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Industrial Synergy Among New Productive Forces: Insights from the Evolution of Solid-State Battery Technology for the Development of Green Energy Equipment

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Abstract: In the context of accelerated global green and low-carbon transformation, solid-state batteries, as a core breakthrough point in next-generation energy storage technology, are not only reshaping the landscape of the new energy industry chain through technological iteration and industrialization but also serving as a typical sample for observing the formation mechanism of new productive forces. Based on the theoretical framework of industrial synergy, this paper analyzes the interactive mechanism between technological evolution in the solid-state battery field, industrial ecology construction, and the upgrading of green equipment in the manufacturing industry. The research shows that the deeply integrated innovation consortium of government, industry, academia, research, and application drives the industrial chain to shift from single-point innovation to systematic synergy by breaking through key technological bottlenecks such as mass production of solid electrolytes and solid-solid interface optimization. This provides a new path for the lightweighting, high safety, and low-carbon development of green energy equipment in the manufacturing industry. Facing the challenges of cost, standards, and ecological synergy, it is necessary to build a trinity system of "technological breakthroughs — scenario innovation — financial support" to accelerate the value transformation of new productive forces in the field of green manufacturing.

Keywords: Solid-state batteries; Green energy equipment; Industrial synergy; Industrial chain innovation

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1. Introduction

Developing new productive forces is an inherent requirement for high-quality economic development in China, with its core being technological innovation leading industrial transformation. Currently, the global green transformation of the manufacturing industry has entered a deep stage. Energy storage technology innovations represented by solid-state batteries, with their advantages of high energy density, inherent safety, and wide temperature range performance, are reshaping the ecology of the new energy industry chain and providing underlying support for the upgrading of green equipment in the manufacturing industry. According to authoritative predictions, the global solid-state battery market size will exceed 250 billion yuan by 2030, with a compound annual growth rate of 32%–44%. China is expected to occupy more than 35% of the global market share. Under this new situation, exploring the interactive mechanism between solid-state battery technology innovation and industrial synergy not only has strategic significance for the new energy industry itself but also provides important insights for manufacturing enterprises to explore development paths for green energy equipment.

2. Theoretical framework

2.1. Theoretical connotation of new productive forces in the field of energy equipment

The essence of new productive forces is an advanced qualitative state of productive forces that is dominated by technological innovation and achieves efficient allocation of key elements. In the field of green energy, its core manifestation lies in breaking through the performance boundaries of traditional energy equipment (such as energy density, cycle life, and environmental adaptability) through disruptive technologies, and achieving dynamic adaptation of technology-market-capital with the help of industrial synergy. Compared with traditional productive forces, new productive forces place greater emphasis on knowledge spillover effects and industrial chain resilience. For example, artificial intelligence accelerates the research and development cycle of solid-state battery materials, improving research and development efficiency by 1-2 orders of magnitude [1].

2.2. Mechanisms of industrial synergy driving technological innovation

Innovation in green energy equipment is highly dependent on cross-industry technological integration:

Vertical synergy: Upstream material innovation (such as solid electrolytes) drives midstream battery process innovation (dry electrode processes), which in turn expands downstream application scenarios (pure electric vehicles, eVTOL aircraft, and other new energy equipment).

Horizontal synergy: Wind, photovoltaic, hydrogen, and storage multi-energy complementary systems rely on battery storage to achieve fluctuation suppression. In 2024, the Power Construction Corporation of China's Jimo offshore photovoltaic project will be coupled with the province's largest green hydrogen production device, forming a "photovoltaic-storage-hydrogen" closed loop.

3. Development status and industrial characteristics of solid-state battery technology

3.1. Comparison of technical routes and iterative trends

Solid-state batteries completely replace liquid electrolytes with solid electrolytes, fundamentally addressing the risk of thermal runaway and supporting the application of lithium metal anodes. The theoretical energy density can reach over 500 Wh/kg, far exceeding the current level of 200–300 Wh/kg for liquid lithium batteries. Based on differences in electrolyte material systems, the mainstream technical routes present a "three-pillar" structure.

Sulfide electrolytes: These have the highest room temperature ionic conductivity ($>10^{-2}$ S/cm), which is close to the performance of liquid electrolytes, and they exhibit good mechanical ductility and low interfacial impedance. However, they are sensitive to water and oxygen, can easily produce toxic hydrogen sulfide, and have high raw material costs. The highly air-stable sulfide electrolyte developed by Zhongke Guneng has solved the problem of material environmental tolerance, and its 100-ton production line is expected to start production at the end of 2024, making it the world's first 100-ton and above sulfur-based solid electrolyte production line.

Oxide electrolytes: These exhibit excellent thermal stability (decomposition temperature >600°C), a wide electrochemical window, and compatibility with high-voltage cathode materials. However, their room temperature conductivity is relatively low (10^{-5}~10^{-6} S/cm), and rigid interfacial contact is poor. Tai Lan New Energy has optimized interfacial contact through a separator-free design, promoting the industrialization of the oxide route.

Polymer electrolytes: These have good processing performance and controllable costs, but they require heating to above 60°C to function normally, and their energy density is limited. BAK Battery adopts a "polymer + oxide" composite route, controlling liquid electrolyte residues to 1%–10% through in-situ solidification technology, balancing performance and cost.

3.2. Overview of global solid-state battery enterprises

The global competition landscape mainly consists of three camps: China, Japan/South Korea, and Europe/America. Japan, South Korea, Europe, and America started early and have intensified research and development efforts in all-solid-state batteries, intending to change the current situation where they lag behind China in liquid lithium batteries. There are many participants in the Chinese market, where leading automobile enterprises and battery enterprises closely cooperate to jointly promote the industrialization process of solid-state batteries.

Globally: Japan has been cultivating the field of all-solid-state batteries for many years, with continuous acceleration of technological innovation and gradually clear mass production timelines. It is currently in a leading position in technology. South Korea has continuously invested in research and development and has begun to build all-solid-state battery production lines. LG and Samsung in South Korea are in advantageous positions. The United States is dominated by start-up companies, and American automakers mainly acquire and invest in start-up battery manufacturers to obtain technological reserves. Representative enterprises include Solid Power, Quantum Scape, and Ionic Materials.

Domestically: Start-up enterprises that have spun off from leading academic talent teams and take solid-state battery research and development and production as their main business, such as Weilan New Energy and Qingtao Energy. Leading enterprises in the traditional lithium battery industry chain include BYD, CATL, Ganfeng Lithium, EVE Energy, Farasis Energy, SVOLT Energy Technology, and Guoxuan High-Tech.

3.3. Industrialization process and collaborative model innovation

The existing solid-state battery industrialization presents a gradual penetration path of "military/aviation → high-end passenger cars → mass market." According to the timeline recently announced by leading enterprises, all-solid-state batteries will start small-batch loading around 2027 and enter the stage of large-scale mass production in 2030 [2]. In this process, the Chinese industry chain accelerates technological transformation through three types of collaborative models.

Deep integration of industry, university, research, and application: The Wu Fan team from the Institute of Physics of the Chinese Academy of Sciences, together with Zhongke Guneng, has achieved the leap from sulfide electrolyte in the laboratory (with more than 100 top journal papers and over 60 patents) to a 100-ton production line. The Central Research Institute and production base collaborate to promote material research and development and smart manufacturing technology. The Academician Ouyang Minggao Workstation, together with multiple parties including "government, industry, university, research, and finance", has established an innovation consortium. Through AI big models, material screening is accelerated, improving research and development efficiency by 1–2 orders of magnitude and saving 70%–80% of research and development costs.

Vertical integration of the industry chain: CATL has built a full-chain capability of "sulfide electrolyte—high-nickel cathode—lithium metal anode" with the goal of achieving small-batch production of all-solid-state batteries with an energy density of 500 Wh/kg by 2027. BYD plans to gradually reduce the application cost of high-end models from demonstration loading in 2027 to large-scale mass production in 2030.

Cross-field equipment collaboration: Yifei Laser and Jinyu New Energy have cooperated to develop special equipment for all-tab solid-state batteries. Through high-dynamic laser processing technology, the electrode coating process is optimized, improving the production line yield of solid-state batteries to over 90% and solving the problems of interface impedance and electrolyte residue control.

Table 1. Mass production timeline and performance targets of solid-state batteries for major enterprises

Company	Mass production start year	Technical route	Target energy density	Application field
CATL	2027	Sulfide, Polymer	500 Wh/kg	High-end electric vehicles
BYD	2030	Undisclosed	>400 Wh/kg	High-end & mainstream vehicles
Changan Auto	2027	Oxide	400 Wh/kg	High-end passenger vehicles
Toyota	2027–2028	Sulfide	>700 Wh/kg	Pure electric vehicles
BAK Power	2025 (semi-solid-state)	Polymer, Oxide	390 Wh/kg	Explosion-proof equipment, eVTOL

4. Collaborative needs of the green energy equipment industry

4.1. Policy-driven solid-state battery technology and industrial implementation

Both the "Made in China 2025" plan issued by the State Council and the "New Energy Vehicle Industry Development Plan (2021–2035)" emphasize the low-carbon development of the automotive industry through the promotion of electric vehicles. The battery industry is urged to conduct research on key core technologies such as positive and negative materials, electrolytes, separators, and membrane electrodes. Additionally, efforts should be made to strengthen technological breakthroughs in high-strength, lightweight, high-safety, low-cost, and long-life power batteries and fuel cell systems, and to accelerate the research, development, and industrialization of solid-state power batteries. It is estimated that battery energy density will reach 400 Wh/kg by 2025 and 500 Wh/kg by 2030.

Since 2020, various departments, including the National Development and Reform Commission, the National Energy Administration, and the Ministry of Industry and Information Technology, have issued policies to promote the development of the battery industry. These policies aim to accelerate the research and development of solid-state batteries, strengthen the study of solid-state battery standard systems, and expedite the deployment of new energy storage batteries, new energy general aviation power technology, and equipment fields [3]. Government-funded basic research projects are also open to support different technical routes, such as polymers and sulfides, encouraging qualified enterprises to conduct research and development related to all-solid-state battery technologies, covering the entire chain from basic research to application development.

4.2. Low-altitude economic equipment and new energy vehicles

Low-altitude economic equipment, such as eVTOL aircraft, requires a battery energy density of ≥300 Wh/

kg and has special requirements for battery volume and weight. Similarly, in the new energy vehicle market, the penetration rate of pure electric vehicles is increasing year by year. However, commonly used lithium iron phosphate and ternary batteries still cannot meet the market demand for long battery life, high safety, and fast charging speed. These pain points will be gradually resolved with breakthroughs in solid-state battery technology, driving the development of related equipment industries and upstream and downstream equipment in the battery industry chain.

4.3. New power systems

Clean energy sources such as wind, solar, and hydrogen energy can rely on battery storage to stabilize power transmission and grid integration. Conventional liquid and semi-solid batteries have limitations in terms of charge-discharge cycles, lifespan, safety, and specific capacity, making them suitable only as auxiliary means of regulating the power grid. However, with the maturation of solid-state battery technology, it is expected to reduce the cost per kilowatt-hour while improving the basic performance of batteries mentioned above. This will greatly expand the application of chemical batteries in the field of energy storage and enable their widespread use as a safe, stable, and efficient method of power grid regulation.

5. Enlightenment for the green development of the manufacturing industry

5.1. Driving equipment performance improvement

The high safety and high energy density characteristics of solid-state batteries provide core support for the lightweight and long-lasting performance of green equipment:

Aerospace and low-altitude economy: eVTOLs (Electric Vertical Take-Off and Landing aircraft) require battery energy density >400 Wh/kg and absolute safety. Ganfeng Lithium has developed a 500 Wh/kg-class all-solid-state battery and has delivered verification samples to eVTOL companies. Its 10Ah-class battery cell supports operation in extreme environments from -40°C to 200°C. Sunwoda plans to launch a 500 Wh/kg all-solid-state battery in 2027, significantly improving aircraft range and economy.

Engineering machinery and construction robots: Hefei Li-ion Battery Innovation Center has customized a 350 Wh/kg solid-state battery pack for construction robots, which reduces weight by 40%, supports high-rate discharge and fast charging, and solves the bulky and safety risk issues of traditional lithium batteries in heavy equipment.

Grid energy storage systems: NARADA released a 783Ah ultra-high-capacity solid-state battery with a cycle life of over 10,000 times and a volumetric energy density of >430Wh/L, contributing to cost reduction and efficiency improvement in energy storage systems.

5.2. Creating a new green manufacturing model

The industrialization of solid-state batteries promotes the transformation of the manufacturing industry towards "zero-carbon manufacturing" and "smart factories."

Low-carbon production processes: The 1 GWh solid-state battery project of Dejia Energy in Huzhou adopts fully physical energy storage technology, reducing production energy consumption by 30% and thermal runaway risk by 90% compared to liquid batteries, achieving a wide temperature range application from -40°C to 80°C.

Intelligent production line upgrades: The new processes required for solid-state batteries, such as electrode sheet forming and multi-layer stacking, drive equipment companies to develop specialized technologies. Yifei Laser's solid-state battery cell assembly and module pack system integrates laser micromachining and closed-loop quality monitoring, providing an example for upgrading traditional battery production lines.

Innovative circular economy model: The increasing proportion of precious metals such as lithium and cobalt in solid-state batteries promotes the establishment of a "material recovery-regeneration-reuse" closed loop. Academician Ouyang Minggao's team has suggested advanced planning for solid-state battery recycling standards and building a key material recycling network [4].

6. Market prospect analysis and suggestions for industrial collaboration and optimization

6.1. Market prospect analysis

The global market scale of the solid-state battery industry is showing an exponential expansion trend. According to the latest industry data, the global solid-state battery market size is expected to reach US$18 billion (approximately RMB 120 billion) by 2025, with China accounting for 48% of the global market, becoming the largest single market and exceeding RMB 57 billion in size.

The core growth drivers come from three major areas: Firstly, new energy vehicles, where the demand for solid-state batteries in the electric vehicle sector is expected to exceed 30GWh by 2025, accounting for 70% of the overall demand, and the penetration rate of high-end models will exceed 15%. Secondly, the low-altitude economy, where the eVTOL aircraft market is expected to reach a scale of RMB 1.5 trillion by 2025. Solid-state batteries account for 10%–20% of aircraft costs and need to meet energy density requirements of over 300 Wh/kg. Thirdly, energy storage systems, where the global energy storage market will exceed US$150 billion by 2025. Solid-state batteries are accelerating penetration due to their inherent safety, and three major solid-state battery energy storage projects in China have already started bidding with procurement demands exceeding 412 MWh.

Currently, development bottlenecks are focused on three aspects: cost pressure, lack of standards, and insufficient ecological collaboration. The material cost of all-solid-state batteries reaches RMB 2/Wh, which is 3–5 times that of liquid batteries. Sulfide electrolyte precious metals account for a high proportion, and large-scale cost reduction relies on industrial chain collaboration. Solid-solid interface impedance testing methods and thermal runaway evaluation systems are not yet unified, restricting product certification and market promotion. The technical routes of materials, cells, and equipment enterprises are scattered. For example, the oxide route requires special sintering equipment, which has low compatibility with existing production lines.

6.2. Suggestions for industrial collaboration and optimization

Build a trinity system of "technological breakthroughs—scenario innovation—financial support":

At the technical level, universities should strive for national special technology fund support based on their technological research and development capabilities, cooperate with mature industrial application enterprises, and jointly establish solid-state battery innovation centers. These centers should promote the rapid industrialization of scientific and technological achievements such as solid electrolytes, cathode materials, and solid-solid interface technologies. Additionally, they should reduce usage costs through production equipment improvements, production efficiency enhancements, and yield improvements.

At the scenario level, through policy guidance, implement solid-state battery application demonstration projects in emerging fields such as new energy vehicles, energy storage systems, and the low-altitude economy. This will provide a transformation platform for product applications from experimentation to mature mass production, driving the growth of market demand.

At the financial level, utilize ultra-long-term special national debt to provide investment subsidies for various stages of solid-state battery technology breakthroughs, from research and development to mass production (such as the 2025 national special policy). Establish risk compensation funds to share the research and development risks of start-up enterprises.

To build an industrial ecological alliance, form a "material-cell-automobile enterprise-equipment" consortium to promote the localization of core equipment. Provide targeted support for key equipment such as coating machines and hot press forming equipment in battery material production to achieve localization and replacement. Take the lead in formulating safety testing (such as needle puncture and thermal runaway) and cycle life evaluation standards for solid-state batteries, promote the internationalization of Chinese solutions, and establish international standard discourse power.

7. Summary and outlook

The iteration of solid-state battery technology is not only a revolution in the field of energy storage but also a vivid practice of new productive forces in green manufacturing. Through deep collaboration between government, industry, academia, research, and application, China has made breakthrough progress in key areas such as solid electrolyte research and development, mass production, and high-energy-density cell development. This provides solid support for the lightweight, high-safety, and low-carbon development of green energy equipment in the manufacturing industry. With continuous technological breakthroughs in the battery industry in recent years and the accelerating industrialization of solid-state batteries, it is necessary to further strengthen the closed-loop ecological construction of "material innovation—equipment upgrading—scene application" and transform technological advantages into market competitiveness.

There are two issues that need to be addressed in the collaborative development of the battery industry chain in the future. Firstly, the technical barriers for electrolytes in solid-state batteries are high, and upstream manufacturers producing all-solid-state electrolytes have strong bargaining power. Balancing innovation incentives and the efficiency of industrial chain cooperation is key to the healthy and benign development of the industry. Secondly, different technical routes for solid electrolytes and cathode materials have flourished in recent years. Grasping the direction of future technological maturity and achieving industrial breakthroughs pose significant opportunities and challenges for equipment manufacturing enterprises that are preparing to enter the market. As Academician Ouyang Minggao said, "The market share of all-solid-state batteries does not need to reach 50%. Replacing just 1% is a breakthrough significance" [5]. This process will not only reshape the energy industry landscape but also provide a replicable collaborative innovation paradigm for the green transformation of the manufacturing industry.

Disclosure statement

The author declares no conflict of interest.

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