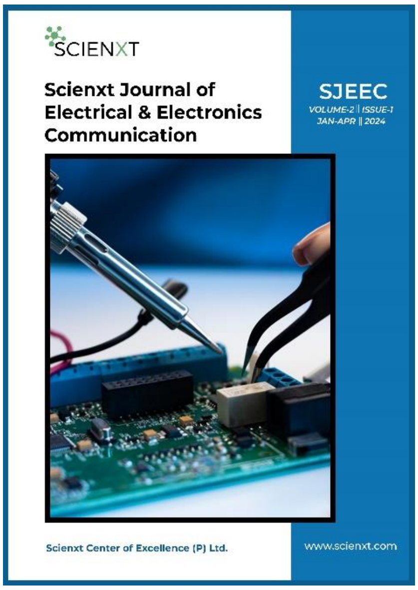

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A comparative study of lithium-ion and sodium-ion batteries for hybrid electric vehicle

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Abstract:

Lithium-ion batteries (LIBs) and sodium-ion battery- ies (SIBs) are two promising candidates for hybrid electric vehi- cles (HEVs), which require high-performance and low-cost energy storage systems. There are trade-offs between the advantages and disadvantages of these two types of batteries, such as energy density, power density, cost, safety, and environmental impact. In this paper, we review the current state-of-the-art of LIBs and SIBs for HEVs and compare their performance, challenges, and opportunities. We also discuss the potential of hybrid battery packs that combine LIBs and SIBs to achieve synergistic benefits and overcome their respective limitations. SIBs are not yet ready to replace LIBs in HEVs, but they may complement them in some applications, especially in moderate-range and low-temperature scenarios. It recommends further research and innovation to improve the electrochemical properties, materials, and engineering of SIBs, as well as to optimize the design and management of hybrid battery packs.

Keywords:

Hybrid Electric Vehicles, Sodium-ion Batteries, Lithium-ion Batteries

1. Introduction:

The development and optimization of energy storage sys- tems are critical steps in the search for environmentally friendly transportation options. Because of their high energy density and dependable performance, lithium-ion batteries have dominated the market for electric vehicles among other options. But the search for more affordable and eco-friendly substitutes has generated much interest in sodium-ion batteries as possible competitors for hybrid electric vehicles (HEVs). The unprecedented growth of the electric vehicle market, coupled with the ever-escalating demand for energy storage solutions, necessitates a comprehensive comparative analysis between lithium-ion and sodium-ion batteries. While lithium- ion batteries have undoubtedly revolutionized the electric vehicle industry, recent advancements in sodium-ion battery technology have unveiled promising prospects, challenging the hegemony of their lithium-based counterparts. Sodium-ion batteries have emerged as promising alternatives to lithium-ion batteries, primarily due to the abundance and lower cost of sodium resources. Recent advancements in materials science and electrochemistry have significantly enhanced the perfor- mance and stability of sodium-ion battery technology. Novel electrode materials, such as hard carbon, sodium transition metal oxides, and sodium layered oxides, have been explored to improve energy density and cycling stability.

Policymakers and industry participants looking to create a more robust and sustainable supply chain for batteries for electric vehicles have also taken notice of the scalability of sodium-ion battery production. The wider ionic radius of sodium ions as opposed to lithium ions contributes to the intrinsic safety advantages of sodium-ion batteries, which increase their attractiveness for widespread use in electrified transportation systems.The ongoing research efforts to fully realize the potential of sodium-ion battery technology are however hampered by issues like lower energy density when compared to their lithium-ion counterparts, limited cycle life, and the requirement for additional optimization in electrode materials and electrolytes. Notwithstanding these obstacles, sodium-ion battery research is seeing a promising trajectory toward commercial viability in hybrid electric vehicles thanks to the quick speed of innovation and growing investments in the field. The goal of this comparative study is to provide insight into the competitiveness and potential of sodium-ion batteries versus lithium-ion batteries in the electrification of transportation, given the ever-changing landscape of energy storage technologies.

2. Comparison of batteries:

2.1. Lithium-ion batteries:

Lithium-ion batteries represent a significant innovation in HEV technology, offering higher energy density, longer cycle life, and lighter weight compared to traditional lead-acid and NiMH batteries. Their ability to store more energy in a smaller and lighter package has enabled the development of more efficient and compact hybrid vehicles. While known for their reliability when properly managed with sophisticated Battery Management Systems (BMS), challenges such as thermal runaway and capacity fade over time are addressed through improved battery chemistries, thermal management systems, and robust safety features. In addition to high energy density and reliability, lithium-ion batteries offer fast charging capabilities and have become increasingly affordable due to advancements in manufacturing processes. Their versatility makes them suitable for a wide range of hybrid and electric vehicles, from mild hybrids to plug-in hybrids and fully electric vehicles.

2.2. Sodium-ion batteries:

Sodium-ion batteries (SIBs) have emerged as compelling alternatives to their lithium-ion counterparts, primarily due to several inherent advantages. One notable advantage is the abundance and widespread distribution of sodium resources, making SIBs potentially more cost-effective and environmen- tally sustainable. Additionally, SIBs exhibit inherently safer characteristics compared to lithium-ion batteries, attributed to the larger ionic radius of sodium ions, which reduces the likelihood of dendrite formation and thermal runaway events. The scalability of sodium resources further enhances the potential for large-scale deployment of SIBs, offering a resilient alternative for electrified transportation and stationary energy storage applications. Moreover, recent advancements in materials science and electrode design have led to significant improvements in the performance and stability of SIBs, paving the way for their commercial viability in the evolving land- scape of energy storage technologies.

3. Current scenario:

Lithium-ion batteries (LIBs) have established themselves as the predominant energy storage solution in hybrid electric vehicles (HEVs), owing to their high energy density, cycling stability, and widespread availability. In the current market, LIBs continue to dominate due to their well-established man- ufacturing infrastructure, extensive research and development, and proven track record in various applications, including HEVs. The availability of lithium resources, although finite, remains sufficient to meet the current demand for LIBs, with ongoing efforts to improve extraction techniques and explore alternative sources. LIBs boast relatively high energy densities compared to other battery chemistries, providing HEVs with longer driving ranges and improved overall performance. This high energy density allows HEVs to operate efficiently while minimizing the size and weight of battery packs, thereby enhancing vehicle efficiency and reducing emissions. Addi- tionally, LIBs exhibit excellent cycling stability, enabling them to withstand thousands of charge-discharge cycles without significant degradation in performance. This cycling stability is essential for HEVs, where frequent charging and discharging occur during stop-and-go driving conditions and regenerative braking. Despite their advantages, ongoing research and de- velopment efforts are focused on further enhancing the energy density, cycling stability, and cost-effectiveness of LIBs to meet the evolving needs of HEVs and the broader electric ve- hicle market. Strategies such as the development of advanced electrode materials, optimization of electrolyte compositions, and improvements in battery manufacturing processes aim to push the boundaries of LIB performance and drive continued innovation in the field of electric transportation.

Sodium-ion batteries (SIBs) are emerging as promising alternatives to lithium-ion batteries (LIBs) in the context of hybrid electric vehicles (HEVs), offering several advantages in terms of energy density, cycling stability, and resource availability. Unlike lithium, sodium resources are more abun- dant and widely distributed, potentially reducing concerns regarding resource scarcity and geopolitical dependencies. This abundance translates into potentially lower production costs and increased accessibility for large-scale deployment in HEVs and other applications. While SIBs typically exhibit lower energy densities compared to LIBs, recent advancements in electrode materials and electrolyte formulations have shown promising improvements, narrowing the gap between the two chemistries. Moreover, SIBs demonstrate notable cycling sta- bility, capable of enduring numerous charge-discharge cycles without significant degradation. This cycling stability is crucial for HEVs, where durability and reliability are paramount, especially in demanding driving conditions.The larger ionic radius of sodium ions compared to lithium ions contributes to the enhanced safety profile of SIBs, reducing the risk of dendrite formation and thermal runaway events. This inherent safety advantage is particularly advantageous in HEVs, where stringent safety standards must be met to ensure driver and passenger safety. In terms of availability, sodium resources are more widely distributed geographically compared to lithium, potentially reducing supply chain vulnerabilities and increas- ing resilience. Efforts to improve SIB technology continue, with ongoing research focusing on developing novel electrode materials, optimizing electrolyte formulations, and enhancing manufacturing processes to further enhance performance, en- ergy density, and cost-effectiveness.

Overall, SIBs hold significant promise as viable alternatives to LIBs in HEVs, offering advantages in terms of resource availability, safety, and cycling stability. Continued research and development efforts are essential to unlock the full poten- tial of SIBs and accelerate their adoption in the electrification of transportation.

4. Simulation model:

A sodium ion battery's construction involves meticulous selection and arrangement of its key components to optimize performance. Within its electrodes, the negative electrode boasts a 64-µm thick layer of hard carbon, providing a sturdy foundation for ion transfer and storage. On the flip side, the positive electrode comprises Na3V2 (PO4)2F3 (NVPF), with a slightly thicker layer of 68-µm, ensuring efficient sodium ion insertion and extraction. The electrolyte solution, a crucial mediator, consists of 1M NaPF6 dissolved in EC0.5:PC0.5 (w/w), facilitating ion mobility and maintaining electrochem- ical stability. Additionally, user-defined interpolation polyno- mials fine-tune kinetic rate constants, diffusion coefficients, electrolyte conductivity, and equilibrium potentials, optimiz- ing the battery's overall performance and longevity. Through meticulous construction and precise parameterization, sodium- ion batteries emerge as promising contenders in the realm of energy storage, offering a potent combination of efficiency and reliability for diverse applications. Na+ is used in the SIB chemistry as the redox species in the electrode reactions and for electrolyte charge transport rather than Li+. Na+ has the following advantages over Li+: more plentiful; and possibly less of an environmental impact. The chemistry of SIB and LIB are very similar; the equations for charge and mass transport, electrode kinetics, and electrode particle intercalation are frequently the same.

In exploring various discharge rates for sodium-ion battery- ies, a Parametric Sweep analysis delves into the effects of different current densities, ranging from 1 to 12 A/M+. This systematic approach allows researchers too comprehensively as- sess battery performance under diverse operational conditions. To ensure the integrity of the simulations, a Stop Condition node is strategically integrated into the Time-Dependent Solver node, halting the simulation once the cell voltage descends below the critical threshold of 2 V. By incorporating this stop mechanism, the analysis not only provides insights into the battery's behavior at different discharge rates but also safe- guards against potential over-discharge scenarios, enhancing the accuracy and reliability of the findings.

5. Research gaps and opportunities:

In energy storage applications, sodium-ion batteries (SIBs) hold promise as a replacement for lithium-ion batteries (LIBs). This is particularly true for hybrid electric vehicles (HEVs), which have specific needs such as high power density, ex- tended cycle life, and affordability. But when it comes to materials, design, and performance for HEVs, SIBs have many opportunities as well as challenges. These two lengthy paragraphs provide a summary of some of the opportunities and research gaps in the field of SIBs for HEVs.Utilizing the benefits of sodium metal anodes, which have a high theoretical capacity (1166 mAh g+), low potential (-2.71 V vs. SHE), and widespread availability, is one of the main opportunities for SIBs for HEVs. But sodium metal anodes also present several difficulties, including poor interfacial stability, dendritic formation, and corrosion, all of which can result in safety risks and reduced performance. As a result, several methods have been put forth by researchers to enhance sodium metal anodes, including the use of solid-state elec- trolytes, synthetic SEI layers, protective coatings, and three- dimensional porous structures. Furthermore, it has recently been reported that novel sodium metal anodes, like sodium- carbon composites, sodium alloys, and sodium intermetallics, have improved electrochemical properties and stability for SIBs. These anodes present fresh opportunities for creating safe, high-capacity. The development of high-voltage and high-power cathode materials, which can raise SIBs' energy and power densities, presents another chance for SIBs for HEVs. Unfortunately, the majority of the currently available cathode materials for SIBs, including Prussian blue analogues, polyanionic compounds, and layered oxides, have low rate capabilities, poor cycling stability, and low operating voltages (below 4 V vs. Na/Na+), which restricts their use in hybrid electric vehicles. To achieve higher operating voltages (above 4 V vs. Na/Na+), higher power capabilities, and better cycling stability, researchers have looked into a variety of cathode ma- terials for SIBs, including fluorinated oxides, niobium-based compounds, and organic materials. Additionally, because they combine the benefits of both oxide and sulfide cathodes—such as high capacity, high voltage, and high conductivity—hybrid cathode materials, like oxide-sulfide composites, have been investigated for SIBs. These cathodes present new possibilities for creating high-efficiency and reasonably priced SIBs for HEVs.

6. Conclusion:

Sodium ion batteries (SIBs) and lithium ion batteries (LIBs) are two of the most promising energy storage technologies for hybrid electric vehicles (HEVs), which require high power density, long cycle life, and low cost. However, in terms of materials, design, and performance, LIBs and SIBs encounter several opportunities as well as challenges. This review paper has compared and contrasted Anode, cathode, and electrolyte component characteristics, performance, and challenges of LIBs and SIBs. SIBs are primarily advantageous because of their low reactivity and abundance of sodium, which contribute to their long cycle life, high safety, and low cost. Because of the small size and high potential of lithium, LIBs have three main advantages: high efficiency, high power density, and high energy density. The low energy density, low power density, and poor stability of SIBs, as well as the high cost, high risk, and restricted availability of LIBs, are some of the disadvantages of both SIBs and LIBs. The future scope of SIBs and LIBs for HEVs lies in the development of novel and improved materials, structures, and interfaces that can overcome the current limitations and enhance the performance of both battery types. Utilizing the benefits of sodium metal anodes, creating high-voltage and high-power cathode ma- terials, refining electrolyte formulations and interfaces, and investigating solid-state and hybrid electrolytes are a few of the exciting research avenues. Moreover, the environmental and social impacts of SIBs and LIBs should also be considered, such as resource scarcity, recycling, and disposal issues. SIBs and LIBs have the potential to be instrumental in facilitating the shift of HEVs towards a clean-energy, sustainable future by tackling these opportunities and challenges.

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