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Development of Lithium and Its Downstream Power Battery Industry Chain in China

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Abstract: The high-quality development of lithium resources and their corresponding downstream power battery industrial chains is crucial for the steady development of strategic emerging industries and China's economic transformation. Therefore, the implications of lithium development and adoption of its downstream power battery industrial chain, which comprises resource exploration, smelting processing, key materials and products, and recycling, were analyzed in this study. Subsequently, the necessity for the high-quality development of a relevant industrial chain was investigated and its basic situation analyzed. Owing to natural and ecological constraints, the expansion of domestic lithium ore production is restricted, resulting in a sharp increase in China's import risk because of the international competition for limited resources. Moreover, the core patents on technologies such as cathode materials and electrolytes are monopolized by foreign companies, a gap still exists between domestic and international standards for key materials and battery technology, the accumulation of emerging technologies is insufficient, the secondary recycling system for waste power battery resources is incomplete, and the industrial order needs to be regulated. Therefore, stage development goals for 2025 and 2035 were proposed focusing on the high-quality development of lithium and its downstream power battery industry chains. The proposed construction path was structured around the innovation of key materials and products including the construction of a safe and stable resource supply system using multiple dimensions, development of key materials and new battery technologies by improving the lithium battery technology system and talent reserves, and promoting the coordinated development of all links in the industrial chain. Consequently, the following suggestions were proposed: (1) improving the top-level design to form an integrated management model of the entire industry chain, (2) increasing the financial support to enable the mutual promotion of basic and applied research, (3) encouraging cooperation among the enterprises in the upstream and downstream links to enhance the synergistic effect of the industrial chain, and (4) improving industry–university–research cooperation to cultivate interdisciplinary talent in the industrial chain.
Keywords: lithium; power battery; industrial chain; high-quality development

1 Introduction

The development of lithium batteries as an important carbon reduction option has been rapidly increasing owing to the worldwide pressure to reduce carbon emissions. In addition, China's lithium consumption has maintained a high growth rate in recent years (average annual growth rate of 24%) owing to the rapid development of the new energy vehicle industry, with a lithium consumption of 2.29×10^5 t (calculated by lithium carbonate equivalent) and sales of 80 GW·h of on-board power batteries to dealers in 2020 [1]. Presently, China is the largest lithium consumer, downstream materials producer, and battery producer worldwide. Various related industries are in the early stages of this accelerated rise and have a major strategic opportunity to participate in the international competition for lithium.

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To support the orderly development of China's automotive power battery industry, the Ministry of Industry and Information Technology, National Development and Reform Commission, and other departments have issued policies and specific requirements to be implemented by 2025 based on various factors influencing power battery products such as their performance and safety, industrial scales, key materials and components, and intelligent production equipment to implement the gradual utilization of power batteries, establish a whole lifecycle traceability system that promotes the efficient recycling of resources, and clarify the responsible organizations for power battery recycling and maintenance of the power battery coding system [2,3]. In terms of the academic and industrial research, several studies have been conducted on lithium and its downstream power battery industry chain. Considering resource exploration, the progress of resource exploration in lithium-rich areas in Sichuan Province, the quality of the lithium resources in the national salt lake, and the current status of the beneficiation process and development have been summarized [4–7]. Considering smelting and processing, the development scale of various types of processed lithium salts and development of enterprises were analyzed [8]. Considering the key materials and battery products, a comparison of the status of key materials used domestically and internationally in research and development (R&D) technology was completed and the problems facing the development of key materials in China analyzed to propose target tasks for 2035 [9–11]; Moreover, the production processes and technology paths of links in the lithium industry chain and leading enterprises were investigated [12]. However, a lack of research on the tandem nature of lithium and its downstream power battery industry chain still exists in the available literature, making the high-quality development of lithium and the power battery industry chain necessary.

Based on this necessity, the composition of the industry chain, including resource exploration, smelting and processing, key materials and products, and recycling, was studied to identify the problems and the objectives, explore the path influencing the innovation of key materials and products, and propose countermeasures for the development of this research in related industries.

2 Implications of lithium development, composition of power battery industry chain, and necessity for high-quality development

2.1 Implications of the development of lithium and power battery industry chain

Industrial chains refer to the complete chain of production from raw materials to end-product manufacturing. This, in essence, represents the relationship between supply and demand as well as input and output of each industry; it is also the image representation of the close relationship between the industrial sectors based on technical and economic links [13,14]. In this study, the development of lithium and its downstream power battery industry chain was divided into four links: mineral resources, smelting and processing, key materials and products, and recycling, which are interlinked, mutually-constrained, and interdependent, with products, production technologies, investments, and other related methods [15].

Resource exploration mainly refers to the exploration and mining of lithium, which involves the development and utilization of different lithium resource types such as spodumene, lepidolite, and salt lakes. Resource exploration is at the upstream of the industrial chain, is indispensable for the smelting and processing industry, and is the material basis for forming the whole industrial chain.

Smelting and processing represents the non-ferrous metal smelting and processing of lithium salt, which involves the processing and production of lithium carbonate, lithium hydroxide, lithium hexafluorophosphate, lithium bis(fluorosulfonyl)imide, and other products. The corresponding product scale, production process, product quality, and other conditions restrict the production and development of key materials.

The key materials and products refer to automotive lithium power batteries and the key components required for their production. They include key materials containing lithium, which are mainly ternary cathode materials, iron phosphate cathode materials, and electrolytes. They also include the R&D capabilities of key materials, production technology standards, and other factors that directly affect the performance standards of downstream products. The battery products were mainly divided into ternary power batteries and lithium iron phosphate power batteries, where different technical development lines affect the selection and development of key material types.

Recycling mainly refers to the extraction and reuse of lithium in end-of-life automotive power batteries, which is an effective means of improving the efficiency of resource utilization and directly alleviating the supply problem in the resource exploration stage.

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2.2 Necessity for the high-quality development of lithium and its downstream power battery industry chain

The high-quality development of lithium and its downstream power battery industry chain will be highlighted by the comprehensive, efficient and green utilization of domestic lithium resources, breakthroughs in core technologies for deep-processed lithium salts, the use of key materials and different battery products, quality assurance of various products and technological research, the development of industrial capabilities to international standards, orderly and adequate recycling of end-of-life power batteries, and the smooth circulation of all links in the industry chain. Moreover, the scale and structure of the industry chain should be reasonable, the industry chain should be independently controllable, the scientific and technological innovation should be collaborative, and the shortcoming links should be improved. Therefore, there is an urgent need to accelerate the high-quality development of lithium and its downstream power battery industry chain, as highlighted under the four aspects below.

First, there is a need to achieve a smooth transition from fuel to new energy vehicles and accelerate the reduction in the energy risks. China's oil resources are scarce, with the oil import dependency reaching 72% by 2021. The current energy consumption in China has not yet reached its peak; therefore, if the oil consumption continues to increase, the national energy security risks will be exacerbated. In the transportation sector, the adoption of advanced power batteries can significantly reduce the gap in the driving experience of fuel and new energy vehicles, thereby aiding the smooth transition from fuel to new energy vehicles while simultaneously reducing the oil consumption in the transportation sector and dependence on foreign oil.

Second, the need to enhance the application of new energy power in multiple scenarios to achieve the carbon peaking and carbon neutrality strategic goals. As an energy storage device, high-quality lithium power batteries can make efficient use of new energy sources such as wind, light, and water. It can also be scaled up to meet various requirements for application in the aviation and aerospace fields, ships, and other major equipment, thereby providing a strong baseline for the control of the carbon emission intensity and improving the structure of clean energy use.

Third, the need to accelerate the formation of a new development pattern in which the domestic cycle is the mainstay and the domestic and international cycles are mutually reinforced. Typically, international competition is fierce, and the trend of reverse globalization poses a challenge for the division of labor in international supply chains and cooperation model. Therefore, the only way to effectively cope with international competition and ensure that domestic production and supply are not affected at critical moments is by accelerating the high-quality development of lithium and its downstream power battery industry chain to realize the independent control of the industry chain and enhance the level of self-circulation in the domestic economy.

Fourth, the need to achieve high-quality economic development in China. The lithium industry is an important strategic emerging industry that urgently needs to shift toward the use of middle- and high-end international value chains, and the product structure needs to be based on high technology content and a high value-added system model. Therefore, the industrial chain should be able to support and enhance China's economic development in an efficient manner.

3 China's lithium situation and power battery industry chain

3.1 Resource exploration

China is rich in lithium resources, ranking fourth in the world in lithium reserves (approximately 8×10^6 t) at approximately 7% of the world's total reserves [16,17]. Presently, the world's large-scale lithium resources are mainly salt lakes, spodumene, and lepidolite. Lithium-rich clay has been tested as a potential resource by some enterprises in Mexico, but has not yet been implemented commercially on a large scale. In China, the large-scale lithium resources from salt lakes are mainly distributed in Qinghai Province and Tibet Autonomous Region. Spodumene is mainly distributed in Sichuan Province and lepidolite is mainly distributed in Jiangxi Province. There are also clay-type resources of a certain scale, which have good development prospects.

Compared to the high-quality resources found overseas, domestic lithium resources are characterized by relatively low grades of hard rock, complex compositions in salt lakes, high magnesium-lithium share, and relatively high extraction difficulty. For example, the grade of methyl spodumene in Sichuan Province is 1.3%–1.5%, whereas the grade of Australian Greenbush spodumene reaches 2.1%. The collective proportions of magnesium and lithium in China's salt lakes such as Charkhan, Dachaidan, and Yiliping are 1577, 134, and 90.5, respectively, whereas those in Chile's Atacama Salt Lake and Bolivia's Uyuni Salt Lake are only 6.4 and 18.6%, respectively.

Lithium production in China is growing at a fast rate, but its production is still limited. The average annual growth rate of lithium production in the world between 2015 and 2020 was 20%, whereas China's average annual growth rate for the same period was as high as 45%. China's current production is 7.5 × 10^4 t, representing approximately 17% of the world's total production. Jiangxi and Qinghai provinces are the most important lithium resource producers in China, accounting for 80% of the country's total production. Although the Sichuan Province and Tibet Autonomous Region are rich in resources, production growth in the short term is very limited owing to environmental protection constraints, a harsh alpine and high-altitude environment, and long infrastructure construction cycles.

The domestic resource development market is relatively concentrated, with the top five production companies having a combined share of 93%. The main mining companies are Yichun Tantalum Niobium Mine Co., Ltd., Qinghai Salt Lake Industry Co., Ltd., Western Mining Group Co., Ltd., Ganzi Rongda Lithium Co., Ltd., Qinghai HXR Lithium Tech Co., Ltd., and Tibet Mining Development Co., Ltd.

Compared to overseas mining mines, the extraction and production costs of domestic lithium mines are high. In 2021, the cost of production at one of the world's major lithium mines was less than 2900 USD/t, and the cost of mining high-quality spodumene projects in Australia has not exceed the global average. Currently, the extraction costs of China's Jiangxi Yichun lepidolite, East-West Terrace Genel, and other projects are higher than 3700 USD/t, which is approximately 30% higher than the world average [18].

3.2 Smelting and processing

China produces a wide range of lithium salts and its production is rapidly growing. The average growth rate from 2015 to 2020 was 32%, and the production in 2020 was 2.46 × 10^5 t, accounting for approximately 67% of the world's total production [19]. A basic pattern has been developed of importing large amounts of mineral resources for smelting, processing, and exporting the downstream products produced. The production concentration is high, with the top five enterprises including Jiangxi Ganfeng Lithium Co., Ltd, Tianqi Lithium Co., Ltd., Shenzhen Chengxin Lithium Group Co., Ltd., and Sichuan Yahua Industrial Group Co., Ltd. accounting for more than 80% of the market share [20,21]. The scaling of the production capacity for lithium deep-processing products is still in its expansion stage, but the full capacity has not been utilized owing to the limited incremental supply of imported lithium ore resources.

The new lithium bis(fluorosulfonyl)imide salt (LiFSI) is expected to become an electrolyte for second-generation batteries, and Chinese enterprises are actively investing in this layout. In 2020, Shanghai Chemspec Technology Co., Ltd. and Shenzhen Capchem Technology Co., Ltd. mass-produced the LiFSI. The domestic construction capacity is about 6800 t (accounting for 90% of the world's total production capacity), which is significantly faster than the production capacity overseas.

The production technology and quality of battery-grade lithium carbonate, battery-grade lithium hydroxide, lithium hexafluorophosphate, and other advanced products have reached international standards and are able to meet the supply needs of key downstream material enterprises in China and popular overseas enterprises. For example, battery-grade lithium hydroxide products produced by Jiangxi Ganfeng Lithium Co., Ltd. are used to support international mainstream brands of automotive lithium battery products, and high-purity crystalline lithium hexafluorophosphate products produced by Do-Fluoride New Materials Co., Ltd. are supplied to international mainstream electrolyte companies, such as UBE Co., Ltd. and Soulbrain Co., Ltd.

The lithium salt production process of Chinese enterprises is developing in the direction of intelligence and greening. Tianqi Lithium Co., Ltd. built the world's first fully automated battery-grade lithium carbonate production line with an annual capacity of 2 × 10^4 t. Companies such as YOUNGY Co., Ltd. are also building highly automated lithium salt plants. Although lithium salt processing is a high energy-consuming industry that generates pollutants in the production process, some ore-based lithium extraction enterprises have reduced their total energy consumption and "the three waste" emissions by improving their production processes and adopting circulating heating in the outer jacket of the acid kiln.

3.3 Key materials and products

3.3.1 Cathode material

China's cathode-material production scale is large, accounting for more than 50% of the world's total production. Currently, the mainstream cathode materials for automotive power batteries are ternary materials and lithium iron phosphate materials. In 2020, the output of ternary cathode materials in China was 2.1 × 10^5 t, accounting for approximately 40% of the world's output [22]. The development trend of ternary cathode materials is high nickel

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and low cobalt, and the output of low-end products, such as nickel-cobalt-manganese (NCM) 333 and NCM523, accounted for 57% in 2020, while the output of NCM811 and NCM523 accounted for 50%. The output of high-end high-nickel products, such as nickel-cobalt -aluminum (NCA), only accounted for 23% of the unbalanced structure. Moreover, the domestic output of NCA materials is not high, mainly because the NCA materials have higher technical barriers than NCM and have stricter requirements for production processes, humidity, and other conditions. The development path of China's ternary batteries is dominated by NCM, which makes it difficult to produce a linkage effect between the materials and products, and the NCA production power of material enterprises is insufficient.

The concentration in the domestic high-end product market is high. Taking NCM811 as an example, the combined market share of Ningbo Ronbay Technology Lithium Battery Material Co., Ltd. and Tianjin B&M Science and Technology Co., Ltd. is as high as 84%. In terms of the product quality, the products of key enterprises are of good quality and have entered the supply chain of mainstream international battery manufacturers. Presently, domestic products meet China's downstream battery production needs; however, high-end cathode precursor materials are still partially dependent on imports.

In 2020, the output of lithium iron phosphate cathode materials in China was the highest worldwide at approximately 1.42×10^5 t. Lithium iron phosphate is safe and has a long cycle life; however, it is produced less in foreign countries because of its low volumetric energy density. Recently, domestic structural innovations, such as module-free blade batteries, have significantly improved the volume energy density of lithium iron phosphate batteries, which is better than ternary batteries in the case of subsidies, thus driving the material end of lithium iron phosphate material production rebound. Domestic lithium iron phosphate power battery market development is better than that overseas. The cathode material is self-produced and sold, and is mainly supplied to domestic battery manufacturers. The relevant enterprises have a high degree of production concentration.

In terms of R&D and the production of new materials, the production technology of ultra-high nickel materials of some domestic enterprises has entered the international forefront. For example, Ni90 series ternary materials have achieved domestic and international bulk supply, Ni95 series products have completed international customer verification, and Ni98 series products have entered the R&D stage. Although a number of domestic enterprises have made technical arrangements in the area of nickel-cobalt-manganese-aluminum (NCMA), there is a gap with the advanced international level. However, some enterprises have completed process characterization and trial production of lithium-rich manganese-based materials to ensure the development of new downstream battery products.

Owing to the late start in technology R&D, China's enterprises have not accumulated enough basic core patents for key materials. For example, the basic core patents for NCM materials are owned by 3M Co., Ltd. in the United States and the patents for NCA materials are mainly held by Japanese and South Korean enterprises. Recently, domestic research institutes and enterprises have conducted certain modifications to the original patents, but they are still restricted by the influence of the international market.

3.3.2 Electrolyte

The electrolyte is composed of a lithium salt, solvent, and additives. In 2020, the quantity of electrolyte for power batteries in China was approximately 8.8×10^4 t, accounting for approximately 50% of the world's output [23], and the exported amount was more than 3×10^4 t, mainly supplied to Japanese and South Korean enterprises [24]. The combined output of the top five enterprises such as Guangzhou Tinci Materials Technology Co., Ltd. and Shenzhen Capchem Technology Co., Ltd. accounted for 78% of the domestic market. Domestic enterprises can produce lithium hexafluorophosphate electrolytes to meet the demand for electrolyte production, and functional additives for electrolytes, such as vinylidene carbonate and fluorinated vinylidene carbonate, for large-scale applications have also been localized. As international mainstream electrolyte companies have unique additive formulations, Chinese companies still denpend on imports regarding the design of some functional additives.

3.3.3 Power battery

China's power battery production scale ranks first in the world, with an installed capacity of 63.3 GW·h of power batteries in 2020, accounting for approximately 40% of the world's installed capacity. Contemporary Amperex Technology Co., Ltd. and BYD Co., Ltd. are the leading companies in China's power batteries, with a combined share of 70% of the installed capacity in China [25,26]. Presently, the mainstream types of automotive power batteries are NCM ternary batteries, NCA ternary batteries, and lithium iron phosphate. Chinese enterprises have weak technical accumulation in NCA ternary batteries, and the development route is dominated by NCM ternary batteries and lithium iron phosphate batteries. In terms of battery packaging integration, domestic enterprises have broken through the NCM battery and lithium iron phosphate without module technology, which has reduced production costs while improving the energy density of the battery packs. A high degree of automation in battery production can improve the product consistency. While the automation rate of international first-class enterprises is nearly 80%, the automation rate of China's advantageous enterprises is approximately 50%, and many enterprises are only 20%.

In terms of battery technology trends, the energy density remains as the core factor. From the perspective of the cathode materials used in batteries, battery companies in Japan and South Korea have developed ultra-high nickel batteries with nickel contents exceeding 90% in the NCM, NCA, and NCMA systems, respectively. Some companies have also announced that mass production is imminent. In China, SVOLT Energy Technology Co., Ltd. has made a breakthrough in NCMA battery technology, but is yet to mass produce it. Lithium manganese iron phosphate batteries can increase the energy density by 10% to 20% by retaining the stability of the iron and lithium materials. Therefore, some enterprises have formed technological reserves and production capacity layouts based on this. Lithium-rich manganese-based batteries have become a potential development direction owing to their theoretical advantages of high capacity, low cost, and good safety, allowing Zhejiang Aoyou Power Co., Ltd. to achieve small-scale mass production. In terms of the electrolyte morphology, the energy density of liquid batteries has reached its theoretical limit (350 W·h/kg), and the development direction has changed to solid-liquid hybrid and all-solid-state batteries. Although foreign companies have accumulated more research on solid-state batteries and invested heavily in R&D, domestic companies are weak in their original innovation and accumulation of experience in solid-state electrolyte technology.

3.4 Recycling

Recycling of power batteries in China is still in its initial stages of development. The first scale retirement stage of power batteries commenced in 2020 with a cumulative retirement volume of approximately 2×10^5 t. However, the actual recycling volume was only 41% and the volume of recycling and reusing lithium resources was approximately 2×10^4 t. However, the recycling efficiency was poor. Presently, domestic power battery recycling systems are divided into two recycling processes: step-by-step utilization and disassembly recycling. When the residual energy of the power battery is less than 80%, it is used in a step-by-step manner according to the following sequence: low-power electric vehicle, power grid energy storage, home energy storage, scrap batteries. Lithium iron phosphate batteries are more suitable for step-by-step utilization because of their high cycle times. The government has set various requirements for recycling entities with regard to power battery dismantling, storage, safety, and environmental protection operations. They have also raised the threshold for recycling enterprises, and the recovery rate of nickel, cobalt, manganese, and lithium in power batteries. Moreover, management measures for dismantling and recycling have been published [27–30], and an integrated national monitoring and traceability management platform for the recycling and utilization of new energy vehicles and power batteries was established to conduct the entire lifecycle tracing of automotive power batteries. This allowed the tracing of the source and direction, and control of the node. Overall, the use of the existing policy is not mandatory, and the rate of integration of scrap power batteries in the formal channels after recovery is still very low. Therefore, standardization needs to be done based on a universal industrial order.

In terms of power battery recycling technology, Guangdong Brunp Recycling Co., Ltd. and GEM Co., Ltd. have achieved international standards, and the recovery rates of lithium, nickel, cobalt, manganese, and other metal elements in scrapped batteries (in good packaging) are higher than current standards.

4 Problems encountered in the development of lithium and power battery industry chain in China

4.1 Constraints of the natural environment, ecological protection, and restriction on the expansion of the lithium mines

In the short term, lithium resources in Sichuan Province and Tibet Autonomous Region are difficult to exploit on a large scale. The average altitude of the Zabuye Salt Lake in Tibet is 4422 m, while the altitude of most salt lakes, such as the Atacama Salt Lake in Chile, the Charkhan, and East-West Terrace Genel in Qinghai are over 2000 m. High altitudes result in low temperatures, which reduces evaporation rate of brine. In addition, the construction of facilities is difficult, and the poor geographical conditions restrict the potential scaling of production. Owing to

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current environmental protection policies and other influences, the expansion of lithium ore production in the Sichuan Province is restricted. Although many companies have mining rights, the number of companies entering the normal mining industry is very small.

4.2 The competition for lithium resources is becoming fiercer and the risk of overseas imports has increased

Global carbon emission constraints are becoming increasingly strict, and many countries are currently focused on guaranteeing the development of their domestic lithium resources and downstream supply. The *Energy Resources Governance Initiative* [31] was introduced in the United States to strengthen cooperation with resource-rich countries regarding mining development. The *U.S. Supply Chain Executive Order* was implemented to conduct supply chain investigations for products such as high-capacity batteries. Moreover, the Department of Energy's Mineral Resources Sustainability Division was established to secure the lithium supply chain, and the *National Blueprint for Lithium Batteries 2021—2030* [32] was released to promote investment in the lithium battery industry chain. Simultaneously, the European Union diversified its overseas lithium supply sources to reduce security risks in the supply chain, promote technological advancements in the local battery industry, and enhance the secondary use of lithium batteries [33]. Therefore, lithium ore shortages will further intensify the competition for lithium resources. This is currently evident in China, whose import of lithium resources is highly dependent on a single country, thereby exposing potential supply risks during this tense international situation.

4.3 Core patents such as cathode materials and electrolytes have become a hindrance for the development of the industry due to their late distribution

Cathode materials are essential for the production of lithium power batteries. However, the core patents for ternary cathode materials are held by 3M Co., Ltd. in the United States, the core patent for lithium iron phosphate cathode materials is registered to Quebec Hydro in Canada, and various other patents for electrolyte and diaphragm bases are registered to Japanese and South Korean companies. Therefore, mainstream enterprises worldwide need to purchase these patent licenses to use these materials. Because the patent layout of key materials developed by Chinese enterprises started relatively late, and the patent content is concentrated on the functionality and at the application level (such as adjusting and improving the formula ratio), it lags far behind in terms of original innovation patents. Foreign enterprises therefore rely on their patents, which gradually builds up a patent barrier for the key materials of lithium batteries, and inevitably resulting in China's companies being at a disadvantage when participating in international market competition. The patent layout constructed by foreign enterprises dominates in terms of its technical aspects and high profitability, making the corresponding technical system increasingly difficult to circumvent [9].

4.4 Gaps of key materials and battery technologies between domestic and international advanced standards, and lack of a common direction

Despite China being at the forefront of the production capacity of battery materials, a gap still exists between China and foreign enterprises in terms of high-end products. For high-nickel ternary cathode materials, Japanese and South Korean enterprises began R&D early, which allowed them to have a high degree of technological maturity. A comparison of the product performance and production processes of international and domestic companies shows the existence of a gap. Some high-performance cathode material precursors and battery electrolyte functional additives are still partially dependent on imports. Moreover, there is a gap in the energy density, manufacturing accuracy, and temperature adaptation range of single cells at the domestic and international market standards. In addition, China's key materials and battery technology systems lack the required development momentum due to the lack of basic R&D factors. The distribution of R&D products, which is highlighted by the new generation of all-solid-state batteries, has significantly lagged behind those of superior companies such as the Toyota Motor Corporation of Japan, which may lead to a continued widening of the technology and product gap [34,35].

4.5 The secondary recycling system of waste power battery resources is incomplete and the industrial order needs to be regulated

China's new energy vehicle industry is rapidly developing, and the number of retired power batteries is expected to grow rapidly in the future. Research data from the China Automotive Technology and Research Center Co., Ltd. indicated that the total number of retired power batteries in China in 2025 will be approximately four times higher than that in 2020. Making full use of secondary resources is an important means of alleviating the resource supply constraints; however, the current scale for lithium power battery recycling is small, a recycling industry chain system has not yet been established, the concentration of the recycling industry is low, and the industry is still in a chaotic stage. Moreover, the current power battery recycling management methods do not provide sufficient coverage and make supervision more difficult because of the scattered distribution of small enterprises. Therefore, the secondary use of hydrofluoric acid and other fluorine-containing compounds that decompose during the production process should be highlighted and the corresponding transportation and disposal, which may be corrosive and toxic to the environment and result in potential ecological and environmental problems, should not be ignored. In addition, the testing of retired batteries should follow the standards for automotive power batteries, and the high cost of testing and lack of technology and talent reserves for assessing the residual value of batteries should be addressed to ensure the high-quality development of the recycling industry.

5 Development goals and paths for lithium and power battery industry chain in China

5.1 Development goals

The basic capabilities of the industry and level of the industry chain should be improved by focusing on the needs of the national development strategy. Consequently, the domestic resource security capabilities will be strengthened, the comprehensive utilization of resources will be improved, and resource development cooperation in different regions overseas will be enhanced. Moreover, “dual circulation” will be conducted on the basis of the rational use of domestic and international resources. To conduct research on cutting-edge technology, the investment in scientific and technological R&D should be increased and collaborative innovation in the entire industry chain should be promoted to improve the level of resource recycling. Therefore, China’s lithium and downstream power battery industries can be globally competitive.

5.1.1 The goals for 2025

Investment in the resource exploration will be maintained to steadily increase the domestic supply capacity and improve the level of comprehensive utilization of resources. Enterprises will be encouraged to cooperate with other countries in resource exploration and development, import sources and lithium resource types will be diversified, and the concentration of lithium resources imports will be reduced rationally. At the end of the smelting and processing, the production energy consumption will be gradually reduced, and the proportion of intelligent chemical plants will be increased. For the materials and products, the product structure will be optimized, the international market competitiveness will be enhanced, and the proportion of high-end products will be increased from the current proportion of approximately 25% to more than 40%. The R&D investment will also be reasonably increase and restraining technologies developed to reduce the technology gap between China and other countries in terms of the new generation of batteries worldwide. Moreover, the level of recycling management will be improved and a national unified platform for a power battery recovery system established so that the recovery rate of end-of-life power batteries is more than 95%, and the non-ferrous metal recovery rate fully meets national standards.

5.1.2 The goals for 2035

The level of comprehensive utilization at the resource end will be significantly enhanced, with decentralized and diversified sources of lithium resources, a significant easing of supply tensions and a steady enhancement in the level of the extraction technology. The smelting and processing industry will be of a moderate scale and achieve a high degree of automation, intelligence, and green production. The competitiveness the materials and products at the international market will remain leading, with high-end products accounting for no less than 70%, and the effect of scientific and technological synergy and innovation in the entire industry chain will be prominent. The basic R&D capabilities of original theories will be significantly enhanced, and key technology systems will reach the international standards. In addition, the resource recycling system will be mature and complete, with end-of-life power batteries being recycled in a comprehensive and orderly manner, and the recovery rate of valuable metals further increased to support the "domestic recycling" of lithium resources.

5.2 Development paths

5.2.1 Constructing a safe and stable resource supply system considering multiple dimensions

Increasing domestic mining search efforts and improving the number of lithium exploration blocks placed, focusing on reasonable, orderly, and environmentally friendly blocks, promoting the development and utilization of

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domestic lithium resources, improving the capacity of domestic lithium resource supply, and protecting domestic resource supply.

The stability of the lithium supply should be improved by diversifying the sources of imports and types of lithium supply. Attention should be paid to the new trend of international lithium resource exploration and production, and plans to import lithium resources from multiple sources to diversify the sources of imports. Large-scale production of lithium-rich clays and other resources should be promoted as new sources of supply to diversify the supply of lithium.

Lithium resource reserves should be strengthened, including product reserves and orefield reserves; for the former, appropriate reserves of primary and high-purity grade lithium salts, with a focus on key material types that do not have strong domestic production capacity; for the latter, mines that have poor development conditions and are difficult to exploit in the short term should be included in the list of mineral reserves.

The construction of a power battery recycling management system should be established to enhance the supply capacity of secondary lithium resources. It is necessary to reasonably increase the concentration of the secondary recycling market to raise the basic threshold for recycling enterprises, elevate the relevant recycling policy to the legal level, implement it in accordance with the law, and improve supervision to ensure that recycling enterprises standardize the establishment of a lifecycle traceability system for power batteries. It is essential to improve the testing standards system for retired power batteries to guarantee the standardized and orderly recycling of used lithium batteries, and substantially improve the efficiency of resource utilization.

5.2.2 Developing key materials and new battery technologies by improving the lithium battery technology system and talent reserves

Based on the existing lithium battery technology system, ultra-high-nickel low cobalt or cobalt-free multi-cathode materials, new lithium iron cathode materials, and corresponding cell batteries can be used for mass production. Focusing on application potential, key materials and their batteries based on lithium-rich manganese-based cathode materials and high-voltage nickel-manganese spinel cathode materials should be actively developed, a complete lithium technology system with complete elements should be established, and an ecologically sound research environment should be created.

Further improving the R&D of semi-solid battery electrolyte technology as a technology transition and enhancing the basic research theory, providing solid conditions for theoretical research and technological innovation of all-solid batteries are necessary. It is also necessary to focus on the all-solid-state battery material system, actively carry out international patent layout, and form our own intellectual property rights and independent product applications for a new generation of battery technology systems with high energy density and high safety.

5.2.3 Promoting the coordinated development of all links in the industrial chain while focusing on innovation of key materials and products

For the resource exploration, the configuration and application of automated mining equipment, high-speed communication networks, and intelligent production management system platforms should be promoted and the mine production objects and processes dynamically monitored via intelligent monitoring. Further increasing of the application ratio of the filling mining method and maintaining green and waste-free development should also be ensured. For ore resources, the development and application of pre-concentration technology before separation and new high-efficiency pre-separation equipment should be conducted to improve ore separation recovery. The R&D of ore flotation reagents should be intensified, focusing on the development of efficient environmental protection, low-temperature resistance, and strong selectivity of new collectors. For salt lake resources, further optimization of the key agents required for various extraction processes (such as precipitators and extractants) and development of low-cost, high-efficiency, green, and environmentally friendly lithium extraction technologies for salt lakes suitable are required.

At the end of smelting, automatic control of the entire production process, improvement in the accuracy of chemical measurement, reduction in the consumption intensity of energy and auxiliary materials, and improvement in the stability and consistency of product performance are required. It is necessary to implement policy guidance actively, standardize the entry conditions for lithium salt processing enterprises, issue green production standards for processing plants, and optimize the industrial capacity structure.

At the recycling end, improving the degree of mechanization, improving the classified management of different waste batteries, and improving the recovery rate of valuable metals are required. The comprehensive recovery and utilization level of key materials should be improved, such as electrolytes, which are difficult to recover and have low economic value. It is necessary to develop short-process, closed-loop recovery technology, implement the harmless management of waste liquor during the recovery process, and reduce the pollutant emission intensity.

6 Countermeasures and suggestions

6.1 Improving the top-level design to form an integrated management model of the entire industry chain

The relevant ministries and commissions should form a national lithium industry chain management coordination group in cooperation with key enterprises in all segments of the lithium industry and the power battery industry chain. The group will be responsible for the development of each link in China's industry chain, the formulation, implementation, and evaluation of relevant policies, and providing clarification on the implementation of key platforms and development of the constraints of each link. Moreover, the group will be charged with monitoring technological advancements, policy measures, and major platforms launched in the international industry chain, conducting timely discussions, and analyzing the shortcomings and management defects in the domestic industry chain. It is also responsible for ensuring the effective integration of resources, enhancing the research efforts on the weak links in the industry chain, and forming an efficient management model for the integration of the entire industry chain.

6.2 Increasing financial support to enable the mutual promotion of the basic and applied research

A national fund should be established to provide continuous investment for basic research on the weak links in the industry chain. For scientific projects supported by the fund, an evaluation mechanism that is in line with the characteristics of basic research must be established and semi-elastic and long-term evaluation systems should be implemented. The evaluation frequency should be reduced properly and classification evaluation be accurately implemented. Considering the necessity of this fund, attention should be paid to the efficiency of capital use and vitality of innovation in its management. Simultaneously, the fund will support the increasing demand for innovative research resources that employ key advanced materials and lithium-ion technology applications. It will also motivate industry leaders to integrate such systems in their projects and gradually accumulate their R&D and production experiences to realize the coordination, coherence, and mutual promotion of basic and applied research.

6.3 Encouraging cooperation among enterprises in the upstream and downstream links to enhance the synergistic effect in the industrial chain

The National Lithium Industry Chain Management Coordination Group should establish an exchange platform for lithium and its downstream power battery industry chain enterprises and encourage domestic lithium industry chain enterprises to join. It should also support encouragement policies and regular offline exchanges to promote technical exchanges and industrial cooperation between upstream and downstream enterprises in the lithium industry chain. Moreover, by focusing on the technical connection and support of upstream and downstream enterprises, the group will be able to promote production technology cooperation between upstream and downstream enterprises and form an industry chain ecology comprising close cooperation, collaborative innovation, and symbiotic development.

6.4 Improving industry–university–research cooperation to cultivate interdisciplinary talents for the industrial chain

To improve the development of lithium and its downstream power battery industry chain, university education resources can be relied on to conduct professional cross-integration based on the industry demand and precisely train compound technical and management talents for the industry chain. This can be achieved by reorganizing and optimizing the State Key Laboratories toward the development of geological and environmental studies based on the lithium resources endowment in the different regions of China, development of engineering technology, and comprehensive utilization of resources to meet the demand for basic research in the upstream of the industrial chain and match the innovative needs for the development of the applied research. Additionally, research institutes and universities should be encouraged to actively implement the transformation of technological achievements, support in-depth cooperation between enterprise R&D centers and relevant institutions, and promote market demand-oriented industry–university–research cooperation.

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