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Comparative Analysis of Lithium Ion and Sodium Ion Batteries for Electrical Vehicles Application

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Abstract: The widespread acceptance of EVs faces challenges because of exorbitant purchase costs. The modern market is ruled by lithium-ion batteries that represent its primary cost elements. This battery technology delivers exceptional energy density as well as established performance, but it comes with three major disadvantages. While this technology presents high costs along with limited resource availability and manufacturing process and disposal impacts on the environment. The sixth most common crusial element sodium provides battery manufacturers with an efficient and enduring raw material source that exists in large quantities on Earth. Sodium-ion batteries efficiently confront the major issues which affect lithium-ion batteries by decreasing their cost and eliminating material scarcity and temperature-related issues. The batteries address key lithium-ion battery problems by using sustainable materials and existing structures and presenting safer operations while being kind to the environment. The research demonstrates that sodium-ion batteries create a promising approach for sustainable electric vehicle advancement. The development of affordable sustainable electric mobility solutions shows promise to change how energy will be stored in the future.

Keywords: Sodium-ion batteries (SIB), Electric vehicles (EVs), Energy storage, Battery technology, Sustainability, Drive cycle, charge capacity.

I. INTRODUCTION

The world's commitment to sustainable energy solutions speeds up the need for advanced energy storage systems which specifically serve the electric vehicle (EV) industry. Nuclear storage systems known as SIBs represent an emerging energy storage option because sodium exists in abundant amounts while being inexpensive like lithium, yet it shares the same intercalation characteristics.

Sodium-ion batteries demonstrate excellent suitability as electric vehicle power cells through their eco-friendly nature combined with temperature stability and possible manufacturing cost benefits in mass production. The commercial availability of sodium-ion batteries depends on solving problems related to their reduced energy density alongside the instability and short cycling performance of electrode materials relative to Li-ion batteries. Research advances in sodium-ion battery performance have become more promising due to advancements in cathode materials and anode materials and electrolyte formulations and cell design.

The existence of lithium-ion batteries as market leaders mostly stems from their superior energy density plus extended cycle performance but worries about lithium resource scarcity coupled with pricing and insufficient worldwide availability of lithium deposits drives researchers toward developing alternative battery technologies. This paper evaluates the present advancement of sodium-ion batteries for electric vehicles through an examination of their crucial material developments as well as performance evaluations and forecasts for their widespread implementation within transportation systems.

II. LITERATURE REVIEW

The evolution of battery technologies for electric vehicles (EVs) has created widespread research in some of the major areas like thermal management, fault detection, charging strategies, state-of-charge (SOC) balancing, and predictive maintenance.

Liu et al. [1] carried out a thorough performance assessment of commercial graphene-based lithium-ion batteries using specific capacity, internal resistance, and discharge behaviour across temperatures. The results indicated that although graphene batteries marginally enhance energy density, they provide very little improvement in temperature-dependent discharge performance over traditional lithium-ion batteries.

Thermal runaway gas analysis fault detection has been researched by Chen et al. [2], who formulated a fault type identification method according to characteristic concentrations of gases like H_2 and CO. It allows for faster and more accurate detection of thermal runaway due to abuse in lithium-ion energy storage systems compared to conventional battery management systems.

As far as battery pack balancing, Li and Ruan [3] presented an active equalization technique based on flyback transformer topology utilizing SOC differences as the control variable. Simulation studies that they conducted exhibited better balancing performance under various charging, discharging, and idle scenarios, resolving inconsistencies that would naturally occur in large battery packs.

Thermal runaway is still a major issue, and Hao et al. [4] employed simulation methods to investigate heat generation and distribution in lithium-ion batteries. Their findings indicated that internal temperature fields are not uniform, with increased temperatures towards the core, and thus thermal control is essential for maintaining battery safety, particularly at high states of charge (SOC).

Lithium-ion battery remaining useful life (RUL) prediction is now of vital importance to battery management systems (BMS). Umayal et al. [5] investigated using machine learning-based methods, namely Random Forest models, for RUL prediction. Their findings suggested that data-driven methods could surpass conventional methods both in accuracy and prediction efficiency, facilitating proactive maintenance strategies in EV use to maximize battery performance in use, Vu Truong et al. [6] integrated simulation and experimentation to control lithium-ion battery charging and discharging processes. Their research highlighted the need to monitor SOC and State of Health (SOH) parameters closely, especially under fast-charging conditions, to avoid accelerated aging and capacity loss. Optimization of material structure has also been in the spotlight. Wan et al. [7] investigated the influence of electrode particle size and porosity on lithium-ion battery performance through a Newman-based COMSOL simulation. They found that decreasing particle size and increasing porosity improves lithium-ion diffusion and cell efficiency, providing useful insights for future battery design. In a comparative study, Kaloko et al. [8] compared the performance of lithium polymer (Li-Po) and lithium-ion battery packs under different load conditions. Their results pointed out that lithium polymer batteries were thermally more stable, while lithium-ion batteries provided slightly better energy delivery under heavy loads. Lastly, Shafiq and Egger [9] explored the influence of various charging methodologies on lithium-ion, lithium-polymer, and lithium-iron phosphate ($LiFePO_4$) batteries. Their experimental findings indicated that $LiFePO_4$ batteries have better charging effectiveness, especially at 1C levels, and highlighted the importance of well-matched battery technology with suitable charging protocols to provide maximum performance and lifecycle.

III.DRIVE CYCLE

Drive cycles serve as essential evaluation methods that measure vehicle fuel efficiency and emissions together with performance while ensuring uniform testing across technological frameworks of multiple vehicle models. Different drive cycle patterns exist specifically for urban driving scenarios and highway operations. Drive cycles used in practice feature Urban or City Cycles that emulate urban traffic conditions which involve numerous acceleration-deceleration sequences. The Federal Test Procedure 75 (FTP-75) represents a United States Environmental Protection Agency standard for urban driving emulation and the New European Driving Cycle served Europe both as an emissions and fuel consumption testing protocol for city driving patterns.

The data is a representative drive cycle where SOC decreases gradually due to energy usage, current changes with driving conditions, and voltage changes with current and load change. The trend is consistent with representative urban or mixed driving, where there is acceleration and regenerative braking.

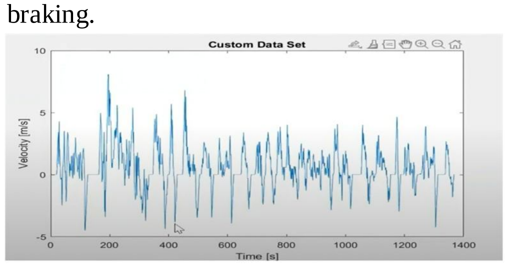

Fig 1 : FTP75 Drive Cycle Input Graph

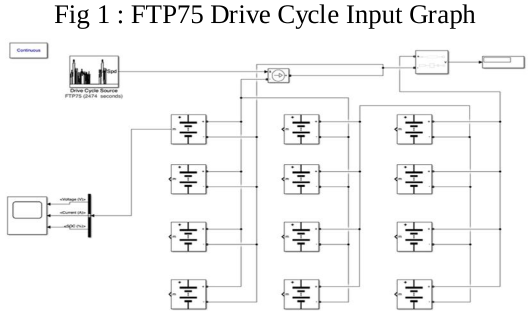

Fig 2 : Simulation for Drive Cycle

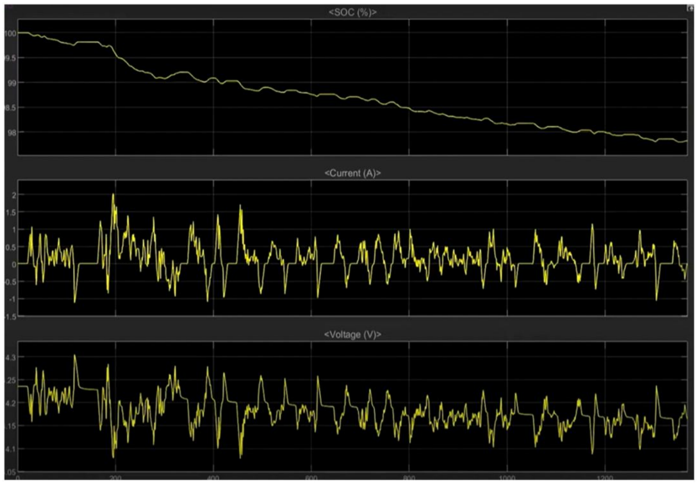

Fig 3 : Output Graph for Drive Cycle

IV. CHARGING ANALYSIS OF LI-ION AND NA-ION BATTERIES

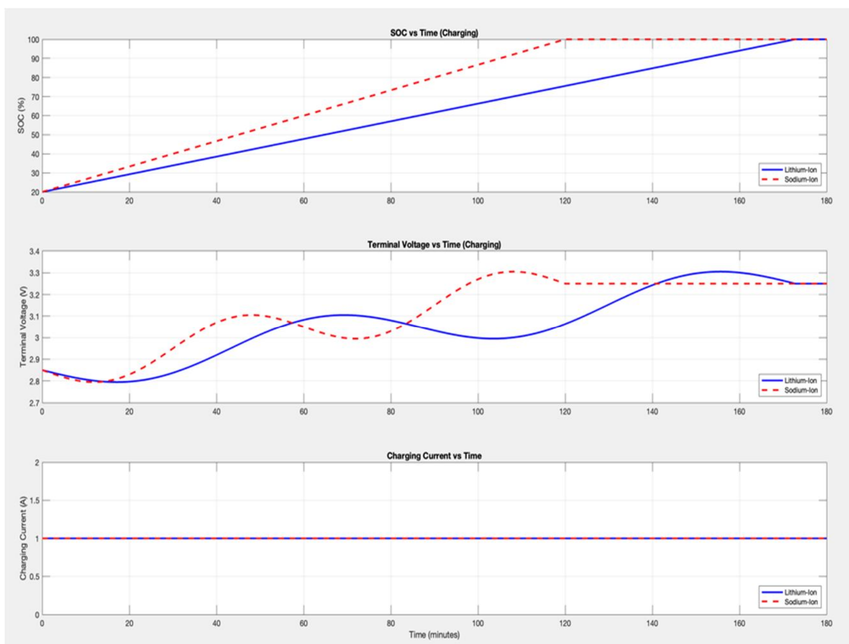

Fig 4 : Simulation Charging Analysis of Li-ion and Na-ion batteries

The charging behaviour of 36V, 50Ah Lithium-Ion and Sodium-Ion battery packs is shown in Fig. 4. The three graphs show SOC, Terminal Voltage, and Charging Current over time during constant current charging.

Plot 1 of Fig. 4 shows that the SOC for both batteries increases steadily from about 20% to 100%. The Sodium-Ion battery reached full charge in about 130 minutes. The Lithium-Ion battery took about 175 minutes. This means the Sodium-Ion battery charged faster under the same current.

Plot 2 of Fig. 4 shows that the Terminal Voltage for both batteries increased smoothly during charging. The Sodium-Ion battery always had a slightly higher voltage than the Lithium-Ion battery. Some small bumps were seen, likely because of changes inside the batteries.

Plot 3 of Fig. 4 shows that the Charging Current stayed close to 1A for both batteries. There were only small changes in current. This shows that the batteries were charged under a stable constant current.

V. DISCHARGING ANALYSIS OF LI-ION AND NA-ION BATTERIES

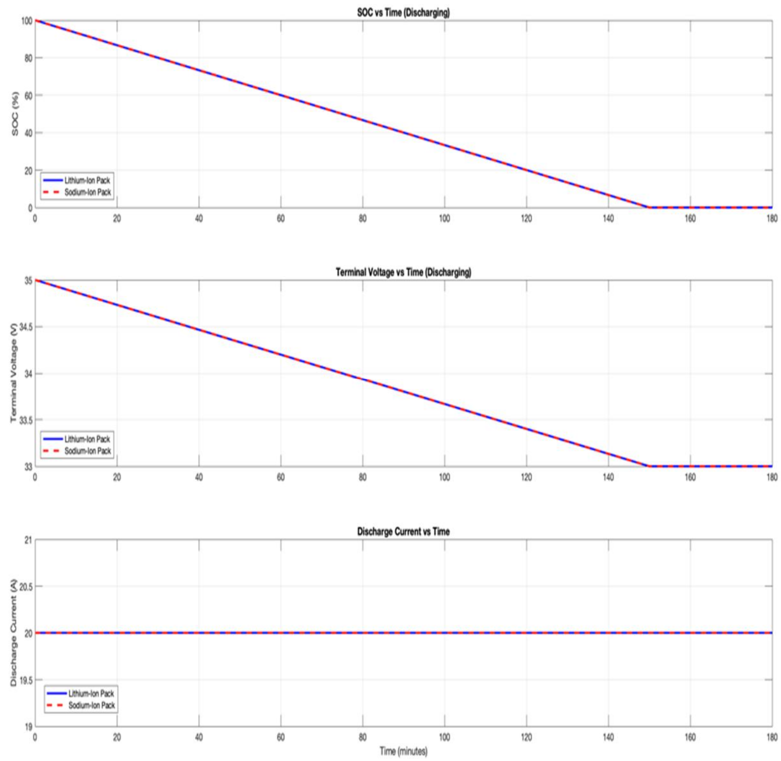

Fig 5: Simulation Discharging Analysis of Li-ion and Na-ion batteries

The nature of discharge for 36V, 50Ah Lithium-Ion and Sodium-Ion battery packs is analysed in fig 5. The following three graphs display the SOC, Terminal Voltage, and Discharge Current vs Time for constant current discharge test:

Plot 1 of Fig. 5 illustrates the State of Charge (SOC) vs. Time for Lithium-Ion and Sodium-Ion batteries to show that both battery packs start at 100% SOC and both drop to 0% within approximately 155 minutes.

Plot 2 of Fig. 5 illustrates the difference of Terminal Voltage vs. Time of Lithium-Ion and Sodium-Ion batteries, with both beginning around 35V and steadily declining to around 33V over about 155 minutes.

Plot 3 of Fig 5 shows the discharge Current comparison with respect to time of Lithium-Ion and Sodium-Ion battery packs, illustrating both battery packs exhibiting a closely stable discharge current around 20A for all along the complete time duration of nearly 180 minutes.

VI. COMPARATIVE OVERVIEW: SODIUM-ION BATTERIES VS LITHIUM-ION BATTERIES

Comparison of sodium-ion and lithium-ion batteries offers some interesting trends in charging and discharging characteristics. Lithium-ion battery charging characteristic is linear and uniform increase in state of charge (SOC) that reaches full capacity within a particular time interval of approximately 175 minutes. For sodium-ion batteries, there is rapid recharge, full-charging time which varies about 130 minutes. But when they are discharged, though both follow a relatively linear decline in SOC, lithium-ion batteries retain their charge somewhat longer, providing additional discharge duration. Voltage performance highlights the differences even more: lithium-ion batteries provide more stable and consistent voltage in charging and discharge cycles, while sodium-ion batteries drop into higher initial voltages at a more rapid rate but stabilize sooner. In addition, discharging and charging currents for both batteries are very similar, but lithium-ion batteries are more capable of adjusting to somewhat prolonged run times. Lithium-ion batteries are better suited from a performance point of view when there are high loads demanded, and long-term stability and longevity are essential. At the same time, sodium-ion batteries are better suited when faster charging and lower expenses are more applicable. Therefore, the decision between the two solutions relies heavily on the specific application requirements.

Parameter	Lithium-Ion Battery Pack	Sodium-Ion Battery Pack
SOC vs Time (Charging)	Gradual increase to 100% SOC over ~175 minutes	Faster SOC rise, reaching 100% in ~130 minutes
SOC vs Time (Discharging)	Linear decrease, maintaining charge slightly better	Linear decrease, slightly faster SOC drop
Terminal Voltage (Charging)	Gradual voltage increase with better stability	Faster voltage rise but earlier stabilization
Terminal Voltage (Discharging)	Slightly higher and more stable terminal voltage throughout	Slightly lower terminal voltage maintained
Current vs Time (Charging)	Constant charging current maintained throughout	Constant charging current maintained throughout
Current vs Time (Discharging)	Constant discharging current maintained throughout	Constant discharging current maintained throughout
Overall Performance	Superior voltage stability and longer discharge duration	Faster charging, cost-effective alternative

Table 1 : Comparison between Lithium-Ion and Sodium-Ion Battery Packs During Charging and Discharging

VII. CONCLUSIONS

As seen from the above graphs, it is clear that sodium-ion batteries are superior to lithium-ion batteries in various ways. Firstly, when being charged, the sodium-ion battery reaches a full charge much faster compared to the lithium-ion battery. While it takes almost 180 minutes for the lithium-ion battery to reach full charge, the sodium-ion battery achieves that in about 120 minutes. This means that the sodium-ion batteries can be charged quicker, something that is quite useful when one needs speed. Additionally, while looking at voltage during charging, the sodium-ion battery shows less fluctuation with a more smooth and consistent growth, while lithium-ion battery's voltage fluctuates more. Level voltage is desirable because it will put less strain on the battery and make it longer lasting. Even though both batteries are charged with the same current, the sodium-ion battery also makes better use of the current. When discharging, both batteries are almost the same, with the same voltage and state of charge drops over time. This means that sodium-ion batteries can supply energy as much as lithium-ion batteries. Overall, sodium-ion batteries charge faster but also deliver acceptable stability and performance on use, and thus they are a solid and good alternative to lithium-ion batteries.

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