



Research Paper

Solid-State Batteries for Electric Vehicles: Materials, Interfaces, and Commercialization Challenges

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Abstract

Solid-state batteries (SSBs) are increasingly recognized as a promising solution for the future of energy storage in electric vehicles (EVs). Their appeal stems from several advantages over conventional lithium-ion batteries, including enhanced safety, greater energy density, and a longer operational lifespan. This study provides a thorough review of recent progress in SSB technology, focusing on advancements in solid electrolytes, electrode materials, and strategies to improve interfacial stability. It also examines key technical challenges hindering the large-scale commercialization of SSBs, such as issues related to manufacturing efficiency, cost-effectiveness, and the scarcity of critical raw materials. Broader factors, such as the influence of geopolitical tensions and rising raw material prices, are analyzed to assess their impact on battery development. Furthermore, the study proposes integrating cutting-edge knowledge of SSBs into the automotive engineering curriculum at the Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology. This initiative aims to prepare future engineers with the expertise and insights necessary to drive innovation in this rapidly evolving field.

Keywords: solid-state batteries, electric vehicles, solid electrolytes, battery interfaces, commercialization challenges

I. Introduction

The rapid expansion of the electric vehicle (EV) industry has led to a substantial increase in the global demand for advanced energy storage systems. Lithium-ion batteries currently dominate this market due to their high energy density and well-established manufacturing processes. However, these conventional batteries still face critical challenges, such as safety risks from flammable liquid electrolytes, limited energy densities, and prolonged charging times. These issues have spurred intense research into alternative battery technologies, with solid-state batteries emerging as a particularly promising solution. Unlike traditional lithium-ion batteries, solid-state batteries utilize solid electrolytes instead of liquid ones. This fundamental shift in design offers multiple advantages. For starters, solid electrolytes are non-flammable, significantly reducing the risk of thermal runaway and fires. Furthermore, the use of lithium metal anodes in place of the graphite anodes found in conventional lithium-ion cells enables much higher theoretical capacity. This allows solid-state batteries to potentially achieve energy densities above 300 Wh/kg, a considerable improvement over current lithium-ion batteries. In addition to enhanced energy density and safety, solid-state batteries promise faster charging speeds and longer lifespans. These characteristics are especially critical for electric vehicles, where limited driving ranges and extended charging times remain key obstacles to broader market acceptance. Consequently, numerous automotive manufacturers and battery producers worldwide are heavily investing in solid-state battery research and development. Industry leaders like Toyota, BMW, Volkswagen, and CATL are at the forefront of these efforts, with some targeting commercial deployment of solid-state battery-equipped EVs by the late 2020s. Despite their potential, several challenges continue to hinder the commercialization of solid-state batteries. One major obstacle lies in the interfaces between solid electrolytes and electrode materials; improper contact at these interfaces can result in high resistance, hinder ion transport, and compromise overall battery performance. Additionally, during charging, lithium dendrite formation can lead to internal short circuits, even within solid electrolyte systems. Another significant hurdle is the complexity of manufacturing these batteries. The production process often requires specialized conditions, such as dry and oxygen-free environments, as well as new techniques that diverge from existing lithium-ion battery manufacturing methods. These requirements drive up production costs and pose difficulties for scaling up industrial operations. As it stands, the cost of manufacturing solid-state batteries is approximately three to five times higher than that of conventional lithium-ion alternatives, thereby delaying their widespread adoption. Economic and geopolitical factors further complicate the development of next-generation

battery technologies. The supply chain for essential materials like lithium, nickel, cobalt, and rare metals remains highly sensitive to geopolitical tensions and trade disruptions. Moreover, global economic pressures such as rising energy costs, inflation, and competition for these critical resources may push battery production costs even higher in the future. This underscores the need for innovations in material alternatives, improved recycling methods, and more diversified supply chains to mitigate these challenges. From an educational standpoint, the rapid advancements in battery technology present both challenges and opportunities for engineering programs worldwide. Universities educating future automotive engineers must continually update their curricula to incorporate the latest developments in EV systems and energy storage technologies. A comprehensive understanding of advanced battery types—such as solid-state, lithium-sulfur, and sodium-ion batteries—will be crucial for students entering this field. At the Faculty of Vehicle and Energy Engineering at Thai Nguyen University of Technology, integrating emerging knowledge about solid-state batteries into academic programs could significantly enhance the training of automotive engineers. Courses focusing on electric vehicles, energy storage systems, electrochemistry, and advanced materials could be enriched by including case studies on key challenges and developments in solid-state battery technologies. Such updates would equip students with a robust foundation in both theoretical principles and practical issues associated with next-generation energy storage solutions.

II. Contents

2.1 Solid Electrolyte Materials for Next-Generation Solid-State Batteries

Solid electrolytes are a critical component for the advancement of solid-state batteries, serving as a replacement for the liquid electrolytes commonly used in lithium-ion batteries. Their primary function is to facilitate lithium-ion transport between the anode and cathode while delivering both electrochemical reliability and mechanical durability. Over the last decade, significant global research has focused on identifying and enhancing solid electrolyte materials with high ionic conductivity, chemical stability, and compatibility with various electrode materials. These efforts have predominantly centered around three main categories of solid electrolytes: oxide-based, sulfide-based, and polymer-based materials. Each class brings unique advantages and poses challenges related to conductivity, manufacturability, cost-effectiveness, and overall performance. Oxide-based solid electrolytes, such as garnet-structured lithium lanthanum zirconium oxide (LLZO), have been widely studied due to their excellent chemical stability and relatively high ionic conductivity, which can reach nearly 10^{-3} S/cm at room temperature. Their natural stability with lithium metal anodes makes them particularly appealing for high-energy-density battery applications. However, oxide electrolytes face challenges like the need for high-temperature sintering during manufacturing, which raises production costs and limits scalability. Additionally, their brittle ceramic nature increases susceptibility to mechanical fractures during battery operation, potentially impacting their long-term reliability. Sulfide-based solid electrolytes are another important area of exploration. Materials like lithium thiophosphate ($\text{Li}_{10}\text{GeP}_2\text{S}_{12}$) offer exceptionally high ionic conductivities—exceeding 10^{-2} S/cm—comparable to liquid electrolytes, which enable faster lithium-ion transport and higher power densities for batteries. Their softer structure also improves interfacial contact with electrodes. However, sulfide electrolytes are highly sensitive to moisture and can release toxic hydrogen sulfide gas upon exposure to air, complicating their handling, storage, and manufacturing processes. Polymer-based solid electrolytes represent the third major class of materials, valued for their superior mechanical flexibility and ease of processing. Polyethylene oxide (PEO)-based systems are extensively studied due to their ability to be fabricated into thin films and their compatibility with established battery manufacturing techniques. Despite these benefits, polymer electrolytes typically suffer from low ionic conductivity at ambient temperatures—often in the range of 10^{-5} S/cm—which restricts their use in high-performance applications like electric vehicles. To overcome these limitations, researchers are exploring composite polymer electrolytes that integrate ceramic fillers into polymer matrices to improve ionic conductivity while preserving mechanical flexibility. Recent advances in material science have paved the way for hybrid solid electrolytes that combine features from different material classes to maximize their strengths. These hybrid systems aim to achieve a balanced mix of properties, such as enhanced ionic conductivity, chemical stability, and mechanical robustness. One promising approach involves embedding ceramic nanoparticles within polymer matrices, which has shown potential for better ion transport and structural resilience. Such developments indicate that future solid-state batteries may rely on multifunctional electrolyte systems capable of simultaneously addressing performance optimization, safety concerns, and production scalability. Globally, progress in solid electrolyte research has accelerated significantly in recent years, driven by ambitious efforts in technology-focused nations like Japan, the United States, Germany, and South Korea. Both government-funded programs and private-sector investments totaling billions of dollars have contributed to advancing next-generation battery technologies. These initiatives seek to resolve existing challenges in solid electrolyte systems, thus paving the way for broader adoption of solid-state batteries in applications such as electric vehicles and other advanced energy-storage solutions.

2.2 Electrode Materials and Lithium Metal Anodes

The choice and design of electrode materials are critical factors that dictate the performance of solid-state batteries. In traditional lithium-ion batteries, graphite is commonly used as the anode material due to its remarkable stability and extended cycle life. However, its theoretical capacity is limited to about 372 mAh/g, which constrains the energy density achievable in current battery technologies. Lithium metal anodes, on the other hand, offer a significantly higher theoretical capacity of approximately 3860 mAh/g and a minimal electrochemical potential, making them ideal candidates for next-generation high-energy-density batteries. The adoption of lithium metal anodes has been made more viable with solid-state batteries, as solid electrolytes can effectively mitigate dendrite growth, one of the most critical safety concerns in conventional lithium batteries. Lithium dendrites, which resemble needle-like structures, form during repeated charging cycles due to uneven deposition of lithium ions on the anode surface. In liquid electrolyte systems, these dendrites can pierce through the separator, causing internal short circuits that may result in battery failure or even thermal runaway. Solid electrolytes, particularly those with high mechanical strength, serve as physical barriers to suppress dendrite propagation, offering a safer alternative. Nevertheless, integrating lithium metal anodes in solid-state batteries introduces its own set of challenges. A primary concern lies in the unstable interface between the lithium metal and the solid electrolyte. During operation, chemical reactions at this interface can create unstable interphase layers that elevate resistance and impair ion transport. Additionally, as lithium undergoes plating and stripping during charge and discharge cycles, significant volume changes occur, leading to mechanical stresses that may result in cracks within the electrolyte or compromised contact between cell components. To overcome these obstacles, researchers have been innovating various techniques to stabilize lithium metal anodes. One prominent approach entails introducing protective interlayers between the lithium metal and solid electrolyte. These interlayers can be composed of thin carbon films, metallic coatings, or artificial solid electrolyte interphase layers, which help minimize interfacial reactions and promote uniform lithium deposition. Another promising research avenue focuses on developing advanced cathode materials compatible with solid-state configurations. High-nickel layered oxides, lithium iron phosphate, and sulfur-based cathodes are among the leading candidates for this purpose. These materials exhibit high capacities and enhanced stability when used with appropriate solid electrolytes. However, successfully integrating these cathodes into solid-state systems demands meticulous engineering to ensure adequate ionic and electronic conductivity across the composite electrode framework. As a result, optimizing composite electrodes has become a critical area of focus in solid-state battery research. These advanced electrodes are designed by mixing active materials, conductive agents, and solid electrolyte particles to form a three-dimensional ion transport network. Properly tuning their composition and microstructure can significantly improve battery efficiency by enhancing ion diffusion and lowering internal resistance. Advancements in electrode materials and lithium metal anode technologies are paramount to unlocking the full potential of solid-state batteries. Progress in these domains will play a pivotal role in driving improvements in energy density, charging speed, and overall durability—key factors for realizing the future of electric vehicle battery systems.

2.3 Interface Engineering and Electrochemical Stability

The advancement of solid-state battery technology is hindered by one of its most intricate scientific challenges: the establishment of stable interfaces between core battery components. Unlike liquid electrolytes, which inherently adhere to electrode surfaces and establish effective conductive contact, solid electrolytes necessitate meticulously tailored interfaces to facilitate efficient ionic transport. Insufficiently developed interfacial contacts can result in elevated resistance, diminished capacity, and accelerated degradation during repeated battery cycles. On a microscopic scale, the interface formed between the solid electrolyte and the electrode exhibits disparities in chemical composition, crystalline structure, and mechanical properties. These differences are often catalysts for interfacial reactions that progressively compromise overall battery performance. For instance, particular solid electrolytes may chemically interact with lithium metal or cathode materials, forming layers of resistive compounds that obstruct lithium ion mobility. Such detrimental reactions are notably prevalent in sulfide-based electrolytes when exposed to high-voltage cathodes. A parallel issue stems from mechanical stresses arising during battery operation. The transfer of lithium ions across electrodes during charge and discharge cycles induces minor volumetric alterations in the electrode materials. In the context of solid-state batteries, these volume fluctuations generate mechanical strain at the junctions between components. Over time, this strain promotes microcrack formation and delamination, which disrupts ionic transport channels and diminishes energy efficiency. In response to these multifaceted challenges, researchers have advanced numerous strategies for interface engineering. A prominent method involves introducing thin protective coatings to electrode surfaces, composed of materials such as oxides, polymers, or nanostructured films that serve as intermediaries between electrodes and solid electrolytes. These coatings are engineered to mitigate adverse chemical reactions while ensuring robust ionic conductivity. Sophisticated characterization tools have further enhanced the understanding of interfacial behavior within solid-state batteries. Techniques including electron microscopy, X-ray diffraction,

and spectroscopic analyses enable the exploration of nanoscale interfacial structures with exceptional precision. These technologies provide critical insights into the fundamental processes governing ion transport, chemical deterioration, and mechanical instability within solid-state systems. Recent research has also focused on devising artificial interphase layers analogous to the solid-electrolyte interphase observed in conventional lithium-ion batteries. Such fabricated interphases are designed to stabilize electrode surfaces and control lithium ion transfer across interfaces. By meticulously engineering the composition and structural characteristics of these layers, substantial improvements have been demonstrated in electrochemical stability and cycle longevity within experimental solid-state battery prototypes. Ultimately, the domain of interface engineering remains pivotal for realizing viable solid-state battery technologies. Progress in this area will play an indispensable role in achieving sustained performance and reliability, especially concerning applications such as electric vehicles.

2.4 Manufacturing Technologies and Commercialization Challenges

Despite their promising advantages, the practical implementation and broad commercialization of solid-state batteries are impeded by significant manufacturing hurdles. While production processes for conventional lithium-ion batteries have matured through decades of industrial refinement, solid-state batteries necessitate entirely novel methodologies encompassing specialized materials, techniques, and equipment that are still undergoing developmental trajectories. A primary technical challenge involves fabricating thin and densely packed solid electrolyte layers that exhibit high ionic conductivity. To meet these requirements, many solid electrolytes require high-temperature sintering to attain optimal crystalline configurations and mechanical robustness. Scaling such processes for mass production poses formidable financial and logistical barriers due to intensive energy demands and elevated operational costs. Additionally, ensuring consistent thickness and defect-free manufacturing of electrolyte layers throughout extensive battery cells remains an intricate technical obstacle. The subsequent challenge is associated with achieving seamless assembly of solid-state battery components while simultaneously ensuring optimal interfacial contact. Unlike liquid electrolytes that adapt readily to surface irregularities, solid materials inherently resist conforming to one another's topographies. Consequently, attaining intimate contact between electrodes and electrolytes often necessitates external forces such as high pressure or innovative fabrication methodologies. These additional requirements elevate manufacturing intricacy while diminishing efficiency. Overcoming these challenges is imperative for the transition of solid-state batteries from laboratory prototypes to commercially viable products. This progression requires addressing both technical constraints in the production of defect-free materials and broader industrial-scale adaptation for mass market adoption. As research efforts continue to refine these methods, achieving cost-effective and reliable manufacturing systems will be central to unlocking the full potential of solid-state battery technology and establishing its relevance within global markets such as renewable energy storage and automotive electrification sectors.

The cost of raw materials significantly influences the commercialization of solid-state batteries. Many solid electrolytes require rare or expensive elements such as germanium, lanthanum, or tantalum, whose scarce global availability often leads to higher production costs and exacerbates supply chain vulnerabilities. As the demand for electric vehicles continues to grow, ensuring stable and reliable access to battery materials will become increasingly critical. Geopolitical dynamics are expected to play a major role in the future of solid-state batteries. Ongoing tensions between nations, trade restrictions, and competition for essential minerals may disrupt supply chains for crucial resources like lithium and nickel. Additionally, rising energy costs and global inflation are likely to increase manufacturing expenses for battery producers. Amid these uncertainties, prioritizing the development of alternative materials and improving battery recycling processes becomes imperative to mitigate long-term risks. Despite these obstacles, the automotive industry remains optimistic about the potential of solid-state battery technology. Several manufacturers have commenced pilot production and introduced prototype electric vehicles featuring solid-state systems. While widespread adoption may require significant advancements over the next few years, continuous investments and ongoing innovations are expected to reduce production costs and improve overall performance.

2.5 Global Energy Trends and Raw-Material Supply Risks in 2026

Global trends in energy usage and resource availability are shaping the future of electrified transportation. By 2026, the electric vehicle market is projected to expand rapidly, bolstered by stricter environmental regulations and government incentives promoting sustainable mobility. However, this growth is accompanied by intensifying competition for raw materials critical for battery production. Key components such as lithium, nickel, cobalt, and manganese remain indispensable in current battery technologies, yet their supply is concentrated in specific regions. For example, South America and Australia hold much of the world's lithium reserves, while cobalt production is heavily centered in the Democratic Republic of Congo. This geographic concentration introduces vulnerabilities tied to geopolitical tensions, shifting trade policies, and disruptions to supply chains. Economic uncertainty further complicates the trajectory of battery technology development. Factors such as military conflicts, volatile fossil fuel prices, and energy crises can impact investments in renewable energy infrastructure

and electric mobility initiatives. While surging oil prices may accelerate the shift toward electric vehicles—and thereby drive demand for advanced batteries—economic instability could hinder government funding for research on new energy storage solutions. Environmental concerns surrounding mining activities for battery-related materials present another challenge. The extraction of resources like lithium and cobalt has been associated with significant environmental and social issues, including overuse of water, land degradation, and unethical labor practices. In light of growing global emphasis on sustainability, researchers and policymakers are increasingly focused on developing greener battery chemistries using more abundant and environmentally friendly materials. These mounting global challenges highlight the urgency of diversifying battery technologies while enhancing recycling systems to create a more resilient supply chain. Solid-state batteries represent a promising avenue by enabling the use of alternative materials and boosting energy efficiency. However, achieving a sustainable ecosystem for battery production will require collaborative efforts involving governments, industries, and academic institutions worldwide.

2.6 Implications for Automotive Engineering Education at Thai Nguyen University of Technology

The rapid advancements in battery technologies, particularly within the domain of electric vehicles (EVs), present both promising opportunities and substantial challenges for engineering education. Academic institutions tasked with cultivating the next generation of automotive engineers must regularly revise and adapt their curricula to remain in step with the evolving landscape of electrical mobility. To that end, a profound grasp of electrochemistry, materials science, and energy storage systems has become an essential foundation for students specializing in the field of automotive engineering. Within Thai Nguyen University of Technology's Faculty of Vehicle and Energy Engineering, the integration of solid-state battery concepts into the academic curriculum represents a strategic step toward fostering expertise in advanced EV technologies. Existing courses covering topics such as electric powertrains, energy storage systems, and automotive electronics could be enriched by the inclusion of specialized modules focused on next-generation battery technologies and the associated engineering intricacies. Equally important is the establishment of laboratory-based learning opportunities that enable students to gain practical, hands-on experience with battery systems. Exercises such as analyzing charge-discharge cycles, performing electrochemical evaluations, and conducting materials characterization not only deepen theoretical understanding but also provide invaluable experiential comprehension of system dynamics. These practical learning approaches bridge the gap between abstract knowledge and applied engineering, equipping students to address real-world technological challenges effectively. Collaborations with industry stakeholders represent another critical avenue for advancing the quality and relevance of automotive engineering education. Establishing strategic partnerships with automotive manufacturers, battery developers, and leading research institutions would provide students access to internships, collaborative research projects, and technology transfer programs. Such initiatives would not only cultivate professional competencies but also enable students to contribute actively to the development of innovative solutions in the EV sector. Moreover, the inherently interdisciplinary nature of battery technologies underscores the need for a holistic approach in engineering education. The field intersects with multiple disciplines, including mechanical engineering, electrical engineering, chemistry, materials science, and environmental studies. Developing integrated courses that transcend traditional disciplinary boundaries is pivotal to equipping students with the systemic perspective required to approach the complexities of sustainable mobility with innovation and agility. By embedding cutting-edge research on advanced battery technologies into its academic offerings, Thai Nguyen University of Technology can position itself as a leader in preparing highly skilled graduates who are equipped to meet the demands of global electrification and renewable energy transitions. Such an approach not only enhances student expertise but also establishes the university's role as a pivotal contributor to clean mobility innovation.

III. Conclusion

Solid-state battery technology symbolizes a transformative frontier for energy storage solutions in next-generation electric vehicles. These batteries offer considerable potential advantages, including improved safety profiles, higher energy density, and extended lifecycle performance—qualities that could redefine EV reliability and operational efficiency. However, significant challenges must still be addressed, such as developing robust solid electrolytes, stabilizing electrode-electrolyte interfaces, and achieving cost-effective manufacturing processes. In addition, macroeconomic factors such as supply chain vulnerabilities for critical raw materials and geopolitical uncertainties pose additional barriers to the widespread adoption of these technologies. To effectively confront these multifaceted challenges, it is vital to incorporate advanced knowledge of solid-state battery systems into automotive engineering education. This integration will empower future engineers to confront pressing technological and industrial issues head-on while fostering the development of sustainable transportation systems that align with global objectives for clean energy transition.

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