Lithium-ion Battery Recycling

Market and Innovation Trends for A Green Future

CAS
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Deloitte.

Preface

The growing demand for sustainable energy solutions has positioned the lithium-ion battery recycling industry at the forefront of global innovation and economic transformation. With the rise in electric vehicles, renewable energy storage, and consumer electronics, recycling lithium-ion batteries has become a critical solution to address resource scarcity and environmental challenges. Recognizing the need for a comprehensive analysis of this rapidly evolving industry, CAS and Deloitte have worked together to develop this in-depth report covering both market and scientific perspectives.

As a division of the American Chemical Society, specializing in scientific knowledge management, CAS offers unparalleled science and technology expertise, continuously building cutting-edge information solutions and the CAS Content Collection™, which covers over 150 years of discoveries. Deloitte, renowned for its market and business analysis, provides a deep understanding of industry dynamics and competitiveness. Together, our scientific depth and business acumen enable us to provide a holistic exploration of the lithium-ion battery recycling industry.

This report showcases the depth and quality of understanding and insight made possible by this unique collaboration. By leveraging the combined strengths of CAS and Deloitte, we aim to deliver actionable insights and solutions to address the pressing challenges of today and shape the innovations of tomorrow.

Interested in comprehensive analysis of critical areas such as drug development, new materials, green energy, or sustainability? Contact us.

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Executive Summary

The rapid growth of electric vehicles has heightened the need for sustainable solutions in battery recycling. By integrating CAS data and scientific expertise with Deloitte's market and business insights, this report explores policies, and market and innovation trends shaping the industry.

Our key findings include:

- **Policy-driven**
  The industry is shaped by tightening mandatory regulations globally, such as Extended Producer Responsibility, hazardous waste management, end-of-life requirements, and recycled content requirement for new batteries, alongside new incentives like tax credits and government funding.

- **Capacity expansion**
  The global recycling capacity for lithium-ion batteries is rapidly expanding across all major regions. At present, established facilities have a combined capacity of approximately 1.6 million tons per year. With the addition of planned facilities, this capacity is expected to surpass 3 million tons annually in the coming years.

- **Technological innovation**
  The publication trends of the three major recycling methods—hydrometallurgy, pyrometallurgy, and direct recycling—show that all three have more patents than journal publications, highlighting the significant commercial interest in this research area.

- **Digital solutions**
  Technologies like digital twins, blockchain, cloud computing, and AI are revolutionizing battery recycling by tracking materials across their lifecycle, optimizing recycling processes, and enabling digital product passports. These tools improve efficiency, enhance traceability, and ensure compliance, driving the circular economy in the battery industry.

- **Cross sector collaboration**
  There is a growing trend of collaboration among materials suppliers, EV producers, auto brands, and recycling companies, with various areas of focus including the development of closed-loop recycling systems, partnerships for regulatory compliance, advancement in recycling technologies, and coordinated efforts to secure sustainable materials supply.

- **Pathway to profitability**
  Strategic pathways to profitability in battery recycling require aligning recycling technologies with material value, optimizing costs through automation and domestic recycling, and leveraging economies of scale. Success involves balancing immediate returns from high-value metals with long-term sustainability and innovation.

Recycling technology innovation and digital solutions are transforming the battery recycling industry, driving improvements in efficiency, recovery rates, and environmental impact. Navigating battery recycling toward a sustainable future is crucial as the demand for electric vehicles (EV) and other battery-powered technologies continues to rise. With the growing number of batteries reaching end-of-life, efficient recycling processes are essential to reduce waste, recover valuable materials, and minimize environmental impact. By implementing supportive regulations, investing in advanced technologies, and fostering collaboration, the battery recycling industry can create a circular economy that not only addresses resource scarcity but also contributes to reducing carbon emissions.

Key Drivers

The battery recycling market is primarily driven by several key factors: tightening environmental regulations, the need for EV supply chain decarbonization, the growing number of retired batteries, and the rising demand for critical materials like lithium, cobalt, and nickel. As governments push for stricter sustainability standards and industries seek to reduce their carbon footprints, recycling has become essential for securing valuable resources and ensuring a more sustainable future.

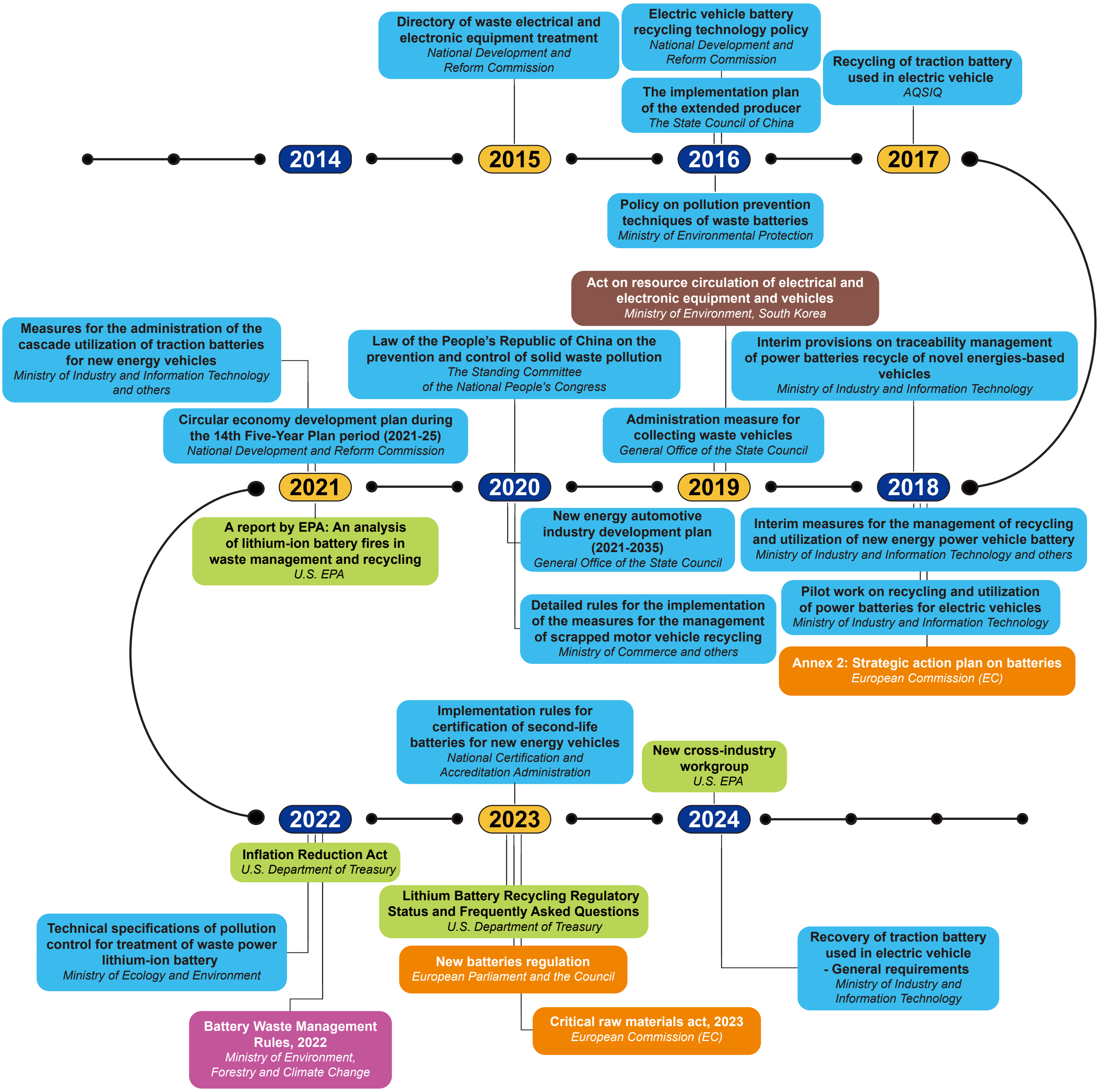
1. Tightening regulations and compliance requirements

The tightening of regulations and compliance requirements is driving the global battery recycling industry forward. Mandatory requirements, such as extended producer responsibility (EPR), hazardous waste management, and end-of-life recycling, are directly shaping the industry. Well-structured recycling policies can reduce safety concerns and the loss of reusable materials from spent lithium-ion batteries (LIBs), while promoting the recovery of scarce resources in a circular economy.[1] Additionally, circular economy policies, industry standards, and government funding are incentivizing growth. This section will provide an overview of the most significant policies prevalent in the U.S., EU and in Asian countries (China, South Korea, India) regarding lithium-ion battery (LIB) recycling over the last 10 years (**Figure 1**).

The European Union (EU) has always promoted sustainable, circular and safe battery technologies through its different policies and regulations. In 2018, the European Commission (EC) has adopted a *Strategic Action Plan on Batteries*[2] which "sets out a comprehensive framework of regulatory and non-regulatory measures to support all segments of the battery value chain"[3] including recycling of LIBs. In 2023, the EU introduced *New Battery Regulations* which cover the entire lifecycle of the batteries, from design to end-of-life.[4] This "cradle-to-grave" regulation promotes circular economy, EPR, sets targets for producers to collect waste batteries, sets a target for lithium recovery from waste batteries of 50% by the end of 2027 and 80% by the end of 2031. This regulation mandates companies to declare their batteries' carbon footprint and meet specific recycled content targets, by 2025. Moreover, it also requires for certain batteries to have a digital passport by 2027, having comprehensive information which will improve transparency and traceability. The new EU battery regulation strengthens sustainability standards for batteries and establishes robust mechanisms to oversee their entire lifecycle, impacting the entire value chain—from production to recycling.

The U.S. government is also taking several initiatives for promoting LIB recycling. The Environmental Protection Agency (EPA) has created federal waste management and recycling laws through the Resource Conservation and Recovery Act (RCRA). In 2021, the EPA has published a report[5] which analyzed the impact of the LIBs if not recycled properly. It also mentioned that "LIBs can be managed as universal waste under the special RCRA hazardous waste (HW) provisions at 40 CFR Part 273." Additionally, the U.S. also issued a federal guideline in 2023 in the form of a memo[6] to "clarify how the hazardous waste regulations for universal waste and recycling apply to lithium-ion batteries." Nevertheless, to date, there is no federal policy which is dedicated to LIB recycling, but the EPA has announced that it is working on a proposed guidance to create a new and separate universal waste category specifically for LIBs, separating it from the current universal waste guidelines, which expected to be issued in mid-2025.[7]

Among all the countries, China has been proactive in proposing and implementing various policies to address LIB recycling. Most of the important policies are highlighted in Figure 1, such as, *the Pollution Prevention Techniques of Waste Batteries* (2016) policy which encompasses the entire LIB lifecycle, from collection, storage, and utilization to treatment, transportation, and disposal.[8] Remarkably, China's Ministry of Industry and Information Technology (MIIT) has taken major steps with respect to used LIBs in 2018. It implemented several policies that not only established guidelines for handling waste batteries, but also developed the technical standards for battery recycling, made recycling the responsibility of manufacturers, ensured battery recycling traceability, and defined the pilot areas for battery recycling.[9] The *Law on the Prevention and Control of Solid Waste Pollution* (2020) introduced the EPR system for automotive traction batteries and banned solid waste imports.[10, 11] Additionally, in the same year, the *New Energy Automotive Industry Development Plan* (2021-2035) was adopted, promoting the legislation of traction batteries recycling.[12] Further, the *Circular Economy Development Plan* (2021) aims to make the circular economy a national priority through recycling, remanufacturing, and reusing resources for the period 2021-25.[13] MIIT has also proposed the *Industry Standard Conditions for Comprehensive Utilization of Waste Power Batteries from New Energy Vehicles* (2024 Edition) which will establish the various requirements for industries engaged in the cascade utilization or recycling of waste batteries. This proposed policy is currently open to public opinion.[14] Other Asian countries, such as India and South South Korea, are also actively working to create an ecosystem for recycling LIBs.[15-18]



Source: CAS analysis based on publicly available information

Figure 1. Timeline highlighting key policies related to Lithium-ion battery (LIB) recycling by various countries/regions. Color code - China (Cyan), United States (Green), Europe (Orange), India (Purple), and South Korea (Brown)

2. Supply-chain decarbonization is being prioritized by auto OEMs

While electric vehicles are regarded as clean for the absence of direct tailpipe emissions from fuel combustion in operation, the production of their LIBs is a significant source of carbon intensity. Producing LIBs accounts for approximately 40-60% of the total emissions produced during an EV's manufacturing process.

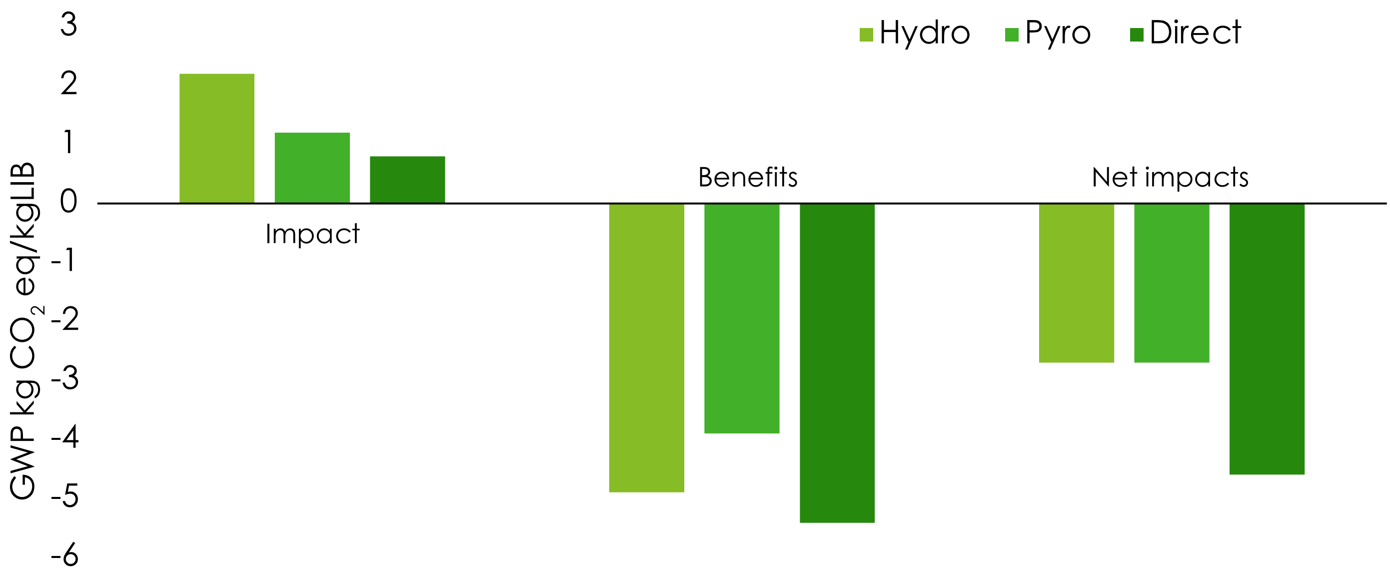
In response to increasing pressure from regulators, investors, and stakeholders for reduced carbon footprints, leading auto OEMs are swiftly advancing their zero-carbon strategies with a particular focus on essential materials, especially batteries (**Figure 2**). As a key target in Volkswagen's carbon-neutral strategy, the group committed to reducing carbon emission by an average of 30% over the entire life cycle compared to 2018 levels. To achieve this goal, Volkswagen launched a pilot facility for recycling vehicle batteries at the beginning of 2021 and plans to adopt a specific circular economy KPI for its upstream battery suppliers.

	Net-zero target	Supply chain decarbonization related to batteries	
	Net-zero Year	Battery carbon footprint management	Battery recycling cooperation
BYD	/	/	Set up recycling facilities with an annual recycling capacity of up to 1.3 GWh
Tesla	/	Established a LCA carbon footprint accounting methods	3 GWh of battery materials were dispatched to recycling partners in 2023
BMW	2050	Trace carbon footprint of components and raw materials by Catena-X, a shared data ecosystem	Cooperate with Huayou Circular in the closed-loop recycling
GAC	2045	/	Cooperates with Greenmax to achieve recycling of batteries
Volkswagen	2050	Set a specific KPI for the topic of circular economy which will be used in battery production	Pilot battery recycling plant for automotive power batteries in Salzgitter
SAIC	2050	/	Cooperate with CATL to promote the recycling of batteries
Lixiang	/	Carried out carbon footprint accounting for all models and ranked top in the C-GCAP	Entrust qualified suppliers to recycle batteries
Mercedes-Benz	2039	Track and measure the carbon footprint of supply chain within the next ten years	Wide use of recycled materials and renewable energy in the production process
Changan	2045	Join the International EPD Passenger Car PCR Standard Working Group	Establish a joint venture with a recycling company for recycling batteries
Geely	2045	Self-developed carbon management information platform	Formed an industrial alliance recycling model with OEMs as the core

Source: Company website, public information, Deloitte research

Figure 2. Leading EV OEMs' net-zero strategies and key tasks related to batteries.

EV batteries contain various minerals such as lithium, nickel, and cobalt, which emit substantial amounts of CO_2 in their mining and refining processes. Therefore, battery recycling and raw materials recovery is an important step toward decarbonization. In addition, battery recycling also helps to reduce energy consumption and carbon emissions in transportation, manufacturing, and other processes. In a research paper published by Fraunhofer IWKS in 2023, the life-cycle environmental impacts of three major recycling routes were evaluated.[19] The study estimates that recycling 1 kg of lithium batteries can reduce carbon emission by 2.7 to 4.6 kg CO_2 equivalent. Among the evaluated methods, direct recycling demonstrated the highest environmental performance (**Figure 3**).



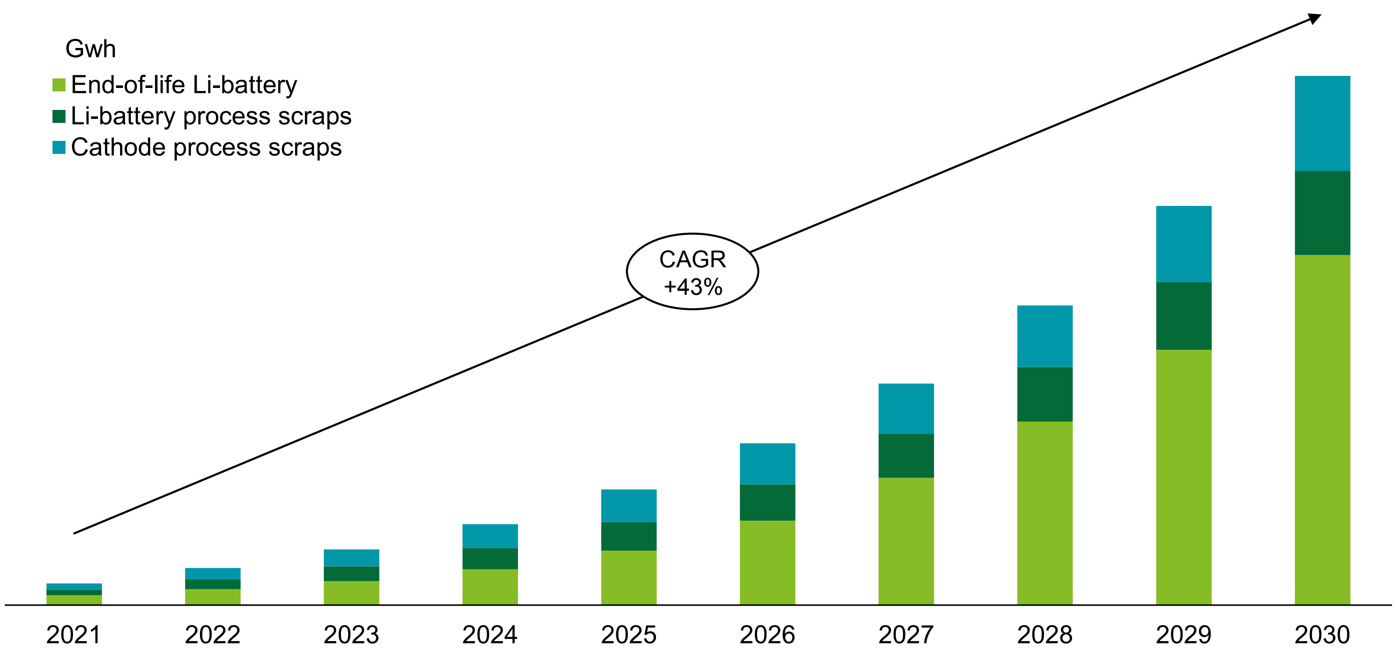
Source: Fraunhofer IWKS

Figure 3. Life-cycle environmental impacts of different recycling routes of LIBs.

3. EV batteries are ushering a wave of retirement

With the rise of the global new energy vehicle market, the installed capacity of EV batteries has risen rapidly. Since the performance of the lithium battery will gradually deteriorate with the increase of use time, the average service life of EV batteries ranges from 5 to 8 years. Therefore, the first batch of EV batteries put into the market are ushering in a "retirement tide". According to Deloitte's estimation, the retirement scale of EV batteries is expected to grow rapidly at a CAGR of 43% from 2021 to 2030 and will reach 1483 GWh per year by 2030.[20] The Chinese market, which leads the global EV market, is also expected to be the largest market in the field of battery recycling, occupying about 70% of the global battery recycling capacity (**Figure 4**).

Facing the upcoming wave of battery retirement, stakeholders are actively developing and applying emerging battery recycling technologies. These efforts aim not only to minimize the negative environmental impact but also to maximize resource utilization by refining and smelting valuable components from retired batteries. As the last piece of the puzzle for the lithium battery industry, the battery recycling market presents large opportunities.



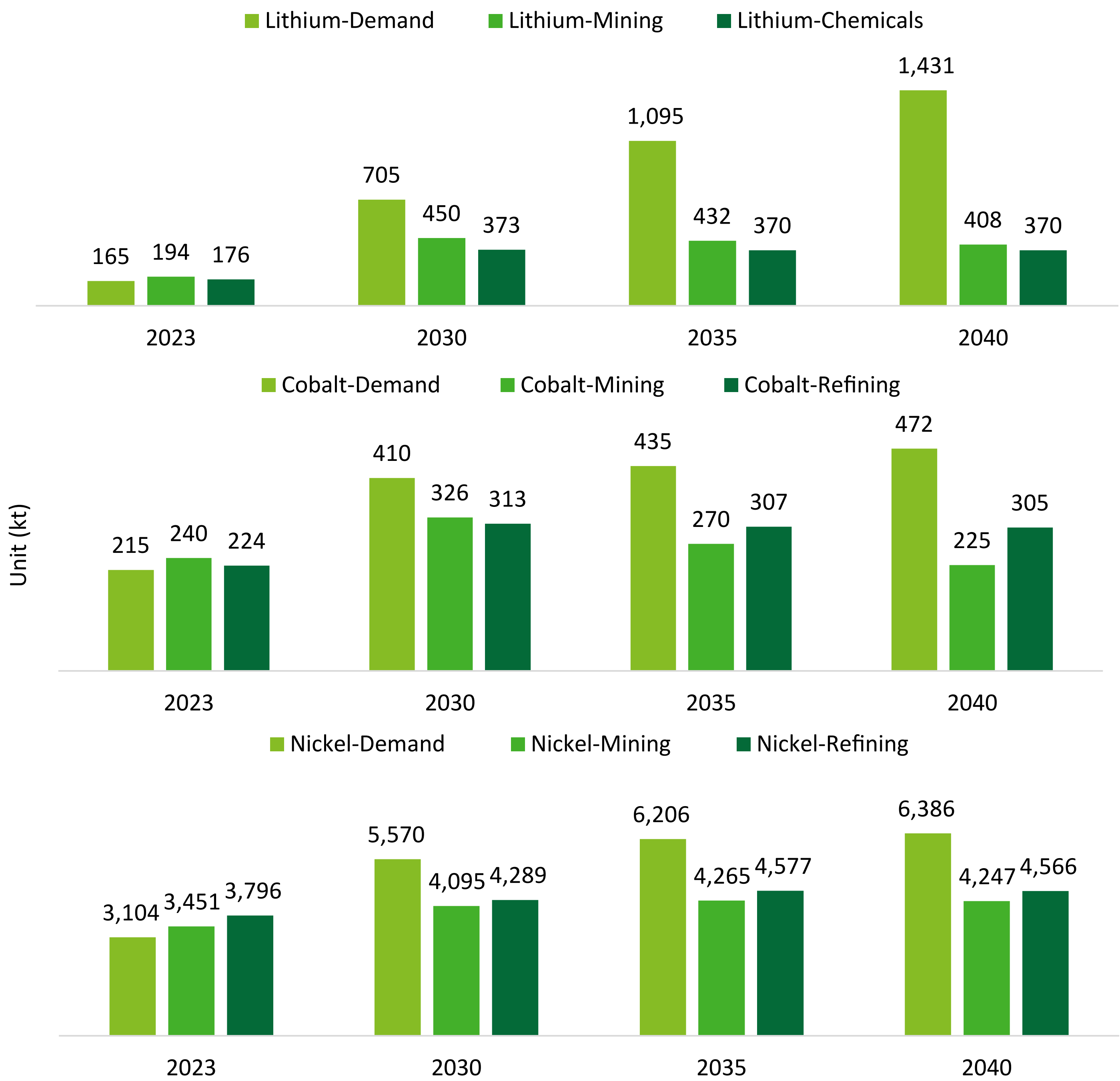
Source: Essence securities, Deloitte Research

Figure 4. The projection of global recyclable end-of-life Li-batteries and battery production scrapes.

4. Recycling to bridge the future supply gap for critical raw materials

The development of the lithium battery industry remains constrained by availability of upstream critical minerals. According to the IEA's forecast, under its net zero emissions by 2050 scenario, global lithium demand will reach 1,431 kt by 2040, which is 7-times higher than current level. Similarly, the demand for nickel and cobalt are expected to double by 2040, reaching 6,386 kt and 472 kt, respectively. Despite the surge in demand for critical minerals, expanding the mining and refining capacity requires high investment and a development cycle of up to several years. Therefore, the critical mineral resource supply and demand gap is expected to emerge and expand gradually after 2035 (**Figure 5**).

Prices of critical materials have fluctuated sharply in recent years, significantly impacting stakeholders across the industry value chain. Although battery material prices dropped considerably in 2024, supply chain volatility persists due to geopolitical tension, trade policy uncertainties, and other global crises. Battery recycling offers the lithium battery industry a pathway to reduce dependence on traditional raw material mining and to mitigate risks of future supply disruptions.



Source: IEA Global Critical Minerals Outlook 2024, Deloitte research

Figure 5. Supply and demand gap for critical minerals.

Market Landscape

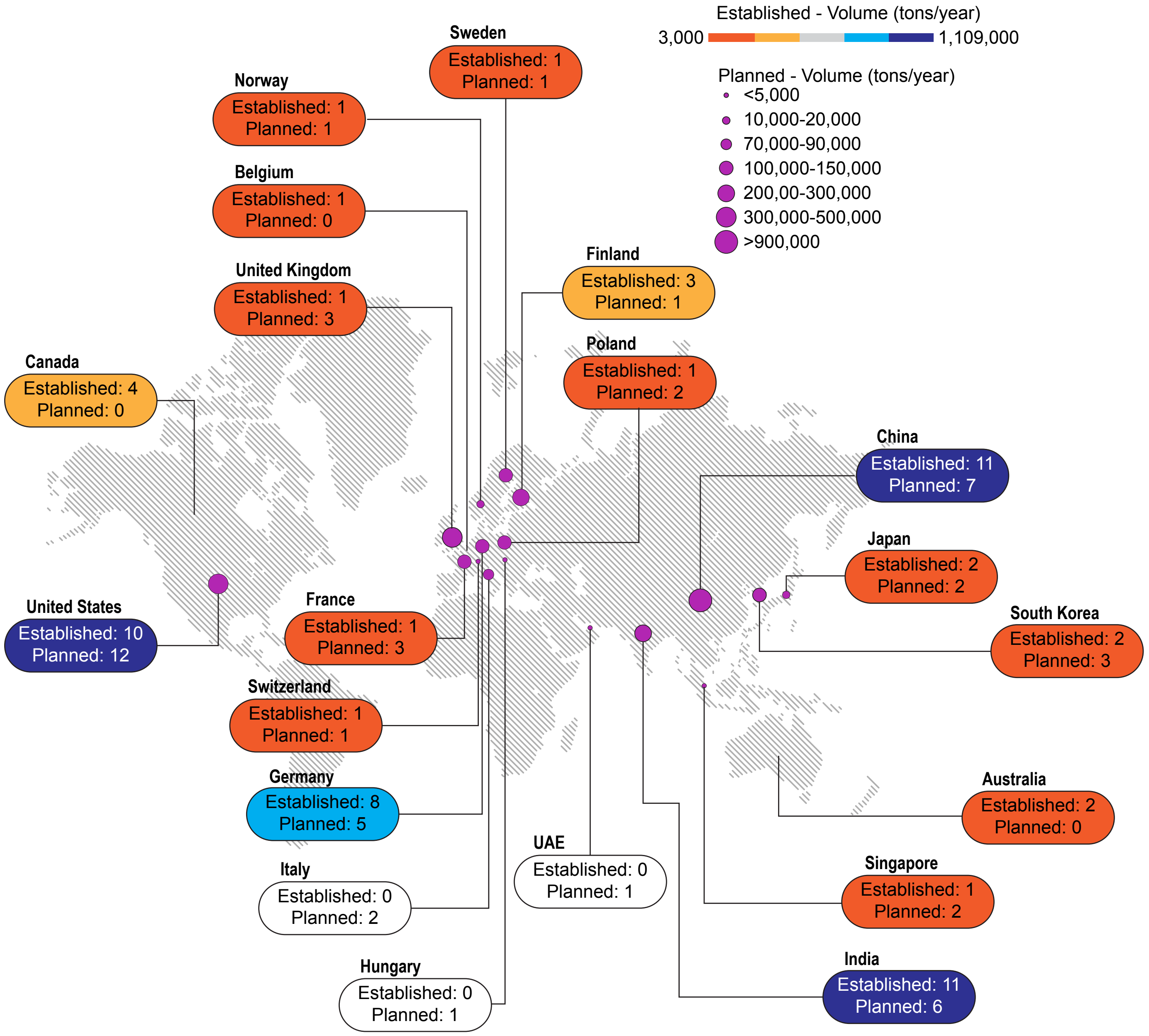
1. Recycling market projection

The global LIB recycling industry is undergoing significant expansion as governments and companies respond to the rising demand. Currently, the capacity of established recycling facilities stands at around 1.6 million tons per year. With the addition of planned facilities, it is expected to surpass 3 million tons per year. All major regions are scaling up their recycling capacities to meet increasing demand, with substantial support from government initiatives and funding.

Asia reigns in terms of the existing recycling facilities that can collectively recycle more than 1,210,000 tons/year (**Figure 6**). Notably, China contributes more than 1,100,000 tons/year, followed by India with 89,900 tons/year capacity. On the other hand, Japan and South Korea have smaller capacities of 6,000 and 28,000 tons/year, respectively. However, China plans to expand their current recycling capacities by 1,220,000 tons/year, while India plans to expand by 260,000 tons/year. With the South Korean government promoting LIB recycling, they aim to increase their recycling capacity by 134,000 tons/year and Japan has also projected to expand by 20,000 tons/year. Furthermore, new facilities are being developed in other markets in Asia.

North America, including the U.S., combined have a total recycling capacity of 144,000 tons/year. Given the projected growth of LIB manufacturing and adoption, these numbers are quite insignificant. The government is supporting the construction of recycling facilities by providing the necessary funding, e.g., DOE and Loan Programs Office (LPO) has announced a conditional loan commitment of $375 million to Li-Cycle U.S. Holdings, Inc. (Li-Cycle) for the construction of the LIB recycling facility in North America.[21] The DOE's funding has spurred a surge in the construction of lithium battery recycling facilities. The U.S. has initiatives underway to expand their current recycling capacity by more than 300,000 tons per year, involving both the improvement of existing facilities and the development of new ones.

Europe collectively has the huge recycling capacity of more than 200,000 tons/year which is spread across the United Kingdom, France, Germany, Finland, Norway, Poland, Sweden, Belgium, and Switzerland. However, implementation of the new battery regulations in 2023 has prompted significant growth in the battery recycling industry, with numerous companies expanding their operations or establishing new facilities. This expansion has resulted in a projected recycling capacity of over 1,120,000 tons/year in Europe, with newer developments in Scotland, Hungary, and Italy, where Scotland alone will have the capacity of 350,000 tons/year. Moreover, Umicore has announced the construction of Europe's largest battery recycling plant, projected to have an annual capacity of 150,000 tons.[22]

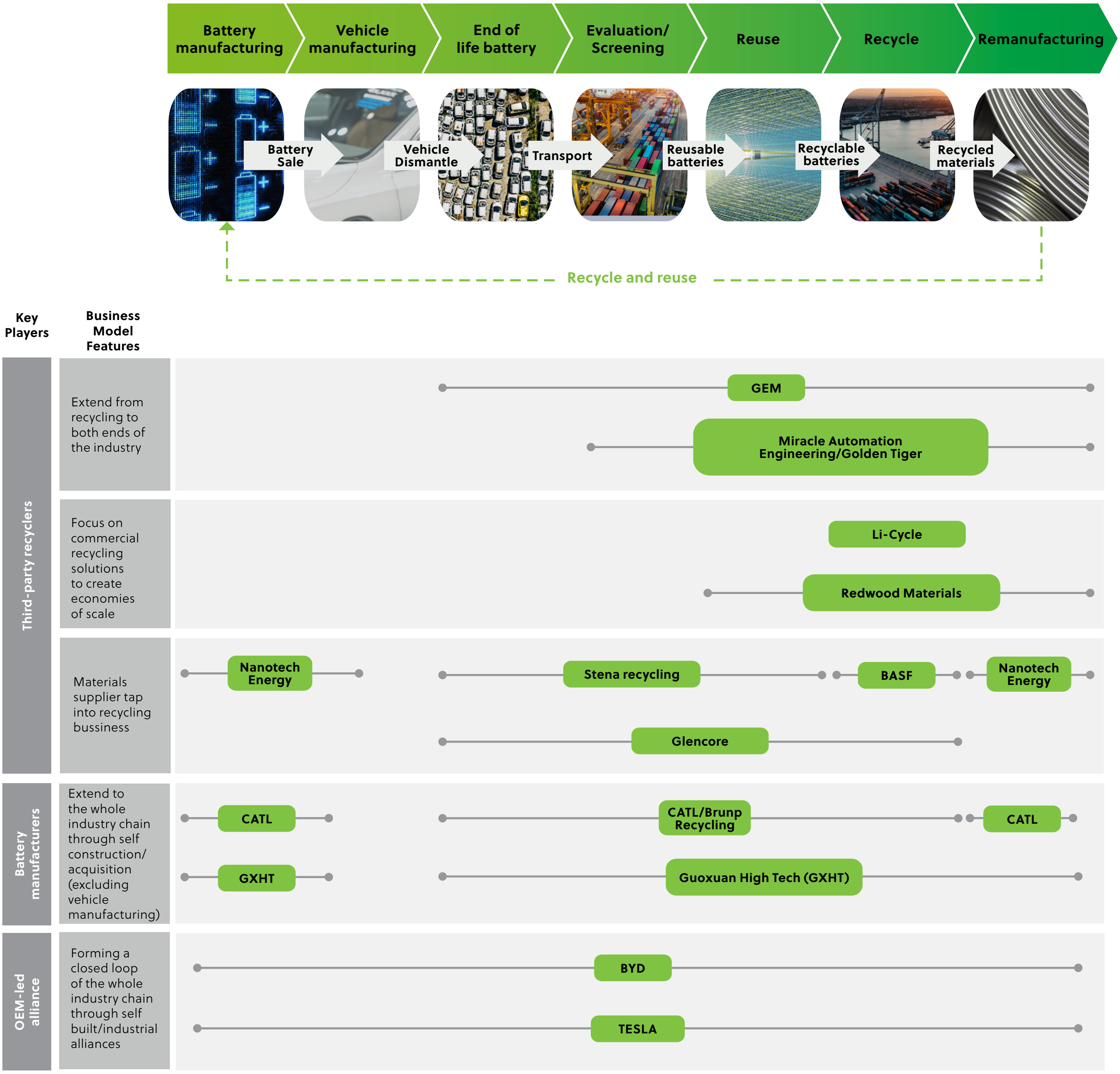


Source: CAS based on publicly available information

Figure 6. Geographical distribution of established and planned recycling facilities for LIBs.

2. Industrial value chain

Lithium battery recycling, with strong development momentum, is taking shape to support a sustainable EV supply chain. Various players, including auto OEMs, battery manufacturers, and third-party recyclers, each bring unique strategies to the industry. These strategies range from covering the entire chain or specializing in specific segments, all aimed at optimizing resources recovery and establishing a closed-loop industrial chain (**Figure 7**).



Source: Company website, public information, Deloitte research

Figure 7. Battery recycling value chain and business models adopted by recyclers.

In the battery recycling value chain, each type of player holds different strengths based on several critical indicators such as feedstock access, technological capability, recycling channels, and others like regulatory influence and sustainability initiatives.

- **Third-party recyclers**
  bring specialized expertise in recycling technology and processes, offering high efficiency in material recovery. However, they rely more heavily on partnerships to access feedstock and recycling channels.

- **Battery manufacturers**
  hold a strong position, with access to feedstock, advanced recycling technology, and strong regulatory influence. Their control over production allows them to secure steady feedstock.

- **Auto OEMs**
  are rapidly strengthening their role, particularly in recycling channels where they have a high level of control through end-of-life vehicle programs and customer networks. Additionally, OEMs prioritize sustainability initiatives to align with regulatory requirements, positioning themselves as influential players over time.

Players along the value chain are striving to build a closed-loop chain for battery recycling, but the key to truly seamless connectivity may hinge on the adoption of a digital product passport (DPP). DPP is a digital record embedded within each battery, containing comprehensive data about its lifecycle—from raw material sourcing and manufacturing details to usage, maintenance, and recycling history. Acting as a digital identity, the DPP provides every stakeholder in the battery recycling value chain with real-time, accurate information on the battery's condition and material composition.

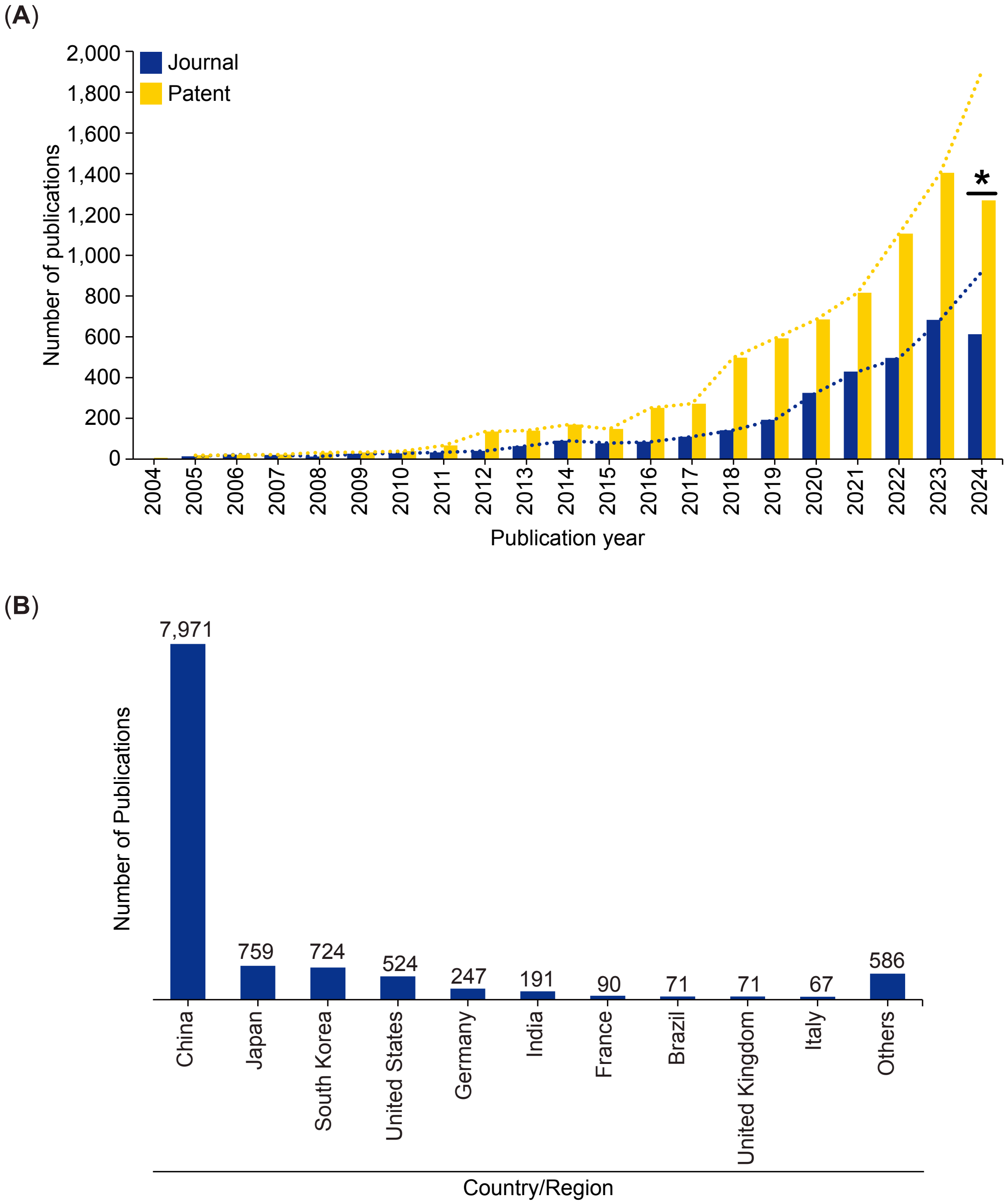
In an industry where multiple stakeholders rely on accurate information to make decisions, the DPP serves as a bridge for connection and collaboration. Furthermore, as the industry faces increasing regulatory pressure for traceable recycling, the DPP facilitates compliance by creating a verified chain of custody from production to disposal. Real-world applications of the DPP are gaining traction in Europe, where companies like BMW[23] and Volkswagen are piloting its use to align with these regulatory standards and enhance operational efficiency.

Technological Innovation

For this report, we leveraged the CAS Content Collection™, one of the largest human-curated repositories of scientific information, providing a treasure trove of information for comprehensive trend analysis of technology innovations. Our subject matter experts crafted a search query, retrieving over 11,000 documents (journal and patent publications) from 2004-2024, ensuring maximum coverage while keeping noise level at minimum. Besides extracting and analyzing bibliographical data from these documents, we also leveraged our indexed concepts and chemical substances for a more thorough analysis in technology development.

1. Power players: Unveiling the global leaders and trends

The strong commercial interest in LIB recycling is evident from the overwhelming patent-to-journal publication ratio of 2:1, compared to the typical ratio of 1:5 (**Figure 8A**). Furthermore, our analysis of the geographical distribution of total publications highlights the dominance of Asian countries in this field, as shown in **Figure 8B**. China has emerged as the leading player, followed by Japan and South Korea. The United States and Germany also hold prominent positions.

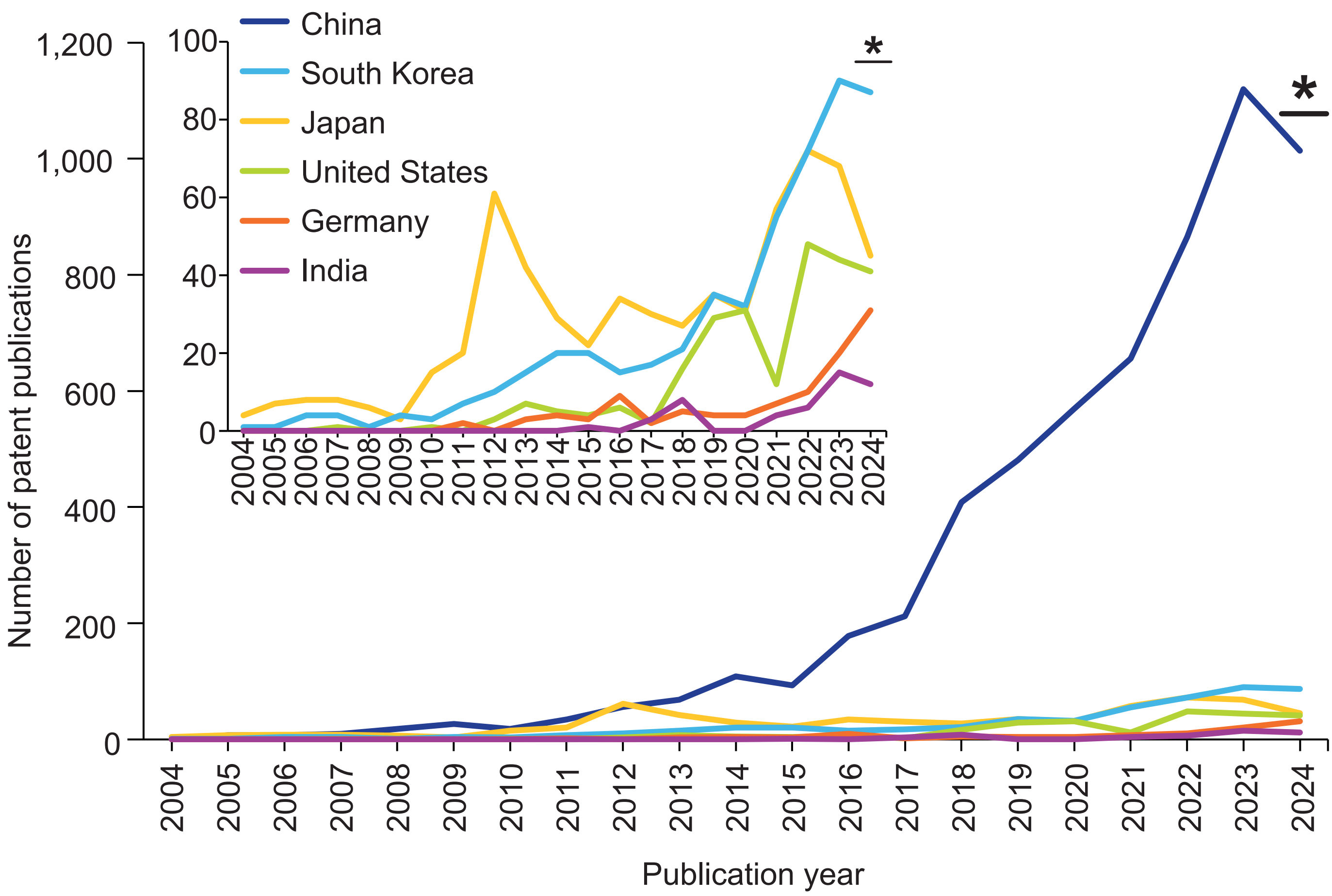


Source: CAS Content Collection

Figure 8. (**A**) Publication trends and (**B**) geographical distribution of publications in the field of lithium-ion battery (LIB) recycling. Data includes journal and patent publications from the CAS Content Collection for the period 2004-2024.

*Data for 2024 is partial and encompasses January to September.

To evaluate commercialization efforts in LIB recycling, we analyzed patent trends in the leading countries (**Figure 9**). China remains the dominant player, but Japan and South Korea are also making significant strides towards commercialization, as evidenced by their increasing number of patents over the years. The United States follows closely behind. Notably, South Korea's exponential patent growth indicates a sharp rise in technological innovation investment.

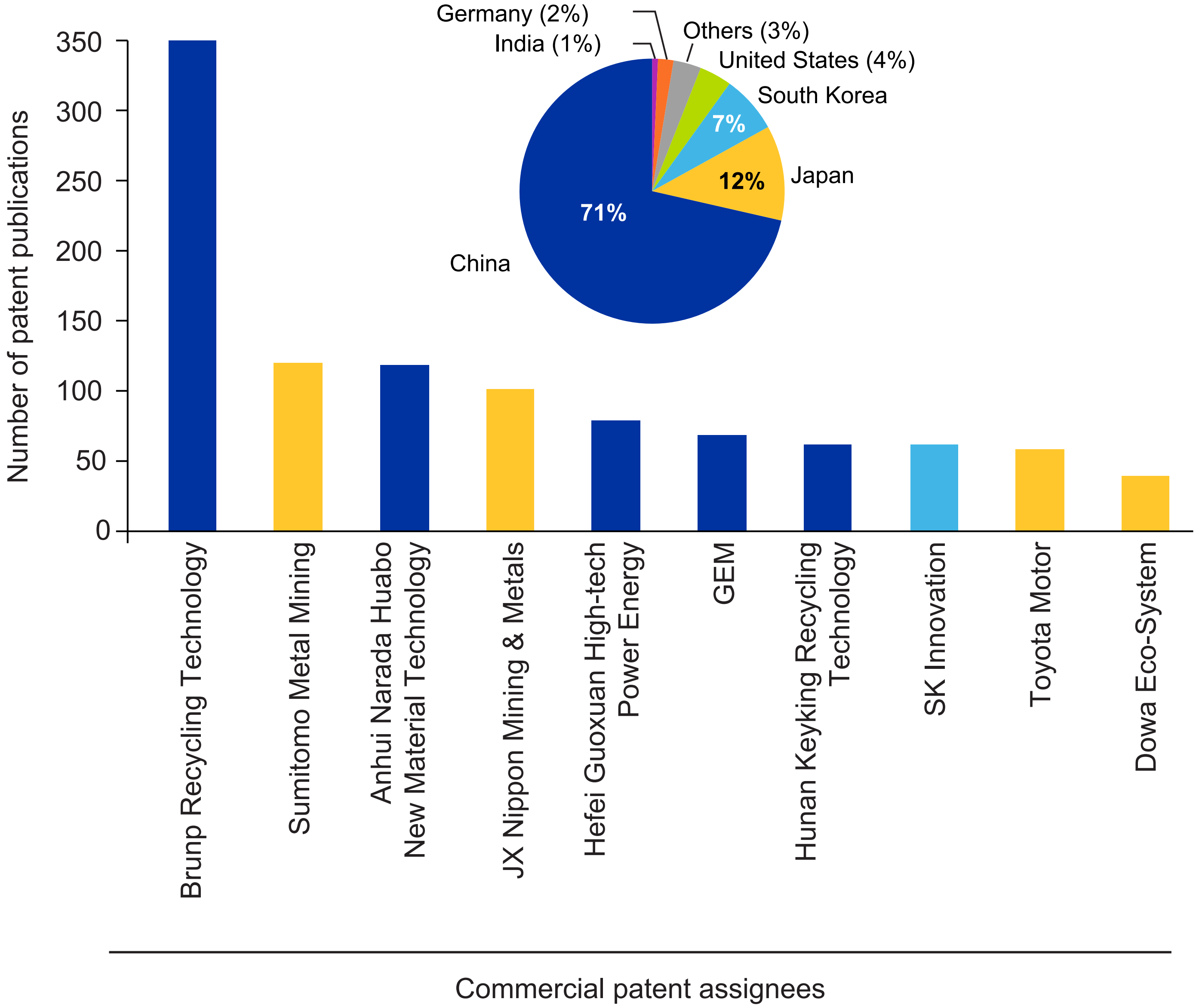


Source: CAS Content Collection

Figure 9. Time trends of patent publications for leading countries/regions. Data includes patent publications in the field of LIB recycling from the CAS Content Collection for the period 2004-2024.

*Data for 2024 is partial and encompasses January to September.

We then identified a list of companies who are leading in LIB recycling technology innovation by numbers of patent publications (**Figure 10**). China's Brunp Recycling Technology, a subsidiary of Contemporary Amperex Technology Co., Limited (CATL) (example patent: CN113957255A[24]), emerged as the most established one in this field, followed by Japan's Sumitomo Metal Mining (example patent: JP2021031760A[25]). The top 10 also included SK Innovation (example patent: WO2022139310A1[26]), from South Korea.



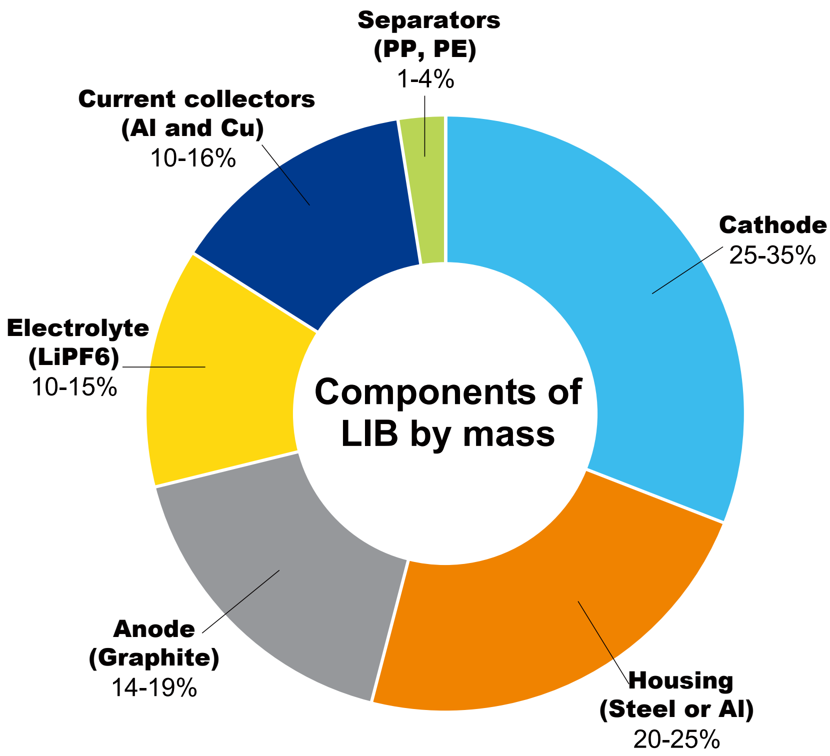
Source: CAS Content Collection

Figure 10. Established/leading commercial entities in the field of lithium-ion battery (LIB) recycling ranked by volume of patents published. Bars have been colored by countries/regions. Shown inset is a pie chart depicting geographical distribution of commercial patent assignees in this field. Data includes patent publications from the CAS Content Collection for the period 2004-2024. Data for 2024 is partial and encompasses January to September.

In addition to these leading companies, we identified a few emerging ones, based on their increasing number of patent filings over the past five years. These included Germany's BASF (example patent: WO2024094725A1[27]), Korea's LG Energy Solution (example patent: WO2024010260A1[28]), United States' Ascend Elements (example patent: US20240304883A1[29]), and China's Wuhan Weineng Battery Asset Co., Ltd. (example patent: CN116387667A[30]) and Tianneng New Material Co., Ltd. (example patent: CN118256726A[31]). While BASF, LG Energy Solution, and Tianneng New Material, are developing methods to recover valuable metals from discarded lithium-ion batteries, Ascend Elements is specifically targeting lithium recycling. Wuhan Weineng Battery Asset is also working on technologies for efficient lithium battery recovery and disassembly. These companies have shown significant growth and innovation and are worth watching in the near future for their potential impact on the LIB recycling industry.

2. Value wins over mass in driving the recycling methodology

At the higher level, one of the crucial decisions for organizations to make is the choice of recycling methodology. Though most components of the LIB contribute around 10-35% of the mass (**Figure 11**), most of the common recycling methodologies are designed to focus on cathodes, which hold the most value. This is because most of the cathodes are composed of materials containing in-demand metals such as Co and Ni.

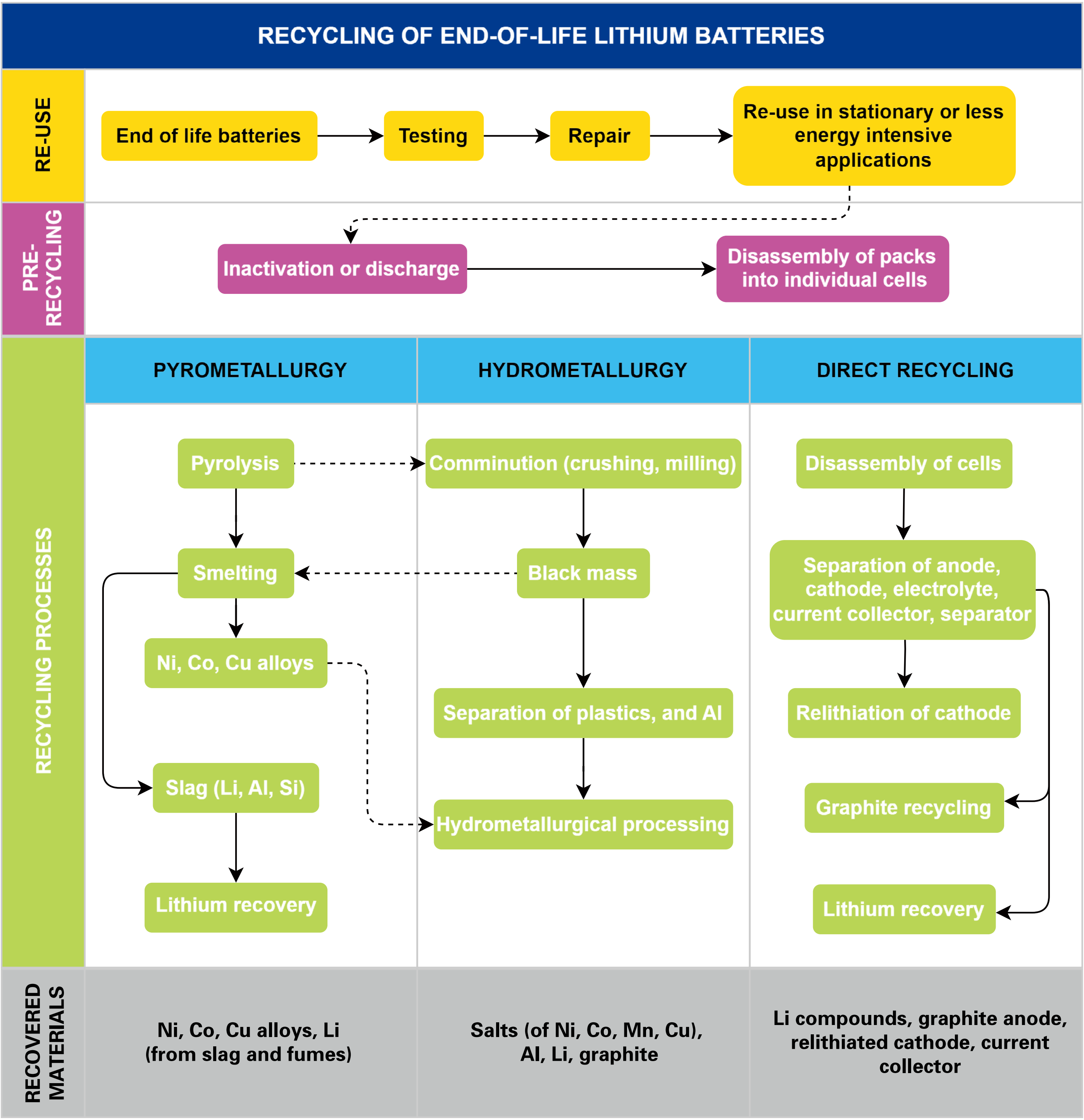


Source: CAS analysis

Figure 11. Percentage contribution by mass from the parts of a typical lithium-ion battery. Adapted from Georgi-Maschler et al.[32]

The recycling process for end-of-life (EOL) LIB is shown in **Figure 12**. In addition to the recycling process, a small percentage of the EOL LIBs are repurposed for less energy intensive applications such as golf carts or photovoltaic energy storage, in a process called echelon utilization.[33, 34] The first step in the recycling process is the deactivation of the batteries. Residual charge in the EOL LIBs can pose risks of thermal runaway and toxic gas release during the recycling, necessitating deactivation. Common deactivation methods include external short circuit, and use of conductive liquids.[35]

The primary recycling approaches for LIBs are pyrometallurgy, hydrometallurgy, and direct recycling,[36] each focused on recovering valuable materials through different techniques. Pyrometallurgy relies on high-temperature treatment, hydrometallurgy uses chemical dissolution, and direct recycling aims to retain the electrode's chemical structure. The metals recovered by these methods have varying chemical compositions. Metals are recovered as alloys from pyrometallurgy often requiring further chemical processing, leading to hybrid approaches that combine hydro- and pyrometallurgical steps, depicted by dotted arrow.

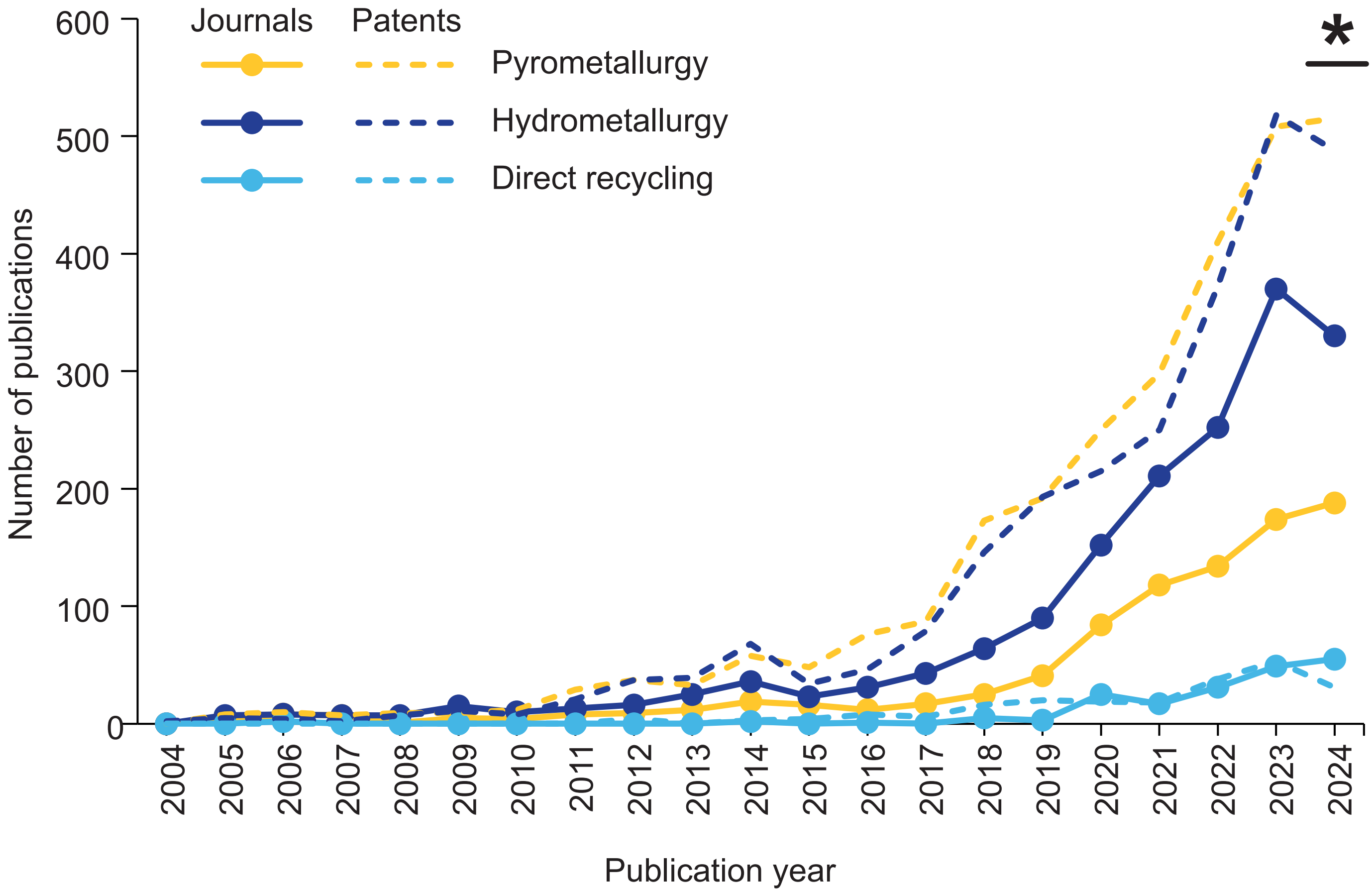


Source: CAS

Figure 12. Key processes and steps involved in lithium-ion battery (LIB) recycling across three major recycling methods – hydro-metallurgy, pyrometallurgy and direct recycling.

3. Leading the charge: Pyrometallurgy and hydrometallurgy remain dominant for LIB recycling

Figure 13 presents the publication trends in pyrometallurgy, hydrometallurgy, and direct recycling using data from the CAS Content Collection. Publications, predominantly patents, reflect the high commercial interest in this field. The overall growth in publications underscores the increasing importance of LIB recycling. Hydrometallurgy has a slight lead over pyrometallurgy in publication volume, while direct recycling lags significantly. The higher share of journal publications in hydrometallurgy suggests ongoing fundamental research into novel, more efficient, cost-effective, and environmentally friendly chemical processes.



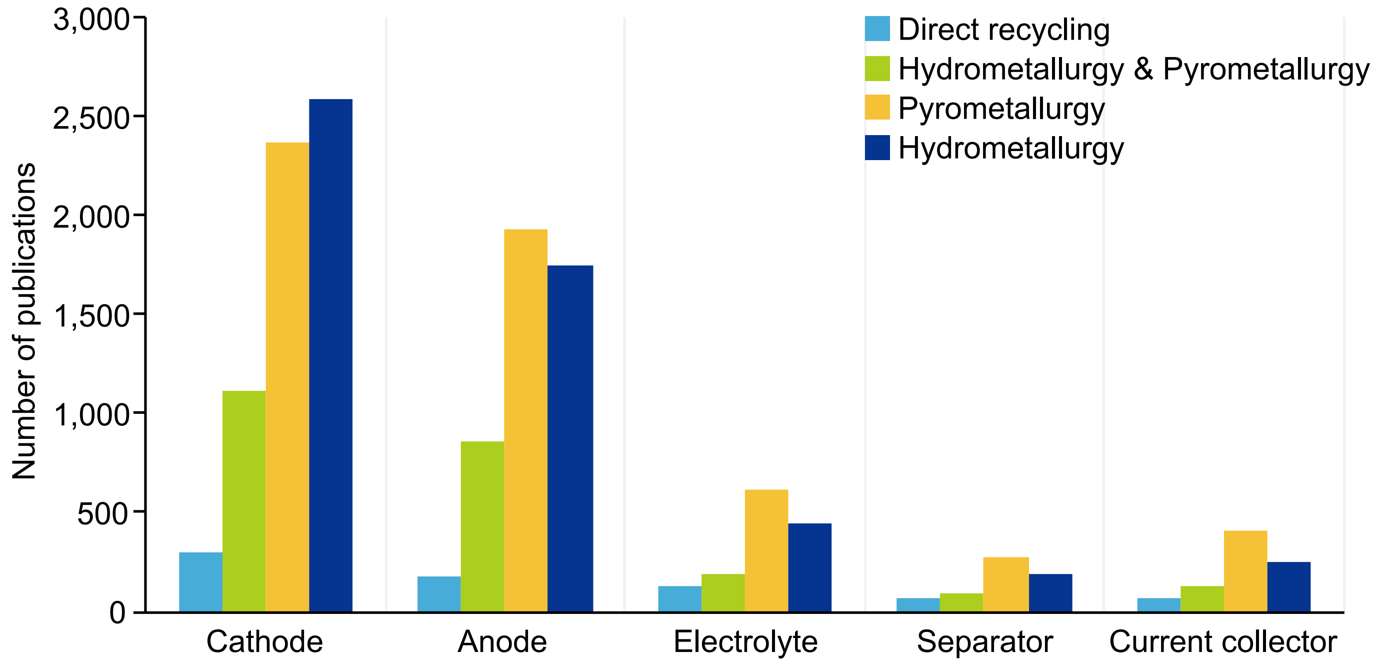
Source: CAS Content Collection

Figure 13. Publication trends of three major recycling methods – hydrometallurgy, pyrometallurgy and direct recycling. Data includes patent publications from the CAS Content Collection for the period 2004-2024.

*Data for 2024 is partial and encompasses January to September.

4. Cathode kings: The critical role of cathode recycling in LIBs

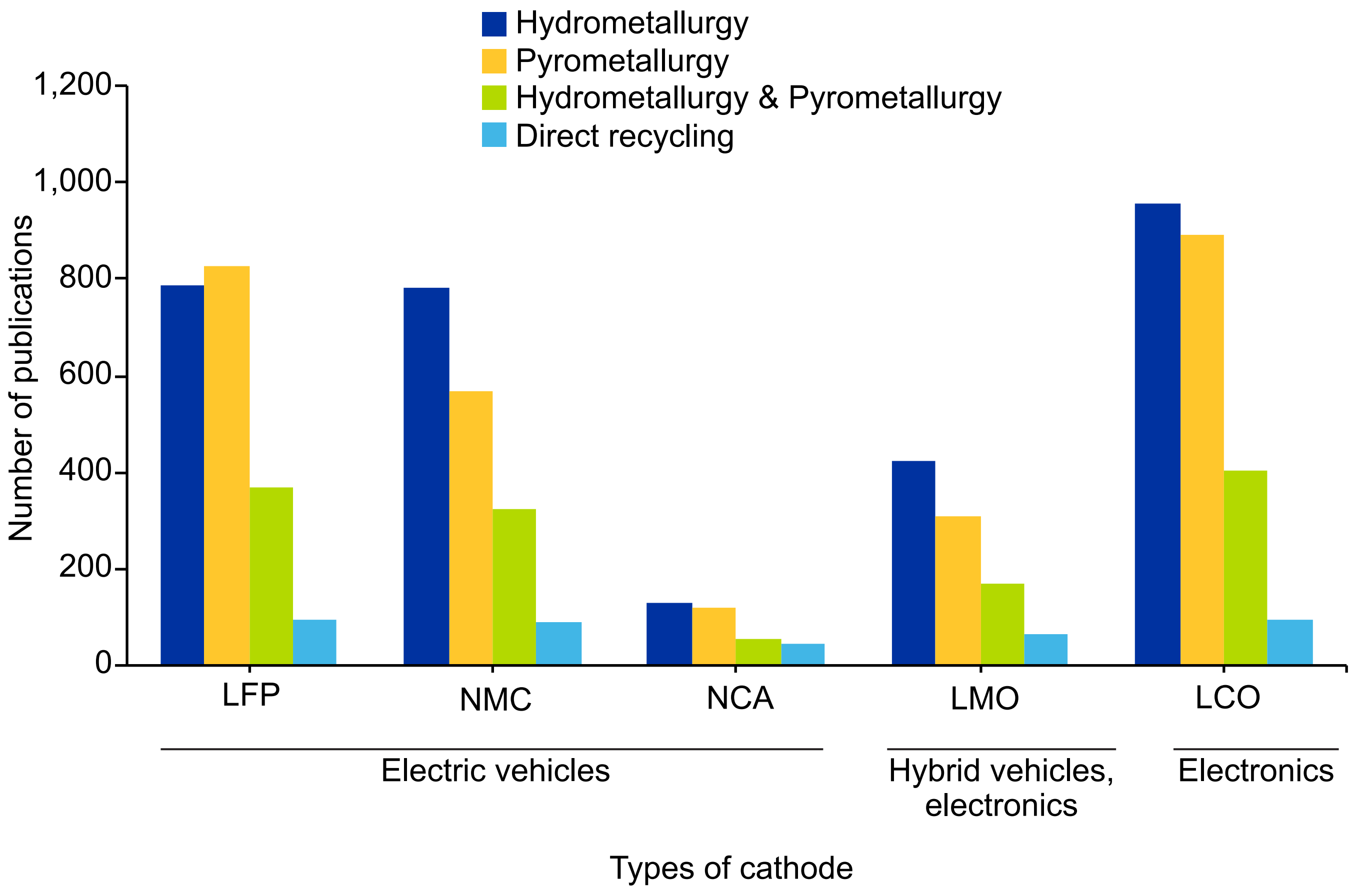
The preferences of recycling methods are often associated with the recycling components of the batteries and the materials to be recovered. **Figure 14** presents the recycling focus for various battery components. The high value of metals like cobalt (Co), nickel (Ni), and lithium (Li) makes cathode recycling a top priority.[37] Interest in anode recycling is driven by recoverable graphite and lithium,[38] while the electrolyte, composed of lithium salts in organic carbonates, also offers lithium extraction potential.[38] Copper, used as the anode current collector, adds to the recycling value of this component.[39]



Source: CAS Content Collection

Figure 14. Publication trends of three major recycling methods – hydrometallurgy, pyrometallurgy and direct recycling with respect to various parts of LIB recycled (cathode, anode, electrolyte, separator, and current collector). Data includes patent publications from the CAS Content Collection for the period 2004-2024. Data for 2024 is partial and encompasses January to September.

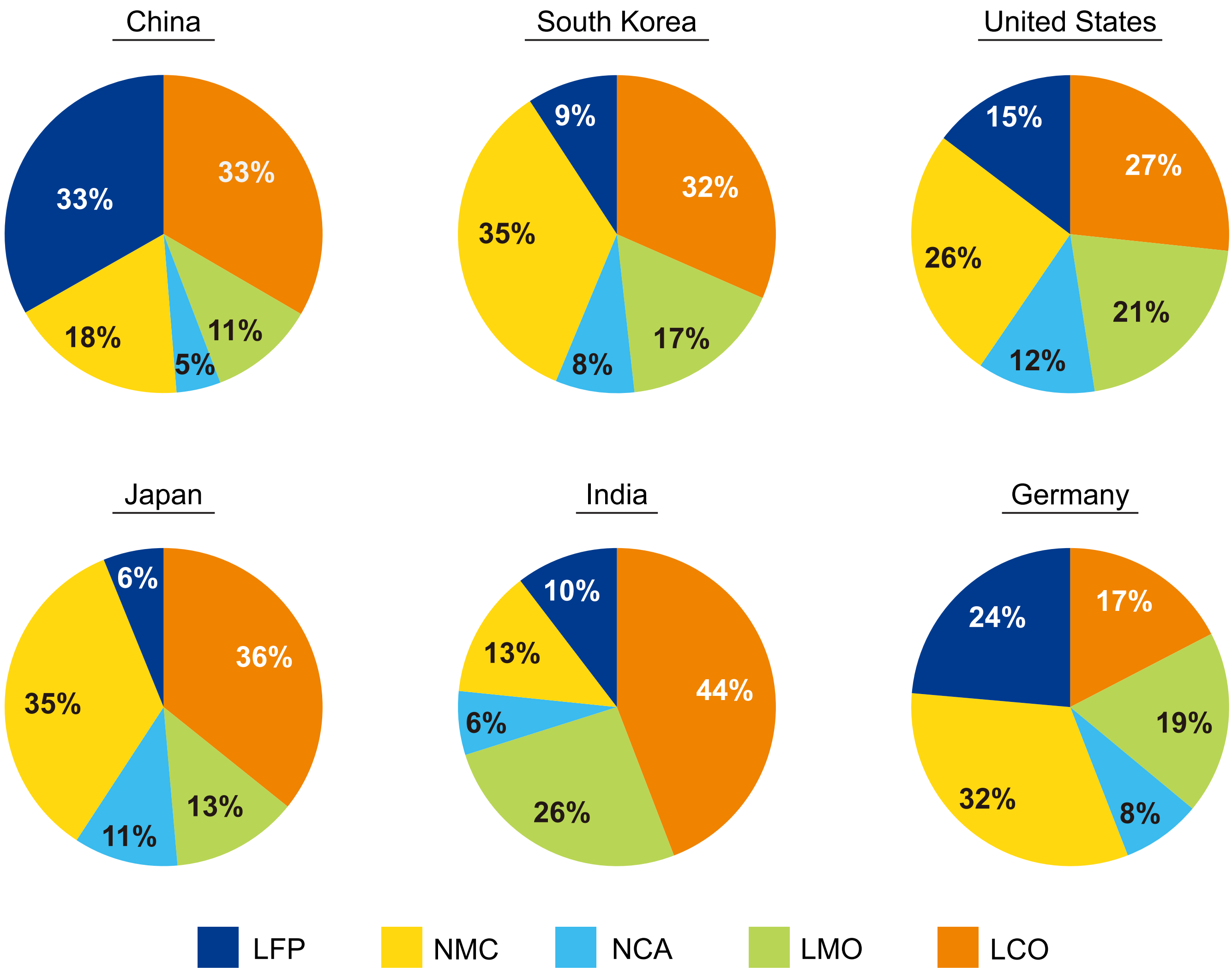
Most of the LIB recycling effort is focused on the cathode, since it holds the most valuable materials, and the composition may slightly vary. **Figure 15** shows the concurrence of common LIB cathode types with recycling methods. Lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA) are three major cathode types associated with EVs. Among them, LFP and NMC are widely adopted, and their recycling methods are broadly discussed in the literature, with a general prevalence of hydrometallurgy, pyrometallurgy, hybrid, then direct recycling. LFP has a slight favor in pyrometallurgy probably due to its low-value metals making hydrometallurgy's chemical requirements less cost-effective.[40] NCA is relatively less utilized and therefore, its recycling is less studied in the literature. Lithium manganese oxide (LMO) is a type of cathode utilized in hybrid automobiles or electronics, whereas lithium cobalt oxide (LCO) is widely used in electronic devices. The publication prevalence of these cathodes recycling also followed the general trends mentioned above.



Source: CAS Content Collection

Figure 15. Publication trends of three major recycling methods – hydrometallurgy, pyrometallurgy and direct recycling with respect to various types of LIBs (LFP, NMC, NCA, LMO and LCO) utilized in various applications. Data includes journal and patent publications from the CAS Content Collection for the period 2004-2024. Data for 2024 is partial and encompasses January to September.

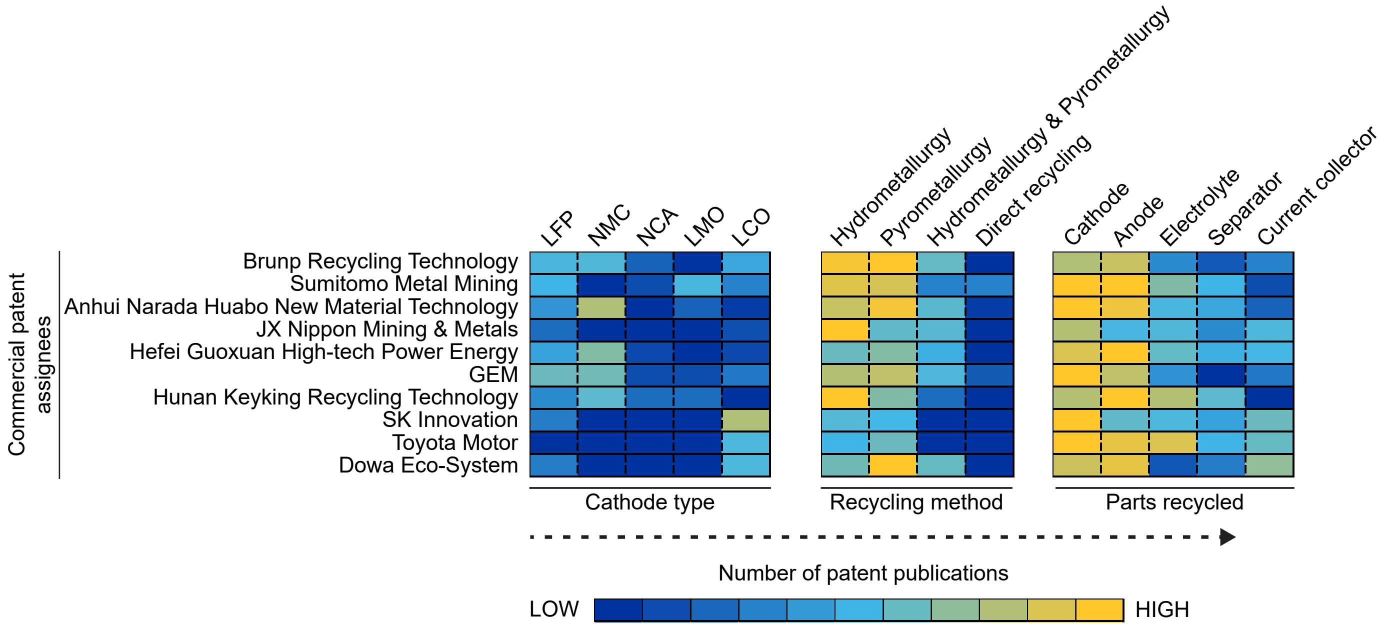
The share of the publications related to various cathode types in different countries is presented in **Figure 16**. China's notable focus on LFP reflects its widespread adoption there, while NMC dominates in other countries, such as South Korea, United States, Japan and Germany, due to its prevalence in EVs. The accessibility of EOL LCO batteries from electronics also boosts LCO recycling research, especially in India and Japan.



Source: CAS Content Collection

Figure 16. Distribution of LIB types (LFP, NMC, NCA, LMO and LCO) for leading countries or regions. Data includes journal and patent publications from the CAS Content Collection for the period 2004-2024. Data for 2024 is partial and encompasses January to September.

The preferred cathode technologies of leading LIB recyclers vary by region (**Figure 17**). Chinese recyclers focus heavily on LFP, aligning with domestic production trends, while recyclers elsewhere balance between NMC and NCA to reflect local LIB production.[41] Both pyro-metallurgy and hydrometallurgy are employed without a clear preference, and some recyclers combine these methods to improve recycling efficiency.[42, 43]

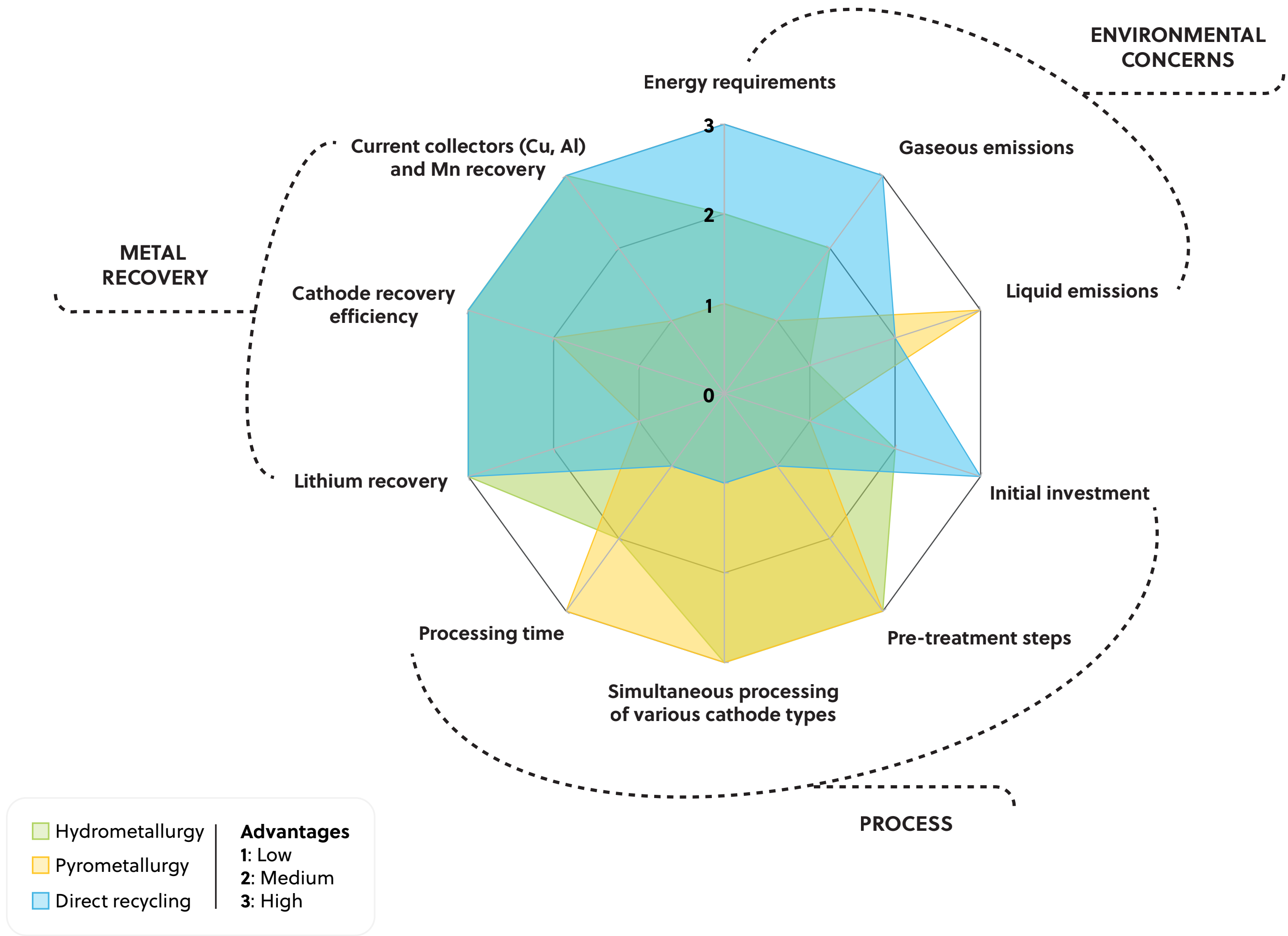


Source: CAS Content Collection

Figure 17. Heat map depicting breakdown of patents by leading commercial patent assignees across LIB types (LFP, NMC, NCA, LMO and LCO), recycling methods (hydrometallurgy, pyrometallurgy and direct recycling) as well as parts of LIB recycled (cathode, anode, electrolyte, separator, current collector). Data includes patent publications from the CAS Content Collection for the period 2004-2024. Data for 2024 is partial and encompasses January to September.

5. Recycling showdown: The ultimate comparison of LIB recycling methods

A comparison of pyrometallurgy, hydrometallurgy, and direct recycling reveals that each method has distinct advantages and drawbacks (**Figure 18**). Pyrometallurgy is highly energy-intensive, needing substantial electricity or fuel to reach necessary temperatures, and generates high gas emissions.[44] Hydrometallurgy, while less energy-intensive, produces considerable liquid waste requiring additional treatment. Pyrometallurgy struggles with recovering lithium, aluminum, and manganese, which often form a slag needing further processing.[45] Direct recycling and hydrometallurgy may require customization based on cathode type, but pyrometallurgy's high-temperature approach can process diverse battery types effectively.



Source: CAS

Figure 18. Radar chart depicting comparison between the three major recycling methods – hydrometallurgy, pyrometallurgy and direct recycling with respect to parameters (environmental concerns, process related and metal recovery).

Future Perspectives

Although the industry currently faces challenges such as high costs, complex recovery processes, or fragmented collection and logistics, the future is promising. Advancements in technology, digital applications, and increased industry collaboration are set to revolutionize the landscape, making battery recycling not only more efficient but also economically viable. As stakeholders invest in smarter solutions, we can expect a new era of sustainable battery management that supports the growing demand for electric vehicles, paving the way for a greener, circular economy.

1. Recycling technology innovations to tap the cost and safety issues

Battery recycling poses several complex challenges, ranging from operational inefficiencies and safety risks to regulatory compliance and environmental impact. One of the major issues is the wide range of different and evolving battery formats, designs, compositions, and chemistry, which complicates the recycling process and requires specialized techniques. This complexity of recycling process, along with the presence of toxic and flammable substances, often are energy-intensive and require costly safety measures.

Government fundings for battery recycling is already in place to tackle the challenges. The U.S. launched The Bipartisan Infrastructure Law in 2022, allocating $200 million to support research, development, and demonstration for electric drive vehicle battery recycling and second-life applications. In 2021, the European Commission approved a €2.9 billion ($3.5 billion) package to support a pan-European research and innovation project for the entire battery value chain. Venture funding for battery recycling is on the rise, with investments in recycling start-ups reaching $4.5 billion in 2023—double the amount from the previous year. Investors range from battery manufacturers and refiners to mining giants and automakers.

Recycling technology innovation and emerging technologies focus on improving metal recovery rates, making recycling processes increasingly economical viable and sustainable. According to IEA, the readiness level of various recycling technologies varies (**Figure 19**).[46] For instance, direct recycling aims to retain the functional structures and chemical compositions of the materials to reduce the energy and environmental costs. Ascend Elements is pioneering a new battery recycling process that avoids conventional shredding and smelting techniques. Instead, they dissolve the batteries' minerals using acid to recover and reuse valuable elements like nickel, cobalt, and lithium. They have facilities in Georgia, Massachusetts, and an upcoming billion-dollar plant in Kentucky.

Novel and promising methodologies such as deep eutectic solvent (DES) and microbe-based leaching are at the early stages of development. Though hydrometallurgy is less energy intensive than pyrometallurgy, the acids used for leaching the metals are toxic and corrosive. DES are emerging as a green alternative to the acids used in pyrometallurgy due to their benign nature, tailorable composition, redox abilities, and reusability.[47] Reports claim that precipitation of the leached elements and reusability of the DES for multiple leaching cycles can be achieved by addition of small amounts of reagents, thus avoiding wastage of the solvents. Though DES seems highly promising, adoption of DES remains limited due to high cost, complex composition, and doubts regarding its reusability.[48] An emerging alternative, bioleaching (or biohydrometallurgy), although it currently lagging behind pyrometallurgy or hydrometallurgy in number of publications, offers a promising, environmentally friendly solution by using microorganisms to extract valuable metals.[49] This approach could reduce reliance on energy-intensive methods like pyrometallurgy and hydrometallurgy. However, bioleaching's slower metal recovery rate, sensitivity to toxic battery compounds, and challenges in scaling present obstacles for industrial application. More research is necessary to optimize this approach for efficiency, scalability, and cost-effectiveness.

TECHNOLOGY	DESCRIPTION	MATURITY 2020	MATURITY 2024	OTHER DETAILS
Pyrometallurgy	Uses high-temperature furnaces (>1000ºC) to melt and separate the battery components	Mature (TRL = 11)	Mature (TRL = 11)	
Hydrometallurgy	Uses aqueous solutions to dissolve the battery components. Includes acidic leaching, extraction, and precipitation	Mature (TRL = 11)	Mature (TRL = 11)	Since 2010, hydro recyclers have received VC funding of $1.2 billion. Funding to be used for commercialization purposes including the construction of new facilities
Direct recycling	Cathode material can be recovered without the use of acids or smelting	Small prototype (TRL = 4)	Large prototype (TRL = 5)	Princeton NuEnergy (PNE) has received over $55 million in funding, Bosch co-led an investment of $36M to Li Industries
Electricity-based recycling	Use of electric currents and voltage to separate the metals	Concept (TRL = 2)	Concept (TRL = 2-3)	
Battery designed for recycling	Designing batteries with recycling in mind, to make disassembly, recycling or even rejuvenation easier, safer and more efficient	Large prototype (TRL = 5)	Large prototype (TRL = 5)	

TRL = Technology Readiness Level

Source: TRL has been taken from IEA ETP Clean Energy Technology Guide and Deloitte GreenSpace Research analysis; public information; Deloitte Research

Figure 19. Evolving battery recycling technologies.

As these technologies advance, industry players are strategically positioning themselves. Chemical giants like BASF and Johnson Matthey are entering the hydrometallurgy space to meet the growing demand for battery-grade chemicals. OnTo Technologies has a patent for a direct recycling method and is collaborating with Johnson Matthey to further develop the technology.

Meanwhile, Cleantech Group's analysis suggests that European and Chinese automakers are expected to leverage direct recycling, driven by the potential for higher returns on extended producer responsibility (EPR) mandates and improved economics for LFP battery recycling.

2. Adoption of digital tools to increase traceability and efficiency

Manual processes often lead to low recovery rates, high costs, and potential safety hazards. Additionally, regulatory pressures require meeting strict standards for recycled content and environmental impact. Without traceability, it becomes nearly impossible, exposing companies to reputational and legal risks.
How can digital tools help in that sense? Digital tools can be applied for tracking materials in lifecycle, automated sorting and disassembling, and optimizing recycling schedule (**Figure 20**). For instance, cloud-based platforms and blockchain technologies allow companies to track and trace the lifecycle of battery materials, from collection to recycling and reintegration into the supply chain. This ensures compliance with environmental regulations and helps stakeholders monitor key metrics, such as material recovery rate and carbon emissions. For example, Volvo and UK startup Circulor worked together on the battery passport solution, which will provide buyers with details about the car battery, such as its composition, the origin of its resources, the amount of recycled material, and its carbon footprint.[50]

	Category	Digital Tools	Key Applications	Impact	Use Cases
	Data Management & Tracking	Digital Twin, Blockchain, Cloud Platform	• Simulate and optimize recycling processes • Track materials through lifecycle • Centralized data storage and real-time tracking	• Enhanced process efficiency • Increased traceability and transparency • Better decision-making	Umicore is leveraging cloud platforms and AI to enhance its battery recycling efficiency by partnering with Microsoft; CATL uses blockchain for material traceability.
	Automation & Robotics	Automated Sorting, Disassembly Robots	• Identify and separate battery materials • Disassemble battery components	• Reduced labour costs and human intervention • Improved safety	Li-Cycle employs robotic arms for disassembly to minimize safety risks.
	Advanced Analytics & AI	Predictive Analytics, Machine Learning	• Optimize recycling schedules • Enhance material recovery processes	• Minimized waste • Maximized resource extraction	Redwood Materials, BYD, Toyota use AI to predict optimal recycling timelines.
	Circular Economy Platforms	Digital Marketplaces, Lifecycle Management Software	• Trading of recycled battery materials • Manage battery inventories and compliance	• Greater market access for recycled components • Improved lifecycle management and sustainability	RecycLiCo develop a digital platform to support trading of recycled battery materials.

Source: Company news, Deloitte Research

Figure 20. Leveraging digital tools for better battery recycling efficiency.

3. Collaboration across the value chain is becoming the key for scaling up

The fragmented supply chain of battery recycling has been one of the most critical barriers to scaling up of the business. In China, only 25% of the retired EV batteries are currently recycled through formal channels, leaving recycling companies with limited control over feedstock quantity and quality. This lack of consistency hinders their ability to scale operations effectively.

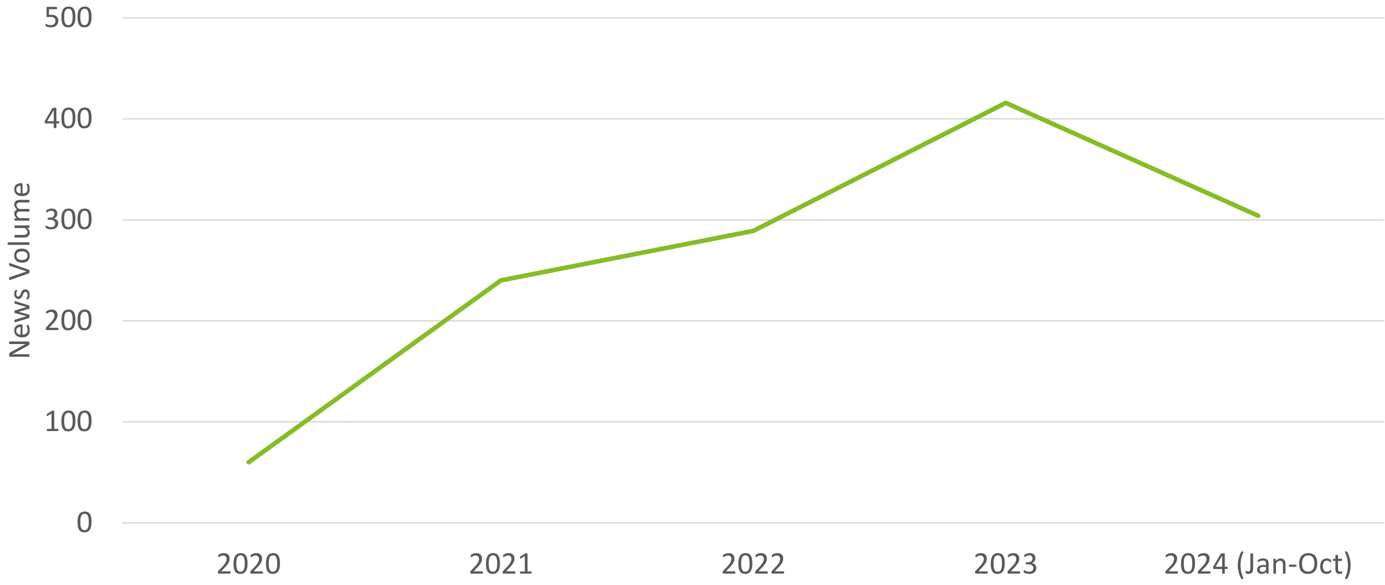
At the same time, the push for a circular economy is driving the development of recycling-designed batteries. Given the 80% of a product's environmental impact is determined during the design phase. Designing batteries for easier recycling will make the disassembly process more efficient and sustainable.

As a result, there is a growing trend of collaboration among materials suppliers, EV producers, auto brands, and recycling companies. By pooling their expertise, these stakeholders can address challenges more rapidly and adapt to industry shifts.

There are several key areas of collaboration emerging within the battery recycling value chain (**Figure 21**). For example, companies are increasingly working together to create closed-loop systems where retired batteries are efficiently recycled back into new batteries. Collaborations between automakers, battery producers, and recyclers are central to this effort.

These areas of collaboration are helping to create a more integrated, innovative, and compliant battery recycling industry laying the groundwork for scalable and sustainable growth.

Growing trend of battery recycling partnerships



Closed-Loop Recycling Systems	• **Telsa & Redwood Materials:** Partner to create a closed-loop recycling process for EV batteries • **Mercedes-Benz, GEM, CATL:** Collaboration to recycle battery materials and feed them back into new battery production
Advanced Recycling Technologies	• **Northvolt & Hydro:** Working on a low-energy hydrometallurgical process for EV battery recycling • **Farasis & Tsinghua University:** Collaborating in the field of safety technology development for batteries
Recycling Capacity Expansion	• **Ganfeng Lithium & Brunp Recycling:** Investing in recycling facilities in China to expand domestic recycling capacity. • **Fortum & BASF:** Developing battery recycling infrastructure in Europe to support large-scale recycling.
Sustainability Standards	• **Global Battery Alliance:** Collaborating to establish standards for ethical sourcing and sustainable recycling of battery materials.
Regulatory Compliance Partnership	• **Redwood Materials & U.S. DOE:** Collaboration to support the U.S. Department of Energy's recycling goals. • **Umicore & EU Battery Directive:** Umicore's work with the EU to meeting recycling efficiency targets
Materials Supply Collaboration	• **Glencore & Samsung SDI:** Partnering to supply recycled cobalt for Samsung's battery production. • **BMW & BASF:** Working together to ensure the supply of recycled cobalt and lithium for battery production
Recycling Process Automation	• **Li-Cycle & KION Group:** Automating lithium-ion battery recycling through advanced robotics
End-of-Life Battery Traceability	• **BYD & VeChain:** Collaborating on block-chain based battery traceability for recycling
Localizing Supply Chain	• **Umicore & LG Chem:** Working together to establish a local closed-loop recycling chain in Europe, reducing reliance on imported materials

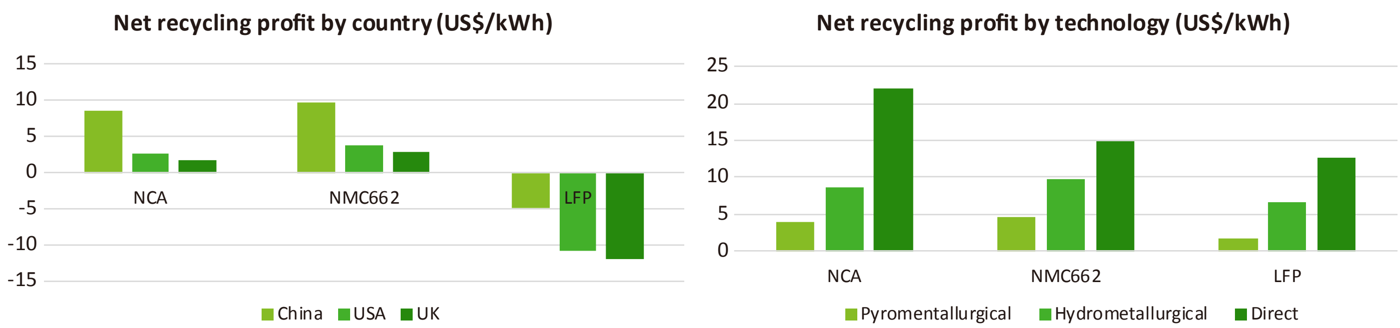
Source: Company news, Deloitte Research

Figure 21. Growing trends of collaboration for battery recycling.

4. Strategic pathways to profitability in battery recycling

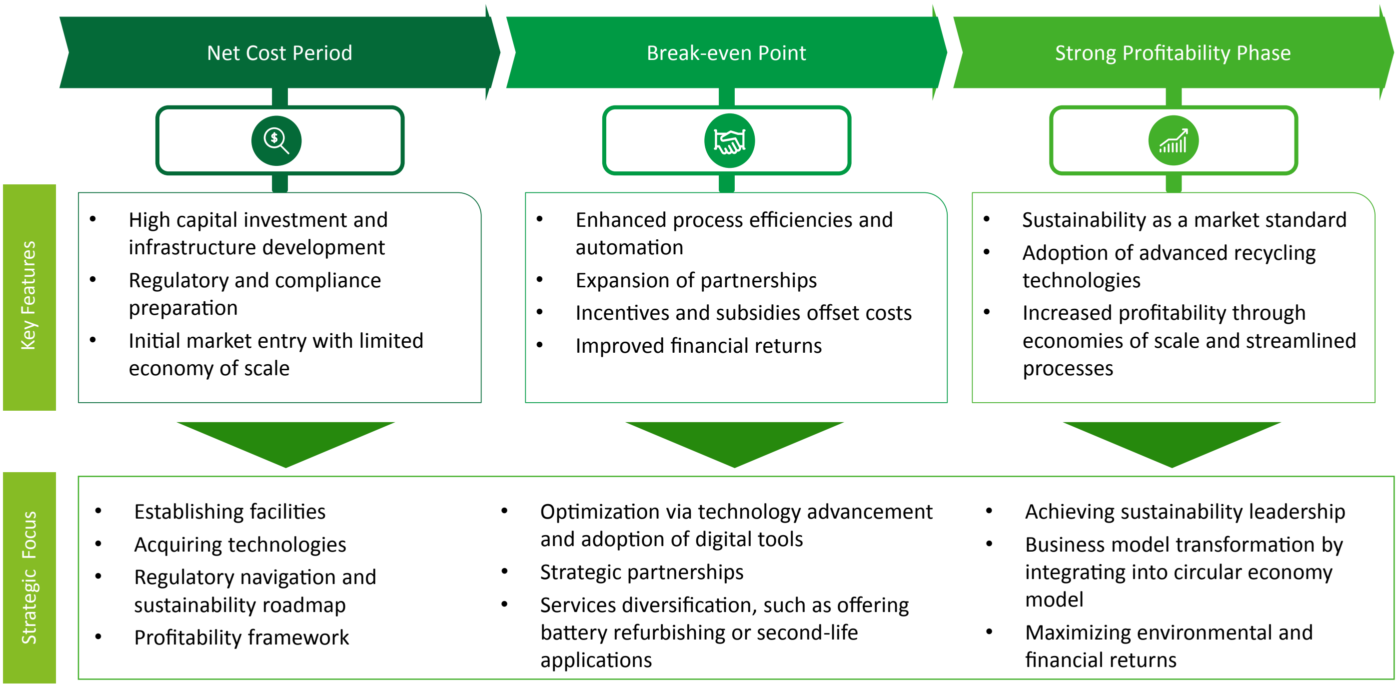
Battery recycling profitability depends on three key factors: recycling costs, the value of recovered materials, and environmental benefits. Recycling costs are influenced by variables such as transportation distances, labor cost, pack designs, battery chemistries, and the choice of recycling technology. To achieve financial viability, recyclers must focus on cost reduction through automation, minimize transportation expenses, and adopt the most effective recycling methods tailored to the value of materials being recovered. Batteries containing high-value critical metals, such as NMC and NCA, yield immediate profitability, particularly when processed using hydrometallurgy to recover cobalt and copper. Conversely, LFP batteries offer significant long-term economic and environmental benefits through reuse before recycling. The selection of recycling technologies—whether pyrometallurgy, hydrometallurgy, or direct recycling—must align with the materials' value and target economies of scale to optimize profitability (**Figure 22**). Beyond the value of recovered materials, Deloitte estimates that the environmental benefits of battery recycling, valued at \$3-\$11 per kWh depending on factors like battery type, carbon pricing, and market conditions, underscore its dual economic and ecological value.[51-53]

Over time, the battery recycling industry progresses through three phases: the net-cost period, the break-even point, and the strong profitability phase (**Figure 23**). In the net-cost period, the industry faces high initial setup costs and regulatory adjustments. The strategic focus for recyclers should be establishing infrastructure, acquiring technologies, and ensuring compliance. At the breakeven point, technological advancements and operational efficiencies start to reduce costs, and market demand for recycled materials grows more stable. Recyclers should focus on process optimization and developing strategic partnerships for consistent material flow. In the strong profitability phase, recyclers must integrate deeply into the circular economy, leverage new technologies for higher recovery rates, and adapt to more stringent global sustainability regulations. Strategic focus shifts to innovation, expanding scale, and ESG alignment. During the journey, economies of scale are crucial, with the break-even point differing based on battery chemistry and recycling technology—for example, 17,000 tons annually for NCA batteries via pyrometallurgy, 7,000 tons for hydrometallurgical, and 3,000 tons for direct recycling in a UK facility.[54] A forward-looking approach should prioritize immediate returns from high-value materials while investing in sustainable practices and reuse strategies to secure long-term profitability and resilience in an evolving market.



Source: Laura Lander, 2021

Figure 22. Net recycling profit comparison.



Source: Deloitte Research

Figure 23. Recycling business economic viability projection and key strategic focuses.

Recycling technology innovation and digital solutions are transforming the battery recycling industry, driving improvements in efficiency, recovery rates, and environmental impact. Advanced methods like hydrometallurgy and direct recycling enable high-purity material extraction with lower energy use. Complementing these technologies, digital tools optimize the recycling ecosystem through lifecycle tracking, resource management, and real-time data on battery health. This integrated approach enhances collection, sorting, and processing while ensuring compliance with sustainability standards. Together, these innovations are building a smarter, more efficient recycling chain, paving the way for a sustainable, circular economy in the battery and EV sectors.

Case Study: Brunp Recycling

Brunp Recycling, as a holding subsidiary of the global leading battery manufacturer CATL, focuses on battery recycling and material recovery business, and has built an efficient recycling system of the entire industry chain of battery with complementary advantages across upstream and downstream. Since its establishment in 2005, Brunp Recycling has built 7 production bases in China and Indonesia and currently has a recycling capacity of 120,000 tons of retired batteries, and over 300,000 tons of recycling capacity under construction. The company has achieved profitability through several strategic initiatives:

- **Technological innovation**
  Brunp has independently developed fully automated recycling technologies and equipment for EV batteries, incorporating proprietary Reverse Product Positioning Design (RPPD) and Directional Recycling Technologies (DRT). The DRT system begins with a green design approach for new battery products, emphasizing reusability and disassemblability to maximize recycling efficiency. These advancements have enhanced operational efficiency and material recovery rates, contributing to cost reduction and increased profitability.

- **Standardized traceability management**
  Brunp recycling has developed an advanced traceability method and standards for recovered materials, integrating traceability codes, interval segments, and product endpoints. This innovative approach addressed common industry challenges, such as ineffective tracking of recycling material proportion data, inconsistencies in process across enterprises, and gaps in product disclosure continuity. By implementing standardized traceability management, Brunp ensures transparency, improves operational efficiency, and sets a benchmark for best practices in the battery recycling industry.

- **Collaboration across the value chain**
  As a subsidiary of CATL, Brunp benefits from a stable supply of end-of-life batteries and manufacturing scrap. To create a circular ecosystem, Brunp Recycling constructs its recycling network jointly with the upstream and downstream of industry chain, including EV manufacturers, Battery manufacturers as well as EV sellers. Notably, Brunp works with leading brands like Mercedes-Benz in China for electric vehicle battery recycling and has established collaborations with Volvo, BMW, FAW-Volkswagen, and GAC-Toyota, among others. Building on its RPPD, Brunp introduced a new engineering technology model, Integration of the Entire Industrial Chain (IEIC), to drive high-quality development of battery recycling industry. Demonstrating its commitment to this approach, Brunp established two IEIC parks in Yichang and Foshan in 2021 and 2022, further strengthening its position as a leader in sustainable battery recycling.

Brunp Recycling has achieved a comprehensive recovery rate of more than 99.6% for nickel, cobalt and manganese for retired batteries, and a recovery rate of more than 91% for lithium. By integrating the battery recycling process and optimizing energy consumption, Brunp has developed a sustainable and cost-effective one-stop closed-loop solution for managing the full lifecycle of batteries, setting a benchmark for green innovation in the industry.

References

1. Qu, T. Assessing and Comparing Different Policies Regarding Recycling Lithium-ion Batteries. Highlights in Science, Engineering and Technology **2022**, 26, 1-5. DOI: 10.54097/hset.v26i.3632 (acccessed 2024/11/27).
2. European commission, E. ANNEX to the COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. 2018. https://eur-lex.europa.eu/resource.html?uri=cellar:0e8b694e-59b5-11e8-ab41-01aa75ed71a1.0003.02/DOC_3&format=PDF (accessed 2024 27th November).
3. European Battery Alliance. https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-battery-alliance_en#:~:text=In%202018%2C%20the%20Commission%20adopted,the%206%20priority%20areas%20below. (accessed 2024 27th November).
4. Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC (Text with EEA relevance). 2024. https://eur-lex.europa.eu/eli/reg/2023/1542/oj (accessed 2024 3rd December).
5. Agency, U. S. E. P. An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling. 2021. https://www.epa.gov/system/files/documents/2021-08/lithium-ion-battery-report-update-7.01_508.pdf (accessed 2024 27th November).
6. Agency, U. S. E. P. Lithium Battery Recycling Regulatory Status and Frequently Asked Questions 2023. https://rcrapublic.epa.gov/files/14957.pdf (accessed 2024 27th November).
7. Battery recycling regulation in 2024 and beyond. 2024. https://www.innovationnewsnetwork.com/battery-recycling-regulation-in-2024-and-beyond/43997/#:~:text=One%20additional%20area%20that%20the,be%20tailored%20to%20lithium%20batteries. (accessed 2024 27th November).
8. Bird, R.; Baum, Z. J.; Yu, X.; Ma, J. The Regulatory Environment for Lithium-Ion Battery Recycling. ACS Energy Letters **2022**, 7 (2), 736-740. DOI: 10.1021/acsenergylett.1c02724.
9. Karlson, P. Executive Summary of Study of Large Format EV Lithium-ion Battery Recycling in China. https://naatbatt.org/wp-content/uploads/2019/03/Executive-Summary-of-China-Recycling-Study-v2-1.pdf (accessed 2024 27th November).
10. Law of the People's Republic of China on the Prevention and Control of Environment Pollution Caused by Solid Wastes (2020). 2020. https://www.fao.org/faolex/results/details/en/c/LEX-FAOC154880/#:~:text=China-,Law%20of%20the%20People's%20Republic%20of%20China%20on%20the%20Prevention,the%20sustainable%20development%20of%20economy. (accessed 2024 27th November).
11. Aaron H. Goldberg, W. L. China promulgates amendment to its Solid Waste Law. 2020. https://www.letsrecycle.com/news/china-promulgates-amendment-solid-waste-law/#:~:text=%E2%80%93%20Extended%20Producer%20Responsibility%20(EPR),recycling%20system%20(Article%2066). (accessed 2024 27th November).
12. New development plan for NEVs unveiled. 2020. https://english.www.gov.cn/policies/latestreleases/202011/02/content_WS5f9ff225c6d0f7257693ece2.html (accessed 2024 27th November).
13. Circular economy gets 5-year regulator boost. 2021. https://en.ndrc.gov.cn/news/mediarusources/202107/t20210728_1292039.html (accessed 2024 27th November).
14. China releases proposed standards for battery recycling. 2024. https://rhomotion.com/news/china-releases-proposed-standards-for-battery-recycling-industry-update/#:~:text=The%20Ministry%20of%20Industry%20and,Batteries%20of%20New%20Energy%20Vehicles%20(accessed 2024 27th November).
15. Battery Waste Management Rules 2022. 2022. https://cpcb.nic.in/uploads/hwmd/Battery-WasteManagementRules-2022.pdf (accessed 2024 27th November).

16. Battery Waste Management Rules, 2022. 2022. https://www.nextias.com/ca/current-affairs/27-08-2022/battery-waste-management-rules-2022-2 (accessed 2024 27th November).
17. ACT ON RESOURCE CIRCULATION OF ELECTRICAL AND ELECTRONIC EQUIPMENT AND VEHICLES. 2023. https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=63675&type=part&key=39 (accessed 2024 27th November).
18. Sung, S.-H. Korea to keep track of EV battery life cycles for recycling. 2024. https://www.kedglobal.com/batteries/newsView/ked202407100017#:~:text=The%20South%20Korean%20government%20will,in%20the%20next%20few%20years (accessed 2024 27th November).
19. Wagner-Wenz, R.; van Zuilichem, A.-J.; Göllner-Völker, L.; Berberich, K.; Weidenkaff, A.; Schebek, L. Recycling routes of lithium-ion batteries: A critical review of the development status, the process performance, and life-cycle environmental impacts. MRS Energy & Sustainability **2023**, 10 (1), 1-34. DOI: 10.1557/s43581-022-00053-9.
20. Deloitte Lithium Battery White Paper Series 3: Lithium Battery Recycling, a Promising Future. 2022. https://www2.deloitte.com/cn/zh/pages/strategy/articles/high-growth-opportunities-in-the-lithium-battery-industry-2022-3.html (accessed 2024 2nd December).
21. LPO Announces a Conditional Commitment for Loan to Li-Cycle's U.S. Battery Resource Recovery Facility to Recover Critical Electric Vehicle Battery Materials. 2023. https://www.energy.gov/lpo/articles/lpo-announces-conditional-commitment-loan-li-cycles-us-battery-resource-recovery#:~:text=The%20U.S.%20Department%20of%20Energy's,recovery%20facility%20in%20North%20America. (accessed 2024 27th November).
22. Umicore Battery Recycling: Capturing profitable growth and enabling a circular and low-carbon battery value chain. 2023. https://www.umicore.com/en/newsroom/umicore-battery-recycling/#:~:text=In%202022%2C%20Umicore%20launched%20a,to%20be%20ready%20by%202026. (accessed 2024 27th November).
23. How BMW Uses Digital Product Passport for Sustainable Innovation ? 2024. https://authentifyit.com/digital-product-passport/case-studies/bmw#:~:text=The%20DPP%20system%20of%20BMW,ownership%20claims%20of%20the%20vehicles. (accessed 2024 2nd December).
24. CHANGDONG, X. Y. Y. H. L. A. Z. X. L. Method for separating and recycling valuable metal in waste ternary lithium batteries. CN113957255A, 2022.
25. AKIRA, Y. T. T. PROCESS FOR RECOVERING VALUABLE METAL. JP2021031760A, 2021.
26. HA, H. B. K., Hyeon Jung; KIM, Sang Ki; KIM, Wan Gi. METHOD FOR RECOVERING ACTIVE METAL OF LITHIUM SECONDARY BATTERY. WO2022139310A1, 2022.
27. RANG, M. W., Wolfram; DUCHARDT, Marc; ZIESCHANG, Anne-Marie Caroline; SEELER, Fabian; ROHDE, Wolfgang; SCHIERLE-ARNDT, Kerstin. LFP BATTERY RECYCLING PLANT AND PROCESS. WO2024094725A1, 2024.
28. SEO, Y. Y., Doo Kyung; KIM, Min Seo; CHOI, Jeong Mi; PARK, Se Ho; LEE, Jeongbae; SEONG, Eunkyu; KIM, Yeon Jun; YU, Hyemin. RECYCLED CATHODE ACTIVE MATERIAL, METHOD FOR RECYCLING CATHODE ACTIVE MATERIAL, AND SECONDARY BATTERY COMPRISING SAME. WO2024010260A1, 2024.
29. Kim, K.-C. G., Eric; Tranape, Benoit. LITHIUM RECYCLING. US2024304883A1, 2024.
30. ZHIXIANG, X. Lithium battery recovery device. CN116387667A, 2023.
31. HAO; SHI LIYONG; ZHU MEILING; WANG YADONG; WANG KE; MA JIA, Z. A. L. Y. P. Y. Z. M. L. Q. L. G. Z. L. H. J. Q. W. P. C. D. H. W. J. Z. Valuable metal recovery method. CN118256726A, 2024.
32. Georgi-Maschler, T.; Friedrich, B.; Weyhe, R.; Heegn, H.; Rutz, M. Development of a recycling process for Li-ion batteries. Journal of Power Sources **2012**, 207, 173-182. DOI: https://doi.org/10.1016/j.jpowsour.2012.01.152.
33. Wang, Y.; Hu, F.; Wang, Y.; Guo, J.; Yang, Z.; Jiang, F. Revolutionizing the Afterlife of EV Batteries: A Comprehensive Guide to Echelon Utilization Technologies. ChemElectroChem **2024**, 11 (4), e202300666. DOI: https://doi.org/10.1002/celc.202300666.

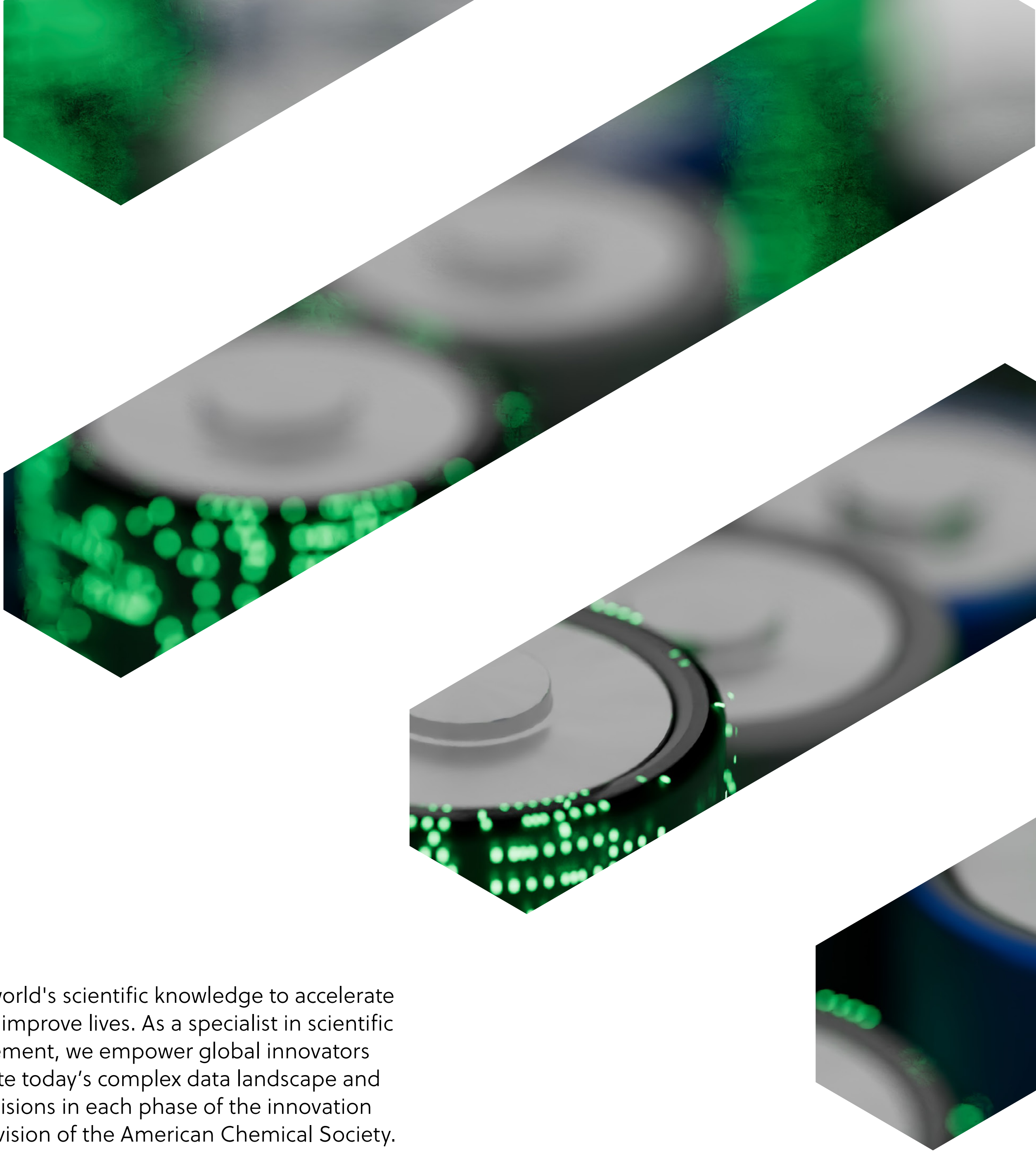
34. Lai, X.; Huang, Y.; Deng, C.; Gu, H.; Han, X.; Zheng, Y.; Ouyang, M. Sorting, regrouping, and echelon utilization of the large-scale retired lithium batteries: A critical review. Renewable and Sustainable Energy Reviews **2021**, 146, 111162. DOI: https://doi.org/10.1016/j.rser.2021.111162.
35. Mikita, R.; Suzumura, A.; Kondo, H. Battery deactivation with redox shuttles for safe and efficient recycling. Scientific Reports **2024**, 14 (1), 3448. DOI: 10.1038/s41598-024-53895-3.
36. Wang, J.; Ma, J.; Zhuang, Z.; Liang, Z.; Jia, K.; Ji, G.; Zhou, G.; Cheng, H.-M. Toward Direct Regeneration of Spent Lithium-Ion Batteries: A Next-Generation Recycling Method. Chemical Reviews **2024**, 124 (5), 2839-2887. DOI: 10.1021/acs.chemrev.3c00884.
37. Muralidharan, N.; Self, E. C.; Dixit, M.; Du, Z.; Essehli, R.; Amin, R.; Nanda, J.; Belharouak, I. Next-Generation Cobalt-Free Cathodes – A Prospective Solution to the Battery Industry's Cobalt Problem. Advanced Energy Materials **2022**, 12 (9), 2103050. DOI: https://doi.org/10.1002/aenm.202103050.
38. Arshad, F.; Li, L.; Amin, K.; Fan, E.; Manurkar, N.; Ahmad, A.; Yang, J.; Wu, F.; Chen, R. A Comprehensive Review of the Advancement in Recycling the Anode and Electrolyte from Spent Lithium Ion Batteries. ACS Sustainable Chemistry & Engineering **2020**, 8 (36), 13527-13554. DOI: 10.1021/acssuschemeng.0c04940.
39. Murdock, B. E.; Toghill, K. E.; Tapia-Ruiz, N. A Perspective on the Sustainability of Cathode Materials used in Lithium-Ion Batteries. Advanced Energy Materials **2021**, 11 (39), 2102028. DOI: https://doi.org/10.1002/aenm.202102028.
40. Fan, E.; Li, L.; Wang, Z.; Lin, J.; Huang, Y.; Yao, Y.; Chen, R.; Wu, F. Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects. Chemical Reviews **2020**, 120 (14), 7020-7063. DOI: 10.1021/acs.chemrev.9b00535.
41. Inclán, I. R. Analysis of global battery production: production locations and quantities of cells with LFP and NMC/NCA cathode material. 2023. https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/globale-batterieproduktion-analyse-standorte-mengen-zellen-lfp-nmc-nca-kathoden.html (accessed 2024 27th November).
42. Recycling of lithium-ion secondary batteries. 2024. https://www.smm.co.jp/en/sustainability/activity_highlights/article_15/ (accessed 2024 27th November).
43. Billmann, R. S. Q. P. L. Comparative study of Li-ion battery recycling processes. 2020. https://accurec.de/wp-content/uploads/2021/04/Accurec-Comparative-study.pdf (accessed 2024 27th November).
44. Liu, S.; Li, Q.; Lu, C.; Tan, L.; Xia, D.; Dong, L.; Zhou, C. Separation and Recovery of Cathode Materials from Spent Lithium Iron Phosphate Batteries for Sustainability: A Comprehensive Review. Industrial & Engineering Chemistry Research **2024**, 63 (32), 13945-13965. DOI: 10.1021/acs.iecr.4c01742.
45. Li, H.; Qiu, H.; Ranneberg, M.; Lucas, H.; Graupner, T.; Friedrich, B.; Yagmurlu, B.; Goldmann, D.; Bremer, J.; Fischlschweiger, M. Enhancing Lithium Recycling Efficiency in Pyrometallurgical Processing through Thermodynamic-Based Optimization and Design of Spent Lithium-Ion Battery Slag Compositions. ACS Sustainable Resource Management **2024**, 1 (6), 1170-1184. DOI: 10.1021/acssusresmgt.4c00064.
46. ETP Clean Energy Technology Guide. 2024. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?layout=list&selectedTechID=9e425da2 (accessed 2024 4th December).
47. Tran, M. K.; Rodrigues, M.-T. F.; Kato, K.; Babu, G.; Ajayan, P. M. Deep eutectic solvents for cathode recycling of Li-ion batteries. Nature Energy **2019**, 4 (4), 339-345. DOI: 10.1038/s41560-019-0368-4.
48. Meles Neguse, S.; Yoon, S.; Lim, H.; Jang, J.; Baek, S.; Jöckel, D. M.; Widenmeyer, M.; Balke-Grünewald, B.; Weidenkaff, A. The Pitfalls of Deep Eutectic Solvents in the Recycling of Lithium-Ion Batteries. Energy Technology **2024**, 12 (4), 2301213. DOI: https://doi.org/10.1002/ente.202301213.
49. Moazzam, P.; Boroumand, Y.; Rabiei, P.; Baghbaderani, S. S.; Mokarian, P.; Mohagheghian, F.; Mohammed, L. J.; Razmjou, A. Lithium bioleaching: An emerging approach for the recovery of Li from spent lithium ion batteries. Chemosphere **2021**, 277, 130196. DOI: https://doi.org/10.1016/j.chemosphere.2021.130196.
50. Carey, N. Volvo to issue world's first EV battery passport ahead of EU rules. 2024. https://www.reuters.com/business/autos-transportation/volvo-issue-worlds-first-ev-battery-passport-ahead-eu-rules-2024-06-04/ (accessed 2024 2nd December).

51. Gaines, L. The future of automotive lithium-ion battery recycling: Charting a sustainable course. Sustainable Materials and Technologies **2014**, 1-2, 2-7. DOI: https://doi.org/10.1016/j.susmat.2014.10.001.

52. Dunn, J. B.; Gaines, L.; Sullivan, J.; Wang, M. Q. Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries. Environmental Science & Technology **2012**, 46 (22), 12704-12710. DOI: 10.1021/es302420z.

53. Swain, B. Recovery and recycling of lithium: A review. Separation and Purification Technology **2017**, 172, 388-403. DOI: https://doi.org/10.1016/j.seppur.2016.08.031.

54. Lander, L.; Cleaver, T.; Rajaeifar, M. A.; Nguyen-Tien, V.; Elliott, R. J. R.; Heidrich, O.; Kendrick, E.; Edge, J. S.; Offer, G. Financial viability of electric vehicle lithium-ion battery recycling. iScience **2021**, 24 (7), 102787. DOI: https://doi.org/10.1016/j.isci.2021.102787.



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