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Research Paper

Beyond Lithium: Sodium-Ion Batteries as a Low-Cost Alternative for Electric Vehicles

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Abstract
The swift expansion of the electric vehicle (EV) industry has intensified the quest for advanced battery technologies capable of outperforming conventional lithium-ion systems. Among the emerging alternatives, sodium-ion batteries (SIBs) have garnered increasing recognition as a cost-effective and environmentally sustainable energy storage solution. This growing interest is driven by the abundance of sodium resources and notable strides in improving electrochemical performance. This study comprehensively reviews the progress of sodium-ion battery technology, delving into its underlying principles, advancements in electrode materials, and comparative characteristics lithium-ion batteries. Furthermore, it examines the impact of global economic factors—such as geopolitical instabilities and escalating costs of raw materials—on battery innovation. Lastly, it suggests strategies to incorporate sodium-ion battery developments into automotive engineering education at the Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology.

Keywords: *sodium-ion batteries, electric vehicles, energy storage, battery materials, sustainable transportation.*

I. Introduction

The global transition toward electrified transportation has magnified the need for cutting-edge battery systems with high energy density, extended operational lifespan, and reduced manufacturing costs. Over the past three decades, lithium-ion batteries have dominated the EV market due to their superior performance metrics and established production infrastructure. However, mounting concerns over finite lithium resources, surging raw material costs, and fragile supply chains have sparked interest in alternative battery chemistries. Particularly prominent among these alternatives are sodium-ion batteries, which have emerged as viable candidates for delivering affordable and sustainable solutions to current energy storage challenges. Lithium reserves are geographically concentrated in specific regions such as South America, Australia, and China, creating significant supply chain vulnerabilities amidst growing global demand for EVs. The resultant rise in lithium prices—exacerbated by geopolitical conflicts around critical raw materials—has underscored the urgency of transitioning toward energy storage systems reliant on more widely available resources. In stark contrast to lithium, sodium is abundant on Earth and readily derived from sources such as seawater and extensive mineral deposits. This prevalence mitigates resource scarcity concerns and provides a considerable economic advantage for sodium-ion battery technologies. Sodium-ion batteries function on electrochemical principles similar to those governing lithium-ion systems. Both involve reversible ion intercalation between an anode and cathode via an electrolyte. However, differences in ion size and mass significantly influence diffusion kinetics and electrode design, presenting unique engineering challenges for sodium-based technology. Despite these obstacles, recent advances in materials science have catalyzed substantial improvements in sodium-ion battery efficiency. Notable innovations include the development of high-performance cathode materials such as layered transition-metal oxides and Prussian blue analogues, alongside optimized hard carbon anodes tailored for accommodating sodium ions. Recent industry prototypes of sodium-ion batteries have demonstrated considerable potential, achieving energy densities ranging from 140–160 Wh/kg. Although these figures fall short when compared to high-performance lithium-ion systems, they remain adequate for certain EV applications and stationary energy storage solutions. Moreover, sodium-ion batteries boast superior thermal stability, with reliable operation across a wide temperature spectrum—from -40°C to 70°C—which is advantageous in extreme environments where lithium-ion systems might underperform. A major competitive edge of sodium-ion batteries lies in their cost-efficiency. The relative abundance and affordability of sodium significantly reduce the raw material expenses associated with battery production compared to lithium-based systems. These economic benefits are likely to gain prominence as the global adoption of EVs accelerates, intensifying demand for accessible energy storage solutions. Despite these promising attributes, sodium-ion batteries face several intrinsic limitations that hinder their competitiveness against lithium-ion systems in high-performance EV applications. Key challenges include their comparatively lower energy density, limitations related to electrode stability, and shorter cycle life. Addressing these constraints will require substantial innovation to enhance performance parameters while resolving scalability issues that affect mass production and integration into current EV architectures. Additionally, the trajectory of battery technology development will be significantly influenced by broader economic and geopolitical dynamics. These external forces play a pivotal role in determining how alternative energy storage solutions evolve to address the demands of an increasingly electrified global landscape.

By 2026, rising fuel prices, geopolitical conflicts, and supply chain disruptions may significantly influence the availability and cost of battery materials. These factors could accelerate the adoption of alternative battery chemistries such as sodium-ion systems, which rely on more abundant and geographically diversified resources.

From an educational perspective, the rapid development of alternative battery technologies requires universities to continuously update their engineering curricula. At the Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, integrating emerging knowledge on sodium-ion batteries into courses related to electric vehicles, energy storage systems, and automotive electrification can enhance students' understanding of future transportation technologies. Such integration will help prepare future engineers to address the technological and economic challenges associated with sustainable mobility.

II. Contents

2.1 Working Principles of Sodium-Ion Batteries

Sodium-ion batteries, akin to their lithium-ion counterparts, harness electrochemical processes to enable energy storage and conversion. Central to their operation is the movement of sodium ions between the cathode and anode via an electrolyte during charge and discharge cycles, while electrons flow through an external circuit to produce electrical energy. This mechanism, known as reversible intercalation, represents the cornerstone of their efficiency in energy storage and retrieval. However, the larger ionic radius of sodium ions compared to lithium ions (1.02 Å versus 0.76 Å) introduces several design challenges. This increased size affects the transport properties of sodium ions within electrode materials and often induces structural strain in host lattices during repeated cycling. Such strain can compromise the structural integrity of the materials, leading to diminished battery capacity over time. Consequently, considerable research efforts are directed toward engineering electrode materials with enhanced capacity to accommodate sodium ions while ensuring stability during prolonged usage. A critical determinant of long-term performance in sodium-ion batteries is the formation and stabilization of the solid electrolyte interphase (SEI) on the anode surface. The SEI layer is pivotal as it prevents ongoing electrolyte decomposition while allowing efficient sodium-ion transport. Optimizing both the formation and durability of this layer remains an essential focus for researchers committed to improving the lifecycle and efficiency of sodium-ion batteries. Parallel advancements in electrolyte chemistry have further enhanced sodium-ion battery performance. Progress in electrolyte formulations has achieved improved ionic conductivity and augmented electrochemical stability under operational conditions, thereby narrowing the performance gap relative to lithium-ion batteries.

2.2 Cathode Materials for Sodium-Ion Batteries

The choice of cathode material plays a decisive role in optimizing energy density, cycle life, and overall functionality in sodium-ion batteries. Due to sodium's larger ionic radius, cathode materials must provide sufficient structural flexibility to enable seamless ion diffusion and reversible intercalation. Current research emphasizes three principal classes of cathode materials that show significant promise for sodium-ion battery applications: layered transition-metal oxides, Prussian blue analogues (PBAs), and polyanionic compounds. Layered transition-metal oxides are among the most extensively studied cathode materials due to their structural affinity with those used in lithium-ion batteries. These materials are generally represented by the formula $NaMO_2$, where "M" refers to transition metals such as manganese, nickel, cobalt, or iron. The layered architecture of these compounds supports the reversible intercalation of sodium ions within interstitial spaces during charge-discharge cycles. These materials exhibit theoretical capacities of 150–200 mAh/g, comparable to certain lithium-ion cathodes. Nevertheless, repeated cycling may lead to lattice distortions and structural degradation due to the larger size of sodium ions. Consequently, strategies such as multi-element doping and modifications to the crystal structure are actively being explored to enhance both long-term stability and electrochemical performance. Prussian blue analogues represent another promising category of cathode materials owing to their distinct open-framework architecture. Composed of metal-cyanide structural frameworks with interconnected three-dimensional channels, these materials facilitate efficient sodium-ion transport while minimizing structural stress during cycling. This results in high rate capabilities and long cycle lives due to their inherent crystalline stability. Additionally, their simple and cost-effective synthesis makes them economically appealing for large-scale manufacturing. Indeed, some commercial prototypes of sodium-ion batteries already utilize PBAs as cathodes due to their balanced performance, scalability, and affordability. An additional class of cathode materials gaining attention is polyanionic compounds, which include sodium phosphates and sodium sulfates. These materials are characterized by robust thermal and mechanical stability thanks to the strong covalent bonds within their crystal matrices. While polyanionic compounds generally exhibit lower energy densities than layered transition-metal oxides, their superior thermal resilience and high safety profile make them particularly suitable for applications requiring enhanced reliability and extended operational longevity.

Recent studies emphasize that optimizing cathode materials remains one of the key research priorities for sodium-ion battery development. Advances in nanostructuring techniques, surface modification, and compositional tuning have demonstrated significant improvements in capacity retention and rate performance. As global research efforts continue to expand, it is expected that new cathode materials with enhanced electrochemical properties will further improve the competitiveness of sodium-ion battery technology.

2.3 Anode Materials for Sodium-Ion Batteries

The advancement of sodium-ion battery technology hinges significantly on the development of appropriate anode materials. Unlike lithium-ion batteries, where graphite is the predominant anode material, graphite performs poorly in sodium-ion systems due to the larger ionic radius of sodium ions, which impedes their efficient intercalation into graphite layers. Consequently, researchers have pursued alternative materials capable of effectively accommodating sodium ions while maintaining structural integrity. Among these alternatives, hard carbon has emerged as the most widely adopted anode material for sodium-ion batteries. Hard carbon comprises disordered carbon structures with nanopores that enable sodium ion storage through both intercalation and adsorption mechanisms. This porous arrangement offers additional sites for sodium ion storage, delivering relatively high reversible capacities of 250–350 mAh/g. Furthermore, hard carbon can be derived from sustainable sources such as biomass or industrial carbon precursors, adding to its cost-effectiveness. Despite its advantages, hard carbon anodes face several challenges. A key issue is the considerable irreversible capacity loss during the initial charge-discharge cycle, mainly caused by the formation of the solid electrolyte interphase (SEI) layer. This phenomenon negatively impacts the overall energy efficiency of the battery. Researchers have worked to mitigate this through strategies such as optimizing the electrolyte composition and employing surface treatments aimed at stabilizing the SEI layer. Beyond hard carbon, other anode materials like metal oxides, alloys, and phosphides have been explored for their potential in sodium-ion systems. Elements such as tin, antimony, and phosphorus are capable of storing sodium ions through alloying reactions that offer very high theoretical capacities. However, these materials often face challenges with significant volume expansion during charge-discharge cycles, sometimes exceeding 200%. Such expansion can result in mechanical degradation and a loss of capacity over time. To counter these obstacles, research has increasingly focused on composite materials that incorporate carbon matrices into high-capacity alloy materials. These hybrid structures help cushion volume changes and enhance structural stability during operation. Advances in nanotechnology and materials engineering have further facilitated the design of nanostructured anodes with improved cycling performance and rate capabilities. In summary, the creation of anode materials that combine both stability and high capacity remains a critical objective in sodium-ion battery research. Continued progress in material innovation and surface modification is essential for enhancing battery performance and supporting their future use in electric vehicle applications.

2.4 Comparison Between Lithium-Ion and Sodium-Ion Batteries

Analyzing lithium-ion and sodium-ion battery technologies reveals important distinctions in their strengths and weaknesses, especially for use in electric vehicles (EVs). Lithium-ion batteries currently dominate the EV market due to their exceptional energy density and established manufacturing infrastructure. Advanced versions can achieve energy densities surpassing 250 Wh/kg, facilitating long driving ranges for EVs. Sodium-ion batteries, by contrast, tend to have lower energy densities, typically between 120 and 160 Wh/kg. This disparity primarily arises from sodium's higher atomic weight and larger ionic radius compared to lithium. As a result, sodium-ion batteries are not yet well-suited for high-performance or long-range EVs. However, they offer adequate performance for applications such as short-distance transportation, urban mobility solutions, and stationary energy storage systems. From an economic standpoint, sodium-ion batteries bring significant benefits. Sodium ranks among the most abundant elements on Earth, and it can be sourced from common and accessible materials such as seawater and sodium salts. Conversely, lithium resources are geographically concentrated and vulnerable to geopolitical fluctuations. The surging demand for lithium in the EV sector has also resulted in dramatic price increases over recent years. Safety is another crucial consideration when comparing these two technologies. Sodium-ion batteries generally exhibit greater thermal stability compared to some lithium-ion chemistries, which reduces the likelihood of thermal runaway incidents. Additionally, they maintain stable performance across a broader temperature range—typically from −40°C to 70°C—making them especially appealing for deployment in extreme environmental conditions. In conclusion, while lithium-ion batteries remain the industry standard for high-performance EVs due to their superior energy density, sodium-ion batteries are emerging as a valuable complementary technology. With their cost advantages, resource abundance, and enhanced safety profile, they show strong potential to address economic and supply chain challenges in the ongoing global transition toward sustainable energy solutions.

2.5 Market Development and Applications of Sodium-Ion Batteries in Electric Vehicles

The commercialization of sodium-ion batteries has gained significant traction in recent years, fueled by growing interest from both academic institutions and industrial innovators. Several battery manufacturers have already launched pilot production lines and introduced commercial sodium-ion products, signaling a shift from experimental research to practical, real-world applications. One major driver behind the adoption of sodium-ion batteries is their lower manufacturing costs. Sodium, being abundant and less expensive than lithium, significantly reduces raw material expenses, offering a competitive edge against lithium-ion technology. This cost advantage makes sodium-ion batteries particularly appealing for entry-level electric vehicles (EVs) and large-scale energy storage systems where affordability is crucial. The automotive sector has started integrating sodium-ion batteries into EVs aimed at budget-conscious markets. These vehicles are primarily designed for urban use, with driving ranges of 200–300 kilometers that meet typical consumer needs. While sodium-ion batteries have slightly lower energy density compared to lithium-ion counterparts, the trade-off is often justified by the overall reduction in vehicle production costs. Another promising development is the emergence of hybrid battery architectures, combining lithium-ion and sodium-ion cells within a single pack. This approach allows manufacturers to balance performance improvements with cost reductions while also decreasing dependence on lithium-based materials. Such hybrid systems show potential for future EV platforms, offering an optimal mix of affordability and efficiency. Market forecasts indicate that sodium-ion batteries are set to occupy an expanding portion of the global energy storage landscape by the late 2020s. Their role is predicted to be particularly prominent in low-cost EVs and stationary energy storage solutions, especially those supporting renewable energy integration.

2.6 Global Challenges in 2026 and Implications for Battery Technologies

The growth of next-generation battery technologies is intrinsically linked to broader geopolitical and economic dynamics. By 2026, global challenges such as ongoing geopolitical tensions, increasing trade disputes, and fierce competition for access to critical minerals like lithium, cobalt, and nickel are expected to heavily impact the battery industry. These issues present substantial obstacles to maintaining secure and stable supply chains. As fossil fuel prices continue to rise, the global transition toward electric mobility is likely to accelerate, simultaneously increasing the demand for more advanced battery systems. However, this heightened demand faces counteracting pressures from supply chain disruptions and inflationary trends that could drive up production costs for battery manufacturing. Against this backdrop, diversifying battery technologies and reducing reliance on finite resources become key strategies for ensuring industry resilience. Sodium-ion batteries offer a viable solution to these challenges, given the widespread availability and more equitable distribution of sodium resources across the globe. Many nations with objectives to enhance their energy security are likely to prioritize investment in sodium-based battery technologies as part of comprehensive energy strategies. From an environmental standpoint, sodium-ion technology aligns well with sustainability goals by lessening dependence on the extraction of scarce metals, thereby mitigating environmental degradation. As global priorities shift toward sustainable energy practices, these batteries are expected to play an increasingly pivotal role in the clean energy transition.

III. Conclusion

Sodium-ion batteries provide a compelling alternative to traditional lithium-ion technology due to their cost-effectiveness, abundant resource supply, and enhanced safety features. Recent progress in areas such as cathode materials, anode design, and electrolyte composition has significantly improved their performance, making them increasingly suitable for inclusion in electric vehicle systems. Nevertheless, challenges remain regarding their energy density and long-term operational reliability. Amid growing economic uncertainties and disruptions within critical supply chains, sodium-based battery technologies are likely to garner heightened interest as a sustainable alternative. Integrating these advancements into automotive engineering curricula is crucial for preparing future engineers with the knowledge necessary to drive innovations in sustainable transportation solutions.

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