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Introduction

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1.1 Production Volume and Distribution of Spent LIBs

Spent lithium-ion batteries (LIBs) exhibit dual characteristics of type differentiation and regional concentration in production volume and distribution.[1–4] In Figure 1.1, as the core source, the end-of-life (EoL) volume of power batteries in China is projected to reach 820,000 tons in 2025. Among them, NCM batteries (accounting for 55%) display a relatively short cycle life (5–8 years) and are concentrated in passenger vehicle-dense areas such as the Yangtze River Delta and the Pearl River Delta. In contrast, LFP batteries (accounting for 45%) are experiencing rapid growth in commercial vehicle-dense areas such as the Chengdu-Chongqing and Beijing-Tianjin-Hebei regions, owing to their extended lifespan of 8–10 years. And, it is anticipated that by 2030, the proportion of LFP batteries in the total EoL power battery stream will rise to 60%. Moreover, the retired consumer electronic batteries contribute about 150,000 tons annually, dominated by LCO batteries (70%), which has a high degree of dispersion, resulting in a formal recycling rate of less than 20%. These batteries are mainly distributed in the Pearl River Delta electronics manufacturing hub (accounting for 35% of the national total) and the cascade-utilization project areas in Jiangxi. As the main force for cascade utilization, the market scale of energy-storage batteries is forecasted to reach RMB 60 billion, with over 85% LFP batteries. Moreover, 40% cascade-utilization batteries are collectively absorbed by northwestern photovoltaic energy storage zones (Qinghai/Ningxia) and north China grid-scale energy-storage areas across the nation. For specialized batteries (such as NCM and lithium metal batteries), their annual EoL volume is around 30,000 tons, concentrated in port cities like Tianjin and Qingdao, as well as high-end recycling project areas in Hunan.

Furthermore, the geographical distribution pattern for recycling batteries is as follows: first, the power batteries recycling network is concentrated in major automotive industry clusters (e.g., Chongqing plans to achieve 90% coverage); second,

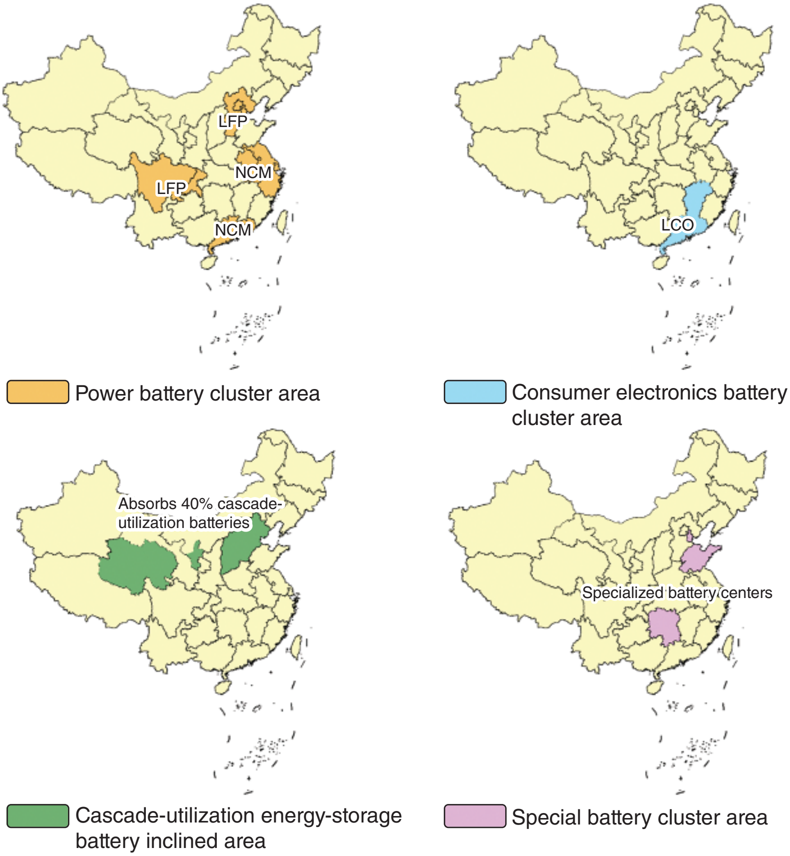

Figure 1.1 Geographical distribution of spent LIBs and recycling networks in China.

consumer electronic batteries recycling primarily relies on the Pearl River Delta electronics manufacturing cluster; third, cascade-utilization energy-storage batteries recycling is preferentially directed toward the northwest energy bases.[5] In addition, significant differentiation exists in technological recycling pathways: owing to their high-value cobalt and nickel content, NCM batteries are prioritized for recycling and regeneration (hydrometallurgical recovery rates ≥ 98%).[6, 7] Conversely, LFP batteries are primarily destined for cascade utilization.[8, 9] Meanwhile, policy drivers have emerged as critical variables. Initiatives such as the Carbon Border Adjustment Mechanism (CBAM) in the European Union (EU) and regional pilot programs (e.g., the battery traceability system in Chongqing) in China are accelerating industry standardization. Therefore, given the projected continuous increase in EoL battery volumes, the synergistic optimization of geographical deployment strategies and technological pathways will be the cornerstone for achieving highly efficient resource circulation.

1.2 Strategic Significance of Spent LIBs Recycling

As shown in Figure 1.2, the recycling of spent LIBs holds multidimensional strategic importance for global sustainable development, encompassing resource security, environmental governance, climate action, and industrial restructuring.[1, 10] From a resource security perspective, critical metals such as lithium (Li), cobalt (Co), and nickel (Ni) are geographically concentrated in a few countries (e.g., Chile for Li, the Democratic Republic of Congo [DRC] for Co), posing significant geopolitical risks. Therefore, the recycling industry enhances supply chain resilience through material regeneration. According to the data from the International Energy Agency (IEA), recycled materials are projected to meet 35% of global Li demand and 50% of Co demand by 2040, meanwhile reducing the carbon footprint of mining to 20% of virgin ores and cutting water consumption by 90%.[11, 12]

In terms of environmental governance, recycling systems mitigate the cross-border migration risks of hydrofluoric acid (HF) generated by $LiPF_6$ decomposition. Moreover, according to UN statistics, it can also prevent approximately 500,000 tons of electronic

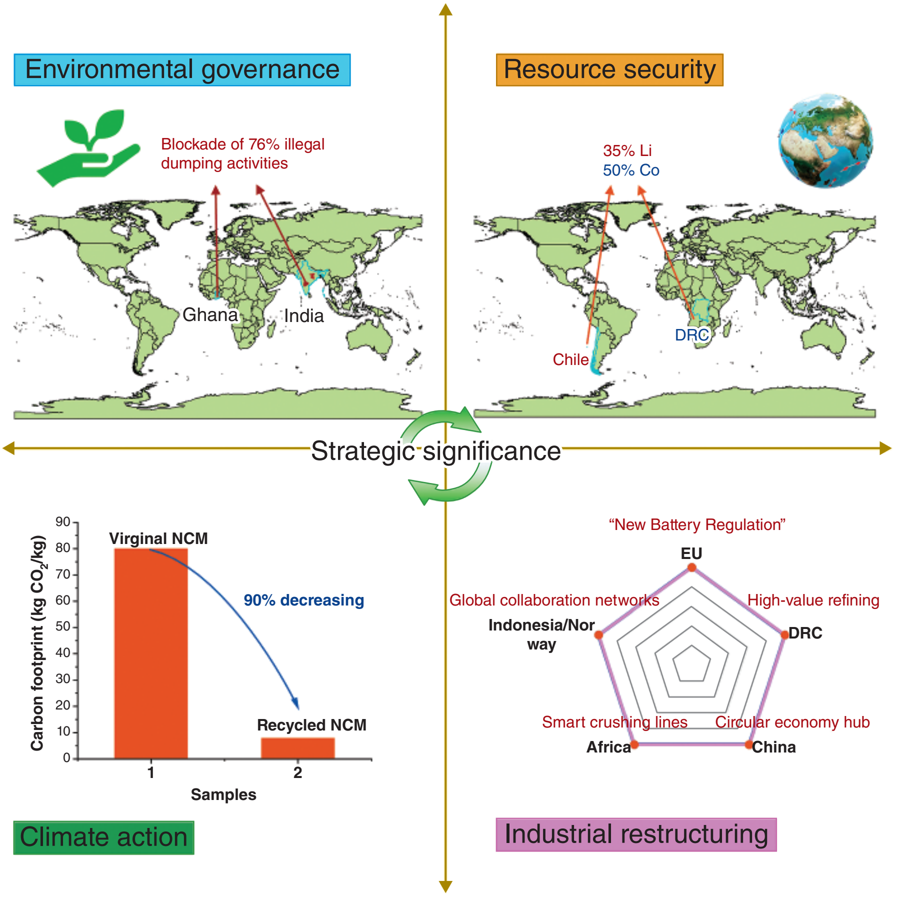

Figure 1.2 Global impact of LIBs recycling.

batteries (accounting for 76% of the total) from entering informal dismantling networks (such as Ghana, India, and other regions) annually, thereby avoiding heavy metal contamination of 75 million cubic meters of land.

For climate action, recycling serves as a pivotal lever for carbon neutrality. The carbon footprint of recycled NCM materials is about 8 kg CO_2/kg, which is 90% lower than that of virgin materials (80 kg CO_2/kg). By 2040, 530 million tons of annual CO_2 emissions (equivalent to the UK's annual emissions) would be reduced by LIBs recycling in the global transportation sector. Additionally, cascade utilization of batteries can lower the cost of photovoltaic energy storage systems by 40%, accelerating renewable energy adoption.

Regarding industrial restructuring, recycling is reshaping global value chains. Specifically, the "New Battery Regulation" in the EU mandates a minimum 12% recycled Co and Ni content by 2030, driving cost reductions in cell manufacturing for developed countries.[13] And, resource-rich nations like the DRC are transitioning to high-value refining industries, while China is upgrading from the "world's factory" to a "circular economy hub" with a projected CNY 200 billion recycling industry by 2030. In conclusion, through modular technology dissemination (e.g., smart crushing lines in Africa) and global collaboration networks (Chinese enterprises in Indonesia, European plants in Norway), the recycling industry has emerged as a civilizational project for achieving "resource-environment-climate" synergy and will underpin humanity's sustainable future.

1.3 Global Industrialization Landscape of Spent LIBs Recycling

The global LIBs recycling industry has evolved into a multipolar collaborative network, which is characterized by regional strategic specialization and technological diversification.

In Europe, the regulation-driven closed-loop hub model is exemplified, which leverages policy-technical synergy for industrial upgrading. Notable cases are as follows: Tozero in Germany has secured €11 million in financing to build an industrial-scale recycling plant (operational in 2026) with an annual processing capacity of 30,000 tons. And this plant features an innovative aqueous-based carbonation process that eliminates secondary pollution from the strong-acid leaching process. Besides, for CATL, the Hungary-based recycling project is precisely aligned with the requirements of the "New Battery Regulation" in the EU (which states that the Li recovery rate should be no less than 80%). Moreover, companies like Cylib have set industry benchmarks with oxygen-free pyrolysis technology for EU carbon footprint compliance, accompanied by 40% carbon reduction.

In North America, the development of the recycling industry relies on the vertical integration model between automakers and battery manufacturers. For example, LG Energy Solution and Toyota Tsusho have jointly established GMBI, focusing on the "battery-to-battery" closed-loop production, which is expected to process 13,500 tons of spent LIBs by 2026. Meanwhile, they leverage the tax incentives in the Inflation Reduction Act to avoid the EU's carbon barriers.

Asia-Pacific, led by China, drives large-scale and networked expansion of technology. EVE Energy, in collaboration with GEM and Huayou Cobalt, has built a global LIBs recycling network platform, planning to reach an annual production capacity of 120,000 tons by 2030, covering 246 sites across 30 countries, accompanied by the integration of "physical-data-value" flow through blockchain technology. In contrast, VinFast in Vietnam has cooperated with BatX Energies in India to optimize the local supply chain in Southeast Asia.

For the Middle East, the rise of emerging hubs is accelerating. The United Arab Emirates has invested $10.8 million to build the region's first LIBs recycling plant in Abu Dhabi, mainly dealing with batteries from photovoltaic energy storage and electric vehicles, aiming to become the core node of the circular economy in the Middle East.

In conclusion, the collaborative cooperation among these four regions is driving the global resource closed-loop to evolve from "single-point breakthrough" to "system-level reconstruction."

1.4 Full-chain Technological Process for High-value Recycling of Spent LIBs

The high-value recycling of spent LIBs adheres to the strategy that cascade utilization comes first and material regeneration subsequently, comprising the following critical stages in Figure 1.3. At the beginning, the pack-level battery state is detected at the preprocessing and cascade utilization screening stage. Specifically, battery packs with parameters such as capacity, internal resistance, and power that meet the requirements for direct cascade utilization are selected for direct application. In contrast, unqualified battery packs are processed by intelligent disassembly technology to obtain battery cells, and then rapid detection and state evaluation are carried out at the cell level.

In the cascade utilization and safe discharge stage, the qualified cells are classified and recombined into battery packs with high consistency according to the

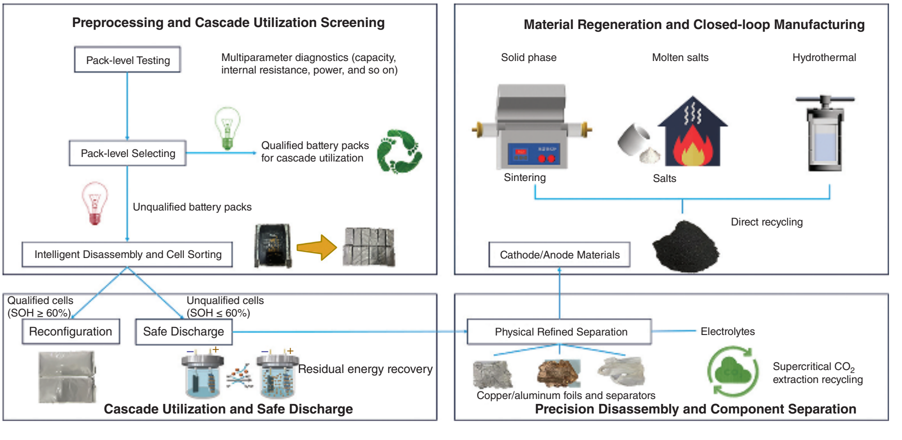

Figure 1.3 Full-chain recycling process flowchart.

requirements of cascade utilization scenarios for secondary use. For the cells that cannot be cascaded, the remaining energy is completely recovered through intelligent discharge technology, while ensuring the safety of subsequent operations.

After complete discharge, the internal components of the battery are completely classified and recycled through precision disassembly technology. Components that can be directly recycled, such as copper/aluminum foils and separators. For products that have caused secondary pollution (such as electrolytes), clean processes should be adopted for recycling or harmless treatment.

In the last stage, for the recycling of cathode/anode materials, according to the type of battery materials and the judgment of the material failure mechanism during the detection process, the material performance is directly regenerated through specific recycling technologies such as solid phase, molten salts, and hydrothermal methods. The regenerated battery materials are reused for the assembly of new LIBs, and the assembled battery packs are reused in various energy storage fields. Thus, high-value circular utilization of LIBs throughout their life cycle is achieved.

1.5 Overview of Global Progress in LIBs Recycling

With the growing global emphasis on clean energy and sustainable development, as efficient and environmentally friendly energy storage devices, LIBs have been widely adopted in electric vehicles, consumer electronics, and energy storage systems.[14] According to a report by the IEA in Figure 1.4, the global EV stock reached 27 million units in 2022, with China and Europe collectively contributing the majority (85%) of global EV sales. Under the Net Zero Emissions by 2050 Scenario, the global EV stock is projected to exceed 350 million units by 2030. Concurrently, the number of EoL EVs is anticipated to grow significantly in the coming years.

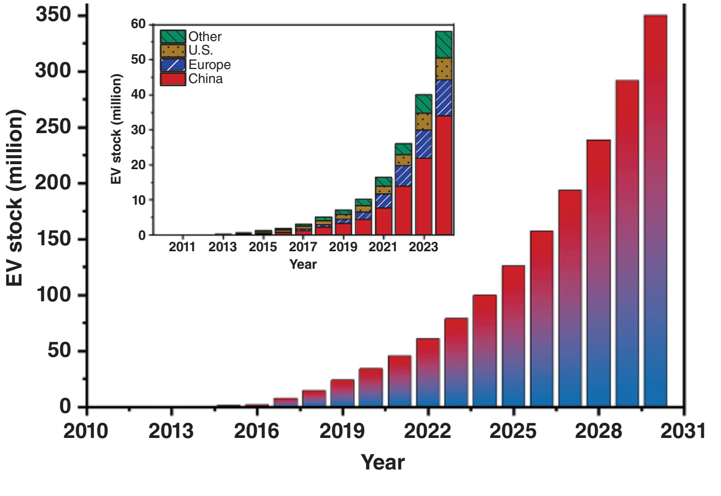

Figure 1.4 EV stock in major economies from 2010 to 2022 and projected stock for the next decade under the Net Zero Emissions by 2050 Scenario.

However, with the large-scale utilization of LIBs, the problem of their postretirement disposal has become increasingly prominent. Improper handling of spent LIBs not only leads to resource wastage but also poses significant environmental pollution risks.[15] Globally, the development of spent LIBs recycling technologies exhibits diversity and rapid advancement. Countries are adopting varying strategies concerning policy support, technological research, and industrial chain development, driving continuous innovation and the industrialization of recycling processes.

The EU holds a leading position in the recycling of EoL LIBs, with its success largely attributable to stringent regulations and policy support.[16] Through directives such as the "Battery Directive" and the "Circular Economy Action Plan," the EU explicitly defines the recycling responsibilities of battery producers and importers, establishing specific recycling targets and timelines. Furthermore, the EU promotes research, development, and demonstration applications of recycling technologies through financial support and scientific projects. For instance, the "pyrometallurgical-hydrometallurgical" combined process developed by Umicore in Belgium has achieved a comprehensive Li recovery rate of over 90%, with an annual processing capacity of 70,000 tons. The EU-funded "Battery 2030+" project aims to develop next-generation battery recycling technologies to enhance recovery efficiency and resource utilization. Complementing these efforts, the newly enacted EU Battery Regulation (2023) mandates minimum recovery rates of 70% for Li and 95% for Co/Ni by 2030.[17]

Japan has also made significant progress in the development of technologies and equipment for the recycling of EoL LIBs. Through regulations such as the "Law for the Promotion of Effective Utilization of Resources" and the "Small Electrical and Electronic Equipment Recycling Law," comprehensive battery recycling systems are established by the Japanese government. Japanese companies like Toyota, Panasonic, and Nissan have invested heavily in battery recycling technology research and equipment manufacturing. For example, Toyota has developed high-efficiency battery dismantling and material separation technologies, while Panasonic focuses on the research and development of automated recycling equipment, enhancing the efficiency and safety of the recycling process. Besides, in collaboration with JX Metal, Honda has jointly developed an automated single dismantling line, where processing capacity achieves 200 batteries per hour, with a metal purity of 99.95%. And through the "Battery to Battery" program, the Japanese Ministry of Economy, Trade and Industry aims to achieve a 50% recycling rate of vehicle battery materials by 2025.[18]

For the United States, strong research capabilities and industrialization capacities are demonstrated in the field of LIBs recycling.[19, 20] The US government has regulated the battery recycling and disposal process through laws and regulations such as the Resource Conservation and Recovery Act. And supported by the funding for research projects, the US Department of Energy has promoted the innovation of recycling technologies. For instance, Argonne National Laboratory in the United States has developed an efficient hydrometallurgical recycling technology that can extract valuable metals from retired batteries. Additionally, companies like Tesla are actively expanding their battery recycling business and have developed automated recycling production lines, enhancing recycling efficiency and resource utilization.

The closed-loop recycling system at Tesla's Gigafactory Nevada achieves a 92% metal recovery rate and displays a processing cost per ton that is 30% lower than the industry average. The cathode material repair technology developed by the ReCell Center in the United States can retain 90% of the original material structure, and the energy consumption is 50% lower than that of traditional processes.[21]

As the largest producer and consumer of LIBs in the world, China has also made remarkable progress in the field of retired battery recycling in recent years.[22–24] The Chinese government has defined the recycling responsibilities of battery manufacturers, sellers, and consumers through policies such as the "Interim Measures for the Recycling and Utilization of Power Batteries in New Energy Vehicles" and established recycling service networks. Moreover, China has implemented substantial policy support through national science and technology programs and industrial funds to promote the research, development, and industrialization of battery recycling technologies. Leading companies such as CATL and BYD have actively expanded their battery recycling businesses, developing advanced physical and chemical recycling technologies that significantly contribute to the improvement of the recycling industry chain. As of 2023, there are 156 battery recycling enterprises certified by the Ministry of Industry and Information Technology, with an annual processing capacity of over two million tons. Notably, Brunp Recycling (a CATL subsidiary) has established the world's largest hydrometallurgical recycling facility, boasting an annual processing capacity of 120,000 tons. Additionally, GEM Co., Ltd. has developed an innovative multistage crushing-sorting-leaching process that achieves remarkable recovery rates of 98.5% for Ni/Co and over 85% for Li_2CO_3.

In general, the evolution of EoL LIBs recycling systems demonstrates three defining characteristics: policy-driven support, technological innovation, and industrial chain optimization. Countries have promoted the continuous progress of recycling technologies and the industrialization process through regulations, policy support, and scientific research projects. In the future, with the further maturation of technologies and the gradual improvement of policies, the recycling of EoL LIBs will play an increasingly important role globally, making greater contributions to sustainable resource utilization and environmental protection.

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