Evaluating the Effects of Charging Rates on Lithium-Ion Battery Performance in Electric Scooters

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Abstract

Lithium-ion (Li-ion) batteries are widely used in electric scooters due to their high energy density and long cycle life. However, their charging characteristics significantly impact efficiency, safety, and durability. This study examined the effects of varying constant current (C-rate) charging rates (0.1C, 0.5C, and 1.0C) on charging time, temperature stability, and battery health. The results demonstrated that higher C-rates substantially reduced charging time from 10 hours 40 minutes at 0.1C to 1 hour 40 minutes at 0.5C, and only 1 hour at 1.0C. However, higher C-rates also increased thermal stress, which could accelerate battery degradation. Chargers operating at 0.5C and 1.0C included cooling fans to regulate temperature, whereas the 0.1C charger, lacking active cooling, exhibited elevated temperatures, and posed thermal risks. To enhance safety and potentially extend battery life, an automated 70% capacity cut-off was introduced to prevent overcharging. These findings highlight the trade-off between charging efficiency and battery lifespan, suggesting that although faster charging reduces downtime, it may adversely affect long-term battery health. Further research involving multiple charge cycles is needed to assess the long-term effects and optimise charging strategies for Li-ion batteries in electric scooters. This study contributes to knowledge by providing critical insights into the balance between charging efficiency, and battery longevity, and provide support to the development of optimised charging strategies for Li-ion batteries in electric scooters. Further studies involving multiple charge cycles are recommended to quantify long-term effects and enhance charging protocols for safer and more durable battery use.

Keywords: Battery Health, Charging Efficiency, Electric Scooters, Lithium-ion Batteries, Thermal Management

1.0 Introduction

Electric cars have become the viable solution to combat the growing problem of climate change and diminishing reliance on oil products. Nevertheless, their development faces questions like an increased battery range, the cost, durability of the batteries, and the extensive network of charging stations [1]. This paper investigates the current trends on the widespread of electric vehicles in the world over the last few years based on the following arguments that have been advanced in recent studies. Last year in 2023, sales amounted to 13.9 million, which would represent roughly 18% of all vehicles sold – up from 14% in 2022. This is due to good growth in adoption of Bluetooth, especially as demand spreads to the mainstream markets in the key continents. Current leaders are China, Europe and United States where single country China is accounting 60% of new electric vehicle sales [2], [3]. This is mainly dependent on the carrying capacity and energy storage abilities of the EVs thus calling for improvement of infrastructure [4]. Traditional charging infrastructure is now joined by DC fast charging that is faster than AC ones, and important for long distance traveling and other cases when constant maximum power charging is needed making it an important part of future mobility of electric vehicles [5].

As with any electric motorcycle, electric scooters utilize DC fast chargers, just like the EVs, because of their superior charge rate and power compared to the existing AC chargers. The charging process entails linking of the motorcycle DC charging interface to the fast charger so that direct current is supplied to the battery of the motorcycle. However, it is crucial to be certain that the charging port of the motorcycle to the certain standard of DC fast charging used at the charging station [6], [7]. Current inconsistency low charging standards across different areas and models may also bring about various problems including inefficiencies and even damaging the battery when wrong charger from a different model is connected [10]. Therefore, there exist great necessity to provide solutions that ensure safe and efficient charging of electric scooters especially given the increasing demand for fast charging.

In general, fast charging calls for batteries that can handle high energy flow rates without being deleteriously impacted regarding their durability. As can be observed, the perfect characteristics of an EV battery are one that has a long lasting, high energy and power density and one that can be recharged quickly in different climates [6]. This would enable long distance travel with duration of stop over that can hardly be measured. Unfortunately, establishing such ideal characteristics has been quite mitigating due to the physical constraints associated with battery material [7]. One of the main challenges is to reconcile high energy density with the mechanical properties of the electrodes. As energy density rises, so does driving range; however, problems like heat are further elevated, and they are not friendly to battery longevity. Temperature is another parameter that is essential in charging as both low and high temperatures charge the batteries [8]. When charging at lower temperatures, both charge rates and maximum voltage must be limited to prevent the formation of dangerous compounds, such as lithium metal on the surface of the battery, which greatly reduces battery capacity [9]. This presents a difficulty of sustaining high charging rates together with the effects of temperature on battery durability.

Comparing DC fast chargers with the traditional AC chargers, one of the most significant differences is the speed at which an electric vehicle (EV) is charged. AC chargers require several hours to fully charge an EV, which means the battery can be charged to 80% using DC fast chargers in approximately 30 minutes [5]. Reducing the charging time to such a minimal level makes DC fast charging most appropriate for long-distance trips and any circumstance that requires instant power recharging. But DC charging is not without some problems. The faster charging rates prove to be more stress on the battery also leading to increased heat production and thus, if not well regulated, faster battery degradation. However, AC charging will take longer to deliver its charge, and since it is less likely to cause any reactions within the battery, this type of charging is considered by many to be less lethal on battery life, yet it takes longer charges. The comparison between the time taken for charging using the DC and AC charger is an indication of the work done in regard to speed at the expense of battery heating [10].

The effects of temperature extend beyond the battery itself and also affect the performance of the charging equipment. For example, the efficiency of 50 kW chargers drops from 93% at 25°C to just 39% at -25°C, as Battery Management Systems (BMSs) regulate power output at lower temperatures to safeguard the battery [11]. This illustrates the limitations of current fast-changing technologies, especially in regions with extreme climates, where charging efficiency may be substantially reduced [12]. Some chargers are designed to operate at temperatures as low as -25°C while maintaining around 70% efficiency, although others may fail to function altogether at such low temperatures [13], [14].

Another important consideration for fast charging is battery design. For an EV to benefit from rapid charging without suffering from thermal or structural degradation, the battery must exhibit high energy density, robust power handling capabilities, long cycle life, effective thermal management, and high charging efficiency [15]. Although lithium-ion batteries remain the preferred technology due to their relatively high energy density and lightweight design, they face challenges when subjected to fast charging cycles, particularly concerning heat generation and aging [16]. To meet the demands of fast charging, manufacturers have focused on improving the energy density of these batteries. Commercially available batteries that can charge at 4C rates (within 15 minutes) maintain usable energy densities exceeding 150 Wh/kg [17]. Table 1 shows the comparison of battery specifications from various companies [17], [18]. However, despite advancements in battery technology, fast charging can still adversely affect long-term battery performance, particularly when temperature effects are considered.

Fast charging and energy density can significantly affect battery life, particularly when temperature is factored in. Early research suggests that higher temperatures might accelerate cell aging by speeding up the formation of the solid-electrolyte-interphase (SEI). While high temperatures can improve

Table 1: Comparison of battery specifications from various companies

Company	Material of anode/ cathode	Charging rate (Max.)	Energy density
CATL	Graphite/NMC (Nickel Manganese Cobalt Oxide)	4C	215 Wh/kg
Enevate	Si (Silicon)/NMC	9C	350 Wh/kg
Microvast	PC (Polycarbon)/LMO (Lithium Manganese Oxide)	4C	190 Wh/kg
Kokam	Graphite/NMC	4C	152 Wh/kg

fast charging but also speed up battery wear. To maximize battery performance and lifespan, it's essential to balance fast charging with good heat management [19]. According to Arrhenius law, they observed a shift in the ageing mechanism from SEI formation at T > 25°C to lithium plating at T < 25°C. According to Gao et al. [20], 3Ah graphite/LFP cells had the best cycle life at 25°C and a considerably reduced life at 10°C. According to Ecker et al. [21], the cycle life of a 53Ah graphite/NMC cell has reduced substantially from 4000 cycles at 20°C to 40 cycles at 0°C. Meanwhile, a 16Ah graphite/NMC cell loses 75% of its capacity after only 50 cycles at 5°C [22], [23]. These findings show that even at mild temperatures, lithium plating is a major danger that can have a significant impact on battery performance, thereby underscoring the need for advancements in both battery chemistry and fast charging technologies [23].

Despite challenges, ongoing advancements in battery chemistry and charging technology offer potential solutions to improve the efficiency and safety of fast-charging systems. Innovations in battery management systems, thermal control technologies, and new battery chemistries may help mitigate temperature fluctuations and extend battery lifespan, though further research is needed to fully resolve these issues, particularly in optimizing charging speeds while preserving battery longevity and overall performance. Although a substantial body of research exists, significant gaps remain concerning the impact of varying constant current (C) charging rates on battery performance.

While prior studies have predominantly examined the effects of high C-rates, limited research explores how moderate C-rates, such as 0.1C for standard chargers and 0.5C and 1.0C for fast chargers, influence charging duration, temperature stability, and battery health under real-world conditions. Therefore, the aim of this study is to address this gap by investigating these effects to provide critical insights into optimal charging conditions for enhancing EV battery performance and lifespan. A deeper understanding of the relationship between C-rate and battery health will support the development of more efficient, reliable, and durable charging strategies for electric vehicles, especially electric scooters, where fast charging is essential to user experience and operational efficiency.

2.0 Methodology

The experiment was conducted in two phases. In the first phase, three chargers with different charging rates 0.1C, 0.5C, and 1C were tested on a Lithium-ion 60V 20Ah battery, where 0.1C represented the standard charger and 0.5C and 1C represented fast chargers. Key parameters measured included the State of Charge (SOC), battery and charger temperatures, and power consumption, with the battery discharged to 52V after each test. In the second phase, the chargers were assembled inside a compartment designed to simulate a charging station, consisting of two fast chargers equipped with a protection device and a cut-off switch. Once assembled, the functionality of the chargers was validated, as illustrated in Figure 1, flowchart of the charging station. Initially, the user turned the programmable cut-off switch from OFF to ON, it powered the constant current charging board (10A) and heat sink, which charged the 60V battery via the CCCB output. The voltage sensor measured the battery voltage every minute, and when the battery reached 80% SOC, a signal triggered the programmable cut-off switch to break the circuit, stopping power flow to the charging board and heat sink, while the indicator light turned ON.

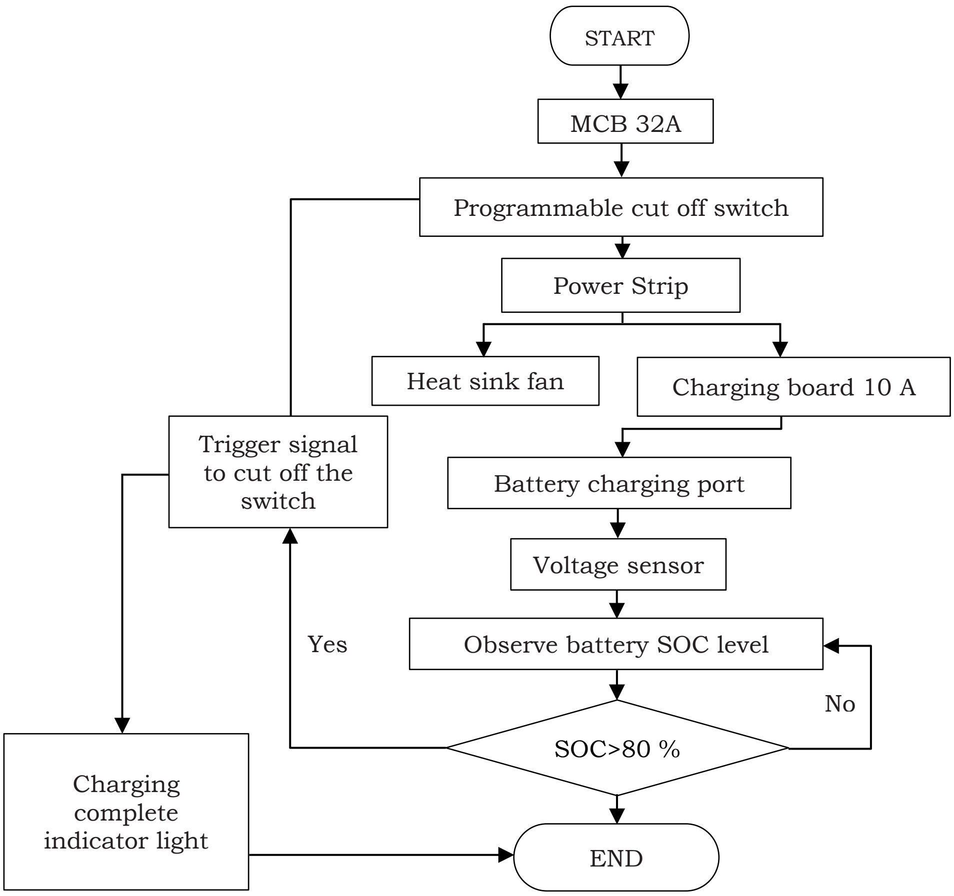

Figure 1: The work process flowchart of the charging station

The Lithium-ion battery in this research, with a 1200 Wh capacity, a maximum discharge rate of 20 Ah, and an operating voltage of 52 V - 67 V, is optimized for energy efficiency and versatility. For the charging modes, the study uses 0.1C for standard charging, while 0.5 C and 1.0 C are used for fast charging, with a cut-off voltage of 67 V. Table 2 shows the detail information of the battery specification for the Li-ion battery type. Meanwhile, the charger specifications for three types of charger type are presented in Table 3.

Table 2: Battery specification

Battery type	Lithium-Ion
Battery capacity	1200 Wh
Maximum discharge	20 Ah
Operating voltage	52 V-67 V

Table 3: Charger specifications

Charger type	Standard Charger	Fast Charger	Fast Charger
Constant current charger	Yes	Yes	Yes
Charger current	2A @ 0.1C	10 A @ 0.5C	20A @ 1.0 V
Cut off voltage	67V	67V	67V

Charging times and temperature measurements are closely linked in evaluating battery performance and safety. Fast charging can elevate battery temperature, and if not carefully managed, this can negatively impact performance and reduce battery lifespan. By monitoring temperature during the charging process, we can ensure that the battery stays within safe operating limits, thus improving its efficiency and longevity.

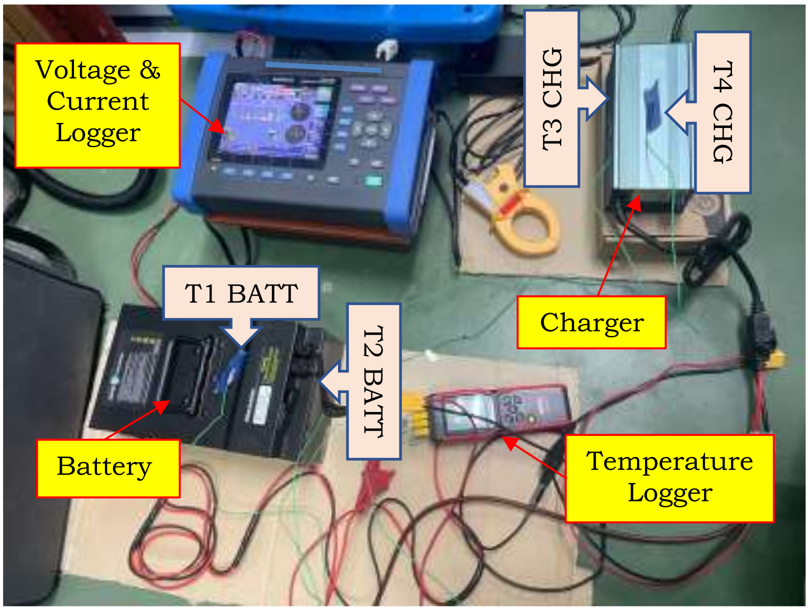

Figure 2: Experimental setup during battery charging phase

Figure 2 shows the experimental setup during battery charging phase for this project. Temperature was recorded using the temperature logger UNI-T UT325F ±(0.2%+0.5°C) device, which features four channels for connecting thermal sensors. Two temperature sensors were mounted on the battery body, while the other two were placed on the charger body. The state of charge (SOC) was measured using the Hioki PW3198 Data Logger (Voltage: ±0.1% of nominal voltage, Current: ±0.2%). Voltage was recorded every five minutes, and power consumption was measured using a conventional power meter at the power supply plug before it was connected to the charger.

3.0 Results and Discussion

The charging duration and power consumption for each charger varied significantly across the 0.1C, 0.5C, and 1C rates. At the 0.1C rate, the charger took the longest, reaching 10 hours and 40 minutes with a low power draw of 120W, resulting in moderate power consumption over a lengthy period. When using the 0.5C charger, the duration dropped about ~84% to 1 hour and 40 minutes with a higher power rating of 200W, reflecting increased efficiency. The 1C charger, operating at 750W, achieved the fastest charge time of just 1 hour or 90.6% reduction in time. This variation in charging speed and power usage demonstrates how higher current rates reduce charging time but consume power at a faster rate, making them more suitable for quick charging situations. The loss of battery capacity can be determined by reading the voltage after the charger is turned off for several minutes. For the 0.1C, 0.5C, and 1C chargers, the loss in capacity in terms of voltage ranges from 0.1V to 1.5V, or from 2Wh to 30Wh in terms of energy. This indicates that higher charging rates not only enhance time efficiency but also may increase the loss of battery capacity, which is an important factor for daily and long-term use. Figure 3 shows the behaviour of the SOC charger with 0.1C ,0.5C and 1C while charging between 52V to 67V.

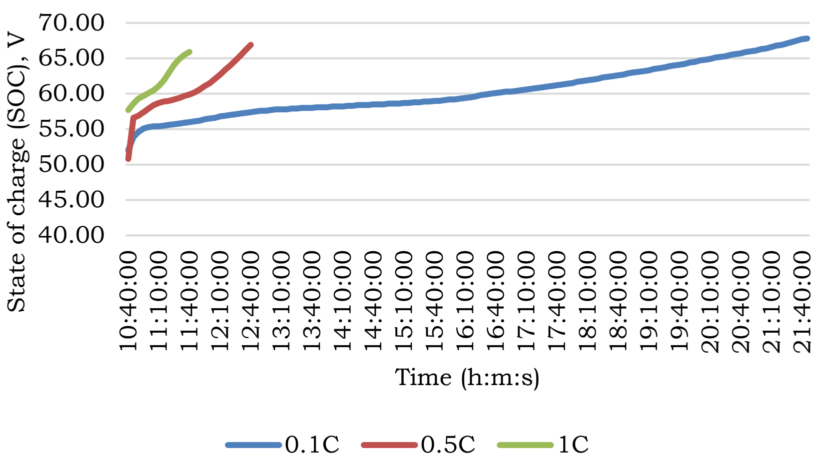

Figure 3: Battery voltage versus charging time

The temperature profiles of both the battery and the charger reflect differences associated with varying charging rates, as shown in Figure 4, which presents the temperature profile at a standard charging rate of 0.1C. The data indicate that the battery temperature remains stable within a range close to ambient room temperature (21°C to 25°C), suggesting minimal thermal impact when charged at a lower rate. In contrast, the charger demonstrates a marked temperature increase, beginning at 25°C and reaching up to 42°C during continuous charging. This increase is likely due to the absence of a cooling fan in the 0.1C charger, which leaves no active mechanism to dissipate heat effectively.

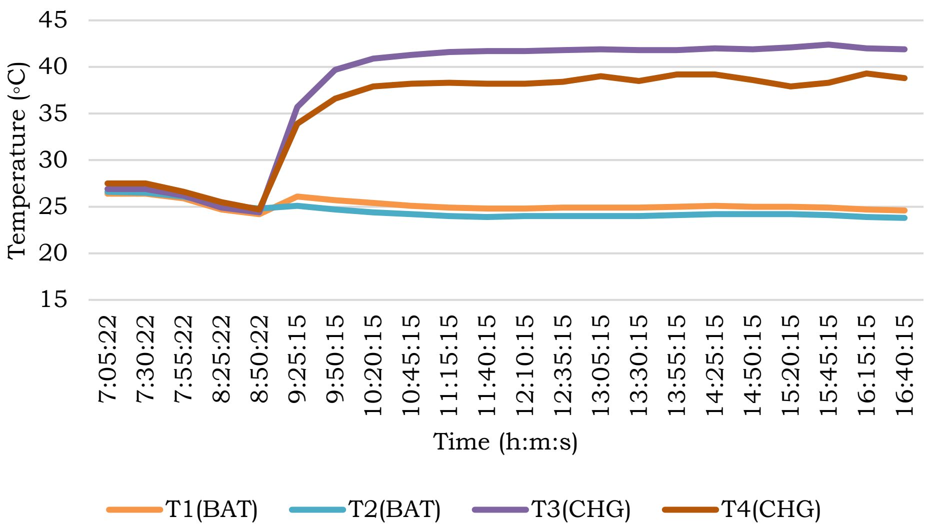

Figure 4: Temperature profile of the battery and charger during charging at 0.1C (T1 BAT, T2 BAT – Thermal sensor attached to the battery bodies), (T3 CHG, T4 CHG – Thermal sensor attached to the charger bodies)

Figure 5 presents the temperature profile when using the 0.5C fast charger. The battery temperature remains consistent with ambient room temperature, ranging from 25°C to 27°C, which indicates effective thermal management within the battery. In contrast, the temperature profile of the charger body shows that it remains below 24°C and maintains stability throughout the charging period. This stability can likely be attributed to the presence of a cooling fan, which effectively prevents excessive heat accumulation within the charger.

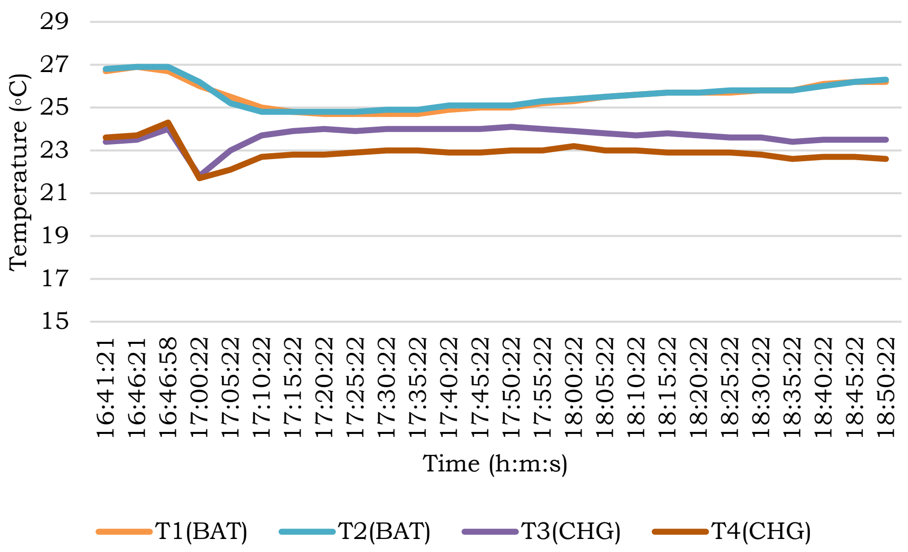

Figure 5: Temperature profile of the battery and charger during charging at 0.5C

Further, Figure 6 presents the temperature profile for the 1C fast charging rate, showing that the battery temperature remains within the range of 25°C to 26°C. This stability indicates that even at the maximum charging rate, the battery's thermal stability is not compromised. The temperature profile of the 1C charger body also shows that the temperature remains within the range of 23°C to 24°C throughout the charging process. The controlled temperature profile at the 1C rate highlights the importance of active cooling in ensuring safe fast charging without the risk of thermal damage to the charger.

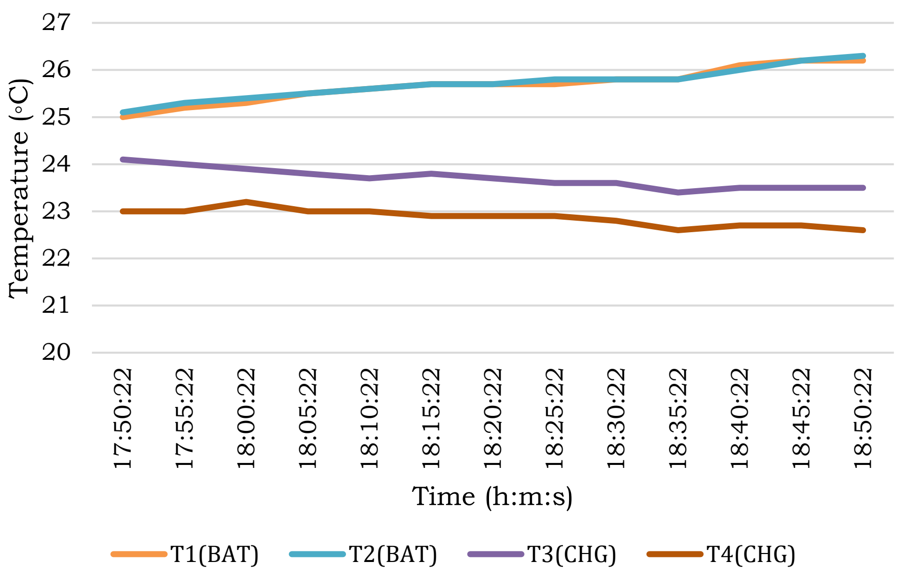

Figure 6: Temperature profile of the battery and charger during charging at 1.0C

The results from examining charging times and temperature measurements provide key insights into the battery's overall reliability and safety. Shorter charging times are desirable, but they must be balanced with effective temperature control to prevent overheating. By analysing these two aspects together, we can better understand how fast charging impacts battery health, helping to optimize both performance and durability for safe, long-term use. Figure 7 shows the charging station prototype that was successfully developed.

Figure 7: The charging station prototype

4.0 Conclusion

In conclusion, this study evaluates the performance of lithium-ion (Li-ion) batteries during the charging process using constant current chargers at 0.1C, 0.5C, and 1.0C rates. The findings reveal a significant reduction in charging time with higher charging rates, with the 0.5C charger reducing the duration by approximately 84%, and the 1.0C charger cutting the charging time by around 90% compared to the 0.1C charger. While faster charging enhances convenience, it may contribute to faster battery degradation, as higher rates could accelerate capacity loss over time. Temperature profiles reveal that chargers with cooling fans (0.5C and 1.0C rates) maintain lower battery temperatures, whereas the 0.1C charger, lacking a fan, results in a rapid rise in temperature. The study also confirms the effectiveness of the charging station's cut-off mechanism, which halts charging once the battery reaches 70% capacity, potentially extending battery life and preventing overcharging. These findings have important implications for optimising charging strategies in electric scooters, balancing charging speed with battery longevity to improve overall performance. From a commercial perspective, the insights could lead to the development of more efficient and reliable charging infrastructure, enhancing the attractiveness of electric scooters for consumers and manufacturers alike. By implementing controlled charging rates and advanced temperature monitoring, manufacturers can improve battery safety, efficiency, and lifespan, contributing to the growth of the electric vehicle market. Future research should focus on conducting long-term studies to assess the impact of different charging rates on battery life over multiple cycles and explore the integration of renewable energy sources into charging stations. Additionally, further investigation into the scalability of these technologies could support their commercialisation in other small electric vehicles, ultimately promoting safer, more sustainable battery solutions across various industries.

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Author Contributions

Mohd Hisham Mokhtar: Conceptualisation, Methodology, Data Curation; **Mohd Khairol Nizam Mohd Anuar**: Software, Writing-Original Draft Preparation; **Nazelira A Rahim**: Software, Writing-Reviewing and Editing; **Mohd Firdaus Mohd Ab Halim**: Conceptualisation, Methodology, Validation, Supervision.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest in the manuscript.

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