COMPARATIVE PERFORMANCE ANALYSIS OF LEAD ACID AND LI-ION BATTERIES OF E-BIKES USED IN SRI LANKA

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Degree of Master of Science

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November 2024

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Thesis submitted in partial fulfillment of the requirements for the degree

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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The above candidate has carried out research for the Master's thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Dr. (Ms.) R.M.T. Damayanthi

UOM Verified Signature

10-02-2025

Signature of the Supervisor: Date:

DEDICATION

I would like to dedicate my M.Sc. research dissertation to my beloved parents and my husband, who throughout my life have continuously provided me with their utmost support, guidance, and encouragement. Their love and sacrifices have constituted the base of my achievements, and without them, this work would not have been in place.

ACKNOWLEDGEMENT

I would like to take this opportunity to express my sincere gratitude to everyone who supported me throughout this project on the battery performance evaluation of E-bikes. Their motivated help, invaluable feedback, and open guidance were essential to the successful completion of this work. I deeply appreciate their insightful opinions on the various challenges I encountered during the project.

My heartfelt gratitude goes to Eng. Roshani Costa (Research Engineer) and Eng. Ananda Namal (Former Director General) of the National Engineering Research and Development Centre of Sri Lanka for their unwavering encouragement and support, which were instrumental in the successful completion of this project. I also extend my sincere thanks to Eng. Dilrukshi Hettiarachchi (Engineer) for providing access to the laboratory facilities, which played a vital role in my research. Their invaluable assistance and guidance have been greatly appreciated.

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Finally, I would like to extend my thanks to all the lecturers, colleagues, and individuals who provided the necessary facilities and support for my research project. Their contributions have made this work possible.

ABSTRACT

The use of electric vehicles is highly popular nowadays. When considering electric vehicles, E-bikes and electric three-wheelers are the most popular in Sri Lanka due to their affordability. Evaluating the performance of E-bikes requires a focus on battery performance. In this research, specific drive cycles were initially analyzed to identify current consumption and speed variations. Using the mean values derived from drive cycle analyzing, battery performance was evaluated. The number of cycles of the battery was considered the primary performance measurement characteristic. Both lead-acid and lithium-ion batteries were tested, with samples representing the maximum and minimum capacities of each type used in E-bikes in the Sri Lankan market. The batteries were discharged under laboratory conditions to 100% Depth of Discharge (DOD), and temperature variations were recorded. Meanwhile, the consumer usage patterns of E-bikes were identified, considering the Asian context. Based on this, the number of cycles for each battery type considering the temperature, was calculated based on daily consumer usage patterns. From this, the replacement time of each battery type and the economic benefit for consumers were calculated. The findings indicate that although lithium-ion batteries have a higher initial cost compared to lead-acid batteries, they offer a longer lifespan, and greater cost-efficiency over time. As a result, lithium-ion batteries were identified as the most suitable option for Sri Lankan E-bike users. This research provides valuable insights for consumers and policymakers to make informed decisions about battery choices for E bikes.

Keywords: E bikes, Life cycle, Temperature, Battery

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LIST OF ABBREVIATIONS

Abbreviation	Description
HHI	Herfindahl-Hirschman Index
CL	Cycle Life
Q_{diss}	Total heat dissipation
q_{conv}	Heat dissipated by convection
q_{rad}	Heat dissipated by radiation
$q_{exhaust}$	Heat dissipation by exhausting gas
T_{case}	Surface temperature
$T_{ambient}$	Ambient temperature
h	Convective heat transfer coefficient
A	Area
SOH	State of Health
SOC	State of Charge

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CHAPTER 1

INTRODUCTION

This chapter focuses on providing the research background of electric bikes (E-bikes). It outlines the identification of the problem addressed by the research and presents the proposed solution. Additionally, it covers the research objectives and methodology, offering an overview of the entire study.

1.1 Research background

In Sri Lanka, there has been an economic crisis for the past five years, leading to a fuel shortage. People had to queue up for long periods of time to get gasoline for their vehicles, which caused much inconvenience in transportation. This situation drove many people towards electric vehicles as an alternative. Of the available EV options, from cars to electric bikes, the affordability of e-bikes made them the preferred choice for most individuals; hence, expansion occurred in the electric bike market.

While there has been this growth, no standardized methodology for performance evaluation was followed in the local market. Due to the lack of regulation, suppliers have imported electric bike parts and assembled them in Sri Lanka with inadequate testing on performance. In fact, there is a strong need for a proper evaluation framework to assure the quality and reliability of these vehicles. The performance of the battery is, therefore, crucial in this context, since the battery is literally the key to running a bike and its efficiency.

Electric bikes use two types of batteries: lead-acid and lithium-ion. While the lead-acid battery is available in 72V, 60V, and 48V configurations, the battery pack normally includes either six 12V batteries, four 12V batteries, or five 12V batteries, depending upon the requirement of the bike. Lithium-ion batteries are made available in sealed 72V units with battery cells inside them. Evaluating the performance of these batteries is essential to assessing the overall performance of electric bikes, as the battery's efficiency and durability are critical to the bike's functionality and long-term viability.

1.2 Research problem identification

Basically, electric bikes in Sri Lanka use either lead-acid or lithium-ion batteries. Due to their lower initial cost, lead-acid batteries are the most preferable choice among consumers. However, this preference is primarily driven by immediate affordability, with many consumers lacking awareness of lithium-ion batteries' long-term performance advantages and overall cost-effectiveness.

The critical issue is that purchasing decisions are frequently based on the initial price rather on battery performance and lifetime. There is currently no comprehensive technical research in Sri Lanka resulting in detailed, data-driven comparisons of the long-term performance of lead-acid and lithium-ion batteries, taking into particular account how critical factors like temperature affect their durability and efficiency. This is a very serious concern, considering the importance of temperature in a battery's operating life cycle, especially for a tropical country like Sri Lanka.

The absence of thorough, comparative research creates a gap in the market where consumers cannot make informed selection based on long-term benefits. This highlights the need for a focused evaluation of battery performance, specifically to provide insights into the advantages and disadvantages of each battery type in the Sri Lankan context. Addressing this knowledge gap is crucial for helping consumers make more informed and sustainable decisions when selecting batteries for electric bikes.

This unmet need for reliable data and a clear understanding of battery performance under local conditions define the market requirement and problem that this research seeks to address.

1.3 Research solution

This research compares lead-acid and lithium-ion batteries through their performance using temperature analysis during operation. The study will try to identify how temperature affects the life span of both battery types and give crucial insights into their durability under realistic conditions. Furthermore, there will be an economic analysis that provides the two different battery types' long-term financial benefits, considering the factors such as lifespan, maintenance, and replacement costs.

By integrating performance and economic analyses, the outcome of this research will provide consumers with critical information to make more value-based decisions based on long-term benefits rather than immediate costs. The findings from this study could eventually help to direct the industry toward implementing more efficient and sustainable battery technologies, therefore driving electric mobility toward better performance and cost-effective solutions.

1.4 Research objectives

- Main objective:

To analyze the performance of Lead-acid and Lithium-ion batteries in electric bikes (E-bikes) used in the Sri Lankan market, focusing on how temperature affects battery lifespan, and to recommend the most suitable battery type for Sri Lankan consumers, considering long-term performance and cost-effectiveness.

- Specific objectives:

1. To analyze the temperature variations of Lead-acid and Lithium-ion batteries, focusing on how these factors influence battery performance and lifespan in real-world conditions.
2. To analyze the long-term economic benefits between Lead-acid and Lithium-ion batteries in Sri Lankan market.
3. To provide insights that will help consumers to make decisions when purchasing E-bikes, considering the long-term benefits of each battery type.

1.5 Methodology

1. Comprehensive literature review
2. Data Collection
    a. Measure the speed and current variation of an E-bike by doing a road run, considering the specific distance and identifying the mean current for discharging batteries of E-bikes.
    b. Measure the battery performance characteristics:
        i. Measuring equipment and sensor selection
        ii. The test setup preparation
        iii. Measurements were obtained of temperature variations at discharging of selected Li-ion and Lead-acid batteries of E-bikes in a laboratory.
3. Data Analysis
4. Key findings and discussion
5. Recommendations
6. Future works

CHAPTER 2

LITERATURE REVIEW

2.1 Trend to use E bikes

Around the world, e-bikes are quickly changing urban mobility by providing a more effective and environmentally friendly option to traditional modes of transportation. Many users, the elderly, and others who travel longer distances can now ride a bike thanks to the electric-assist feature. E-bikes are popular for short-distance transport in nations like China, which has the biggest e-bike market worldwide. This reduces pollution and dependency on cars in the most of the countries. And considering the cost involve per kilometer is less when using E bikes in European countries like Germany[1] .

E-bikes are especially helpful for first- and last-mile connections because they easily integrate with public transit, increase convenience, and promote multimodal travel. They also provide a workable answer for communities looking to cut back on fuel, traffic, and pollution. E-bikes are becoming a more affordable, healthier, and ecologically friendly form of transportation due to changes in gasoline prices globally and an increased emphasis on sustainability. This is helping to create more livable, greener urban settings worldwide.

In 2012, an estimated 31 million e-bikes were sold globally, with estimation to reach 47.6 million by 2018. However, e-bike sales data remain limited due to inconsistencies in definitions across regions and the absence of public registration processes. Available data reveal that China accounted for approximately 93% of global e-bike sales in 2012 leading to a scenario where the number of e-bike owners is roughly double that of car owner[2].

Sri Lanka is actively pursuing advancements in the electric vehicle (EV) sector through various initiatives. According to the May 2020 report, "Study on Infrastructure and Enabling Environment for Road Electric Transport in SAARC Member States" by the India Smart Grid Forum, the country has registered 4,200 electric vehicles and 900 electric motorcycles, signaling growing adoption of EV technology.

To support this, the government introduced a Framework for Electric Mobility in 2019. This aims at guiding EV-related efforts. This framework focuses on creating a supportive ecosystem by addressing areas such as policy development and infrastructure expansion. Additionally, the Sustainable Energy Development Action Plan for EVs outlines an ambitious goal to convert 10% of the national vehicle fleet to EVs by 2030. It will pave the way for a significant expansion of the EV market in Sri Lanka.

Apart from that, the Sri Lanka Sustainable Energy Authority (SLSEA) is encouraging the private sector to develop the EV charging network. These efforts aim to accelerate the establishment of accessible and widespread charging infrastructure[3].

In 2023, Sri Lanka's electric scooter market observed a Herfindahl-Hirschman Index (HHI) of 7,062. Further, it indicates a moderate decrease compared to the HHI of 9,930 recorded in 2017. This shift suggests the market is progressing toward a highly concentrated state. The HHI measures market competitiveness among exporting countries, ranging from 0 to 10,000. A lower index value signifies a greater number of players or exporting countries participating in the market, while a higher index indicates fewer players or exporting countries dominating the market [4].

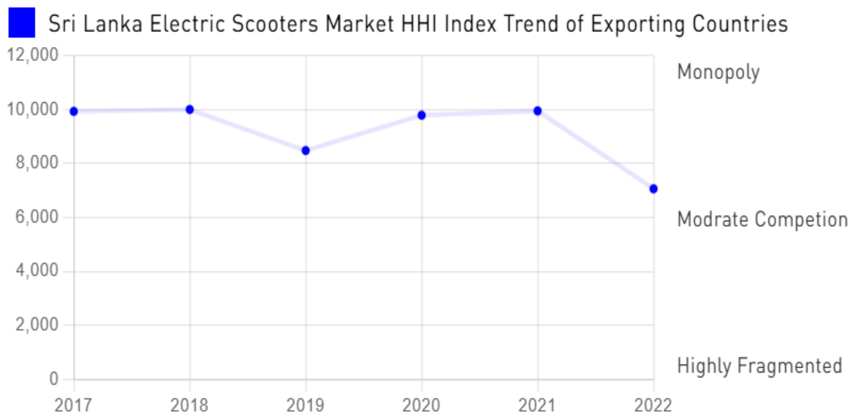

Fig. 2.1: Sri Lanka electric scooters market HHI index trend of exporting country

2.2 Classification of E bikes

Currently, E-bikes in Sri Lanka are powered by two main types of batteries. Those are. Lead-acid and lithium-ion. These batteries are commonly available in three voltage configurations. Those are 48V, 60V, and 72V. Lead-acid battery packs in e-bikes consist of multiple 12V batteries connected in series, with 48V packs using four batteries, 60V packs using five, and 72V packs using six. In contrast, lithium-ion batteries are typically supplied as sealed 72V packs. Those contain multiple lithium-ion cells arranged to deliver the required voltage and capacity for the motor. The battery capacities vary depending on the power requirements of the e-bike motor. Lithium-ion batteries in the Sri Lankan market usually range from 30 Ah to 45 Ah. Lead-acid batteries range varies from 23.3 Ah to 38 Ah. This variation in battery types and capacities caters to diverse performance requirements and consumer preferences in the e-bike market.

2.2.1 Main parts of E bikes

The primary energy-consuming component of an e-bike is its Brushless DC (BLDC) motor. The power ratings typically vary from 300W to 2000W depending on the model and intended use in the Sri Lankan market. In addition to the motor, e-bikes are equipped with other electrical components that contribute to overall energy consumption. Those are a charging port, a DC-DC converter, a display unit, signal lights, brake lights, and other auxiliary systems. These components are essential for the functionality and convenience of the user. However, those consume negligible power compared to the BLDC motor.

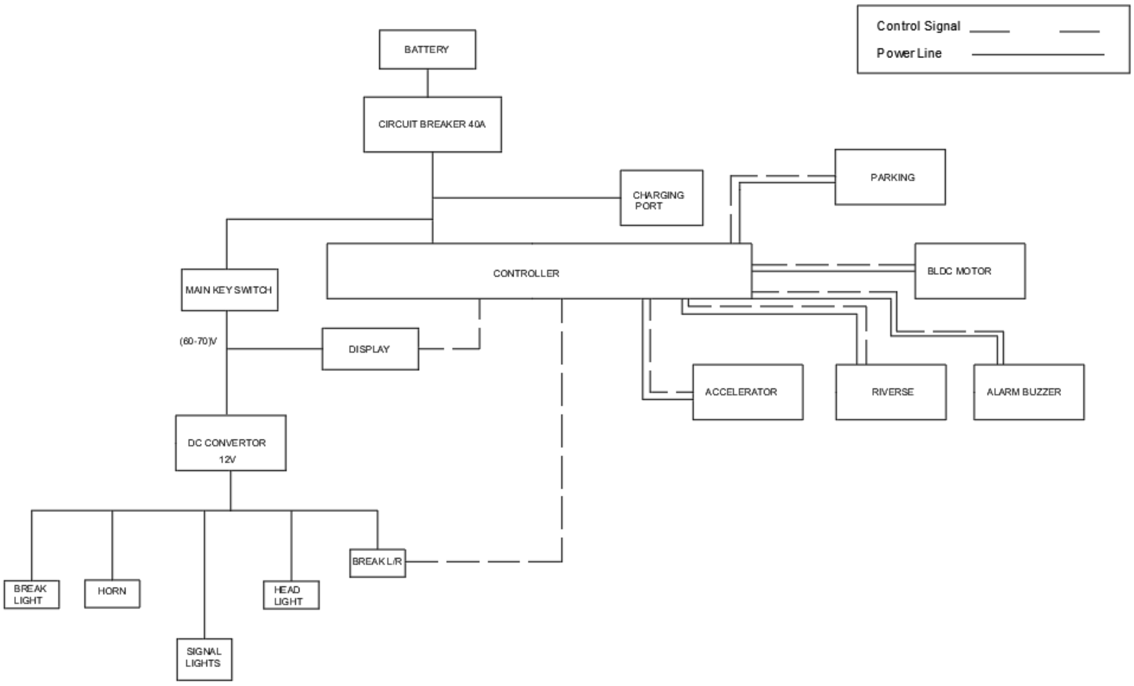

Fig. 2.2: Electrical configuration of E-bikes

2.3 Performance analysis of E bikes

E-bike performance, either for use or when making purchases, is a crucial consideration. The general performance of an E-bike is determined by numerous factors. Among them, battery performance presents one of the most critical parameters. A higher capacity battery offers longer ranges on a single charge compared to a lower capacity battery. Moreover, the battery cycle life- that is, the number of charge and discharge cycles-can greatly affect performance and bike life.

Another important feature in E-bikes is the performance of the motor. This tells a lot about the power and efficiency of the bike. The torque, speed, and weight also show the overall performance of the E-bike because they determine acceleration, handling, and usability.

The other crucial factors to consider when making the purchasing decision include the frame design and the quality of materials used in E-bikes, as these ensure durability and comfort in riding. Above all, the braking system, efficiency in energy conversion, cost, and maintenance requirements should also be carefully considered when purchase an E-bike[5].

2.3.1 Importance of performance analysis of E bikes.

E-bike performance analysis is important for optimizing efficiency, ensuring safety, and enhancing user experience in vehicle usage in urban and rural[2]. Evaluating parameters like battery life, energy consumption, and temperature variations enables manufacturers to improve design and reliability, ensuring vehicles meet user needs under real-world conditions. E-bike performance evaluation supports informed decision-making for consumers and policymakers, encouraging the adoption of sustainable transport while identifying areas for technological innovation and market growth.

2.4 Battery performance analysis

The performance of the battery is of critical importance when evaluating the overall performance of an E-bike. Considering that the battery has a great influence on efficiency, range, and reliability, considerable emphasis needs to be placed on thoroughly analyzing and understanding its performance characteristics.

2.4.1 General characteristics of battery performance

There are several characteristics of battery performance. Those are

1. Nominal voltage of the battery
2. Battery capacity
3. Self-discharge rate
4. Charge efficiency
5. Internal resistance
6. Float life and cycle life
7. Safety performance
8. Temperature characteristics

In general, lead-acid batteries have a capacity that depends on the rate of discharge and operating temperature. Normally, the capacity becomes lower when the battery discharges at lower rates, but it improves with higher discharge rates. The self-discharge rate of lead-acid batteries is the reduction in stored energy of the batteries as functions of time, while it is not used and kept far from any load. The basic reason of this effect can be rooted in some chemical reaction in the cells of the battery structure.

The charging efficiency indicates about how well the electrical energy is converted to chemical energy in the battery during charging, reflecting the overall capability of energy conversion. Cycle life is usually defined as the number of charge-discharge cycles a lead-acid battery can undergo before a certain specified capacity loss occurs. This parameter is of particular importance for systems in operation that require frequent cycling, such as renewable energy storage systems and electric vehicles.[6]. Apart from this, a cut of voltage is considered for lithium-ion batteries. Cut-off voltage is the minimum allowable voltage of the battery[7].

2.4.2 Performance of valve-regulated lead-acid batteries for E-bikes

In one of the research study done in India, field tests have been conducted to evaluate the performance of valve-regulated lead-acid batteries for E-bikes, considering various driving routes in India, including urban, gradient, highway, and rural routes[8]. K-type thermocouples have been attached to the battery pack, and temperature values have been recorded while driving on these routes. The primary objective of the study was to analyze the temperature variations of the battery under actual driving conditions.

According to Figure 2.3, the highest temperature has been recorded during the afternoon on the gradient route. Additionally, as shown in Figure 2.4, the influence of ambient temperature on energy consumption has also been identified and analyzed. In this, only the temperature variation of the battery while driving has been analyzed. However, it has not considered the temperature impact on the performance of the battery or the E-bike.

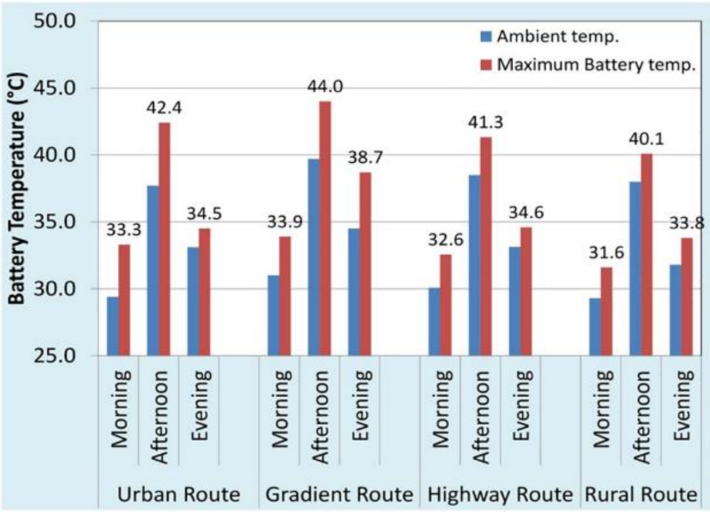

Fig. 2.3: Comparison of battery surface temperature of new batteries during different routes.

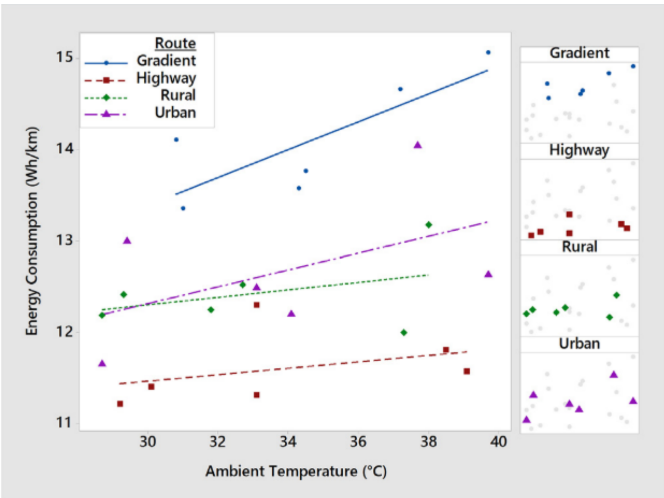

Fig. 2.4: Influence of ambient temperature on total energy consumption during a field test.

2.4.3 Temperature impact for the battery performance

Battery manufacturers have assessed the impact of temperature on cycle life by analyzing the percentage reduction relative to a reference temperature of 20^0C. It has been observed that between 20^0C and 50^0C, the number of charge-discharge cycles decreases as the temperature increases. According to Arrhenius' law, every 10^0C increase above 20^0C reduces the battery's lifespan by approximately 50%[9]. Based on this principle, a mathematical model[10] has been developed to quantify the relationship between temperature and battery lifespan.

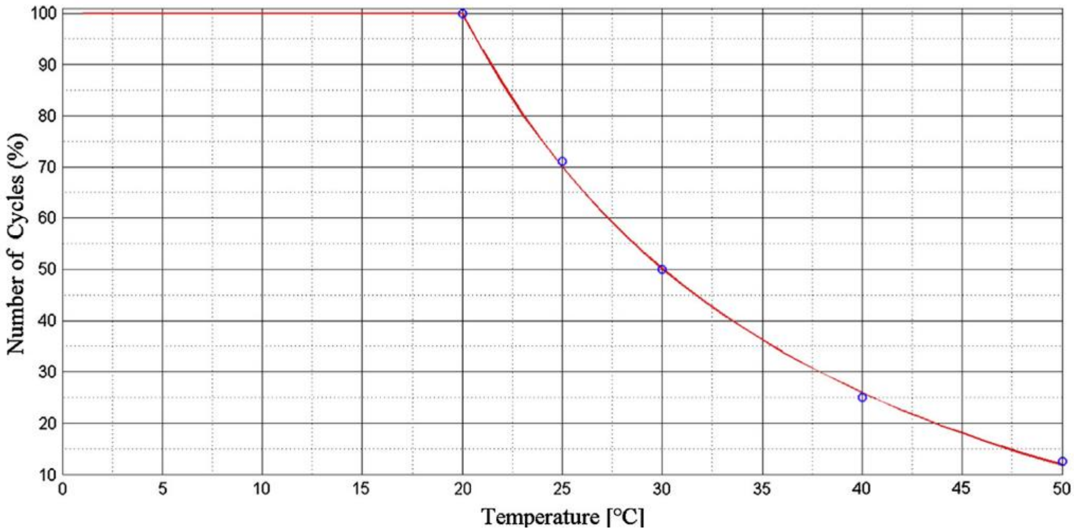

Fig. 2.5: Influence of the temperature on the maximum number of cycles.

$$N_{c(T)}\% = \begin{cases} 1 & 0<T\leq 20\,^{\circ}\mathrm{C} \\ 37.68T^{-1.101} \quad -0.3897 & T>20^{\circ}\mathrm{C} \end{cases} \quad \text{------------ Eq. (1)}$$

Figure 2.5 illustrates the variation in the number of cycles with temperature considering the equation 1. The graph highlights the impact of temperature on the battery's cycle life. It demonstrates a decrease in the number of cycles as the temperature increases, in accordance with the mathematical relationship obtained.

Temperature variations in lithium-ion batteries significantly impact their performance. An increase in temperature during charging and discharging can harm the battery's functionality. there are few factors can cause for the battery degradation mainly. Those are temperature, discharging current rate, charging rate ,depth of discharge (DOD) and time intervals between full charge cycles[11]. The operation at high temperature during charging and discharging will negatively affect the battery performance[12]. Elevated temperatures accelerate the degradation of critical components such as the electrolyte, electrodes, and separator, leading to reduced battery efficiency and lifespan.[13].A severe degradation at 60 ^{0}C has been identified by using two types of 10 Ah single cells from two manufacturers by testing at room temperature and 60 ^{0}C

[14]. Figure 2.7 shows the effect of ambient temperature on the cycle life of lithium-ion battery.

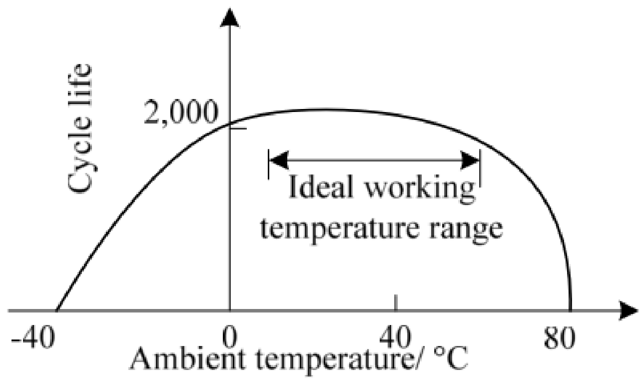

Fig. 2.6: Effect of ambient temperature on lithium-ion battery cycle life.

A modeled equation has been created to identify the relationship between cycle life and the temperature[15]. Equation 2 shows mathematically modelled equation for the relationship between temperature and the cycle life. Here a value is 0.0039, b value is 1.95 and the c is 67.51. And d value is the number of cycles in 0 ^{0}C[15].

$CL = a.T^3 - b.T^2 + c.T + d$ ------------ Eq. (2)

There is a relationship between the internal temperature and the surface temperature of the battery. Internal temperature increase of the battery due to electro chemical reactions inside the battery and the internal resistance of the battery. However, the surface temperature of the battery is lesser than internal temperature due to the heat transfer through the casing. In some research, it has been identified that during charging and discharging, the temperature rising rate almost increases linearly with time in the batteries[16].

2.4.4 Effect of internal temperature to external temperature

The internal temperature of a battery, influenced by electrochemical reactions and resistive heating, often exceeds the surface temperature due to heat dissipation through the battery casing. In the case of a lithium-ion battery, the temperature distribution within the core is higher than that at the surface. Figure 2.10 illustrates the temperature variation along the x-axis of the battery. The solid line represents the core temperature distribution, while the dashed line depicts the surface temperature[13].According to that, in lithium ion battery there is no significant temperature difference between the core temperature and surface temperature. Therefore, when analyzing thermal behavior of lithium ion batteries, the surface temperature is considered[17].

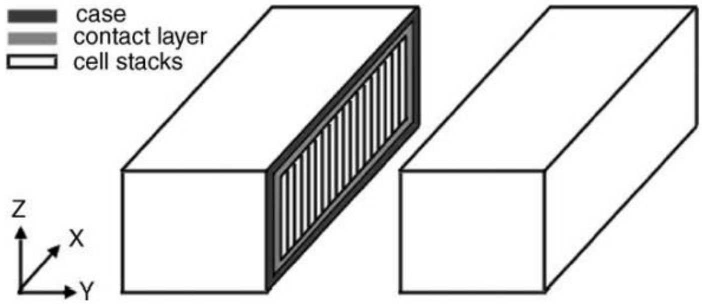

Fig. 2.7: Schematic representation of a typical lithium-ion battery

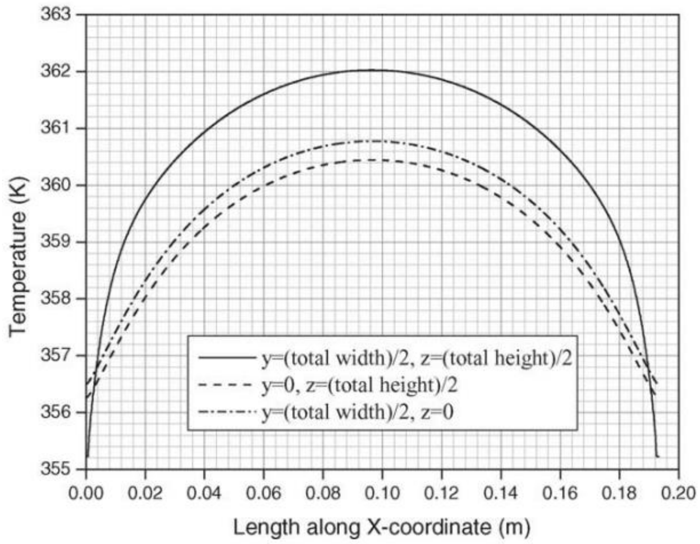

Fig. 2.8: Temperature distribution along the X-coordinate at the end of the 3C discharge procedure.

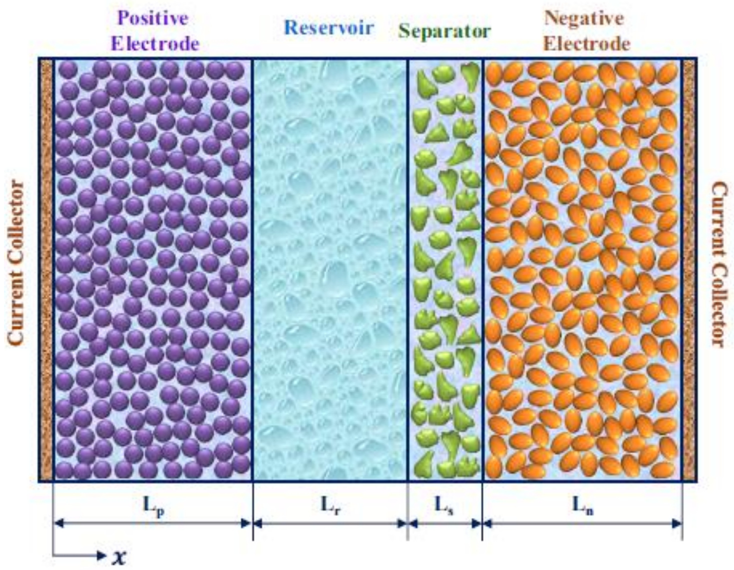

Fig. 2.9: Schematic of lead-acid cell.

As illustrated in Figure 2.11, the lead-acid battery is constituted of a positive electrode of PbO_2, an electrolyte reservoir, a porous separator, and a negative electrode of Pb. The reservoir is filled with an ionic conductive medium of H_2SO_4, which allows the flow of ions between electrodes. The separator maintains the cathode and anode apart to prevent short circuits [18].

The overall reaction occurring within the core of the lead-acid battery can be described as follows:

$$Pb_{(s)} + PbO_{2(s)} + 2H_2SO_4 \underset{Charge}{\overset{Discharge}{\rightleftarrows}} 2PbSO_{4(s)} + 2H_2O$$ ------------ Eq. (3)

There are different heat dissipation mechanisms in the battery as heat convention, ration to ambient and heat dissipation by exhausting gas. Total heat dissipation can be calculated by following equation 4.

$$q_{diss.} = q_{conv.} + q_{rad.} + q_{exhaust.}$$------------ Eq. (4)

Since the present battery model are sealed type heat dissipation by exhausting gas can be omitted. And the heat transfer from the radiation is negligible. Therefore, total heat dissipation is equal to heat transferred by convection. When the battery case is exceeding the ambient temperature battery start to dissipate the heat by convection. The following equation 5 shows the heat dissipation by convection.

$$q_{conv.} = hA(T_{case} - T_{ambient})$$ ------------ Eq. (5)

Within a lead-acid battery, the temperature distribution is not uniform, as illustrated in Figure 2.15. The case surface temperature differs from the internal temperature, and this variation can be determined by solving the energy equations within the battery case[19]. However, in this study, the maximum temperature from six data points have been considered for calculations. As a result, the temperature non-uniformity was omitted from the analysis.

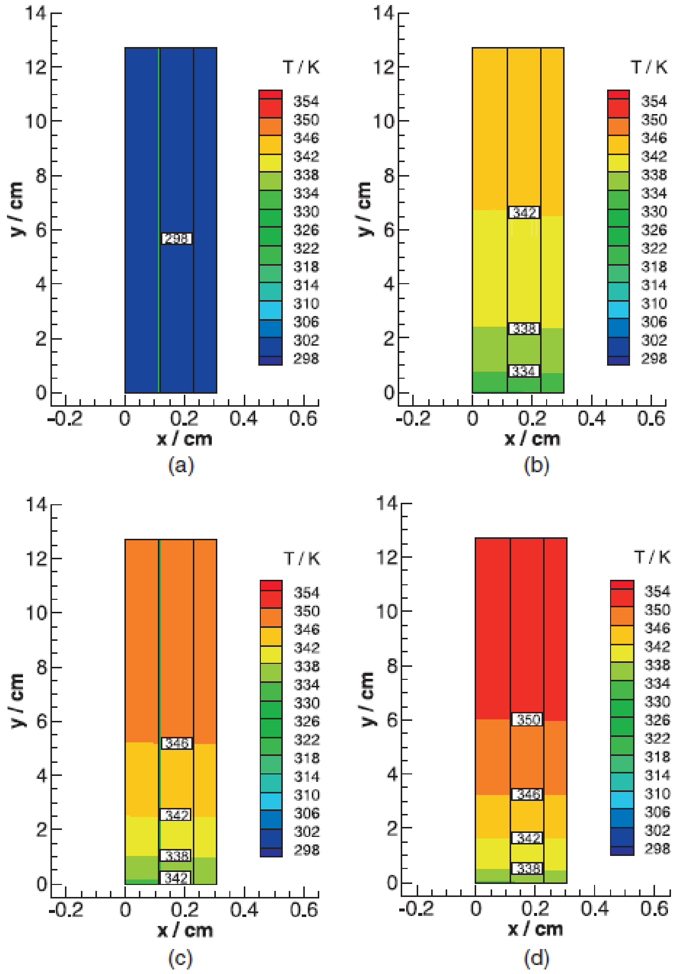

Fig. 2.10: Temperature contours at different time levels.

2.5 Drive cycle analysis of E bikes

A drive pattern, also known as a driving cycle, refers to a representation of how a vehicle is typically driven over a specific period. It includes variations in speed, acceleration, deceleration, idling, and stops that occur during a journey. Drive patterns are often influenced by factors such as traffic conditions, road types, terrain, and driving habits. The drive cycle analysis aims to evaluate the performance of the vehicle. Based on the road's drive patterns, the energy consumption of the E-bike can be determined[8]. When analyzing drive patterns, it is important to consider both the traffic behavior and the road conditions. [20] Therefore, in this research, an initial test run was conducted to identify the energy consumption of the E-bike. Based on this, the battery performance was assessed.

CHAPTER 3

EXPERIMENTAL DESIGN AND DATA COLLECTION

This chapter describes the experimental design and the data collection procedure of the batteries and the E-bike. It focuses on setting up the experimental environment ensuring that it closely represents the real situation as well as the techniques employed to collect important information such as the changes in temperature and discharge rates.

3.1 Approach to experiment

The experiment in this research is more concerned with identifying the performance of lead-acid and lithium-ion batteries considering the temperature dependence on their life span. Given that the higher the temperature of the battery, the lesser its life, the discharge phase of the battery will be used to evaluate the performance of the battery in order to imitate the use of an E-bike in real life driving condition.

As the driving conditions of an E bike are to be simulated, experiment will focus on the battery's discharge process as that is where the most significant temperature variation occurs. A correlation between temperature increase and battery degradation can be created by systematically measuring and analyzing these temperature changes. This approach provides a clear understanding of each battery's performance under typical operational conditions of an E bike.

To accurately assess battery discharge, Current consumption during E-bike operation must be identified under actual driving conditions. The current consumption of E-bikes varies depending on road and traffic conditions. Therefore, a road with suitable conditions for this test road run was selected, including traffic conditions such as acceleration, cruising, idling, and deceleration. This approach assumes that current consumption is measured across a full range of operating conditions, providing a comprehensive understanding of the E-bike’s energy usage during typical driving situations.

3.2 Test run experiment

3.2.1 Experimental setup

To evaluate the performance of the E-bike under real-world conditions, a test route was selected around the Ekala area, which included slopes, bends, and road dampers to simulate typical road conditions. The test was conducted at approximately 11 a.m. with an ambient temperature of 29 ^{0}C with two persons on bike.

A clip-on meter was used to monitor the current variations during the test. The detached clip of the meter was attached to the main power line from the battery's output to capture accurate, current readings throughout the run as shown in figure 3.2. The clip-on meter was positioned near the E-bike's speedometer to facilitate simultaneous speed and current value observation. Additionally, a camera was mounted to continuously record the meter readings during the entire test duration to capture all of the data for further analysis as shown in figure 3.1.

Fig. 3.1: Test setup for road run measurements.

Fig. 3.2: Attachment of clip-on meter clip to the main power line.

3.2.2 Data collection of the test road run

Using the data collected during the road test run, plots of speed vs time and current vs time will be generated. These plots are useful in understanding the dynamic performance of the E-bike and provide insights into its corresponding power consumption during a road test. These plots enable further understanding of how the battery behaves under various road and traffic conditions: including acceleration, deceleration, and steady-state operation[21].

3.3 Experimental set up for lab testing

3.3.1 Lead acid battery discharge

In this experiment, two types of lead-acid battery packs were discharged at the discharge current obtained during test road run. Each battery pack consisted of six 12V batteries connected in series, forming a 72V system. One battery, labeled B01, had a capacity of 32.3 Ah, while the second battery, pack, labeled B02, had a capacity of 23 Ah.

Six K-type thermocouples were attached to each battery pack to monitor the batteries' temperature during discharge. The thermocouples were connected to a six-channel thermometer for continuous temperature recording.

As shown in Figure 3.3, a tungsten resistive load was used to discharge the battery packs. The battery packs were connected in series, such as placed inside the E-bike and linked to the resistive load. A multi-meter was connected to the circuit to measure the discharge current, while a voltmeter was used to measure the voltage across the battery packs.

One side of the battery pack was connected to the fixed point of the resistive load, and the other was connected via a movable hook. The hook attached to the resistive load was adjusted by varying the connection point to maintain a constant current during the test.

This setup allowed for precise voltage, current, and temperature monitoring, ensuring accurate data collection throughout the battery discharge.

Fig. 3.3: Laboratory experimental set up for Lead acid battery testing.

Fig. 3.4: Instruments used for the measurements.

3.3.2 Lithium-ion battery discharge

In addition to the discharge tests conducted on the lead-acid battery packs, a similar procedure was followed for lithium-ion battery packs. Two lithium-ion batteries were tested, each with a 72 V, similar to the lead-acid setup. Lithium-ion battery B01 had a capacity of 45 Ah, while Lithium-ion battery B02 had a capacity of 30 Ah.

As with the lead-acid battery discharge test, six K-type thermocouples were attached to each lithium-ion battery and connected to a six-channel thermometer to monitor temperature variations during discharge.

The same experimental setup used for discharging the lead-acid batteries was applied here. A tungsten resistive load was used to discharge. A multi-meter was used to measure the current, and a voltmeter was connected to monitor the voltage of the batteries.

One side of the lithium-ion battery was attached to the fixed point of the resistive load, while the other was connected via a movable hook as shown in figure 3.5. This arrangement allowed for adjustments to maintain a constant current during the discharge process, similar to the lead-acid battery test.

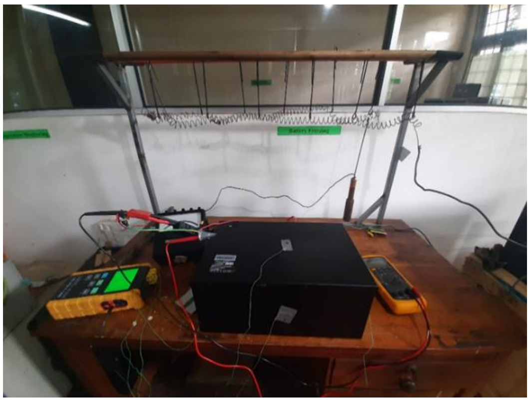

Fig. 3.5: Laboratory experimental set up for lithium-ion battery testing.

CHAPTER 4

ANALYSIS OF RESULTS

4.1 Experimental results

4.1.1 Road run data analysis

Figure 4.1 illustrates the current variation over time during the road test of the E-bike. The current value fluctuates significantly throughout the test. It indicates variation in power demands due to changes in driving conditions such as acceleration, deceleration, and possibly terrain variation. Peaks in the current value, some reaching nearly 60 A, suggest moments of increased power usage, likely during rapid acceleration or uphill climbs of the E-bike. In contrast, the drops to near-zero current may correspond to coasting, downhill stretches, or idle periods when the bike was stationary, such as at traffic stops. The mean current value of this road run is 16.64 A, and it reflects the overall average current consumption under these conditions. Here, the mean current value provides a baseline for understanding the battery's performance and energy consumption during regular use on this road route. These variations in the current value of this road run offer critical insights into how the power system of the e-bike responds to real-world driving scenarios.

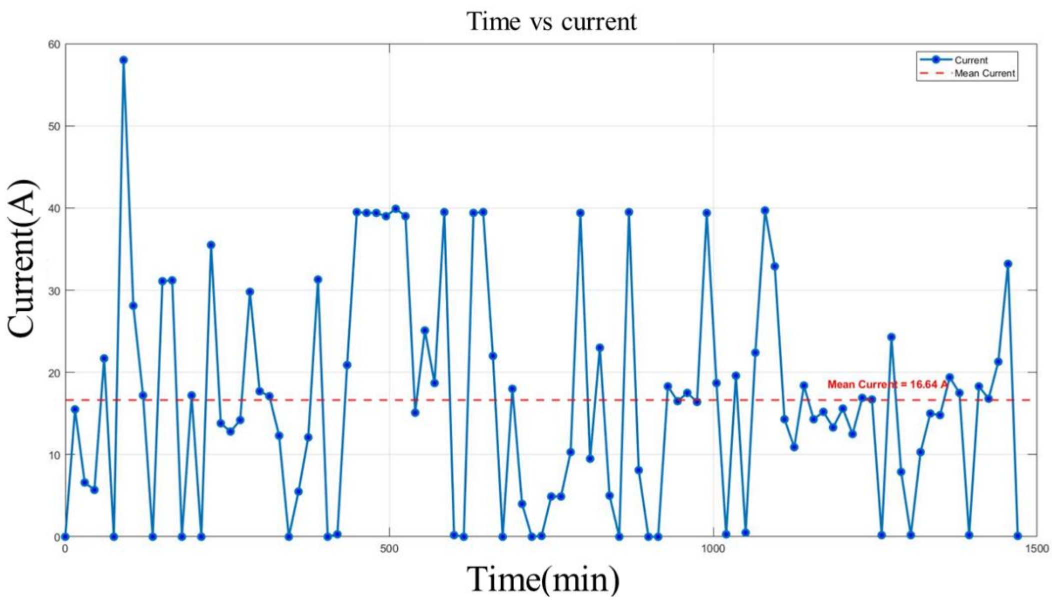

Fig. 4.1: Current variation over time for road run.

The mean current value of 16.64 A, obtained from the analysis, was used to plan the battery discharge at a current rate of 17 A. This discharge rate is selected based on average operating conditions observed in real-world usage. It ensures a more realistic and consistent assessment of the battery's performance during controlled road testing.

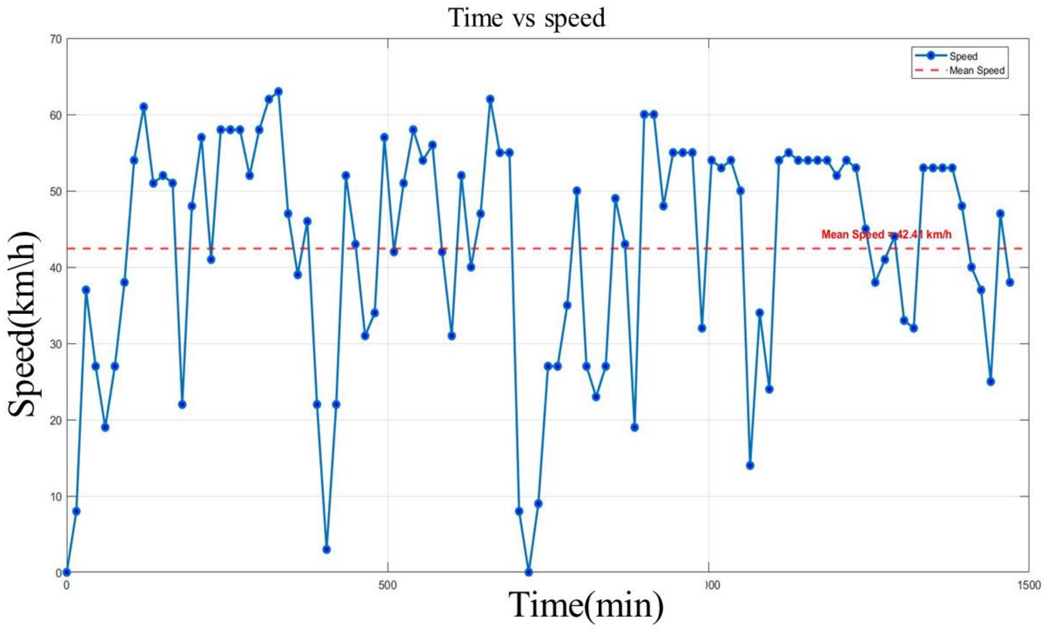

Fig. 4.2: Speed variation over time for road run.

Figure 4.2 shows the variation in speed over time during the road test of the e-bike. The speed fluctuates, with peaks reaching over 60 km/h. It reflects periods of acceleration or on flat and downhill stretches. Conversely, there are noticeable drops in speed, sometimes close to zero; those reflect periods of deceleration or stops and due to traffic signals or obstacles on the route. According to this, the average speed recorded during the test is 42.4 km/h. It shows a balanced speed, taking into account the effects of acceleration, deceleration, and idle times. This average speed indicates the typical operating conditions of an e-bike in real-world traffic conditions.

4.1.2 Temperature analysis during battery discharging of lead acid batteries

The first step in the experiment involved collecting temperature data for Lead-Acid Battery Pack B01 during its discharge. The test setup, shown in Figure 3.3, was used to discharge the battery pack. Further, this Lead-acid Battery Pack B01 was discharged at three different current levels, 17 A, 20A, and 25A, to compare the temperature variation under each condition. This procedure shows how the battery's temperature changes when discharging at higher current rates. It clearly shows the thermal behavior and potential risks of overheating when the battery is pushed to handle more power.

TABLE 4.1: TEMPERATURE AND VOLTAGE VARIATION OVER TIME FOR LEAD ACID BATTERY PACK B01

	17A discharging		20 A discharging		25 A discharging	
Time (Min)	Voltage (V)	Max. Temp. (^{0}C)	Voltage (V)	Max. Temp. (^{0}C)	Voltage (V)	Max. Temp. (^{0}C)
0	74.9	29.7	75.1	29.1	74.5	29.1
5	74.7	29.5	73.8	29.52	72.2	29.7
10	74.5	29.8	73.5	29.93	71	30.4

15	74.3	30	73.1	30.33	70.8	30.5
20	74.1	30.3	72.8	30.72	70.6	30.8
25	73.8	30.4	72.4	31.1	70.4	30.9
30	73.4	30.7	72.1	31.47	70.3	31
35	73.1	30.9	71.6	31.83	70	31.1
40	72.7	31.1	71.2	32.18	69.9	31.8
45	72.4	31.1	70.7	32.52	69.1	32.6
50	72	31.2	70.3	32.85	68.4	33.1
55	71.6	31.3	69.8	33.17	67.6	33.7
60	71.2	31.3	69.2	33.48	66.6	34.5
65	70.7	31.4	68.7	33.78	65.3	35.1
70	70.2	31.6	67.9	34.07	62	35.8
75	69.8	31.6	67.2	34.35	61.8	35.9
80	69.1	31.7	66.3	34.62		
85	68.5	31.7	65.1	34.88		
90	67.8	31.8	63.1	35.13		
95	67.1	31.8	62	35.37		
100	65.1	32				
105	64.8	32.2				
110	63.1	32.4				

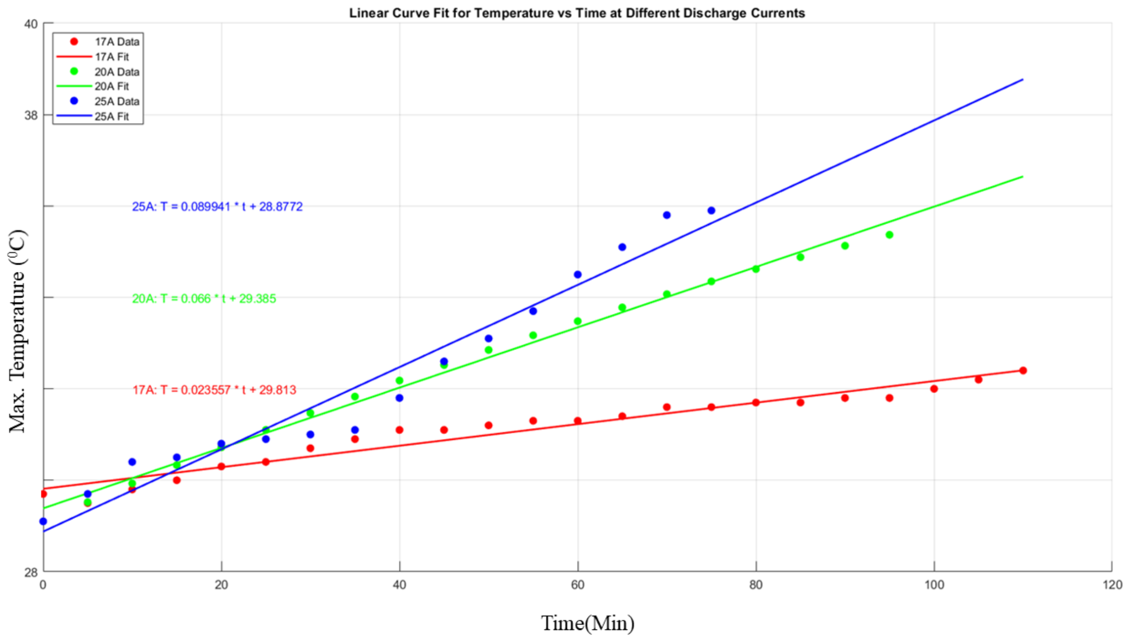

Fig. 4.3: Comparison of temperature variation of discharging at 17 A, 20A and 25 A for lead acid battery pack B01.

Figure 4.3 shows maximum temperature rise of the lead-acid battery pack during discharge at three current levels, 17A, 20A, and 25A. This graph shows that the greater the current, the larger is the temperature rise. The curve fits reveal that at 25A discharge rate, the temperature rises the fastest and after 50 minutes, it reaches around 34^0C. By contrast, the temperature rise is much more gradual for the 17A discharge, remaining below 32^0C for the entire duration. The current of 25A exhibits a greater rate of increase because at this level, more power is dissipated as heat. These results give evidence to the thermal difficulties posed by higher discharging currents. It also points out the thermal management for battery design under higher load conditions.

In sequence, Lead-Acid Battery Pack B02, with capacity 23 Ah and 72 V nominal voltage, was discharged with a constant current of 17 A for the same test conditions as lead-acid battery pack B01. This test would compare the thermal behavior of the battery pack under the same current condition in the case of Battery Pack B01. The detailed data collected during the process of this discharge for lead acid battery B02 are shown in Table 4.2 and figure 4.4. This dataset provides insight into the temperature rise and voltage drop of lead acid Battery Pack B02 during discharge at 17 A current.

TABLE 4.2: TEMPERATURE AND VOLTAGE VARIATION OVER TIME FOR LEAD ACID BATTERY PACK B02 DISCHARGING AT 17 A

Discharge current 17 A		
Time (Min)	Voltage (V)	Temperature (^{0}C)
0	72.2	29.5
5	72.2	29.9
10	71.8	30.2
15	71.3	30.5
20	70.8	30.9
25	70.1	31.2
30	69.5	31.5
35	68.7	31.7
40	67.9	31.9
45	66.9	32
46	66.6	32.1
47	66.4	32.2
48	66.2	32.3
49	65.9	32
50	65.7	32.4
51	65.5	32.5
52	65.2	32.6
53	64.9	32.7
54	64.6	32.7
55	64.23	32.8
56	63.85	32.9
57	63.39	32.9
58	63	33

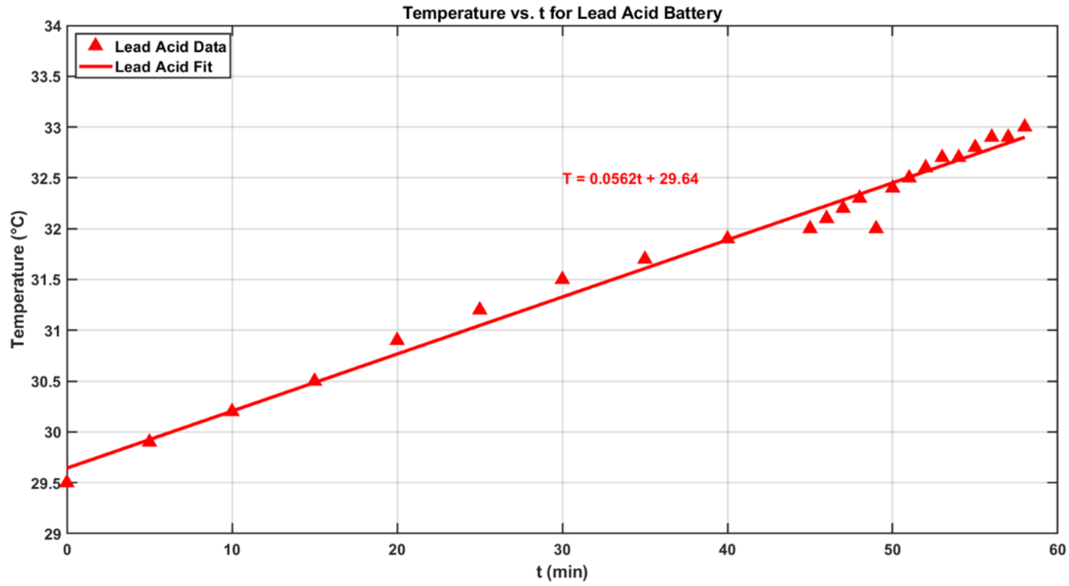

Fig. 4.4: Temperature behavior of lead acid battery pack B02.

4.1.3 Temperature analysis during battery discharging of lithium ion batteries

Next, the discharging process for the lithium-ion battery began. The lithium-ion Battery B01 was of 45 Ah and 72 V and was discharged at three different current values. Those are 17 A, 20 A, and 30 A. The aim of discharging in three current values was a comparison of how the temperature of the battery responds to an increase in current levels. That means observing thermal behavior under higher discharge rates. Data obtained during the test for in Table 4.3. Figure 4.5 shows the temperature variations for each current value. Also, it illustrates explicitly the relationship between the discharge rate and the rise in temperature.

TABLE 4.3: TEMPERATURE AND VOLTAGE VARIATION OVER TIME FOR LITHIUM ION BATTERY B01

	17 A discharging		20 A discharging		30 A discharging	
Time (Min)	Voltage (V)	Max. Temp. (^{0}C)	Voltage (V)	Max. Temp. (^{0}C)	Voltage (V)	Max. Temp. (^{0}C)
0	76.6	29.1	77.6	29.2	77.2	28.9
5					74.3	29.3
10	75.1	29.2			74.2	29.6
15			74.6	29.3	74.1	29.9
20	75.1	29.4			74	30.2
25					73.9	30.6
30	75	29.8	74.5	29.7	73.8	30.9
35					73.7	31.1
40	74.9	29.8			73.6	31.2
45			74.2	30.2	73.5	31.3
50	74.7	29.9			73.4	31.5
55					73.2	31.6
60	74.6	30	73.9	30.5	73	31.7

65					72.8	31.8
70	74.5	30.2			72.4	32
75			73.7	30.8	71.9	32.3
80	74.3	30.3			71.4	32.4
85					70	32.7
90	74.2	30.4	73.4	31.2	66.2	32.9
91					64	33
92					61.3	33.2
93					58.5	33.3
100	74	30.6				
105			72.7	31.6		
110	73.7	30.7				
120	73.3	30.8	71.6	31.9		
130	72.7	31				
135			69.2	32		
140	72	31.1	65.9	32.2		
141			64	32.3		
142			61.6	32.4		
143			58.2	32.4		
150	69.7	31.2				
155	64.4	31.3				
156	63	31.4				
157	59	31.5				
158	58.5	31.6				

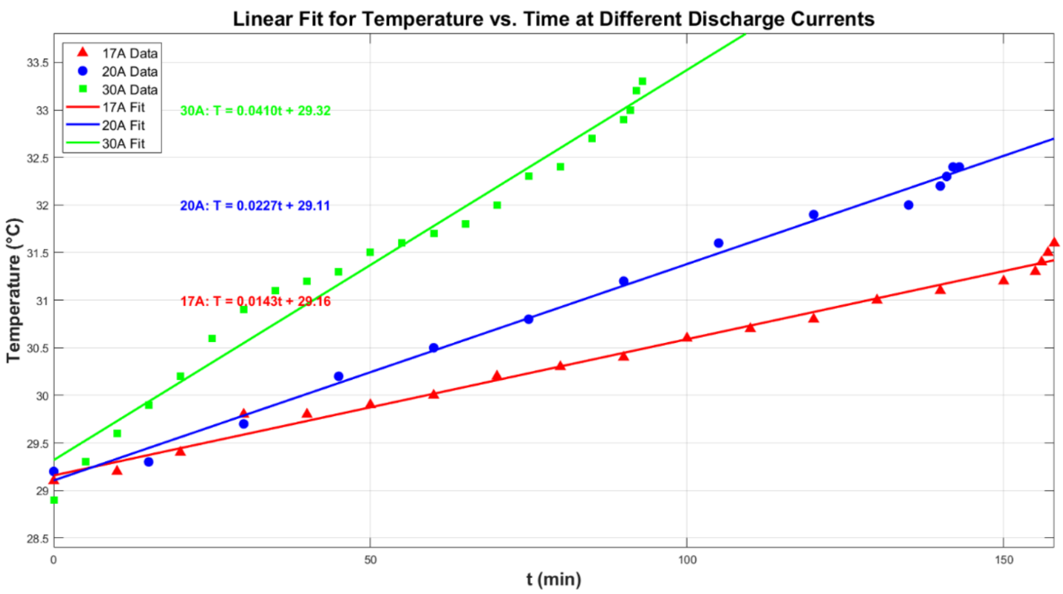

Fig. 4.5: Comparison of temperature variation of discharging at 17 A, 20A and 30 A for lithium-ion battery B01.

As indicated in the graph figure 4.5, the temperature increases faster when the discharge current is higher. The discharge at 30A has the steepest increase in temperature and reaches about 33.3^{0}C while that at 17A is the slowest. The maximum temperature of 17 A discharge is below 31.6^{0}C within that test. The curve fits for each discharge rate further explain the trend of higher current rates leading to an increase in temperature over time. It also provides more emphasis on the fact that thermal management is required with a high discharging current. Besides, the more the temperature, the faster the degradation of the batteries.

As the next step, the Lithium-Ion Battery B02 was also tested for discharge with a capacity of 30 Ah and 72 V. The same arrangement was made as depicted in Figure 3.5. This was discharged using a constant current of 17 A to observe the thermal behavior. Table 4.4 depicts the data obtained and Figure 4.6 represents the temperature variation during the discharge process.

TABLE 4.4: TEMPERATURE AND VOLTAGE VARIATION OVER TIME FOR LITHIUM-ION BATTERY B02 DISCHARGING AT 17 A

Discharge current 17 A		
Time (Min)	Voltage (V)	Max. Temp. ^{0}C
0	79.4	29.1
5	77.7	29.2
10	77.4	29.3
15	76.2	29.6
20	76.1	29.7
25	76	29.8
30	75.8	30
35	75.6	30.1
40	75.3	30.3
45	74.9	30.5
50	74.2	30.6
55	73.3	30.8
60	72.1	30.9
65	70.9	31
70	69.8	31.1
75	68.7	31.2
80	67.4	31.4
85	66.1	31.4
90	64.8	31.4
95	64.1	31.5
100	62.6	31.6
105	57.6	31.7

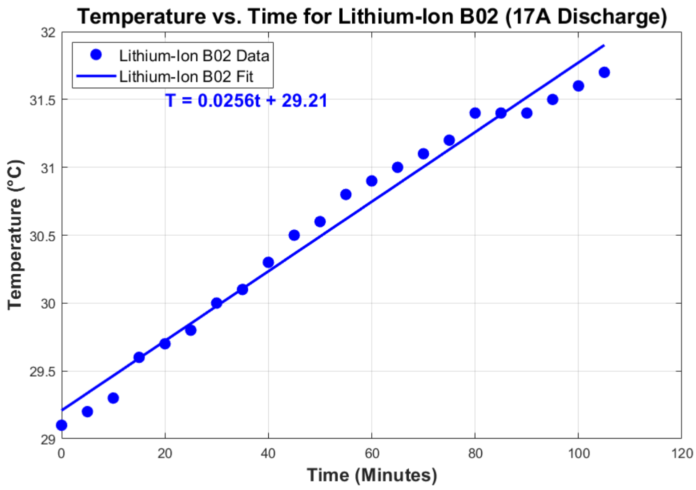

Fig. 4.6: Temperature behavior of lithium-ion battery B02

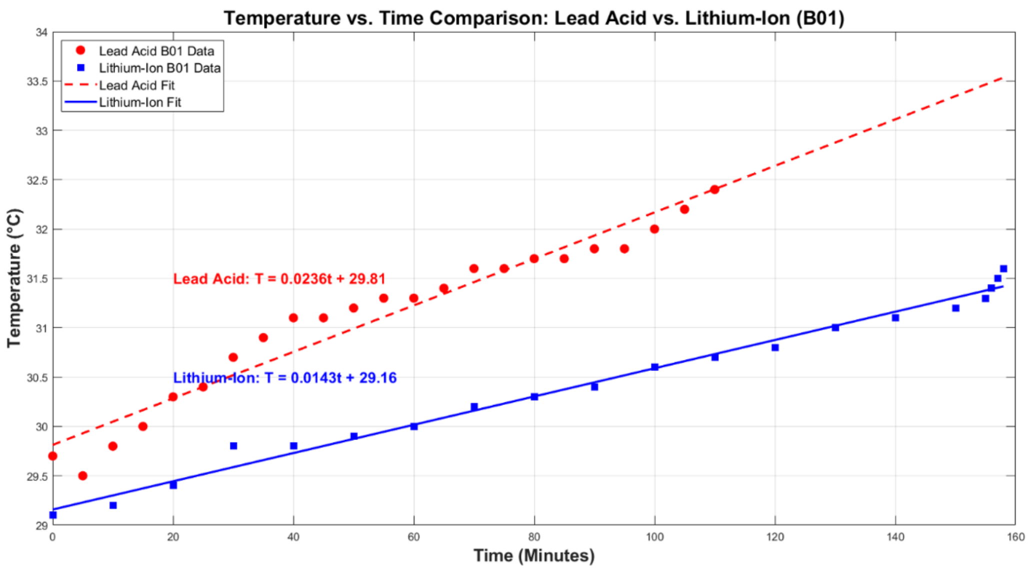

Fig. 4.7: Temperature behavior comparison of Lead acid battery pack and lithium-ion battery B01.

Figure 4.7 compares the temperature rise between Lead-Acid Battery B01 and Lithium-Ion Battery B01 during discharge in 17 A current value. It illustrates that the lead-acid battery shows a more significant temperature increase, reaching around 32^0C. Compared to that, the lithium-ion battery remains below 31 ^{0}C. The curve fits show that the lead-acid battery has a higher temperature rise rate, as indicated by the more significant linear coefficient in its equation. The lithium-ion battery again demonstrates superior thermal performance with a slower and more controlled temperature increase.

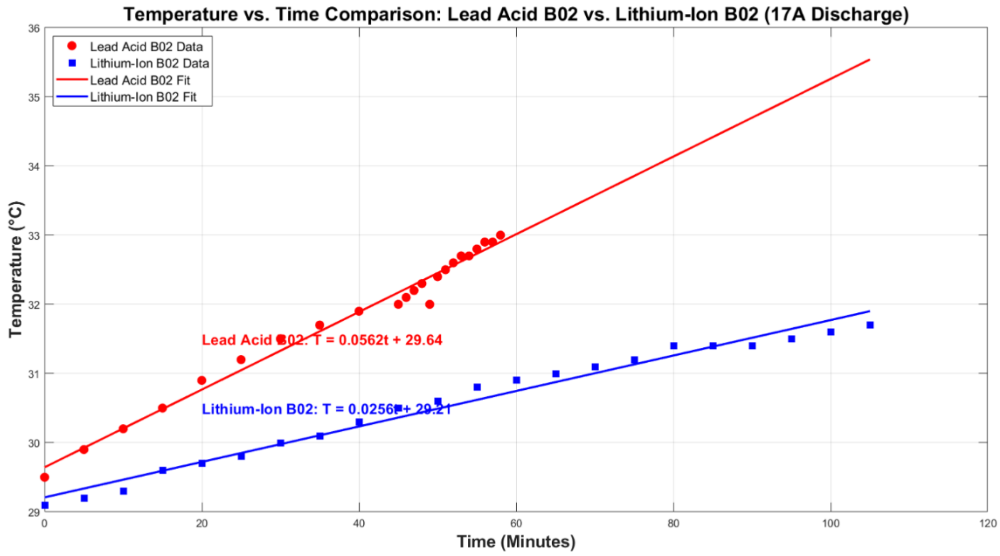

Fig. 4.8: Temperature behavior comparison of Lead acid battery B02 and lithium-ion battery B02.

Figure 4.8. compares the temperature rise over time between Lead-Acid Battery B02 and Lithium-Ion Battery B02 during discharge at 17 A discharging rate. The graph shows that the lead-acid battery experiences a more rapid temperature increase than the lithium-ion battery. The temperature of the lead-acid battery reaches approximately 32.5^{0}C. However, the lithium-ion battery remains below 31^{0}C during the same period. The curve fits illustrate that the rate of temperature increase of lead-acid batteries is higher. In contrast, the lithium-ion battery exhibits a slower and more gradual rise. And figure 4.9 shows the comparison of temperature of all the batteries in this study.

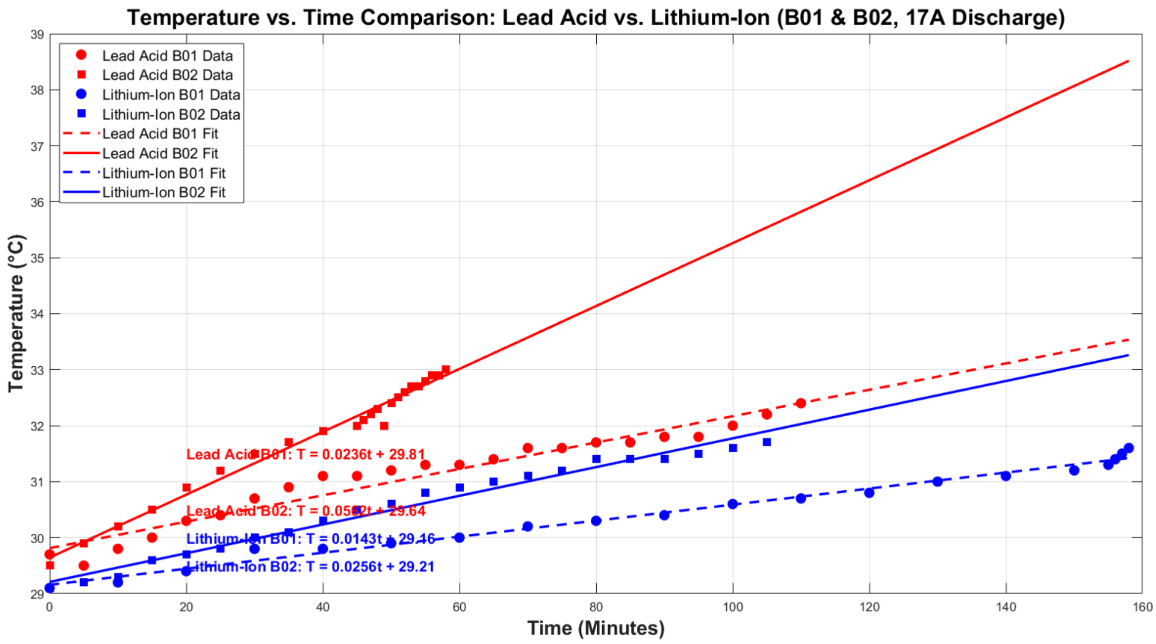

Fig. 4.9: Temperature behavior comparison of all the batteries in two battery set B01 and B02.

4.2 Calculations of battery life cycles and replacement times

For lead acid battery B01;

For the calculations, B01 lead-acid battery which discharges at 17A resulting in a temperature of approximately 31.2^{0}C was considered, assuming the average daily travel time as 50 minutes [22]. Based on this temperature and the modeled equation 6,[10] accounting for temperature impact on lead-acid battery B01 life, the reduction in cycle count was calculated. The initial cycle life at a baseline temperature of 20^{0}C was obtained from the manufacturer's data sheet for each lead-acid battery. Figures 4.9 and 4.10 display the cycle counts for lead-acid battery models B01 and B02 according to the manufacturer's data.

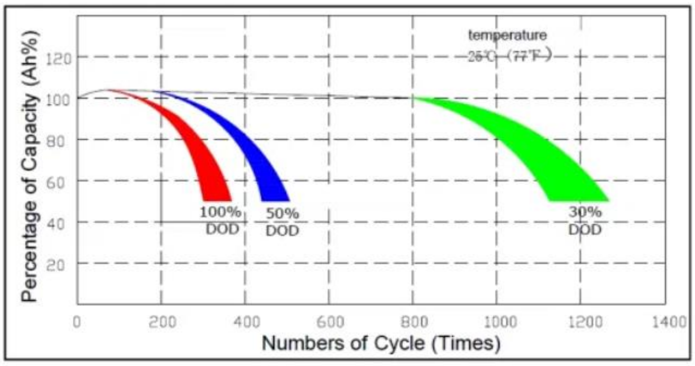

Fig. 4.10: Number of cycles of lead acid battery B01.

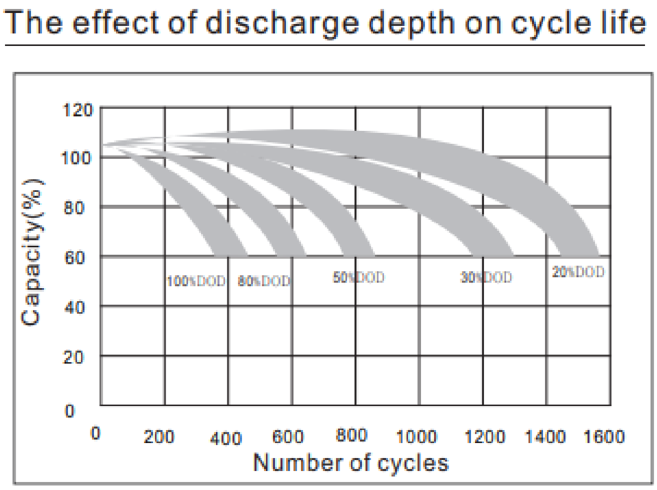

Fig. 4.11: Number of cycles of lead acid battery B02

Number of cycles at 20 ^{0}C is 380 cycles according to the manufacturer data sheet.

$N_C\% = 37.68 \times 31.2^{-1.101} - 0.3897$ ------------ Eq. (6)

$N_C\% = 46.3\%$

$N_C = 0.463 \times 380$

$N_C = 176$

For lead acid battery B02;

With a travel time of 50 minutes, the temperature of Lead-Acid Battery B02 reached 32.1^{0}C. Based on this elevated temperature, the reduced number of cycles was calculated. According to the manufacturer's datasheet, Battery B02 achieves 475 cycles at the standard temperature of 20^{0}C.

$$N_C\% = 37.68 \times 32.1^{-1.101} - 0.3897$$

$$N_C\% = 43.7\%$$

$$N_C = 0.437 \times 475$$

$$N_C = 208$$

For lithium-ion battery B01;

With a travel time of 50 minutes [22]and a discharge current of 17A, the lithium-ion battery's temperature reached 29.9^{0}C. Using the modeled equation 7, for lithium-ion battery performance[15] and this observed temperature, the number of cycles for the lithium-ion battery was calculated. The initial number of cycles is 2000 cycles at 25 ^{0}C.

Basic Info.

Model NO.	SPN72V45/SPF72V45	Size	Small
Nominal Voltage	72V	Nominal Capacity	45ah
Energy	3240wh	Cycle Life	>2000 Times @80dod
Maximum Charge Current	45A; 80A 20min	Maximum Continuous Discharge Curren	45A; 80A 20min
Communication	LCD/Can/RS485	Housing Material	Stainless
Dimension	360*230*160	Weight	19.5kg
Certification	CE, Un38.3	Warranty	3 Years
Transport Package	Carton	Trademark	Sunpack
Origin	China	HS Code	85076000
Production Capacity	500000 PCS/Year		

Fig. 4.12: Manufacturing details of lithium-ion battery B01

$N_c = aT^3 - bT^2 + cT + d$ ------------ Eq. (7)

$$N_c = 0.0039T^3 - 1.95T^2 + 67.51T + 1468.56$$

$$N_c = 0.0039 \times 29.9^3 - 1.95 \times 29.9^2 + 67.51 \times 29.9 + 1468.56$$

$$N_C = 1848$$

For lithium-ion battery B02;

As Figure 4.13, the cycle counts of Lithium-Ion Battery B02 are 2000 cycles at the standard temperature of 25^{0}C. While operating at 0^{0}C, the cycle count has been calculated as 1468.56 cycles. For a daily travelling time of 50 minutes, the rise in observed battery temperature is 30.6^{0}C. The number of cycles at the increased temperature is calculated as follows:

$$N_c = aT^3 - bT^2 + cT + d$$

$$N_c = 0.0039T^3 - 1.95T^2 + 67.51T + 1468.56$$

$$N_c = 0.0039 \times 29.9^3 - 1.95 \times 29.9^2 + 67.51 \times 29.9 + 1468.56$$

$$N_C = 1820.2$$

Basic Info.

Model NO.	72v30ah	Discharge Rate	2c
Size	Customized	Accessories Type	Battery
Rated Capacity	>1000MAH	Standard Voltage	72V
Usage	Electric Motorcycle	Electrolyte	Li-ion
Cycle Life	2000times	Capacity	30ah
Charge Current	15A	BMS	Normal BMS
Case	Iron Case/ Customized	Discharge Port	Customized
Transport Package	Carton with Foam	Specification	1pcs one carton
Trademark	no	Origin	Jiangsu
HS Code	8507600000	Production Capacity	1000PCS/Months

Fig. 4.13: Manufacturer’s details of lithium-ion battery B02.

The first comparison was between Battery Set 01, comprising Lead-Acid Battery B01 and lithium-ion Battery B02. Assuming the average daily travel time of a consumer is 50 minutes, from the discharge data represented in Table 4.1, it can be observed that the lead-acid battery B01 takes two days to complete the discharge. In other words, one discharge cycle is completed in two days, which also means that the battery has to be recharged in two days.

Similarly, for Lithium-Ion Battery B02, based on the discharge data of Table 4.3; while operating at a discharge current of 17A within the same 50-minute daily travel time, it would take three days to reach a full discharge. Hence, the lithium-ion battery will experience a complete discharge cycle after every three days.

In this regard, and based on these observations, the following calculations were done to analyze the impact of these discharge cycles on battery performance and longevity.

Lead acid battery B01:

- Number of cycles that can be used by consumer per year $= \frac{365}{2}$

$$= 182.5$$

- Number of replacement of the battery per year $= \frac{182.5}{\text{Reduced number of cycle}}$

$$= \frac{182.5}{176}$$

$$= 1.04 \text{ batteries}$$

- Replacement time of a battery $= \frac{\text{Reduced number of cycles}}{182.5}$

$$= 0.96 \text{ years}$$

Lithium-ion battery B01:

- Number of cycles that can be used by consumer per year $= \frac{365}{3}$

$$= 121.7$$

- Number of replacement of the battery per year $= \frac{121.7}{\text{Reduced number of cycle}}$

$$= \frac{121.7}{1848}$$

$$= 0.066 \text{ batteries}$$

- Replacement time of a battery $= \frac{\text{Reduced number of cycles}}{121.7}$

$$= 15.2 \text{ years}$$

The second battery set's comparison involved analyzing both lead-acid battery B02 and lithium-ion battery B02. A 50-minute travel time was used to calculate the number of cycles for each battery, the same as the first battery set (B01),

For lead-acid battery B02, operating at a discharge rate of 17 A, as specified in Table 4.2, the battery reaches full discharge in approximately 1.4 days, considering 50 minutes of travel time. This result indicates that the battery requires recharging every 1.4 days to complete a full cycle within this period.

At the same time, the lithium-ion battery B02, based on the data presented in Table 4.4, requires 2.1 days to reach full discharge under the same 50-minute daily travel conditions. Consequently, the lithium-ion battery B02 undergoes one cycle every 2.1 days.

Following these parameters, additional calculations were performed under the specified conditions further for battery set B02.

Lead acid battery B02:

- Number of cycles that can be used by consumer per year $= \frac{365}{1.4}$

$$= 261 \text{ cycles}$$

- Number of replacement of the battery per year $= \frac{261}{\text{Reduced number of cycle}}$

$$= \frac{261}{200}$$

$$= 1.305 \text{ batteries}$$

- Replacement time of a battery $= \frac{\text{Reduced number of cycles}}{261}$

$$= \frac{200}{261}$$

$$= 0.76 \text{ years}$$

Lithium-ion battery B02:

- Number of cycles that can be used by consumer per year $= \frac{365}{2.1}$

$$= 173.8 \text{ cycles}$$

- Number of replacement of the battery per year $= \frac{173.8}{\text{Reduced number of cycle}}$

$$= \frac{173.8}{1820}$$

$$= 0.095 \text{ batteries}$$

- Replacement time of a battery $= \frac{\text{Reduced number of cycles}}{173.8}$

$$= 10.5 \text{ years}$$

4.3 Travelling time per unit energy consumption

The batteries used in this study are in different capacities. Specifically, Battery Set B01 consists of a 32.3 Ah lead-acid battery (B01 Lead-Acid) and a 45 Ah lithium-ion battery (B01 Lithium-Ion). Meanwhile, Battery Set B02 comprises a 23 Ah lead-acid battery (B02 Lead-Acid) and a 30 Ah lithium-ion battery (B02 Lithium-Ion). Therefore, the distance per ampere-hour (Ah) for each battery type was calculated to make an equitable comparison between these batteries. This provides some understanding of each battery's energy efficiency in terms of a unit of charge.

For this calculation, the drive cycle's mean speed was considered, as illustrated in Figure 4.2, with an average speed determined to be 42.4 km/h. Here, the speed serves as a standardized parameter by ensuring consistency across calculations. Because of that, this comparison provides a clearer view of the performance characteristics of each battery under similar driving conditions by calculating the distance per Ah considering the mean speed.

The following sections present calculations for each battery in Battery Sets B01 and B02.

Lead acid battery B01:

Time to fully discharge the battery at 17 A current	= 110 minutes
Battery capacity	= 32.3 Ah
Distance travel considering mean speed	= 42.4 × 110/60
	= 77.73 km
Distance per 1 Ah	= 77.73/32.3
	= 2.4km/Ah
Total distance that battery can travel	= distance travel per 1 discharge × reduce cycles
	= 77.73x176
	=13,680.48 km

Lithium-ion battery B01:

Time to fully discharge the battery at 17 A current	=158 minutes
Battery capacity	= 45 Ah
Distance travel considering mean speed	= 42.4 × 158/60
	= 111.65 km
Distance per 1 Ah	= 111.65/45
	= 2.5km/Ah
Total distance that battery can travel	= distance travel per 1 discharge × reduce cycles
	= 111.65×1848
	= 206,329.2km

Lead acid battery B02:

Time to fully discharge the battery at 17 A current	=70 minutes
Battery capacity	= 23 Ah
Distance travel considering mean speed	= 42.4 × 70/60
	= 49.5km
Distance per 1 Ah	= 49.5/23
	= 2.2km/Ah
Total distance that battery can travel	= distance travel per 1 discharge × reduce cycles

	= 49.5x208
	=10,296 km
Lithium ion battery B01:	
Time to fully discharge the battery at 17 A current	=105 minutes
Battery capacity	= 30 Ah
Distance travel considering mean speed	= 42.4 x 105/60
	= 74.4 km
Distance per 1 Ah	= 74.4/30
	= 2.5km/Ah
Total distance that battery can travel	= distance travel per 1 discharge × reduce cycles
	= 74.4x1820
	=135,408km

4.4 Cost-benefit analysis

An economic analysis was conducted to evaluate the replacement costs associated with each battery type in two different battery sets. Starting with Battery Set B01, the lead-acid battery cost was referenced at 36.1 USD per unit, based on manufacturer details provided. Meanwhile, the price of the lithium-ion battery B01, which is 450 USD per unit. The following cost calculations were carried out to assess the economic implications of each battery type over the intended usage period using price values.

Initial cost of lead acid battery pack B01	= 36.1 × 6
	= 216.6 USD
Initial cost of lithium ion battery	= 450 USD
Usable life span of lead acid battery B01	= 0.96 years
Usable life span of lithium ion battery B01	= 15.2 Years
Considering 15.2 years number of replacement of	$= \frac{15.2}{0.96}$
Lead acid battery	=15.8 times

For the replacement of lead-acid batteries over a 15.2-year period, the costs have been calculated by incorporating both inflation and the potential scrap value. In the Sri Lankan market, the scrap value of a used lead-acid battery is approximately 180 LKR per kilogram, as determined through a market survey. An economic inflation rate of 2.4% was also considered to reflect future price adjustments accurately. The following calculations were carried out for Battery Set B01 based on these parameters.

Considering lead acid battery B01;

Scarp value	= Battery weight × number of batteries in the battery pack ×180
	= 10.6×6×180
	=11,448.00 LKR
	=39USD
Net cost at year t	= Initial battery cost× $(1+\text{inflection rate})^{t}$ - Scrap value

Based on calculations, the estimated replacement interval for the lead-acid battery model B01 is 0.96 years. Consequently, over a 15.2-year period, the battery is expected to require approximately 15.8 replacements. Table 4.5 presents the detailed calculations conducted to estimate the total cost over this 15-year timeframe.

Total cost of using lead acid battery B01 for E bike for

For 15.2 years (as table 4.5) = 3299.8 USD

Total cost of using lithium-ion battery B01 for an E bike for

15.2 years = 450 USD

TABLE 4.5: COST OF LEAD ACID BATTERY B01 FOR 15 YEARS

No of battery	Time the battery Replacement (year)	Year No	Cost USD	
1	0.96	0	216.6	= $[216.6\times(1+0.024)^{0}]$
2	1.92	1	182.184	= $[216.6\times(1+0.024)^{1}-39]$
3	2.88	2	187.4924	= $[216.6\times(1+0.024)^{2}-39]$
4	3.84	3	192.9282	= $[216.6\times(1+0.024)^{3}-39]$
5	4.8	4	198.4945	= $[216.6\times(1+0.024)^{4}-39]$
6	5.76	5	204.1944	= $[216.6\times(1+0.024)^{5}-39]$
7	6.72	6	210.031	= $[216.6\times(1+0.024)^{6}-39]$
8	7.68	7	216.0078	= $[216.6\times(1+0.024)^{7}-39]$
9	8.64	8	222.128	= $[216.6\times(1+0.024)^{8}-39]$

10	9.6	9	228.395	= [216.6× $(1+0.024)^9$-39]
11	10.56	10	234.8125	= [216.6× $(1+0.024)^{10}$-39]
12	11.52	11	241.384	= [216.6× $(1+0.024)^{11}$-39]
13	12.48	12	248.1132	= [216.6× $(1+0.024)^{12}$-39]
14	13.44	13	255.004	= [216.6× $(1+0.024)^{13}$-39]
15	14.4	14	262.0601	= [216.6× $(1+0.024)^{14}$-39]
	Total		3299.829	

The analysis proceeded with considering Battery Set B02. According to manufacturer details, the lead-acid battery B02 is priced at 4000 INR, as illustrated in Figure 4.15. The lithium-ion battery B02 is priced at 350 USD, as depicted in Figure 4.18. Based on these values, the subsequent calculations were performed.

Initial cost of lead acid battery pack B01	= 4000 × 6
	= 47.64 ×6
	= 285.84USD
Initial cost of lithium-ion battery	= 350 USD
Usable life span of lead acid battery B01	= 0.77 years
Usable life span of lithium-ion battery B01	= 10.5 Years
Considering 15.2 years number of replacement of	= 10.5/0.77
Lead acid battery	=13.6 times

For the replacement of lead-acid batteries over a 13-year period, the costs were calculated by factoring in both inflation and the potential scrap value, as previously done for Battery Set B01. Using these parameters, the following calculations were conducted for Battery Set B02.

Considering lead acid battery B01;

Scarp value	= Battery weight × number of batteries in the battery pack
	×180
	= 6.8×6×180
	= 7,344.00 LKR

= 25USD

Net cost at year t = Initial battery cost × (1+inflection rate) t

- Scrap value

From the calculations, the estimated replacement interval for the lead-acid battery model B01 is 0.77 years. Consequently, for a 10.5-years period, it is estimated that there could be around 13.6 replacements. The summary of how the total cost over a 10.5-years period was estimated is given in Table 4.6.

The total cost of using lead acid battery B01 for E bike for

For 10.5years (as table 4.6) = 3894 USD

Total cost of using lithium-ion battery B01 for an E bike for

10.5 years = 350 USD

TABLE 4.6: COST OF LEAD ACID BATTERY B02 FOR 10.5 YEARS

No of battery	**Time the battery replacement (year)**	**Year No**	**Cost USD**	
1	0.8	0	285.84	$= [285.84\times (1+0.024)^{0}]$
2	1.6	1	267.7002	$= [285.84\times (1+0.024)^{1}-25]$
3	2.4	2	274.725	$= [285.84\times (1+0.024)^{2}-25]$
4	3.2	3	281.9184	$= [285.84\times (1+0.024)^{3}-25]$
5	4	3	281.9184	$= [285.84\times (1+0.024)^{3}-25]$
6	4.8	4	289.2844	$= [285.84\times (1+0.024)^{4}-25]$
7	5.6	5	296.8272	$= [285.84\times (1+0.024)^{5}-25]$
8	6.4	6	304.5511	$= [285.84\times (1+0.024)^{6}-25]$
9	7.2	7	312.4603	$= [285.84\times (1+0.024)^{7}-25]$
10	8	7	312.4603	$= [285.84\times (1+0.024)^{7}-25]$
11	8.8	8	320.5594	$= [285.84\times (1+0.024)^{8}-25]$
12	9.6	9	328.8528	$= [285.84\times (1+0.024)^{9}-25]$
13	10.4	10	337.3452	$= [285.84\times (1+0.024)^{10}-25]$

	Total	3894.443

Similarly, the cost of using the lead-acid battery model B02 over a 15.2-year period was also calculated for comparison purposes. Table 4.7 presents the detailed cost calculations for this timeframe.

Total cost of using lead acid battery B01 for E bike for

For 15.2 years (as table 4.7) = 6061 USD

TABLE 4.7: COST OF LEAD ACID BATTERY B02 FOR 15.2 YEAR

No of battery	**Time the battery replacement (year)**	**Year No**	**Cost USD**	
1	0.8	0	285.84	= [285.84× (1+0.024)^{0}]
2	1.6	1	267.7002	= [285.84× (1+0.024)^{1}-25]
3	2.4	2	274.725	= [285.84× (1+0.024) ^{2}-25]
4	3.2	3	281.9184	= [285.84× (1+0.024)^{3}-25]
5	4	3	281.9184	= [285.84× (1+0.024)^{3}-25]
6	4.8	4	289.2844	= [285.84× (1+0.024)^{4}-25]
7	5.6	5	296.8272	= [285.84× (1+0.024)^{5}-25]
8	6.4	6	304.5511	= [285.84× (1+0.024) ^{6}-25]
9	7.2	7	312.4603	= [285.84× (1+0.024)^{7}-25]
10	8	7	312.4603	= [285.84× (1+0.024)^{7}-25]
11	8.8	8	320.5594	= [285.84× (1+0.024)^{8}-25]
12	9.6	9	328.8528	= [285.84× (1+0.024)^{9}-25]
13	10.4	10	337.3452	= [285.84× (1+0.024)^{10}-25]
14	11.2	11	346.0415	= [285.84× (1+0.024)^{11}-25]
15	12	11	346.0415	= [285.84× (1+0.024)^{11}-25]
16	12.8	12	354.9465	= [285.84× (1+0.024)^{12}-25]

17	13.6	13	364.0652	$= [285.84\times (1+0.024)^{13}-25]$
18	14.4	14	373.4028	$= [285.84\times (1+0.024)^{14}-25]$
19	15.2	15	382.9645	$= [285.84\times (1+0.024)^{15}-25]$
	Total		6061.905	

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 Discussion

While this research is focused on the relationship between temperature and performance of E bikes batteries, its core relation lies in the impact on the battery lifespan for two battery types. This relationship is inversely proportional, as evidenced by the finding that as operating temperatures increase, the overall lifespan of the battery decreases. This is even more so the case with lead-acid batteries, which shows a significant decrease in recoverable life cycles over the time period compared to lithium-ion batteries under similar conditions. By contrast, lithium-ion batteries show less effect from temperatures and therefore continue the span of an operating life as the temperature goes up or down.

While comparing the long-term costs of each battery type, lithium-ion batteries, though more expensive to purchase, become more cost-effective over the period. This is because they would last longer and thus would not need to be changed frequently, which outweighs the higher investment in them. On the other hand, lead-acid batteries are cheaper in their initial purchase but result in higher accumulated costs owing to their short lifespan and the requirement for more replacements.

Therefore, lithium-ion batteries are highly recommended for consumers in Sri Lanka who seek reliability and long performance in e-bikes. Their durability, resistance to high-temperature degradation, and overall cost-effectiveness compared to lead-acid batteries make them a more sustainable and economically beneficial choice.

5.2 Key findings

For this study, two different sets of batteries were used: B01 and B02. Each contained a lead-acid and a lithium-ion battery with different capacities to reflect both the maximum and minimum capacity conditions. Battery set B01 is composed of a lead-acid battery with a capacity of 32.3 Ah, while the lithium-ion battery has a capacity of 45 Ah. Battery set B02 consists of a lead-acid battery with a capacity of 23.3 Ah and a lithium-ion battery with 30 Ah capacity.

The capacity varies from a minimum of 23.3 Ah to a maximum of 38 Ah for those e-bikes that are fitted with lead-acid batteries, while for e-bikes fitted with lithium-ion batteries, capacities vary between 30 Ah and 45 Ah. This comparison shows the spread of maximum and minimum capacities with lead-acid and lithium-ion batteries in E-bike applications, and this spread may have implications for performance and range.

TABLE 5.1: PARAMETER COMPARISON OF BATTERIES

	Maximum capacity		Minimum capacity	
	Lead acid B01	Lithium ion B01	Lead acid B02	Lithium ion B02
Capacity	32.3Ah	45Ah	23.3 Ah	30Ah
Initial cost USD	216.6	450	285.84	350
Usable cycles	176	1848	200	1820
Charging requirement (days)	2	3	1.4	2.1
Usable No of Years	0.96	15.2	0.77	10.5
Cost USD	3299.8 for 15 years	450 for 15 years	3886 for 10 years	350 for 10 years
Cost USD for 15 Years	3299.8	450	6003.743	700

Table 5.1 compares two types of batteries, Lead-Acid and Lithium-Ion, in battery sets B01 and B02. In there the comparative parameters are capacity, initial cost, usable cycles, charging frequency, usable lifespan in years, and the total cost over a 10- and 15-year period. By presenting this data, the table highlights critical differences in performance and cost-efficiency. That will helpful for determining the more suitable battery type for E bike application based on longevity and financial considerations.

The Lithium-Ion batteries used in E-bikes in Sri Lankan market (45Ah for B01 and 30Ah for B02) demonstrate higher energy storage capabilities than the Lead-Acid models (32.3Ah for B01 and 23.3Ah for B02). This suggests that Lithium-Ion batteries can sustain longer operational times between charges, aligning with their reputation for higher energy density. Furthermore, the initial costs are considerably different between the two types, with Lead-Acid batteries initially costing $216.6 and $285.84 for B01 and B02, respectively. Meanwhile, the Lithium-Ion models are priced at $450 for B01 and $350 for B02. Although Lithium-Ion batteries generally have a higher upfront cost, their enhanced cycle life and efficiency can often justify this investment over time.

When analyzing long-term usability and cost, Lithium-Ion batteries are highlighted. With usable cycles 1848 for B01 and 1820 for B02, they are significantly higher than the Lead-Acid models, which offer only 176 and 200 cycles for B01 and B02. When comparing usable lifespans of 15.2 years for Lithium-Ion B01 and 10.5 years for Lithium-Ion B02 with lead acid batteries, those have less than one year for both Lead-Acid models under the same usage conditions. Consequently, the total cost for Lead-Acid B01 reaches $3299.8 over 15 years. Meanwhile, Lithium-Ion B01 costs only $450. Therefore, this table highlights the economic and operational advantages of Lithium-Ion batteries for long-term applications despite the initial higher expense.

TABLE 5.2: USABLE RUNNING DISTANCE COMPARISON OF BATTERIES

	Lead acid battery B01	**Lithium ion battery B01**	**Lead acid battery B02**	**Lithium ion battery B02**
Time to discharge the battery at 17 A(min)	110	158	70	105
Battery capacity (Ah)	32.3	45	23	30
Traveling distance per one discharge considering mean speed 42.4 km/h (km)	77.7	111.65	49.5	74.4
Distance per 1 Ah (km/Ah)	2.4	2.5	2.2	2.5
Total length that can be used per battery in reduced number of cycles (km)	13,680	206,329	10,296	135,408

Table 5.2 presents a comparative analysis of the performance characteristics of the two types of batteries, Lead-Acid B01 and B02, and Lithium-Ion B01 and B02. Key metrics include discharge time at a current draw of 17A, battery capacity, and travel distance per discharge cycle by assuming an average speed of 42.4 km/h. Furthermore, it includes efficiency in terms of distance per ampere-hour (Ah) and the total distance achievable per battery over its usable lifespan considering reduced cycle counts. This data highlights the practical implications of each battery type in terms of travel range, endurance, and operational efficiency by considering specified mean speed and the average current.

Regarding discharge time, the Lithium-Ion batteries show a more prolonged duration at discharging current 17A. Lithium-ion battery B01 discharges in 158 minutes, and lithium-ion battery B02 discharges in 105 minutes. When it comes to the Lead-Acid B01 and B02 models, they discharge in 110 and 70 minutes, respectively. This suggests that Lithium-Ion batteries sustain a more extended operational period per charge. It represents their suitability for applications requiring prolonged energy output for e-bikes.

Travel range and efficiency are additional strengths of Lithium-Ion batteries. For example, under a mean speed of 42.4 km/h, Lithium-Ion B01 can support 111.65 km per discharge, while Lead-Acid B01 reaches 77.7 km. Distance per ampere-hour for the Lithium-Ion models (2.5 km/Ah) is higher than the Lead-Acid models (2.4 and 2.2 km/Ah). Over their usable lifetimes, the Lithium-Ion batteries also support significantly longer total travel distances due to their higher cycle life, with B01 reaching 206,329 km and B02 covering 135,408 km, while Lead-Acid B01 and B02 provide only 13,680 km and 10,296 km, respectively. This table underscores the superior endurance and efficiency of Lithium-Ion batteries, making them a more cost-effective choice over the long term.

5.3 Future studies

In future works, the environmental impact is planned to be considered.

When analyzing the environmental impact of Lead-Acid and Lithium-Ion batteries, it's essential to consider several factors. Here, recycling feasibility, potential landfill contributions, annual import rates, and the costs and benefits associated with recycling practices should be considered when considering environmental impact. Each type of battery has separate environmental implications. It can be during its lifecycle and after disposal. And it can influence overall sustainability and impact assessments.

Lead-acid batteries are widely recycled. Because processes are already established and for extracting and materials such as lead and sulfuric acid can be reused. However, the recycling process has its own environmental impact. For instance, during the recycling process, lead contamination and acid leakage are happened. It has significant risks to soil and water systems. Therefore it should be properly managed. The emissions from lead-acid recycling facilities can also affect air quality. And it impacts both environmental and human health. Despite these issues, the high recycling rate of Lead-Acid batteries reduces their contribution to landfills.

On the other hand, Lithium-ion batteries face a much lower recycling rate. It is because of the complexity, cost, and technical challenges associated with recycling processes. Currently, only a small fraction of Lithium-Ion batteries are recycled. Most lithium-ion batteries end up in landfills at the end of their life. This causes a significant environmental concern. Lithium-ion batteries contain materials like lithium, cobalt, and nickel, which can leach into soil and water, causing potential hazards. Moreover, the accumulation of these batteries in landfills could become a long-term environmental challenge. And it will lead to resource depletion and increased landfill waste.

Therefore Future research should be focused on enhancing Lithium-Ion recycling methods and how to make them more cost-effective and efficient way

REFERENCES

[1] C. Wortmann, A. M. Syré, A. Grahle, and D. Göhlich, "Analysis of electric moped scooter sharing in berlin: A technical, economic and environmental perspective," *World Electr. Veh. J.*, vol. 12, no. 3, 2021, doi: 10.3390/wevj12030096.

[2] E. Fishman and C. Cherry, "E-bikes in the Mainstream: Reviewing a Decade of Research," *Transp. Rev.*, vol. 36, no. 1, pp. 72–91, 2016, doi: 10.1080/01441647.2015.1069907.

[3] ReGlobal, "Decarbonising Transport: Overview of Sri Lanka's EV Market," 2024. https://reglobal.org/decarbonising-transport-overview-of-sri-lankas-ev-market/ (accessed Nov. 17, 2024).

[4] 6Wresearch, "Sri Lanka Electric Scooters Market Report," 2024. https://www.6wresearch.com/industry-report/sri-lanka-electric-scooters-market-2020-2026 (accessed Nov. 17, 2024).

[5] E. Nesbo, "How to choose an eBike: 8 key features to look for," 2022. https://www.makeuseof.com/how-to-choose-an-ebike-key-features/ (accessed Nov. 18, 2024).

[6] JYC Battery Manufacturer, "The Characteristics and Performance Parameters of Lead-Acid Batteries," 2024. https://www.jycbattery.com/the-characteristics-and-performance-parameters-of-lead-acid-batteries/ (accessed Nov. 20, 2024).

[7] Electricity and Magnetism, "Characteristics of Lithium-ion Batteries," 2024. https://www.electricity-magnetism.org/electric-battery/characteristics-of-lithium-ion-batteries/ (accessed Nov. 20, 2024).

[8] J. M. Bhatt, P. V. Ramana, and J. R. Mehta, "Performance assessment of valve regulated lead acid battery for E-bike in field test," *Mater. Today Proc.*, vol. 49, no. xxxx, pp. 2058–2065, 2021, doi: 10.1016/j.matpr.2021.08.305.

[9] R. Hutchinson, "SANDIA REPORT TEMPERATURE EFFECTS ON SEALED LEAD ACID BATTERIES AND CHARGING TECHNIQUES TO PROLONG CYCLE LIFE," 2004. [Online]. Available: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

[10] T. M. Layadi, G. Champenois, M. Mostefai, and D. Abbes, "Lifetime estimation tool of lead-acid batteries for hybrid power sources design," *Simul. Model. Pract. Theory*, vol. 54, pp. 36–48, 2015, doi: 10.1016/j.simpat.2015.03.001.

[11] S. M. Rezvanizaniani, Z. Liu, Y. Chen, and J. Lee, "Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility," vol. 256, pp. 110–124, 2014.

[12] K. Qian, C. Zhou, Y. Yuan, and M. Allan, "Temperature Effect on Electric Vehicle Battery Cycle Life in Vehicle-to-Grid Applications," no. 1, pp. 1–6, 2010.

[13] S. C. Chen, C. C. Wan, and Y. Y. Wang, "Thermal analysis of lithium-ion batteries," *J. Power Sources*, vol. 140, no. 1, pp. 111–124, 2005, doi: 10.1016/j.jpowsour.2004.05.064.

[14] M. Dubarry *et al.*, "Identifying battery aging mechanisms in large format Li ion

cells," *J. Power Sources*, vol. 196, no. 7, pp. 3420–3425, 2011, doi: 10.1016/j.jpowsour.2010.07.029.

[15] N. Omar *et al.*, "Lithium iron phosphate based battery - Assessment of the aging parameters and development of cycle life model," *Appl. Energy*, vol. 113, pp. 1575–1585, 2014, doi: 10.1016/j.apenergy.2013.09.003.

[16] J. J. An, S. Chen, and K. Yang, "Temperature characterization analysis of LiFePO4/C power battery during charging and discharging," *J. Therm. Anal. Calorim.*, vol. 99, no. 2, pp. 515–521, 2010, doi: 10.1007/s10973-009-0623-1.

[17] M.-S. Wu, K. H. Liu, Y.-Y. Wang, and C.-C. Wan, "Heat dissipation design for lithium-ion batteries."

[18] A. Babak, V. Esfahanian, and F. Torabi, "Discharge , rest and charge simulation of lead-acid batteries using an efficient reduced order model based on proper orthogonal decomposition," *Appl. Energy*, vol. 173, pp. 152–167, 2016, doi: 10.1016/j.apenergy.2016.04.008.

[19] F. Torabi and V. Esfahanian, "Study of Thermal-Runaway in Batteries II . The Main Sources of Heat Generation in Lead-Acid Batteries," vol. 160, no. 2, pp. 223–234, 2013, doi: 10.1149/2.030302jes.

[20] S. H. Kamble, T. V. Mathew, and G. K. Sharma, "Development of real-world driving cycle: Case study of Pune, India," *Transp. Res. Part D Transp. Environ.*, vol. 14, no. 2, pp. 132–140, 2009, doi: 10.1016/j.trd.2008.11.008.

[21] R. M. T. D. I D M H Jayantha, H D C Hettiarachchi, S M V P D Senananayake, Kapila Peris, "Examining Electric Bike Performance in Sri Lanka comparing battery performance: A Practical Study," 2024.

[22] C. R. Cherry, H. Yang, L. R. Jones, and M. He, "Dynamics of electric bike ownership and use in Kunming, China," *Transp. Policy*, vol. 45, pp. 127–135, 2016, doi: 10.1016/j.tranpol.2015.09.007.

[23] 2025 Monolithic Power Systems, "How Resistance, Temperature, and Charging Behaviors Impact Battery SOC and SOH," 2025. http://www.monolithicpower.com/learning/resources/how-resistance-temperature-and-charging-behaviors-impact-battery-soc-and-soh#:~:text=At higher temperatures%2C battery performance,more quickly at higher temperatures. (accessed Feb. 02, 2025).

APPENDIX - A : THE CURRENT DATA AND SPEED DATA VALUES OF TEST RUN

TABLE A.1 : CURRENT DATA VALUES OF TEST RUN

Time (s)	**Current (A)**
0	0
15	15.5
30	6.6
45	5.7
60	21.7
75	0
90	58
105	28.1
120	17.2
135	0
150	31.1
165	31.2
180	0
195	17.2
210	0
225	35.5
240	13.8
255	12.8
270	14.2
285	29.8

300	17.7
315	17.1
330	12.3
345	0
360	5.5
375	12.1
390	31.3
405	0
420	0.3
435	20.9
450	39.5
465	39.4
480	39.4
495	39
510	39.9
525	39
540	15.1
555	25.1
570	18.7
585	39.5
600	0.2
615	0
630	39.4
645	39.5

660	22
675	0
690	18
705	4
720	0
735	0.1
750	4.9
765	4.9
780	10.3
795	39.4
810	9.5
825	23
840	5
855	0
870	39.5
885	8.1
900	0
915	0
930	18.3
945	16.5
960	17.5
975	16.4
990	39.4
1005	18.7

1020	0.3
1035	19.6
1050	0.5
1065	22.4
1080	39.7
1095	32.9
1110	14.3
1125	10.9
1140	18.4
1155	14.3
1170	15.2
1185	13.3
1200	15.6
1215	12.5
1230	16.9
1245	16.7
1260	0.2
1275	24.3
1290	7.9
1305	0.2
1320	10.3
1335	15
1350	14.8
1365	19.4

1380	17.5
1395	0.2
1410	18.3
1425	16.8
1440	21.3
1455	33.2
1470	0.1

TABLE A.2 : SPEED DATA VALUES OF TEST RUN

Time (s)	**Speed (km/ h)**
0	0
15	8
30	37
45	27
60	19
75	27
90	38
105	54
120	61
135	51
150	52
165	51
180	22
195	48

210	57
225	41
240	58
255	58
270	58
285	52
300	58
315	62
330	63
345	47
360	39
375	46
390	22
405	3
420	22
435	52
450	43
465	31
480	34
495	57
510	42
525	51
540	58
555	54

570	56
585	42
600	31
615	52
630	40
645	47
660	62
675	55
690	55
705	8
720	0
735	9
750	27
765	27
780	35
795	50
810	27
825	23
840	27
855	49
870	43
885	19
900	60
915	60

930	48
945	55
960	55
975	55
990	32
1005	54
1020	53
1035	54
1050	50
1065	14
1080	34
1095	24
1110	54
1125	55
1140	54
1155	54
1170	54
1185	54
1200	52
1215	54
1230	53
1245	45
1260	38
1275	41

1290	44
1305	33
1320	32
1335	53
1350	53
1365	53
1380	53
1395	48
1410	40
1425	37
1440	25
1455	47
1470	38

APPENDIX - B : THE TEMPERATURE VALUES OF CHARGING THE BATTERIES

TABLE B.1: VOLTAGE, CURRENT AND TEMPERATURE VARIATIONS FOR CHARGING OF LEAD ACID BATTERY PACK B01

Time (Min)	Voltage (V)	Current (A)	Temperature (^{0}C)
0	72.0	4.8	29.0
30	73.8	4.8	29.7
60	74.8	4.8	30.5
90	75.8	4.8	31.1
120	76.7	4.8	32.0
150	77.6	4.8	32.8
180	78.8	4.8	33.5
210	79.7	4.8	33.9
240	80.6	4.8	34.3
270	81.7	4.8	34.8
300	83.4	4.8	35.4
330	87.1	4.5	36.5
345	87.4	3.3	37.1
360	87.5	2.5	37.5
375	87.6	2.2	38.0
390	87.7	1.8	38.4
405	87.8	1.5	38.5
420	87.8	1.3	38.6
435	87.8	1.2	38.7
450	87.8	1.0	38.7

455	87.8	0.0	38.8

TABLE B.2: VOLTAGE AND TEMPERATURE VARIATIONS FOR CHARGING OF LI-IN BATTERY (B01) BATTERY CHARGING CURRENT AT 10.1A

Time (Min)	Voltage (V)	Temperature (^{0}C)
0	64.8	30.8
30	75.1	30.9
60	76.4	31.2
90	76.9	31.4
120	77.0	31.5
150	77.2	31.7
180	77.8	32.0
210	77.9	32.1
240	78.0	32.4
270	81.0	32.5
271	83.0	32.6
272	83.6	32.7

APPENDIX - C: THE DEFINITIONS OF BATTERIES AND CALCULATIONS

C ratings of the batteries

- $C\ rating = \frac{Dischaging\ current\ of\ the\ battery}{Battery\ capacity}$

- Considering the Lead acid battery B01

$$C\ rating = \frac{17\ \ A}{32.3\ Ah}$$

$$C\ rating = 0.53$$

- Considering the Li ion battery B01

$$C\ rating = \frac{17\ \ A}{45\ Ah}$$

$$C\ rating = 0.38$$

- Considering the Lead acid battery B02

$$C\ rating = \frac{17\ \ A}{23.3\ Ah}$$

$$C\ rating = 0.73$$

- Considering the Li ion battery B02

$$C\ rating = \frac{17\ \ A}{30\ Ah}$$

$$C\ rating = 0.57$$

Depth of discharge of the batteries

- $DOD \qquad = \frac{Used\ capacity \times 100}{Battery\ capacity}$

- Considering the Lead battery B01,

$$Used\ capacity \qquad = Discharging\ current \times Time$$

$$Used\ capacity \qquad = 17 \times \frac{110}{60}$$

$$Used\ capacity \qquad = 31.16\ Ah$$

$$DOD \qquad = \frac{31.16 \times 100}{32.3}$$

$$DOD \quad = 96.4\%$$

- Considering the Li ion battery B01,

$$Used\ capacity \quad = Discharging\ current \times Time$$

$$Used\ capacity \quad = 17 \times \frac{158}{60}$$

$$Used\ capacity \quad = 44.78Ah$$

$$DOD \quad = \frac{44.78 \times 100}{45}$$

$$DOD \quad = 99.5\%$$

- Considering the Lead battery B02,

$$Used\ capacity \quad = Discharging\ current \times Time$$

$$Used\ capacity \quad = 17 \times \frac{70}{60}$$

$$Used\ capacity \quad = 19.83Ah$$

$$DOD \quad = \frac{19.83 \times 100}{23}$$

$$DOD \quad = 86.23\%$$

- Considering the Li ion battery B02,

$$Used\ capacity \quad = Discharging\ current \times Time$$

$$Used\ capacity \quad = 17 \times \frac{105}{60}$$

$$Used\ capacity \quad = 29.75Ah$$

$$DOD \quad = \frac{29.75 \times 100}{30}$$

$$DOD \quad = 99.1\%$$

SOH (state of health) of batteries

The battery's State of Health (SOH) and State of Charge (SOC) are essential indicators of its overall performance. SOC reflects the current capacity available relative to its full charge. It indicates to users when it's time to recharge. And SOH compares the battery’s current performance to its original. New state 100% SOH of a battery indicates that the battery can still store its nominal capacity. And any lower percentage of SOH shows that it has aged and now holds less charge.

New batteries typically have lower internal resistance. It enables them to deliver power more efficiently with minimal voltage drop and heat generation. However, factors such as electrode degradation, chemical changes, and the buildup of by-products increase their internal resistance.

Because of that, diminishing performance and shortening lifespan happen by reducing power capabilities and accelerating degradation as batteries age. Designers aim to minimize internal resistance by using high-quality materials and optimizing the battery's structure. Because increased resistance not only leads to greater voltage drops but also generates more heat. It is negatively impacting efficiency and durability.[23]

$$SOH\,\% \quad = \frac{Measured\ capacity\ (Ah)}{Rated\ capacity\ (Ah)} \times 100$$

- Considering Lead acid battery B01,

$$SOH\,\% = \frac{31.16 \times 100}{32.3}$$

$$SOH\,\% = 96.4$$

- Considering Lithium ion battery B01,

$$SOH\,\% = \frac{44.78 \times 100}{45}$$

$$SOH\,\% = 99.5$$

- Considering Lead acid battery B02,

$$SOH\,\% = \frac{19.83 \times 100}{23}$$

$$SOH\,\% = 86.2$$

- Considering Lithium ion battery B02,

$$SOH\,\% = \frac{29.75 \times 100}{30}$$

$$SOH\,\% = 99.16$$

APPENDIX - D: MANUFACTURER'S DATA

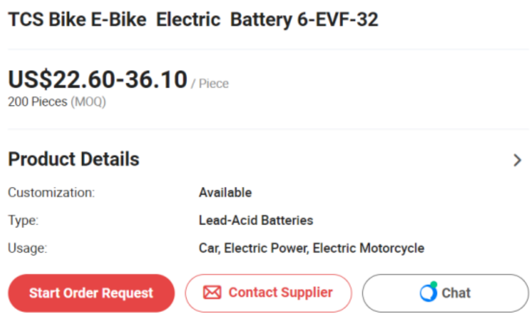

Fig.D.1: Price details of lead acid battery B01

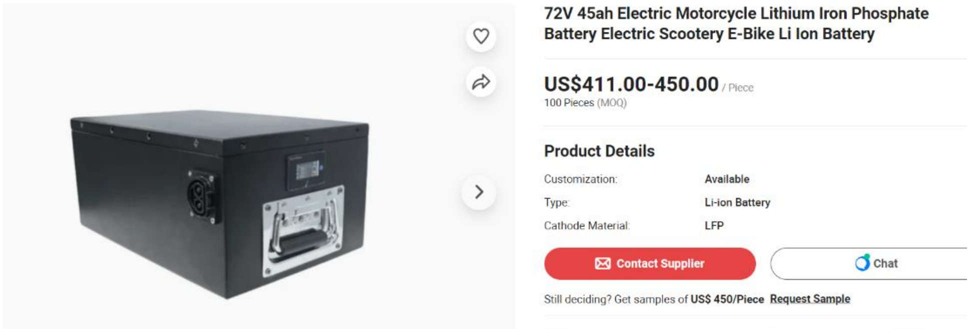

Fig.D.2: Price details of lithium-ion battery B01

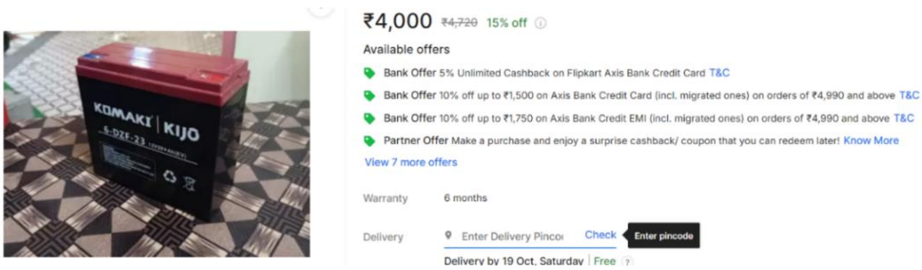

Fig. D.3: Price details of lead acid battery B02

Fig. D.4: Specifications of lead acid battery B02

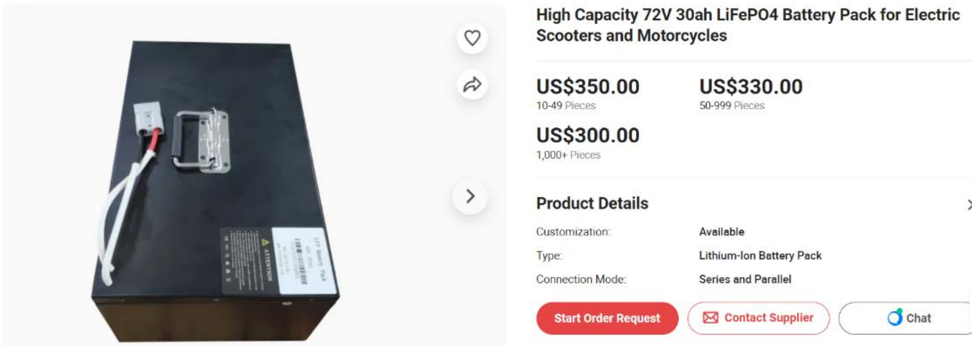

Fig. D.5: Price details of lithium-ion battery B02