of the sun's total alien insolation is scattered throughout the atmosphere, and only a fraction reaches the planet. The cloudier the atmosphere becomes the increased dispersion, the lower the output power, and the reduced value of the short-circuit current. A small variance was observed in the open circuit voltage. Table 2 shows the battery power bank's theoretical maximum power and energy conversion.

**Table 2:** Theoretical maximum power and energy conversion from the battery power bank

| No. of pairs of solar panels | Time (hr) | V (V) | $V_2$ (V) | I (Amp) | $I_2$ (Amp) | P (W) | $P_{maxth}$ (KW) | $P_{max.exp}$ (KW) | $E_{maxth}$ (KWh) | $E_{maxaxp}$ (KWh) | Energy Rate (%) | Energy Density $WhKg^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 8 | 12 | 14.4 | 840 | 685 | 2.52 | 10.08 | 9.864 | 80.64 | 78.912 | 97.86 | 321 |

The battery bank consisted of 2 pairs of batteries with a 12V 210Ah rating and 12V 840Ah when connected in parallel. The theoretical maximum power, $P_{max,th}$, evaluated from the battery bank was $10.08kW$, while the maximum theoretical energy, $E_{max,th,}$ generated from the battery bank was $80.64kWh$. As a result, the capacity increased while the voltage remained constant, with a 14.4V 685Ah sliding change. Experimental maximum power, $P_{max,exp}$, measured was $9.864kW$ while the energy capacity generated from the battery bank, $E_{max,exp}, was$ $78.912kWh$. Therefore, the energy rate or efficiency was 97.86%, while the energy density was 321WhKg-1. Figures 1 to 5 show the current consumed and the voltage from the battery bank for the five months. The figures depict fluctuation in battery capacity (current) owing to backup time and maximum voltage as a function of the month's day. The graphs demonstrated that the battery bank's maximum voltage output is 14.4 volts, with a minor variance. The rise and fall of power production can be reasonably stable (or uniform) on some days but can also be characterized by very significant variations on other days. The more energy is consumed, the more effective the battery supply becomes. Also, capacity is not constant; it varies from day to day.

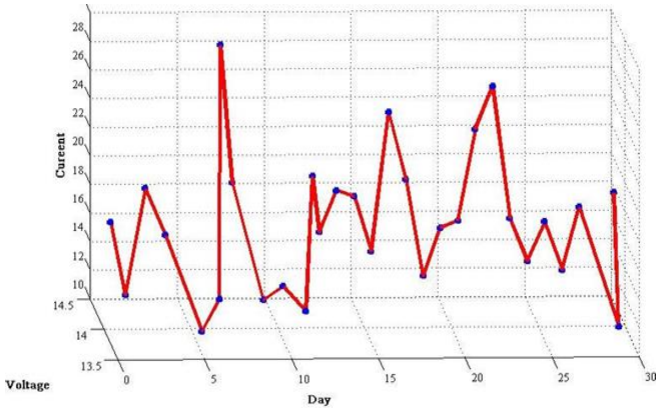


**Figure 1:** Graph of current consumed and maximum voltage from the battery power bank in November 2021

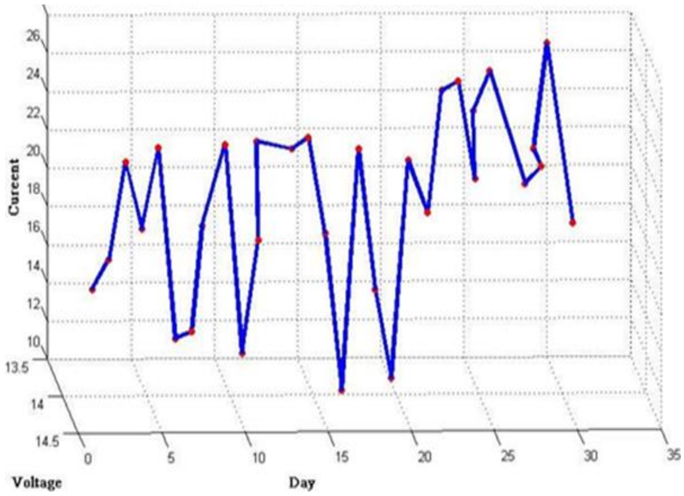


**Figure 2:** Graph of current consumed and maximum voltage from the battery power bank in December 2021

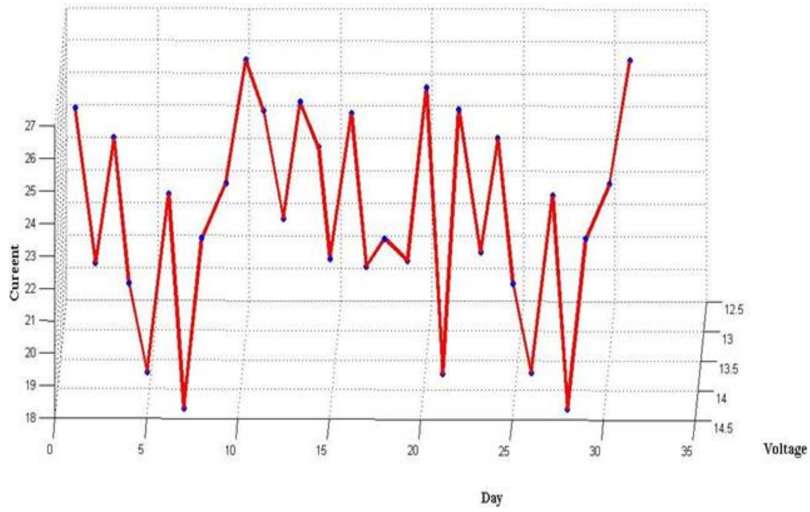


**Figure 3:** Graph of current consumed and maximum voltage from the battery power bank in January 2022

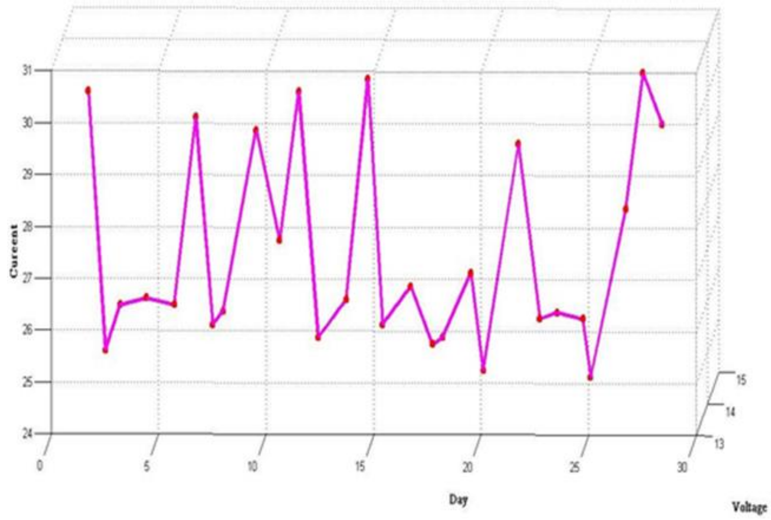


**Figure 4:** Graph of current consumed and maximum voltage from the battery power bank in February 2022

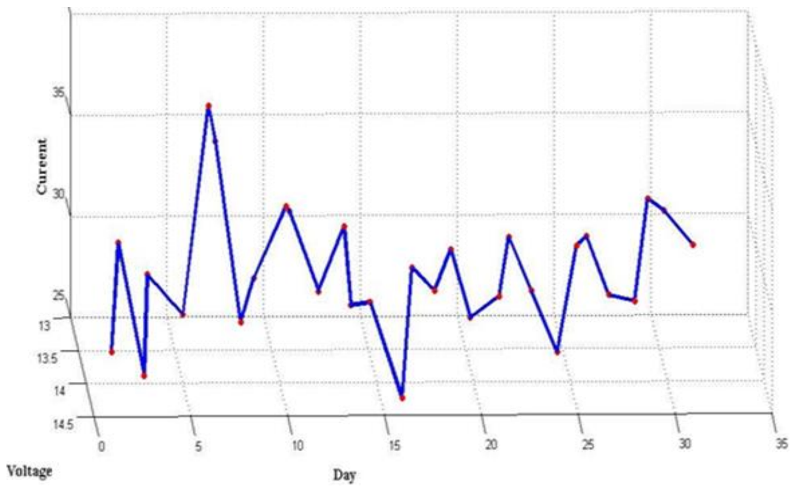


**Figure 5:** Graph of current consumed and maximum voltage from the battery power bank in March 2022

## 5. Conclusion

This study conducted extensive experimental testing to investigate power capacity variation in lithium-ion batteries. The research aimed to shed light on the factors influencing capacity fluctuations and their implications for various applications. The difference between theoretical maximum power and energy obtained from the lithium-ion battery before installation and experimental maximum power and energy obtained experimentally for five months after installation with a solar panel for use by home appliance had shown that the advertised power capacity of the lithium-ion battery is slightly lower than the real capacity of the lithium-ion battery. The theoretical maximum power, P_(max,th), evaluated from the battery bank was 10.08kW, while the maximum theoretical energy, E_(max,th,) generated from the battery bank was 80.64 kWh. Experimental maximum power, P_(max,exp), measured was 9.864kW, while the energy capacity generated from the battery bank, E_(max,exp), was 78.912kWh, while energy density which is the quantity of energy stored per unit mass in gravimetric units or per volume in volumetric units was 321WhKg-1. However, the slight power capacity variation was attributed to the usage and efficiency of the solar panel, which is sometimes affected by cloudy or hazy weather. This varies from day to day and month to month. Extension of this research from 5 months to 12 months is recommended also to enhance the user's experience on power capacity variation of lithium-ion batteries during rainy and dry seasons. This study was conducted in Nigeria and could be extended to other parts of the world with different seasons to enhance users' experience.

Further, the study highlights the multifaceted nature of lithium-ion batteries' power capacity variation and its implications. Addressing these variations is crucial for technological advancement and ensuring the safety and sustainability of battery-powered systems in our modern world. Hopefully, this research will serve as a foundation for continued exploration and innovation in battery technology.

### 5.1. Future Directions

There is a need for further research in this area. Future investigations should delve deeper into advanced battery management systems, improved battery chemistries, and enhanced quality control measures to minimize capacity variations.

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**Ethics and Consent Statement:** This research adheres to ethical guidelines, obtaining informed consent from all participants.

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