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Research Progress Review of Domestic and Foreign Enterprises and Postgraduates in the Field of Solid - State Batteries

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ABSTRACT

This review focuses on the field of solid - state batteries and systematically combs the research status of domestic and foreign enterprises and postgraduates in this field. It elaborates on the basic principles and technical classifications of solid - state batteries, analyzes in detail the research and development focus, achievements and layout of foreign enterprises such as Toyota and Samsung SDI, the exploration and practice process of domestic enterprises such as CATL and BYD, as well as the contributions and innovation points of postgraduate groups in different research directions. By comparing the differences in research at home and abroad, the challenges faced by solid - state batteries are discussed and the future development is prospected, aiming to provide a comprehensive and in - depth reference for further research, enterprise strategic planning and policy formulation in the field of solid - state batteries.

KEYWORDS

Solid - state battery; Enterprise research; Postgraduate research; Technical progress; Development prospect

1 Introduction

1.1 Research Background

Traditional lithium - ion batteries occupy an important position in the modern energy storage field, but they have many limitations. The flammable liquid electrolyte used in traditional lithium - ion batteries is prone to combustion and even explosion in case of improper use or internal short circuit, bringing serious safety hazards. In terms of energy density, it is difficult to meet the requirements of long - range electric vehicles and large - scale energy storage applications in power grids, which restricts the further popularization of electric vehicles. During the charging and discharging process, the volume change of the electrode material will lead to structural damage and pulverization, resulting in a decrease in battery performance and shortened cycle life.

As a new generation of battery technology, solid - state batteries have significant advantages. The use of solid electrolytes improves battery safety, reduces the risk of combustion and explosion, and enables the battery to work stably in a wider temperature range. In terms of energy density, solid - state batteries have great potential for improvement. For example, when using lithium metal as the anode, its theoretical specific capacity (~3800 mAh/g) is much higher than that of the traditional graphite anode (theoretical specific capacity is about 340 - 370 mAh/g), which provides the possibility to increase the energy density of the battery. In addition, solid - state batteries can also inhibit the growth of lithium dendrites. In traditional liquid electrolyte batteries, lithium dendrites are easy to pierce the separator and cause short circuit, affecting the battery life and safety. However, the mechanical strength and special structure of the solid electrolyte can effectively avoid this problem and extend the battery cycle life. Therefore, the development of solid - state batteries is a new trend in the development of new energy electric vehicles and is likely to be a good solution to the problems existing in current new energy electric vehicles.

1.2 Research Purposes and Significance

Revealing Industry Research Hotspots and Trends: Analyzing R&D directions helps identify focuses like solid electrolyte research popularity and electrode-solid electrolyte matching, guiding enterprises and researchers to adapt strategies and stay at the forefront.

Promoting Enterprise Technological Exchange: Displaying achievements and paths enables enterprises to find partners, share resources, and enhance competitiveness through cooperation and learning.

Guiding Postgraduate Research Topics: Presenting the research landscape aids postgraduates in choosing valuable topics considering studied and unexplored areas, ensuring academic and practical value.

Optimizing Resource Allocation: Assessing the status clarifies investment directions, preventing waste and accelerating solid-state battery technology development.

Advancing Industrialization: Integrating research achievements speeds up technology transfer, helps enterprises solve industrial problems, guides postgraduate research, and promotes industry growth and policy formulation.

2 Basic Principles and Technical Classifications of Solid - State Batteries

2.1 Working Principles

Revised Text (50% condensed, all technical points retained): Solid-state batteries (SSBs) operate through Li^+ migration between electrodes and electron transfer in external circuits. During charging, Li^+ deintercalates from cathode lattices (e.g., NCM811), traverses solid electrolytes via dual pathways (surface diffusion: activation energy ~0.2 eV; lattice migration: ~0.5 eV), and deposits as metallic Li at the anode (theoretical capacity: 3,860 mAh/g). Key distinctions from liquid batteries include:

Material System: Li-metal anodes (energy density ↑ 50%) paired with solid electrolytes (solvation-free, cycle life ↑ 30%);

Safety: Non-flammable electrolytes with dendrite suppression (>70% under >1 MPa interface pressure);

Challenges: Initial interfacial impedance >500 $\Omega\cdot cm^2$, reducible to <100 $\Omega\cdot cm^2$ via ALD coating.

Breakthrough: Sulfide electrolytes (e.g., $Li_{10}GeP_2S_{12}$) achieve ionic conductivity >0.01 S/cm, nearing liquid electrolytes (0.01–0.1 S/cm).

2.2 Technical Routes and Material Systems

Solid electrolyte materials are mainly of three types: polymers, oxides, and sulfides. Polymer electrolytes contain a matrix like PEO or PMMA and a lithium salt such as $LiClO_4$ or $LiPF_6$. With a long - chain structure and polar groups for lithium - ion complexing, they conduct ions in the amorphous phase. Their room - temperature ionic conductivity is low (10^{-7} - 10^{-8} S/cm), but modification can raise it to 10^{-4} - 10^{-5} S/cm. They are easy to prepare, can form thin - films, and have low raw - material and equipment costs, though their compatibility with some electrodes needs improvement.

Oxide electrolytes, like garnet - type (LLZO) and NASICON - type (LATP), have a 3D crystal structure with lithium - ion migration channels. Their ionic conductivity is 10^{-4} - 10^{-3} S/cm, and they're stable across a wide temperature range. Preparation is complex, involving high - temperature solid - phase reactions. Some raw materials are costly, but costs may decrease with tech progress. They have good electrode compatibility and can inhibit lithium dendrites.

Sulfide electrolytes, such as Li_2S - P_2S_5 and $Li_{10}GeP_2S_{12}$, have high ionic conductivity (10^{-3} - 10^{-2} S/cm at room temperature) due to a large sulfur - ion radius and weak lithium - ion binding. However, their preparation is complex, requires harsh conditions, and has high costs, limiting commercial use. They have good compatibility with lithium - metal anodes but may react with some cathodes.

Regarding electrode materials, cathodes include $LiCoO_2$, NCM, and lithium - rich manganese - based materials, while anodes include metallic lithium and silicon - based materials.$LiCoO_2$, an early - commercialized cathode, has good energy density but cobalt scarcity restricts its use. Future research aims to improve stability and cycle life through doping/coating and reduce cobalt content.NCM, with more nickel for higher energy density, has stability and safety issues. High - nickel NCM811 is popular. Future trends are increasing nickel, developing cobalt - free/low - cobalt materials, and optimizing preparation and surface modification.Lithium - rich manganese - based materials offer high voltage and capacity, are cost - effective, but face initial capacity loss and voltage drop. Research focuses on solving these issues.Metallic lithium has a high theoretical capacity but forms dendrites, limiting its use. Research focuses on new electrolytes and interface modifications. Silicon - based materials have high capacity but large volume changes. Research aims to prepare nanostructured and composite materials to address this.

Electrode materials impact battery performance. Crystal structure affects lithium - ion movement, electrochemical properties like capacity and voltage affect energy density, and stable structure and interface during cycles are crucial for long - life batteries.

3 Research and Layout of Foreign Enterprises in the Field of Solid - State Batteries

3.1 Enterprise Overview and Selection of Representative Enterprises

Foreign enterprises in the field of solid - state batteries are widely distributed, mainly concentrated in Japan, South Korea, the United States, Europe and other places. The market competition is fierce, and enterprises in various countries are actively investing in research and development and industrialization processes. In this study, Toyota, Samsung SDI, LG Chem, Panasonic and other enterprises are selected as the key research objects because they have significant influence in terms of technological research and development and industrialization processes.

3.2 Enterprise Research and Development Focus and Achievements

Toyota focuses on sulfide solid electrolyte R&D. Its experimental prototype has an energy density of 400 watt - hours per liter. It improves power density by developing highly conductive sulfide electrolytes like $Li_{10}GeP_2S_{12}$ (ionic conductivity up to 0.012 S/cm), optimizing electrode - electrolyte interfaces (using a solid - electrolyte digital model), and enhancing lithium - ion conductivity in active materials.

Samsung SDI pursues high - energy - density solid - state battery design innovation. With significant R&D investment and a professional team, it aims for tech innovation and performance improvement. Challenges include boosting energy density and battery performance, likely addressed through continuous R&D and partnerships.

LG Chem may concentrate on solid electrolyte R&D and battery structure design. Its products may excel in energy density and cycle life. R&D investment and team - building drive tech progress. Facing cost - reduction and production - efficiency improvement, it can respond by optimizing processes and collaborating with academia.

Panasonic delves into halide solid electrolytes. Its solid - state batteries may offer high energy density and stability, with a 2025 commercialization plan. It may cooperate with others to overcome technical hurdles. Battery safety and reliability improvement challenges can be met through tech upgrades and quality control.

3.3 Enterprise Cooperation Network and Industrialization Layout

These enterprises usually have a close cooperation with universities and institutions. Toyota, for example, works with others to do research. This speeds up knowledge sharing, technology transfer, and talent cultivation.

For industrialization, each enterprise has different plans. Toyota in Japan wants to commercialize solid-state batteries from 2028 - 2030. South Korean enterprises like LG Chem and Samsung SDI focus on local chains and plan commercialization before 2027. Panasonic in the US aims for vehicle demonstration application before 2025.

Based on reports and data, these enterprises are competitive. With tech progress and industrialization, their market positions and prospects are likely to get better.

4 Exploration and Practice of Domestic Enterprises in the Field of Solid - State Batteries

4.1 Development Situation of Domestic Enterprises

The development of domestic enterprises in the field of solid - state batteries is promising. Traditional battery enterprises are actively transforming and upgrading, and emerging technology enterprises are constantly emerging. In terms of policy, the state attaches great importance. During the "14th Five - Year Plan" period, a number of major projects have been launched to support the development of solid - state battery technology, like the key special project of new energy vehicles and the key special project of energy storage and smart grid. Meanwhile, a series of plans have been issued to clearly define the goals of accelerating the R & D and industrialization of solid - state power battery technology, providing strong policy support for enterprises. In the market, the rapid development of the new energy vehicle industry and the increasing demand for high - energy - density and high - safety batteries bring broad market space for solid - state battery enterprises. Technologically, the development of lithium - ion batteries in China has laid a certain foundation for solid - state batteries, and some enterprises have achieved large - scale production of in - situ solidified batteries.

4.2 Enterprise Characteristic Research and Innovation Practice

CATL is constantly working on improving the manufacturing process of solid - state batteries. Its products such as condensed state batteries reflect the exploration of technological innovation. Weilan New Energy relies on its core technology platform to develop a number of key technologies such as in - situ solidification, atomic - level bonding and composite metallic lithium. The mass - produced automotive - grade solid - state batteries have significantly improved the endurance and safety performance of electric vehicles.

4.3 Industrialization Process and Challenges

4.3.1 Progress

Some enterprises have established pilot production lines. For example, Beijing Weilan New Energy Technology Co., Ltd. has taken the lead in realizing the large - scale production of in - situ solidified batteries globally and has built a solid - state battery production line with a cumulative capacity of 5.6 GW·h. NIO and Dongfeng Motor have made progress in product certification and market introduction. NIO achieved the installation and road test of solid - state batteries with a mileage of over 1000 km in 2023, and Dongfeng Motor will realize the installation of a new generation of high - specific - energy solid - state batteries in the whole vehicle in 2024, and the products are gradually entering the market introduction stage.

4.3.2 Challenges and Coping Strategies

The commercialization of all-solid-state batteries faces significant technical, financial, and market challenges. Technologically, critical gaps remain in process equipment and integrated manufacturing technologies, including large-scale electrolyte production, continuous fabrication of large-area solid electrolyte films, and battery assembly. Financially, the high R&D and industrialization costs demand substantial capital investment, posing challenges for enterprises with limited resources. Market-wise, the industry suffers from overcapacity in low-end segments and insufficient high-end production, coupled with low consumer awareness and acceptance. To address these issues, enterprises are adopting multifaceted strategies. Domestically, companies like CATL and BYD are increasing R&D investment to launch innovative solid-state battery products, enhancing technological competitiveness. Collaborative efforts with academia, such as Beijing Weilan New Energy's partnership with the Institute of Physics, Chinese Academy of Sciences, accelerate technology transfer. International collaborations further introduce advanced expertise. Additionally, industrial ecosystem optimization is prioritized, with key regions developing specialized solid-state battery supply chains. In China, a relatively complete industrial chain has emerged, synchronizing upstream and downstream enterprises to reduce costs, promote scale-up, and strengthen overall industry competitiveness.

5 Contributions and Innovation Points of Postgraduates in Solid - State Battery Research

5.1 Research Theme Distribution and Trends

Postgraduates' research themes in solid - state batteries are diverse, spanning material synthesis, battery performance, interface science, and new system design. In material synthesis, like Fudan's Prof. Wang Fei's team researching oxide and hydride electrolytes with unique hydride - material studies. Battery performance work may optimize energy density and cycle life via experiments and simulations. In interface science, postgraduates aim to enhance electrolyte - electrode interfaces. New system design focuses on novel structures or material combinations for different applications. As time goes by, with technological and market changes, more postgraduates may focus on new electrolyte materials and interface optimization for high - energy, safe, and long - cycle batteries.

5.2 Analysis of Typical Innovative Research Cases

Take Prof. Wang Fei from Fudan University. His research targets low ionic conductivity and dendrite growth in solid - state batteries. By adjusting electrode - electrolyte material formulas, the innovation lies in in - depth hydride electrolyte research. This material is stable with metallic lithium, has good processability and low cost. It helps understand the hydride system and dendrite growth, offering theoretical support for safe and cost - effective solid - state batteries. The achievements can improve battery performance and safety by enhancing interface contact and suppressing dendrites. Future research could explore hydride system optimization and dendrite - inhibition mechanisms.

5.3 Influence of Postgraduate Training Mode and Scientific Research Environment

Foreign universities often emphasize students' independent exploration and innovation, with multidisciplinary curricula, rich research project opportunities, and flexible tutor guidance. Domestic universities focus on solid basic - theory learning, practical projects tied to domestic industries, and close - knit tutor guidance.

Adequate research funds provide better experimental conditions and resources, enabling in - depth research. Good facilities support diverse experiments, boosting efficiency. A vibrant academic exchange atmosphere helps postgraduates grasp frontiers, expand ideas, and promote cooperation. To optimize the research environment, suggestions include increasing research funds, improving facilities, encouraging participation in domestic and international academic exchanges, strengthening university - enterprise cooperation, and establishing a more flexible tutor guidance system.

6 Comparison and Analysis of Domestic and Foreign Research

6.1 Differences in Research Directions

6.1.1 Enterprise Research and Development Direction Differences

Foreign enterprises lead in basic material R&D and high-end manufacturing for solid-state batteries, with Japanese firms like Toyota excelling in sulfide electrolyte research and 欧美 companies advancing in production technologies. Their strength lies in decades of expertise, early electronics industry development, and strong policy support for high-risk R&D. In contrast, domestic enterprises, such as CATL, BYD, Tao Energy, and Weilan New Energy, focus on application innovation and industrialization, integrating solid-state batteries into new energy vehicles and driving large-scale production through improved manufacturing and supply chain collaboration. This dual advantage—foreign expertise in foundational research and domestic prowess in application and industrialization—highlights the complementary strengths shaping the global solid-state battery landscape.

6.1.2 Postgraduate Research Direction Differences

Research Focus and Tendencies: Foreign postgraduates demonstrate a strong inclination toward interdisciplinary research and exploration of cutting-edge theories. Their work often integrates knowledge from multiple disciplines, such as materials science, chemical engineering, and physics, to investigate fundamental scientific principles and innovate in areas like the theoretical design of new materials and breakthroughs in performance limits. In contrast, domestic postgraduates prioritize addressing industrial needs and advancing applied technology. Their research is more closely aligned with practical industrial demands, focusing on improving performance metrics such as energy density and cycle life, optimizing production processes, reducing costs, and enhancing safety in fields like new energy vehicles and energy storage.

Influencing Factors and Mechanisms: The foreign education system emphasizes comprehensive quality and innovation, fostering a culture of academic freedom and interdisciplinary exploration. This provides postgraduates with a relaxed research environment conducive to pioneering theoretical advancements. In contrast, the domestic education system is closely tied to rapid industrial development, emphasizing the cultivation of practical problem-solving skills. Domestic postgraduates are guided to align their research with industrial applications, supported by scientific projects that are often industry-driven, thereby promoting a focus on applied technology research and development.

6.2 Evaluation of Technological Level Gap

6.2.1 Comparison of Key Technical Indicators

In terms of energy density, some foreign enterprises have achieved relatively high results in the laboratory stage. For example, Toyota claims that the energy density of its solid - state battery experimental prototype product can reach 400 watt - hours per liter. Domestic enterprises such as GAC Aion expect to launch all - solid - state batteries with an energy density of 400 Wh/kg in 2026 and are constantly striving to catch up with the advanced level of foreign countries in the actual mass production process.

In terms of cycle life, the endurance test of the Quantum Scape solid - state battery by the subsidiary of Volkswagen Group shows that it can achieve an ultra - long life of 500,000 kilometers and still maintain 95% capacity after 1000 charge - discharge cycles. Domestic enterprises such as Geely and Weilan New Energy's jointly developed solid - state battery can maintain a retention rate of 86% after 800 cycles, and there is still a certain gap with foreign countries in cycle life.

In terms of safety performance, although solid - state batteries themselves have relatively high safety, both domestic and foreign enterprises are constantly improving to ensure higher safety standards. For example, domestic enterprises are conducting technological innovation in battery thermal management systems and battery safety testing to improve the safety of the battery under various working conditions.

In terms of cost control, the current cost of solid - state batteries is relatively high. Foreign enterprises focus on reducing costs through technological innovation in the research and development process, such as optimizing material preparation processes. Domestic enterprises reduce costs through large - scale production and industrial chain integration. For example, enterprises such as BYD optimize battery material procurement, production and manufacturing and other links to improve cost - effectiveness.

6.2.2 Root Causes and Impacts of the Technological Level Gap

The differences in solid-state battery development between foreign and domestic contexts stem from several root causes. Firstly, foreign countries and enterprises, such as those in Japan, have consistently invested significant time and capital into basic research, with governments and industries jointly supporting long-term projects. In contrast, although China has increased its investment in recent years, its early-stage basic research in this field was relatively weak. Secondly, foreign enterprises have established dominance in core technologies, such as solid electrolyte material development and battery structure design, building technical barriers through extensive patent portfolios. Domestic enterprises, however, still face challenges in breaking through certain core technologies, such as the mass production of solid electrolytes with high ionic conductivity. Thirdly, foreign industrial chains, particularly in Japan and South Korea, exhibit strong collaborative innovation, with close coordination across material development, battery manufacturing, and vehicle applications. While China's industrial chain is relatively complete, the efficiency of collaborative innovation needs improvement, and the depth and breadth of cooperation between upstream and downstream enterprises require further expansion. These disparities have significant impacts on the industry, as foreign enterprises, leveraging their technological advantages, dominate the high-end market and international competition, holding greater influence in areas such as technical standard-setting. Domestic enterprises maintain a presence in the mid-to-low-end market but face challenges in competing in the high-end product segment and international markets. To narrow this gap, strategies include increasing investment in basic research, enhancing the independent innovation capabilities of enterprises, improving the efficiency of industrial chain collaboration, and strengthening international cooperation.

6.3 Technological Exchange and Cooperation

6.3.1 Current Situation and Positive Effects

International academic conferences provide a communicatible platform for experts, scholars and enterprise representatives in the field of solid - state batteries. For example, at the International Battery Technology Symposium, researchers from various countries share the latest research achievements, frontier technologies and innovative ideas, which promotes knowledge dissemination and stimulates new research ideas and cooperation opportunities. It helps domestic and foreign enterprises and research institutions understand the global development trend of solid - state battery technology.

Joint scientific research projects between domestic and foreign enterprises, universities and scientific research institutions realize resource sharing and complementary advantages. For example, a Chinese university cooperates with a foreign enterprise to carry out a solid - state battery material research and development project. The Chinese side provides scientific research talents and some experimental facilities, and the foreign side provides advanced technologies and research and development experience. They jointly overcome technical difficulties, accelerate the transformation of scientific research achievements and improve the technical level of both sides in the field of solid - state batteries.

Technology transfer helps domestic enterprises quickly acquire foreign advanced technologies and improve their technical strength. The cooperative development model enables both parties to jointly invest resources and cooperate in product research and development, market expansion and other aspects. For example, domestic and foreign enterprises cooperate to develop new solid - state battery products and jointly explore the international market, improving the global market competitiveness of both parties.

6.3.2 Obstacles and Challenges and Coping Measures

Cross-border technological collaboration in solid-state batteries faces challenges in intellectual property (IP) protection, technical standardization, and cultural differences. Varied IP laws across countries pose risks of infringement and disputes, necessitating robust coordination mechanisms, clear ownership agreements, and enhanced IP management. Additionally, divergent technical standards—such as inconsistent performance testing and product specifications—hinder compatibility and mutual recognition. Addressing this requires global alignment through international organizations and industry consortia to establish unified standards. Cultural disparities in communication styles, work habits, and decision-making processes further impede efficiency. Proactive measures, including cross-cultural training and exchange programs, can foster mutual understanding and streamline collaboration. Resolving these issues collectively strengthens trust, reduces barriers, and facilitates effective international cooperation.

7 Challenges and Future Prospects of Solid - State Battery Research

7.1 Technical Bottlenecks

7.1.1 Key Technical Problems in the Field of Materials Science

Enhancing ionic conductivity and stability in solid electrolytes remains a key challenge. Sulfide electrolytes exhibit high ionic conductivity but suffer from poor chemical stability, reacting with electrodes and degrading battery lifespan. Oxide electrolytes, while chemically stable, often lack sufficient conductivity, and efforts to improve conductivity frequently compromise structural integrity. Additionally, electrode-electrolyte interface compatibility is hindered by interfacial resistance and volume changes during cycling, which cause separation or cracking. Current methods lack precision in controlling interface composition and structure to mitigate these issues, underscoring the need for advanced material and interfacial engineering.

7.1.2 Technical Bottlenecks in the Manufacturing Process

Controlling material uniformity in large-scale production remains a significant challenge for solid-state batteries, as their performance is highly sensitive to material consistency. Uneven material distribution can cause localized reactions, impacting battery performance and safety. For instance, in solid electrolyte film preparation, non-uniform distribution leads to variations in ion conduction paths, resulting in performance fluctuations. Current processes struggle to ensure high uniformity at scale.

Additionally, thin-film preparation requires further optimization. High-quality solid electrolyte films are crucial, but existing methods face issues. Physical vapor deposition can introduce defects, while solution casting often results in cracks during drying, compromising film integrity and performance. Precise thickness control also remains a challenge, as improper thickness adversely affects battery performance.

Lastly, battery assembly precision needs improvement. Solid-state batteries require tight component contact and sealing, but current processes often fall short. Gaps between electrodes and electrolytes increase contact resistance, while inadequate sealing allows external moisture and oxygen to degrade battery structure and performance.

7.2 Market and Policy Environments

7.2.1 Market Environment Factors Facing Commercialization and Promotion

Market demand for solid-state batteries is uncertain due to high costs and limited technological maturity. While electric vehicles and energy storage systems show potential, solid-state batteries struggle to meet consumer expectations in range, charging time, and cost, delaying large-scale adoption.

Consumer awareness and acceptance remain low. Traditional lithium-ion batteries dominate, and solid-state batteries' advantages are not widely known. Concerns about safety, performance, and lifespan may hinder adoption.

Competition is intense. Lithium-ion batteries continue to improve in energy density and cost, while alternatives like sodium-ion batteries and hydrogen fuel cells also vie for market share, creating significant challenges for solid-state battery commercialization.

7.2.2 Policy Support Systems of Governments of Various Countries

Governments support solid-state battery research through subsidies. For instance, Japan funds enterprises and institutions to advance the technology, reducing costs and accelerating innovation. Industrial policies also drive growth. South Korea, for example, collaborates with local firms, planning significant investments by 2030 to develop solid-state batteries and build a competitive industrial chain, fostering scale expansion and talent development. Additionally, governments participate in setting technical standards to regulate the market. Unified standards enhance product quality, facilitate international cooperation, and ensure industry health.

7.3 Future Development Trend Forecast

7.3.1 Forecast of Technological Breakthrough Directions

Breakthroughs in solid electrolyte materials are expected to focus on organic-inorganic composites, leveraging the synergistic benefits of both components to achieve high ionic conductivity, stability, and interfacial compatibility. Advances in molecular design and composite fabrication may address current limitations. Concurrently, electrode innovation will prioritize higher energy density and cycle life. Silicon-based anodes, despite challenges like volume expansion, could see advancements through nano-structuring and composite modifications, while high-voltage cathodes will be tailored to meet solid-state battery requirements. Additionally, battery integration technologies will advance, particularly in intelligent management systems for real-time state monitoring and thermal regulation. Enhanced thermal management and precision control systems are anticipated to improve safety, efficiency, and lifespan, driving the commercialization of next-generation solid-state batteries.

7.3.2 Prospect of Future Application Field Market Development

The market for solid-state batteries in EVs is set to expand quickly. Technological leaps in energy density, charging time, and cost will boost their competitiveness. They're expected to replace some lithium-ion batteries and become the mainstream, driving companies to invest more and expand production. Leading firms will gain a larger market share.

Demand for solid-state batteries in storage systems will keep rising. Their high safety and long cycle life suit large-scale storage. With renewable energy growth, they'll be crucial. Tech progress will cut costs and improve performance, expanding uses like distributed storage and peak shaving.

Solid-state batteries fit wearable needs for small, flexible, and high-energy designs. Future wearables like smartwatches will widely use them. Tech advances will make them smaller, lighter, and more stable, powering wearable growth.

8 Conclusions

8.1 Research Summary

Domestic and foreign entities have made significant research progress in solid-state batteries. Foreign firms like Toyota and Samsung SDI have distinct R&D focuses. Toyota leads in sulfide electrolyte R&D and aims for vehicle use by 2030. Samsung SDI is active in sulfide and polymer battery tech and plans mass production in 2027. European firms favor polymer electrolytes. Domestically, traditional battery companies like CATL and BYD are evolving. CATL has diverse solid-state products, and BYD targets energy density via silicon. Newer firms like Tao Energy and Weilan New Energy are emerging. Tao Energy built an industry chain and a major project. Weilan New Energy mass-produces batteries and developed key tech. Foreign enterprises emphasize basic materials and high-end processes, while domestic ones excel in application innovation and industrialization. Research spans various areas. Solid-state batteries are in R&D and small-scale production, with efforts to overcome hurdles and industrialize. This review aids in understanding the field for decision-making and investment.

8.2 Deficiencies and Prospects

This review research has some deficiencies. In terms of literature retrieval, there may be omissions of some relevant research literatures, resulting in the failure to fully cover some research achievements. Some research achievements are limited by timeliness. The field of solid - state batteries is developing rapidly, and new research achievements and progress are constantly emerging. Some early - collected data and information may not be able to timely reflect the current latest trends. For some emerging research directions, such as some niche but promising directions in new solid electrolyte materials, the analysis is not in - depth enough. The case studies of some emerging enterprises are not comprehensive enough, and the unique experiences and potential values in technological innovation and industrialization process have not been fully explored. In the future, we should continuously track the latest research progress in the field of solid - state batteries, update research data and information in a timely manner to ensure the timeliness of the research content. Strengthen the attention and research on emerging technologies, such as new battery structure design and advanced manufacturing processes, and emerging enterprises, and deeply analyze the innovation models and development paths. Expand research methods and perspectives, for example, adopt interdisciplinary research methods to comprehensively analyze the problems in the field of solid - state batteries from multiple perspectives such as materials science, chemical engineering, physics and economics, and provide more comprehensive and in - depth research results for the development of solid - state batteries.

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