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Industrialization and Technological Progress of Solid-State Batteries in the New Energy Power Sector

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Abstract: In recent years, the rapid growth of the electric vehicle and energy storage markets has driven significant advancements in power battery technology. While traditional liquid lithium-ion batteries dominate the market, their inherent safety risks and limited energy density have prompted exploration of next-generation technologies. Solid-state batteries (SSBs), which utilize solid electrolytes in place of flammable liquid ones, offer promising advantages in safety, energy density, and high-temperature performance. This paper systematically reviews the working principles and material systems of SSBs, focusing on the three main electrolyte types: polymers, oxides, and sulfides. It also examines key application scenarios in electric vehicles, consumer electronics, and grid storage, highlighting the benefits of SSBs in each sector. Based on data from 2020–2025, the paper analyzes market trends in China and globally, showing exponential growth in both output and investment. Case studies of major industry players including CATL, BYD, and Tesla are discussed, comparing their technological routes and commercialization timelines. Finally, the paper addresses the major technical and industrial challenges facing SSB adoption and proposes development strategies including interface engineering, hybrid electrolyte systems, and policy support. The study concludes that SSBs are likely to play a critical role in the next phase of the energy transition, with large-scale commercialization expected in the early 2030s.

Keywords: Solid-state battery; Solid electrolyte; Energy storage; Electric vehicle; Lithium metal anode; CATL; BYD; Tesla; Sulfide; Oxide; Polymer; Industrialization.

1. Introduction

In recent years, the rapid expansion of the new energy vehicle (NEV) and energy storage sectors has driven continuous innovation in power battery technologies. Although conventional liquid lithium-ion batteries have achieved gradual improvements in energy density, they still rely on flammable liquid electrolytes, posing significant safety risks and facing inherent limitations in further performance enhancement [1]. Solid-state batteries (SSBs), in contrast, replace the liquid electrolyte with a solid-state electrolyte, enabling lithium-ion transport between the anode and cathode through solid ion conductors. While the basic working principle remains similar to traditional batteries, the use of non-flammable solid electrolytes greatly enhances battery safety and opens up potential for higher energy density [2]. Furthermore, SSBs offer a wider electrochemical stability window and improved thermal adaptability, ensuring more reliable performance in extreme environments and enabling faster charging. These advantages make SSBs highly suitable for next-generation applications such as electric vehicles and advanced portable electronics. As such, the emergence of solid-state battery technology is regarded as a critical breakthrough that could fundamentally address the current limitations of liquid lithium-ion batteries [2].

2. Technical Principles and Material Systems of Solid-State Batteries

The fundamental operating mechanism of solid-state batteries (SSBs) is similar to that of conventional lithium-ion batteries. During charging and discharging cycles, lithium ions shuttle between the cathode and anode. However, unlike traditional batteries that use liquid electrolytes, SSBs employ solid-state electrolytes (SSEs) as the ion-conducting medium. During charging, an external electric field drives lithium ions from the cathode through the solid electrolyte and into the anode—typically composed of lithium metal—where energy is stored. Discharging reverses this process, enabling energy release [3].

Compared to liquid electrolytes, solid electrolytes offer additional advantages: they also serve as a physical separator, allowing for a more compact battery architecture, enhanced mechanical integrity, and improved operational safety. Furthermore, SSEs enable the use of high-voltage cathode materials and lithium metal anodes, contributing to significantly higher energy densities [4].

Solid electrolytes are the core materials in SSBs, and they are generally classified into three major categories: polymers, oxides, and sulfides, each with distinct characteristics (as summarized in Table 1).

Polymer electrolytes, such as those based on polyethylene oxide (PEO) or polyvinylidene fluoride (PVDF), are flexible and easily processable. They facilitate good interfacial contact with lithium metal anodes and reduce flammability risks. However, their ionic conductivity is relatively low at room temperature (typically in the range of 10^{-4} to 10^{-3} S/cm), necessitating elevated temperatures (above 60 °C) for optimal performance [5].

Oxide-based electrolytes, including materials like LLZO ($Li_7La_3Zr_2O_{12}$) and NASICON-type structures, exhibit excellent chemical and mechanical stability, and can tolerate high-voltage cathodes while maintaining satisfactory conductivity at ambient temperature. Nevertheless, their production involves high-temperature sintering, leading to increased complexity and manufacturing costs [6].

Sulfide-based electrolytes, such as $Li_{10}GeP_2S_{12}$ and $Li_7P_3S_{11}$, combine high ionic conductivity (reaching up to 10^{-2} S/cm at room temperature) with favorable ductility. These characteristics enhance interfacial contact and simplify fabrication processes. Additionally, sulfides do not require high-temperature processing, offering cost advantages over oxides. However, their sensitivity to moisture necessitates controlled, dry environments during handling and assembly, as they degrade upon exposure to air or humidity [7].

Table 1. Performance Comparison of Three Types of Solid-State Electrolyte Materials

Performance Indicator	Polymer Electrolyte	Oxide Electrolyte	Sulfide Electrolyte
Ionic Conductivity	10^{-4}~10^{-3} S/cm	10^{-4}~10^{-3} S/cm	10^{-2} S/cm
Temperature Adaptability	Above 60°C Required	Wide Range	Wide Range
Flexibility	Good	Poor	Moderate
Mechanical Strength	Poor	Excellent	Moderate
Process Complexity	Low	High (Requires High Temp Sintering)	Moderate (Requires Dry Environment)
Interface Compatibility	Good	Poor	Excellent

Polymer electrolytes offer excellent flexibility and ease of processing but suffer from low ionic conductivity [8]. Oxide electrolytes provide high stability and moderate conductivity; however, their production involves high costs and complex manufacturing processes [9]. Sulfide electrolytes combine high ionic conductivity with good interfacial compatibility and can be fabricated at relatively low temperatures, though their chemical stability is comparatively weaker [10].

3. Application Scenarios and Technical Advantages

Solid-state batteries (SSBs) possess significant potential across various sectors due to their superior safety and high energy density. In the field of electric vehicles, SSBs enable the use of lithium metal anodes combined with high-nickel cathodes, substantially enhancing energy density and thereby extending driving range. Moreover, the solid electrolytes' excellent thermal stability and high voltage tolerance improve both the safety and lifespan of electric vehicle batteries. In consumer electronics, SSBs offer a more compact and lightweight solution without flammable liquid components, meeting stringent safety requirements for portable devices such as smartphones and laptops while enabling higher capacity and thinner form factors [11]. For grid energy storage, SSBs provide longer cycle life and a broader operational temperature range, making them suitable for load balancing and peak shaving applications, which enhances overall system safety and reliability. Overall, SSBs are poised to achieve industrial adoption in electric vehicles, energy storage systems, and consumer electronics, leveraging their combined advantages of "high energy density and enhanced safety [12]."

4. Global and China Market Development Trends (2020–2025)

The global solid-state battery market has experienced continuous growth in recent years. Industry data indicates that global shipments reached approximately 1 GWh in 2023, expected to rise to 3.3 GWh in 2024, and potentially soar to 614.1 GWh by 2030. In terms of market value, Tycorun forecasts the global SSB market will approach USD 1 billion in 2024, with a compound annual growth rate (CAGR) exceeding 40% over the coming years. Figure 1 illustrates the historical and projected global market scale, showing an increase from about USD 620 million in 2021 to nearly USD 1 billion in 2024, with expectations to surpass tens of billions by 2030. This reflects an exponential growth trend in both shipments and market size [3].

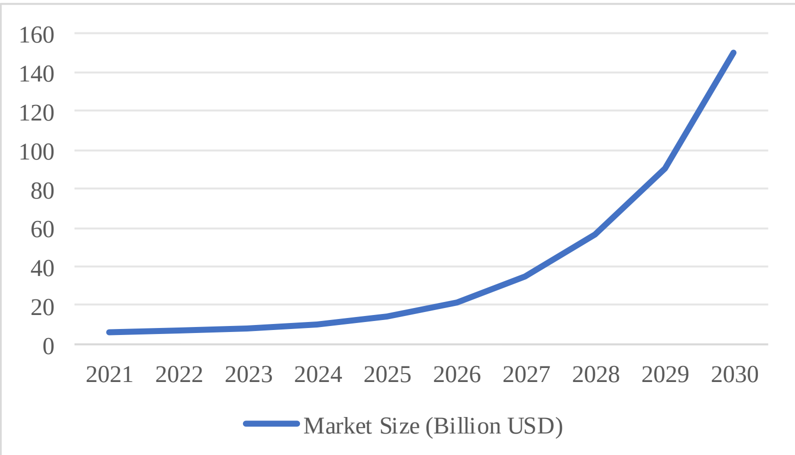

Figure 1. Global Solid-State Battery Market Size Forecast (2021–2030)

In China, the SSB market is also rapidly emerging. According to statistics from China Business Industry Research Institute, the Chinese SSB market size was around RMB 1 billion in 2023, expected to reach RMB 1.7 billion in 2024 and surpass RMB 20 billion by 2030. Tycorun reports that China's SSB shipments rose from 2.5 GWh in 2023 to 7 GWh in 2024, with projections of 10 GWh in 2025. Figure 2 presents the forecasted market growth in China, from approximately USD 120 million in 2024 to USD 630 million (about RMB 4 billion) in 2030, indicating significant growth potential that will drive industry expansion [13].

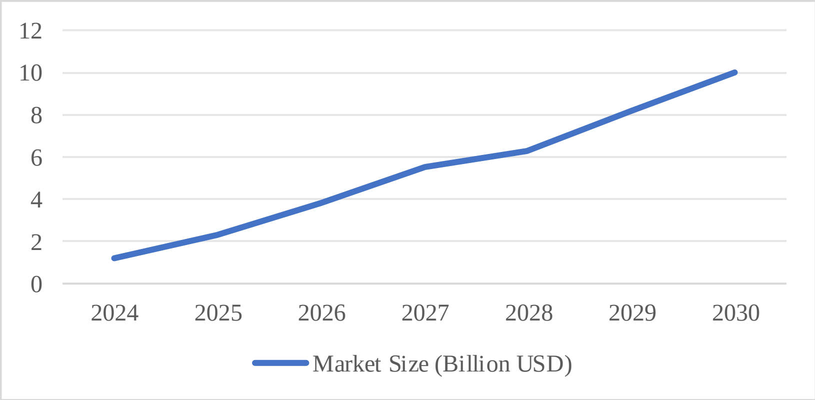

Figure 2. China Solid-State Battery Market Size Forecast (2024–2030)

5. Comparative Case Studies of Leading Companies

Key industry players vary in their technological pathways and commercialization progress. CATL, one of the world's largest power battery suppliers, has invested over a decade in SSB R&D and assembled a dedicated team of around 1,000 specialists. In 2024, CATL announced its all-solid-state battery technology reached a maturity score of 4 out of 9, aiming for a score of 7 to 8 by 2027 to enable small-batch production. Currently, CATL has developed 20Ah prototype cells with plans for pilot production in 2027. BYD initiated its SSB strategy in 2013, making recent breakthroughs in sulfide electrolyte technology. BYD plans to launch its first all-solid-state battery-equipped vehicle in 2027, entering a demonstration phase through 2029 and mass production by 2030 [14]. BYD has already tested 20Ah and 60Ah single cells this year. Conversely, Tesla has yet to announce specific timelines for SSB commercialization, focusing primarily on its 4680 liquid battery and other advanced technologies, with limited public information on solid-state routes. Table 3 summarizes the comparisons among these three companies. Overall, CATL and BYD are advancing prototype development and targeting early 2030s industrialization, while Tesla remains cautious, leaving the large-scale production outlook uncertain [15].

6. Challenges and Development Recommendations

Despite promising prospects, SSBs face multiple challenges. Technically, poor interface contact between solid electrolytes and electrodes results in high interfacial resistance and limits cycle life improvement. Furthermore, current solid electrolytes, especially sulfides, are sensitive to moisture and require dry manufacturing conditions [16]. The high energy density advantage has yet to be fully realized in commercial products. Cost-wise, scarce raw materials and complex fabrication processes render SSBs significantly more expensive than traditional liquid batteries, restricting their penetration in mid- and low-end markets. On the policy front, although governments have introduced support roadmaps, a lack of clear industrial incentives and standardized frameworks for SSBs may hinder market confidence [17].

To address these issues, it is recommended to: (1) intensify fundamental research and industry collaboration focusing on high-conductivity electrolytes, interface engineering, and quality manufacturing to enhance component integration and yield; (2) promote semi-solid transitional technologies that combine small amounts of liquid electrolytes with polymers, oxides, or sulfides as a cost-reduction strategy; (3) strengthen industry chain coordination and investment, scaling up production lines to leverage economies of scale and cost reductions; (4) improve governmental policies and standards, provide R&D and manufacturing subsidies, and accelerate domestic development of critical equipment and materials. Only through comprehensive measures and continuous innovation can SSBs transition from laboratory to market [18].

7. Conclusion

Solid-state battery technology, with its inherent safety and energy density benefits, is set to play a vital role in the industrialization of new energy power batteries [19]. This paper reviewed the development background, working principles, and material systems of SSBs and analyzed their application prospects in automotive, energy storage, and consumer electronics sectors. Market data from 2020 to 2025 demonstrate rapid growth in both global and Chinese markets, with expectations for accelerated expansion and penetration. Leading companies such as CATL, BYD, and Tesla have established solid-state technology roadmaps and commercialization schedules. Although challenges remain, ongoing technological breakthroughs and increased industrial investment suggest that large-scale production is achievable in the early 2030s. Looking forward, solid-state batteries will be critical to enhancing electric vehicle range and safety and advancing the global energy transition.

References

[1] N. Rane, S. Choudhary, and J. Rane, "Enhancing lithium-ion battery performance with emerging electrolyte materials for sustainable energy storage solutions: a comprehensive review and prospects," Available at SSRN 4643648, 2023.

[2] A. Machín, C. Morant, and F. Márquez, "Advancements and challenges in solid-state battery technology: An in-depth review of solid electrolytes and anode innovations," Batteries, vol. 10, no. 1, p. 29, 2024.

[3] F. Thomas, L. Mahdi, J. Lemaire, and D. M. Santos, "Technological advances and market developments of solid-state batteries: A review," Materials, vol. 17, no. 1, p. 239, 2024.

[4] L. Li, H. Duan, J. Li, L. Zhang, Y. Deng, and G. Chen, "Toward high performance all-solid-state lithium batteries with high-voltage cathode materials: design strategies for solid electrolytes, cathode interfaces, and composite electrodes," Advanced Energy Materials, vol. 11, no. 28, p. 2003154, 2021.

[5] C. Che et al., "Challenges and Breakthroughs in Enhancing Temperature Tolerance of Sodium-Ion Batteries," Advanced Materials, vol. 36, no. 28, p. 2402291, 2024.

[6] X. Chen et al., "Practical Application of All-Solid-State Lithium Batteries Based on High-Voltage Cathodes: Challenges and Progress," Advanced Energy Materials, vol. 13, no. 35, p. 2301230, 2023.

[7] M. Liu et al., "Surface molecular engineering to enable processing of sulfide solid electrolytes in humid ambient air," Nature Communications, vol. 16, no. 1, p. 213, 2025.

[8] S. Tang, W. Guo, and Y. Fu, "Advances in composite polymer electrolytes for lithium batteries and beyond," Advanced Energy Materials, vol. 11, no. 2, p. 2000802, 2021.

[9] R. Sharma et al., "Progress and challenges in electrochemical energy storage devices: Fabrication, electrode material, and economic aspects," Chemical engineering journal, vol. 468, p. 143706, 2023.

[10] Y. Zhou et al., "Reliable Sulfur Cathode Design for All-Solid-State Lithium Metal Batteries Based on Sulfide Electrolytes," Advanced Energy Materials, vol. 15, no. 18, p. 2500061, 2025.

[11] X. Fan et al., "Opportunities of flexible and portable electrochemical devices for energy storage: expanding the spotlight onto semi-solid/solid electrolytes," Chemical Reviews, vol. 122, no. 23, pp. 17155-17239, 2022.

[12] Y. Li et al., "Advancements in Electrolytes: From Liquid to Solid for Low-Cost and High-Energy-Density Micro-Sized Silicon-Based Batteries," Advanced Energy Materials, p. 2502284.

[13] A. Zahoor, Y. Yu, S. Batool, M. Idrees, and G. Mao, "The carbon-neutral goal in China for the electric vehicle industry with solid-state battery's contribution in 2035 to 2045," Journal of Environmental Engineering, vol. 149, no. 12, p. 04023082, 2023.

[14] C. Liu and C. Bi, "Current Situation and Trend of Electric Vehicle Battery Business-Take CATL as an example," Technium Soc. Sci. J., vol. 38, p. 324, 2022.

[15] J. Xu, "Strategic Emerging Industry: Analysis of Development of New Energy Vehicles," Politecnico di Torino, 2024.

[16] K. J. Kim, M. Balaish, M. Wadaguchi, L. Kong, and J. L. Rupp, "Solid-state Li–metal batteries: challenges and horizons of oxide and sulfide solid electrolytes and their interfaces," Advanced Energy Materials, vol. 11, no. 1, p. 2002689, 2021.

[17] M. S. S. Danish and T. Senjyu, "AI-enabled energy policy for a sustainable future," Sustainability, vol. 15, no. 9, p. 7643, 2023.

[18] R. Bridgelall, "Solid-State Battery Developments: A Cross-Sectional Patent Analysis," Sustainability, vol. 16, no. 24, p. 10994, 2024.

[19] J. Janek and W. G. Zeier, "Challenges in speeding up solid-state battery development," Nature Energy, vol. 8, no. 3, pp. 230-240, 2023.