Clean Energy Science and Technology 2024, 2(4), 253.
https://doi.org/10.18686/cest253

Review

Intellectual property analysis of recycling technologies for spent power lithium-ion batteries

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CITATION

Dong Y, Zhu H, He W, Li G. Intellectual property analysis of recycling technologies for spent power lithium-ion batteries. Clean Energy Science and Technology. 2024; 2(4): 253. https://doi.org/10.18686/cest253

ARTICLE INFO

Received: 24 October 2024
Accepted: 2 December 2024
Available online: 11 December 2024

Abstract: The rapid expansion and increasing adoption of electric vehicles have significantly amplified the demand for power batteries, making the recycling and treatment of spent power lithium-ion batteries a critical issue for environmental protection and resource conservation. Actively pursuing the development of eco-friendly recycling technologies and enhancing the regulatory frameworks governing the disposal of spent power lithium-ion batteries are concerns worldwide. This paper places a particular emphasis on the role of intellectual property protection in the advancement of spent power lithium-ion battery recycling technologies. By classifying the key technologies in the recycling process, reviewing recent policies and regulations, and conducting a comprehensive analysis of patent applications related to these technologies, this study applies intellectual property analysis to systematically investigate the global trends in technology development, the main technological players, and the key fields of innovation in spent power lithium-ion battery recycling over the past two decades. The findings underscore the crucial influence of intellectual property protection on fostering technological innovation and driving the global advancement of recycling technologies. Finally, the paper summarizes the technical characteristics, focal areas, challenges, and future prospects of spent power lithium-ion battery recycling technologies in the context of global energy transformation and sustainable development, providing strategic guidance for future industrialization, technological innovation, and research directions in this critical field.

Keywords: spent lithium-ion batteries; recycling technologies; technological innovation; intellectual property; patent analysis

1. Introduction

With the rapid development of the global electric vehicle (EV) industry, the production and utilization of power lithium-ion batteries have shown a significant upward trend. According to the Global Electric Vehicle Outlook 2024 released by the International Energy Agency, by the end of 2023, the global stock of EVs surpassed 40 million units, representing a 20% increase compared with 2022. The demand for EV batteries has exceeded 750 GWh, marking a 40% year-on-year growth (**Figure 1**) [1]. Lithium-ion batteries are widely employed as the primary energy storage system in EVs due to their high energy density, excellent thermal performance, long cycle life, and superior safety characteristics [2]. However, lithium-ion batteries have a limited lifespan, typically requiring replacement after 5–8 years, which leads to the generation of a substantial quantity of spent lithium-ion batteries. It is estimated that by 2030, millions of tons of spent lithium-ion batteries will be generated annually worldwide [3]. These discarded batteries contain a large amount of metal resources, such as lithium, nickel, cobalt, and manganese, which possess a significant recycling value. Recycling not only enables the circular use of resources but also reduces dependence on primary mineral resources, mitigating environmental impacts [4]. Moreover, hazardous substances in spent lithium-ion batteries, including heavy metals and electrolytes, pose potential threats to the environment and human health [5]. Improper disposal may result in severe environmental pollution and safety risks [6]. Consequently, the recycling and resource recovery of spent lithium-ion power batteries has emerged as a pressing global issue that requires immediate attention.

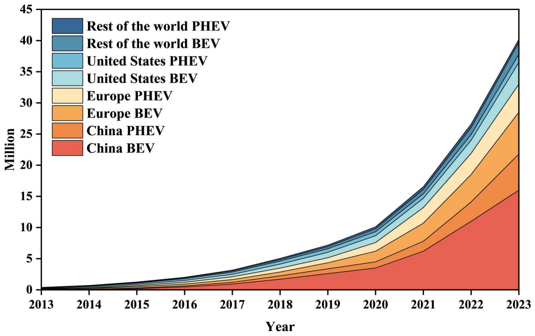


Figure 1. Global production of EVs (2013–2023) [1].

Note: BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle. Includes passenger cars only.

Lithium-ion batteries can be classified into various categories based on their cathode material, such as lithium iron phosphate batteries, lithium manganese acid batteries, lithium cobalt acid batteries, and lithium ternary batteries [7,8]. The most common types of power batteries on the market are primarily lithium ternary and lithium iron phosphate batteries. A typical power lithium-ion battery consists of a cathode made of metal oxide and graphite, an anode made of graphite, an electrolyte (usually containing lithium hexafluorophosphate), a separator, current collectors made of copper and aluminum foil, and packaging components made of stainless steel or plastic [9,10]. Since spent power lithium-ion batteries still have roughly 80% of their capacity left, they are typically used first in echelon utilization to optimize their use value [11]. Subsequently, the batteries are disassembled to recover valuable metal components when the capacity is reduced to less than 20% of the initial capacity [12]. Generally speaking, echelon utilization comprises a series of processes, including screening, dismantling, assessment, detection, sorting, and regrouping [13]. The primary steps in recycling utilization are pretreatment, active material separation, and valuable metal recovery or reuse [14–16]. Currently, the recycling technologies for spent power lithium-ion batteries mainly include hydrometallurgy, pyrometallurgy, bioleaching, and direct recycling. Each of these technologies has its advantages and disadvantages in terms of resource recovery efficiency and environmental impact [17–19].

In response to climate change, the global community is actively advancing carbon neutrality goals, and reducing carbon emissions is a common objective for both governments and businesses worldwide. Simultaneously, governments worldwide are implementing policies and regulations to ensure the efficient management and environmentally responsible disposal of spent power batteries. Notable examples include the European Union's Regulation (EU) 2023/1542, the United States' Inflation Reduction Act, China's Administrative Measures for the Echelon Utilization of Power

Batteries for New-Energy Vehicles, and Japan's revised Power Battery Industrial Strategy. In addition to these environmental regulations, a series of intellectual property protection policies have been implemented, such as China's National Intellectual Property Strategy Outline, the United States' Clean Energy Patent Accelerated Examination Program, and the European Union's Intellectual Property Protection Directive. In the development of recycling technologies for spent power lithium-ion batteries, intellectual property serves as a crucial mechanism for incentivizing technological innovation. It provides a clear reflection of the state of technological advancement and plays a vital role in driving the progress of green technologies and fostering the growth of the environmental industry [20,21]. The concept of intellectual property traces its origins to 18th-century Europe and has evolved into a significant legal framework encompassing various aspects, such as patent rights, copyrights, trademark rights, and trade secrets [22,23]. This mechanism serves to protect the legitimate rights and interests of intellectual labor achievements. A patent is an exclusive right formally granted by the government to an inventor or innovator for a specified period, ensuring the sole ownership of the invention and prohibiting unauthorized making, using, selling, importing, or offering to sell it [24]. This safeguards the innovative interests of the inventor, while preventing infringement. A patent represents a significant aspect of intellectual property, comprising a substantial degree of technical detail and exerting a considerable influence on technological research and development, as well as innovation [25]. It is estimated that making efficient use of patent information can save roughly 40% of research and development expenses and cut research and development time by roughly 60%. The main content of a patent is a technical description document of an invention. Due to the necessity of novelty, the technical data initially presented in a patent is not subsequently disclosed elsewhere, so approximately 80% of the information disclosed in a patent is not available from other sources [26]. Given the close relationship between patents and the output of research, development, and innovation activities, it can be seen that the patent indicator is an effective measure of technological activity [27]. Most current research on spent lithium-ion battery recycling technologies primarily focuses on technology or process discussion [28–33]. Intellectual property analysis of recycling technologies has largely been limited to a few countries, such as the United States, Japan, South Korea, and China [34–36]. For instance, Lin et al. [25] analyzed the patents and literature on rechargeable batteries, exploring the current state of recycling strategies and offering a quantitative description. Similarly, Lee [37] conducted a comparative analysis of battery recycling technology patents from South Korea, China, and the United States, revealing differences in patent activities among these major economies. However, systematic analysis of intellectual property on global spent lithium-ion battery recycling technologies remains limited, with existing studies largely focusing on specific countries or regions. Moreover, the current literature has not fully emphasized the critical role of intellectual property in driving innovation in spent lithium-ion battery recycling technologies. While some studies have explored the relationship between recycling technologies and policy regulations [38], there is a lack of comprehensive analysis of patent trends in lithium-ion battery recycling technologies, as well as a systematic discussion on how intellectual property can stimulate technological innovation and advance the progress of green technologies. With the rapid growth of spent battery recycling applications, the geographical distribution of recycling technologies is also expanding. However, current patent analyses do not fully capture the global dynamics of recycling development. To better understand the global landscape of spent battery recycling technologies, there is a pressing need for quantitative analysis of related intellectual property. Such analysis will not only uncover hotspots and directions for technological innovation but also help predict future trends, providing theoretical support for the global advancement and industrialization of recycling technologies.

This paper aimed to explore the recycling technologies for spent power batteries from an intellectual property perspective. First, key technologies of spent power battery recycling processes were sorted out, with a focus on analyzing relevant policies and regulations in representative countries, patent information data, as well as patent technologies and processes. The methodology of intellectual property analysis was applied to the recycling technologies of spent power batteries, based on the patent information retrieved from the Derwent Innovation database over the past 20 years. Systematic research and analysis were conducted in terms of the total number of patent applications, the distribution of applicants, the distribution of technological fields, etc. The core characteristics, current development trends, and future directions of spent power battery recycling technologies are summarized and discussed in this study. Finally, strategies and suggestions for further advancement in this field are proposed based on global policy guidance.

2. Materials and methods

In this study, we utilized the Derwent Innovation database, which provides patent information from 156 countries and regions worldwide and encompasses 143 million original patents.

For the Derwent Innovation database, the retrieval method was advanced retrieval, the retrieval formula was (TAB=((“power battery” OR “electric vehicle battery” OR “traction battery” OR “drive battery” OR “automotive battery” OR “battery for electric power”) AND lithium) OR TAB=((lithium ADJ4 battery) AND (“new energy vehicle” OR “electric vehicle”))) AND TAB=(recycl* OR resourcing OR reuse OR recovery OR cascade OR echelon OR metallurg* OR *metallurgy OR reclamation OR refine* OR repreparation OR regenerat* OR repair* OR purifi* OR dismantl* OR assessment OR estimation OR “life prediction” OR extract* OR pretreatment OR lech* OR disassembl*). The retrieval time was on 31 May, 2024, and the retrieval scope was from 31 May, 2004, to 31 May, 2024. After manual denoising was conducted to eliminate patent applications unrelated to resourceful recycling technologies of spent power batteries, a total of 2623 relevant patent applications were identified. As the process of publishing a patent application typically spans 16–18 months, it is important to note that patent application data from the past two years should be used for reference purposes only.

3. Recycling technologies status of spent power lithium-ion batteries

As the number of battery cycles increases, the capacity of power batteries gradually decreases. However, a small proportion of spent lithium-ion batteries may retain more than 80% of their original capacity. These batteries can be treated with in-situ repair and capacity enhancement technologies to meet the requirements for EVs and be reused [39]. In-situ repair technology refers to the use of self-healing materials in electrodes and electrolytes, the introduction of specific electrolyte additives, and the incorporation of nanomaterials to repair internal damage and enhance charge retention [40,41]. Capacity enhancement technology is also important for expanding the available capacity of batteries. Various methods, such as using silicon-based anodes, carbon nanotubes, graphene, and structural optimization, can be employed to improve the capacity and performance of lithium-ion batteries [42–44]. When a battery's capacity is less than 80% of its initial capacity, the battery enters the stage of echelon utilization and recycling utilization, which means that it does not meet the criteria for use in EVs [13,33]. However, direct recycling may result in the inefficient utilization of resources. To optimize the effective use of resources, decommissioned power batteries initially undergo echelon utilization. Once its capacity has decreased to less than 20%, the item will be dismantled, recycled, and regenerated. Consequently, there are two primary categories for recycling power batteries: recycling utilization and echelon utilization. According to pertinent research, lithium-ion phosphate batteries have a cycle life of more than 2000 times and a modest rate of capacity degradation, making them the best option available for energy storage [45,46]. In comparison, nickel-manganese-cobalt ternary batteries exhibit a rapid capacity decay rate, rendering them more suitable for resource recovery, particularly for the extraction of nickel, cobalt, lithium, and other valuable metals [47].

3.1. Echelon utilization

Echelon utilization refers to the repurposing of spent power lithium-ion batteries with rated capacities ranging from 20% to 80% for use in applications with lower battery performance requirements based on their performance evaluation criteria. This process typically involves three primary technological phases: screening and disassembly, assessment and detection, and sorting and regrouping [48,49]. Based on the results of battery assessments, the potential applications of echelon utilization are categorized into static and dynamic scenarios [50]. Static applications involve energy storage systems and base stations, including domestic and commercial energy storage products, charging stations, communication base stations, and street lighting. In contrast, dynamic applications pertain to mobile products, such as low-speed electric vehicles, cargo vehicles, and electric bicycles.

The initial stage of echelon utilization for spent power lithium-ion batteries is screening and removal—a highly technical and hazardous process involving the identification and elimination of problematic batteries based on their appearance and performance to prevent safety issues during subsequent dismantling [3]. This step aims to facilitate subsequent repair, standardize components, and prepare the batteries for secondary use in applications with lower performance requirements by retaining their core components and functions to ensure sufficient performance in secondary applications. Li et al. [51] reviewed the latest advancements in end-of-life lithium-ion battery disassembly technology, focusing on two key technological pillars: artificial intelligence and human-robot collaboration. Through benchmarking and analysis, the study offers new research directions and prospects for the sustainable development of battery recycling.

The assessment and detection of spent power lithium-ion batteries is an important step in the entire process of echelon utilization, as it determines the consistency, adaptability, safety, and utilization rate of batteries. Currently, the predominant assessment and detection parameters of the state of spent power batteries encompass state of charge (SOC), state of health (SOH), remaining useful life (RUL), state of power (SOP), and state of function (SOF) [48,52]. SOC mainly refers to the charge carried in the anode and cathode particles of the battery, and accurate estimation of SOC helps to extend the life of lithium-ion batteries [53]. Common methods to estimate SOC include using open-circuit voltage, electrochemical impedance spectroscopy (EIS), Kalman filter technology, and the deep-learning neural network [54–56]. SOH refers to a critical state of battery degradation or capacity decay [57]. Common methods for SOH evaluation include support vector machine, Gaussian process regression, incremental capacity analysis, etc. [48,53,58]. RUL is another parameter for assessing battery degradation, and it differs from SOH in that it represents the remaining charge and discharge cycles of a battery [52,59]. RUL prediction methods utilize equivalent circuit models and electrochemical models [60,61]. SOP refers to the maximum available power that a battery can provide or absorb during a specific period of time, reflecting the battery’s power capability and taking into account operational constraints, such as charge and discharge limitations, voltage, current, and temperature [52,62]. SOP estimation methods include experimental data-based testing, multi-constraint approaches, equivalent models, and filtering techniques [53,63]. SOF is used to describe the ability of a battery to perform load tasks under specific operating conditions, typically related to SOC, SOH, and temperature [53,64]. It reflects the maximum instantaneous output capability or peak power of a battery within the safe operating area. Methods for estimating SOF include approaches based on battery state parameters, instantaneous power demand, joint estimation, and techniques similar to those used for estimating SOP [65,66]. The above methods for assessing battery state can generally be categorized into four types: direct measurement, model-based, data-driven, and integrated methods [53,67,68]. **Table 1** summarizes the advantages and disadvantages of typical methods for estimating battery state.

When the capacity of lithium-ion batteries is reduced to less than 60% of the initial capacity, they tend to exhibit high internal resistance and are prone to thermal runaway. Safety can be improved through various technologies, such as battery thermal management techniques, predictive diagnostics techniques, and heat-stabilized materials [69–71]. Thermal management techniques mainly include air cooling and liquid cooling, as well as cooling via phase-change materials. Liquid and air cooling can effectively dissipate heat generated during operation, while cooling using a phase-change material stabilizes temperature by the absorption of excess heat during the phase change [72–74]. Predictive diagnostic technologies, such as electrochemical impedance spectroscopy, provide real-time monitoring of key battery parameters, enabling the early detection of internal resistance increases or gas generation, which may indicate potential failure [75]. These diagnostics can be seamlessly integrated with intelligent battery management systems, which continuously monitor SOC, temperature, and other critical variables, hence identifying abnormal batteries with precision. In addition, incorporating thermally stable materials and flame-retardant separators into battery designs enhances the thermal stability of cells, reducing the likelihood of internal short circuits and subsequent thermal events [76]. These measures collectively enhance the safety and reliability of batteries operating under degraded conditions.

Table 1. Advantages and disadvantages of typical methods for estimating battery state.

Category	Methods	Applicability parameters	Advantages	Disadvantages	Ref.
Direct measurement methods	Open-circuit voltage	SOC, SOH	• High accuracy • Easy for application	• Offline measurement • Long time • Not real-time application	[65,77]
	Ampere-hour counting	SOC, SOH	• Online measurement • High accuracy in short-term calculation • Low implementation cost	• Accumulated errors • Difficult to consider battery's self-discharge current	[54,77]
	EIS	SOC, SOH	• High accuracy • Non-destructive • Sensitive to battery health • Works in real-time	• High cost • Sensitivity to temperature • Slow response	[45,78]
	HPPC	SOC, SOH, SOP	• High precision • Rich data	• Time consuming • High cost • Temperature-sensitive	[63,79]
Model-based methods	ECM	SOC, SOH, SOP, RUL	• High accuracy • Simple and computationally efficient • Good for real-time estimation	• Limited accuracy in capturing complex phenomena • Parameter drift over time	[53,61,63,80]
	Particle filter	SOC, SOH, RUL, SOP	• Handle highly non-linear and non-Gaussian processes • High accuracy of SOC	• High computational cost • Particle degeneracy	[53,54,61,63]
	Electrochemical model	SOC, SOH, SOP, RUL	• Avoid chatter effect • High accuracy • High calculation speed	• Relationship between SOH and temperature/cycling number is not considered	[81,82]
Data-driven methods	Support vector machine	SOC, SOH	• Small error • High accuracy	• High computational complexity • Large memory consumption	[83,84]
	Neural network	SOC, SOH	• Model-free • No need to investigate failure mechanisms	• Prediction accuracy depends heavily on algorithm and dataset size	[58,85]
Integrated methods	ECM + EIS/ ECM + HPPC/ extended Kalman filter + recursive least square algorithm	SOC, SOH, SOP, SOF	• Improved applicability and accuracy through integration of methods	• High computational cost • Difficult to validate degradation under complex conditions	[52,66,86,87]

Note: EIS = electrochemical impedance spectroscopy; HPPC = hybrid pulse power characterization; ECM = equivalent circuit model.

Battery sorting and regrouping are mostly based on assessment and detection outcomes to accommodate different application scenarios. The applicability of batteries is inherently dictated by their percentage capacity, where those boasting 60%–80% capacity are frequently employed in large-scale energy storage systems and telecommunications base stations, catering to high-demand operations. Batteries within the 40%–60% capacity range, suited for more moderate energy requirements, are commonly integrated into low-speed vehicles and lighting power supply systems. Lastly, batteries featuring a capacity of 20%–40% are typically utilized in small-scale energy storage devices, tailored to meet the needs of compact, energy-efficient applications [33]. Furthermore, application scenarios can be categorized into dynamic (movable) and static (stationary) based on internal battery resistance [48]. When sorting and regrouping the data obtained from assessment and detection, it is imperative to meticulously select the appropriate algorithm. Commonly employed algorithms for classification or clustering include K-means clustering, neural-network-based clustering, density-based spatial clustering of applications with noise, mean-shift clustering, and spectral clustering algorithms, among others [88,89].

3.2. Recycling utilization

3.2.1. Pretreatment

The pretreatment process serves as the initial stage in the recycling utilization of spent lithium-ion batteries, aiming to optimize metal element extraction efficiency and minimize costs. It ensures the safe disassembly of batteries, effectively separates active materials, and significantly reduces impurity content, thereby establishing a solid foundation for subsequent recycling and treatment processes [90,91]. The primary pretreatment procedures can be broadly categorized as discharging, dismantling, crushing, and separation [92]. When power batteries are collected after use, it is important to note that they still have some residual power. During disassembly, there is a risk of the anode and cathode coming into contact with each other, which can lead to short circuits, fires, explosions, and spontaneous combustion if not discharged, resulting in safety issues [93]. Therefore, the first step is to discharge spent power batteries, and common discharging methods include physical and chemical techniques. Physical discharge involves the utilization of external charging equipment to establish a closed-loop pathway for discharge by connecting the conductor and the battery at two terminals [94]. The process of chemical discharge primarily involves depleting the residual electrical charge within a battery through chemical reactions, such as immersing the battery in a conductive solution, discharging it using conductive powder, and undergoing passivation reactions in an electrochemical system [95].

The next step is to disassemble the battery after discharging, achieving the separation of copper foil and aluminum foil from the positive and negative electrode materials, which is usually done through manual or mechanical disassembling methods. Due to the complex structure of the battery pack and the varied connection methods, it is impossible to fully automate the battery pack disassembly process. Manual disassembly is suitable for more complex tasks, such as removing adhesives and splitting components, as it can be more thorough and intelligent in separating materials and components. However, this approach has limitations, such as low processing volume, low efficiency, and safety hazards [2,14]. In the process of handling large battery packs for EVs, the industrial sector often employs automated mechanical disassembly technology, which is known for its efficiency and safety. It can automatically identify and disassemble battery packs, separate key components, and reduce human intervention, but it also has the drawbacks of being incomplete and imprecise [31,96,97]. Currently, many scholars are striving to introduce more advanced fully automated technologies in the theoretical research and technological innovation of battery disassembly, including automatic dismantling systems based on neural-symbolic computing [98], completely automated dismantling devices, and methods utilizing deep learning, artificial intelligence, and sensor technologies. This study employed intellectual property analysis to reveal the future trends and technical feasibility of automated disassembly technologies.

Disassembled power batteries must undergo mechanical crushing to release the electrode materials, and mechanical crushing methods include wet crushing and dry crushing [99,100]. Wet crushing is beneficial for producing fine particles but may pose challenges for subsequent separation processes [101]. Dry crushing can separate components based on their respective characteristics, thereby simplifying subsequent processing procedures [102]. The final step of pretreatment is the separation of active substances, and the methods for separating cathode materials include physical methods, chemical methods, and some new processes. Physical methods encompass gravity separation, magnetic separation, flotation, and electrostatic separation, while chemical methods involve electrolysis, precipitation, and organic solvent processes [31,103,104]. Additionally, new processes encompass pyrolysis, among others. Finally, the black mass is separated for the next step of metal extraction.

3.2.2. Extraction of valuable metals

Following pretreatment, it is imperative to subject spent power batteries to the extraction of valuable metals in order to facilitate recycling and reuse objectives. Currently, recycling technologies for spent power lithium-ion batteries mainly include pyrometallurgy, hydrometallurgy, bioleaching, and direct recycling [28–30].

Pyrometallurgy involves the use of a high-temperature furnace to thermally decompose lithium-ion batteries and remove organic components, such as separators and binders, while reducing metal oxides to alloys composed of lithium, cobalt, copper, iron, and nickel [5]. One of the main advantages of this approach is that it does not require pretreatment steps, such as disassembly or crushing, making it a relatively simple process that has already found applications in industrial production [105]. Zhu et al. [106] developed a carbothermal shock method, which optimizes the pyrometallurgical process at high temperatures, enhancing product quality. Zhou et al. [107] reviewed solid-state reactions and spray pyrolysis techniques, which reactivate active materials in spent lithium-ion batteries for the synthesis of target products. Yin et al. [108] introduced an efficient, one-step, and non-destructive cathode regeneration method, which restores the crystal structure of spent power lithium-ion batteries through rapid Joule heating to achieve re-lithiation. The development of pyrometallurgy has undergone multiple phases, evolving from direct roasting to atmosphere-assisted roasting, additive-assisted roasting, and high-value utilization, reflecting the continuous optimization and upgrading of this technology [109]. Despite certain progress in industrial applications, the process remains energy-intensive and poses environmental challenges, underscoring the need for further optimization and innovation [33].

Hydrometallurgy involves the complete leaching of valuable metals from spent power lithium-ion batteries, followed by the sequential extraction of these metals from the solution through separation and purification [109]. Leaching is the critical step in the hydrometallurgical process, with commonly used leaching agents including inorganic acids, organic acids, alkaline solvents, and deep eutectic solvents. Lei et al. [110] combined inorganic and organic acids and achieved rapid metal leaching, while reducing costs, by optimizing the operating condition. Luo et al. [111] synthesized a deep eutectic solvent using betaine hydrochloride and ethylene glycol, enabling the selective leaching and separation of cobalt, manganese, and nickel from cathode materials. Wang et al. [60] discovered that a mixture of choline chloride and urea, used as a deep eutectic solvent, exhibited strong reducing capability and achieved lithium and cobalt extraction efficiencies of 95% from spent lithium-ion batteries. Although hydrometallurgy can recover most battery components with relatively high purity and lower energy consumption, it involves a series of complex chemical processes and the use of highly corrosive chemicals, leading to a significant amount of toxic waste. Organic acids and deep eutectic solvents have garnered particular interest due to their environmental-friendliness and high leaching efficiency. However, limitations, such as relatively high costs and slow leaching rates, indicate that further optimization and enhancement of hydrometallurgical techniques are still needed [17].

Bioleaching utilizes microorganisms and their metabolites to transfer metals from spent lithium-ion batteries into a solution for extraction. Common microorganisms used in bioleaching include bacteria and fungi [112,113]. This approach offers several advantages, such as environmental safety, low emissions of harmful gases, reduced operational costs, and minimal energy input, making it a promising green alternative to pyrometallurgy and hydrometallurgy [114]. Heydarian et al. [115] employed a mixed microbial culture system and achieved recovery rates of 50.4%, 99.2%, and 89.4% for cobalt, lithium, and nickel, respectively, using a two-step leaching method. Biswal et al. [116] used *Aspergillus niger* strains isolated from Jatropha roots and aerosol samples for leaching, demonstrating that the two-step method (with recovery rates of 82% for cobalt and 100% for lithium) was more effective than the one-step method (with recovery rates of 67% for cobalt and 87% for lithium). Liao et al. [117] designed a novel process, which combined gallic acid with mixed-culture bioleaching, achieving leaching efficiencies of 98.03% for cobalt and 98.02% for lithium, while reducing the toxicity of spent lithium-ion batteries. Despite its advantages, bioleaching faces challenges, such as slow metal dissolution kinetics and limited microbial availability, hindering its industrial application. However, future research holds significant potential in the genetic engineering of microorganisms to enhance the efficiency of this technique [17].

Direct recycling refers to the restoration of the electrochemical performance of spent lithium-ion battery cathode materials through high-temperature crystal reconstruction, which replenishes missing elements, thereby making the materials reusable for the production of new batteries [118,119]. Direct recycling offers significant advantages, including a short reaction time, low cost, and environmental-friendliness. Commonly employed methods are solid-state sintering, molten salt restoration, hydrothermal treatment, and electrochemical regeneration [120]. Zhao et al. [121] proposed a sustainable electrochemical regeneration method using a ligand-chained zinc complex as a structural modulator, which dynamically adjusts metal ion coordination, hence optimizing the structure and performance of spent lithium-ion batteries. Xu et al. [122] introduced an efficient and environmentally benign regeneration method based on defect-targeted healing, which effectively restores battery performance, reduces energy consumption, and lowers greenhouse gas emissions, achieving the direct regeneration of spent lithium-ion batteries. Compared with traditional recycling methods, direct recycling demonstrates clear advantages and significant commercial potential. The four mainstream direct recycling methods exhibit higher profitability and lower pollution compared with those of pyrometallurgy and hydrometallurgy, providing a new strategy for the resource recovery of spent power lithium-ion batteries [123].

3.2.3. Regenerative preparation

For metal elements that have already been leached and purified, many synthetic processes can be used to regenerate and reapply them to the cathode material of power batteries. These methods aim to efficiently and environmentally friendly recover valuable metal elements, while reducing dependence on primary resources. Currently, regeneration methods predominantly include solid-state synthesis, hydrothermal treatment, co-precipitation, and the sol-gel method [124–127].

The solid-state synthesis method, a conventional and extensively employed technique, has been successfully utilized in the regeneration process of cathode materials for lithium-ion batteries. Its fundamental principle involves blending a precursor with a lithium source in a specific proportion and subjecting them to high-temperature heat treatment to achieve a solid-phase reaction, thereby achieving the complete integration of components for the formation of the desired cathode material [124,126,128]. Despite its simplicity, the solid-state synthesis method encounters challenges in impurity removal from cathode materials and potential non-uniform mixing of raw materials, leading to suboptimal electrochemical performance.

The hydrothermal treatment method involves the combination of a cathode material with a lithium-containing solution, followed by low-temperature heating under a hydrothermal condition [125,129]. This approach significantly reduces energy consumption, shortens reaction time, and simplifies the operational process [126,129]. However, its implementation necessitates stringent requirements for equipment pressure resistance, temperature resistance, sealing capability, and corrosion resistance.

The co-precipitation process involves the addition of an appropriate amount of a precipitating agent to a leaching solution, inducing the co-precipitation of metal ions, followed by solid-phase reactions to achieve the desired product [102,130]. Despite its high product purity and metal recovery rates, this technology is characterized by intricate procedural requirements and associated elevated costs [131,132].

The sol-gel method involves the addition of a chelating agent to a leaching solution, resulting in the formation of a sol that is subsequently transformed into a gel before sintering [126,133]. Although this approach effectively harnesses metal ions from the leaching solution to generate materials with a molecularly uniform structure, its intricate operational procedures, protracted preparation cycle, substantial energy consumption, and elevated production costs have emerged as primary factors impeding its widespread industrial implementation [126].

3.2.4. Recycling of other materials

Currently, recovery technologies of key materials, such as anode graphite, electrolyte, and diaphragm, from spent power batteries are receiving extensive attention and undergoing in-depth research from academia. In the field of graphite recovery, various methods have been explored and demonstrated their potential, including thermal decomposition, hydrometallurgy, supercritical extraction, water treatment methods, and microwave processing [32]. Similarly, for the recovery of electrolytes, supercritical CO_2 extraction and organic solvent extraction are widely considered to be the most promising methods due to their high efficiency [48,134,135]. Furthermore, high-temperature treatment and mechanical methods have been employed to some extent in electrolyte recovery. In summary, the technologies for recovering spent power batteries are constantly developing and improving. In **Table 2**, the performances of recycling technologies for spent power lithium-ion batteries in recovering various materials are compared. In **Figure 2**, the current recycling technologies points of spent power batteries are summarized.

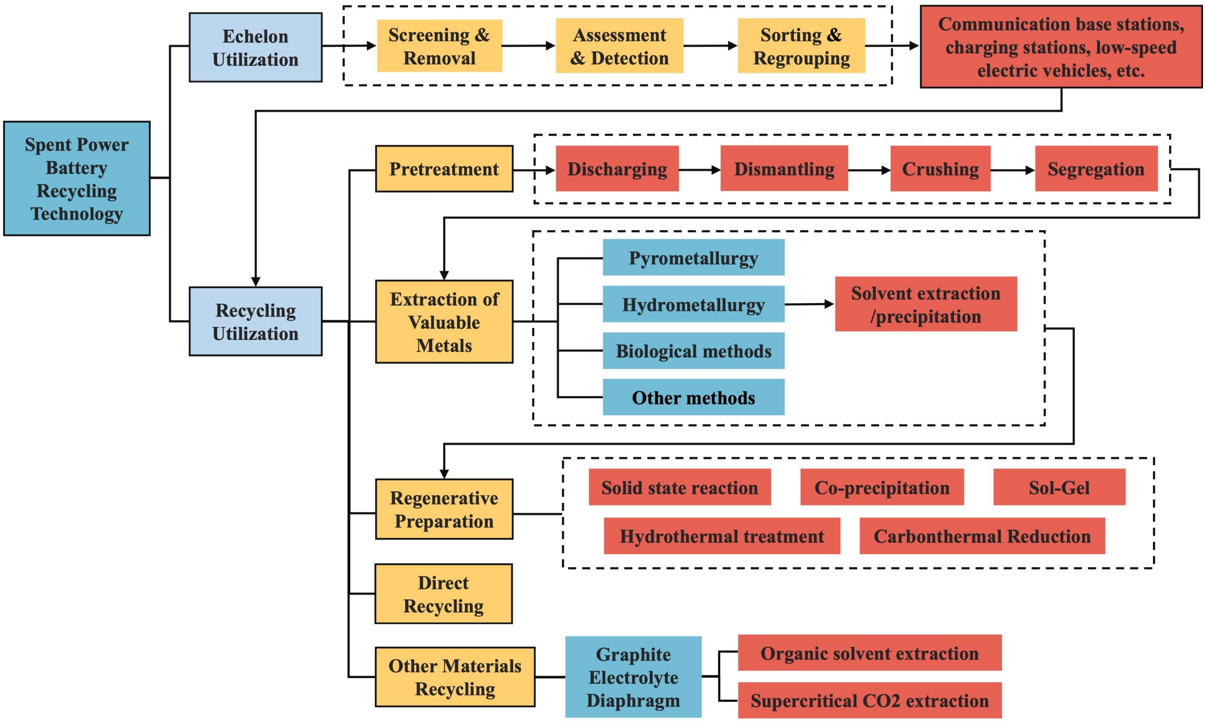


Figure 2. Key technologies for spent power battery recycling process.

Table 2. Performances of recycling technologies for spent power lithium-ion batteries in recovering various materials.

Recycling technology	Advantages	Disadvantages	Recovery rate(s)	Ref.
Pyrometallurgy	• Easy to operate • Short processing duration • High adaptability to various raw materials • High metal recovery efficiency • Suitability for large-scale industrial application	• High energy consumption • High cost • Emission of harmful gases • Loss of metals, such as lithium, in slag phase	Li: 76%–98.2%	[17,119,123]
Hydrometallurgy	• High metal recovery rate • High product purity • High energy and capital efficiency • Low gas emissions	• High consumption of chemical reagents • Secondary pollution from waste liquids • Poor adaptability to different raw materials • Uncertain lithium recovery rate	Li: 71%–100%, Co: 68%–100%, Mn: 34.8%–94%, Al: 35%, Ni: 91%–99.7%	[17,29,89,110,119,123]
Bioleaching	• Low energy consumption • Environmentally friendly • Low operational cost • Minimal use of chemicals	• Long microbial cultivation cycle • Extended reaction time • Microbial tolerance to toxic metals	Li: 49%–100%, Co: 19%–82%, Mn: 20%–98%, Cu: 74.4%–100%, Al: 62%–82%, Ni: 34%–97%	[17,123]
Direct recycling	• Most battery materials can be recovered • Short recovery pathway • Low energy consumption • Environmentally friendly	• Requires complex mechanical pretreatment and separation • Mixed cathode materials may reduce value of recovered products • Limited scalability to industrial levels	Capacity: 86%–93%	[17,123]

4. Intellectual property analysis of recycling technologies

4.1. Development trend analysis of patented technologies

To a certain degree, the number of patent applications reflects the technical process, innovation capacity, research and development investment, market potential, and policy support of different countries in a specific field. Analyzing patent application trends aims to unveil annual application fluctuations and offer insights into application timing and technological advancements. In this section, we analyzed and compared global patent applications on spent battery recycling and utilization technologies over the past two decades to reveal the characteristics and patterns of patent application distribution in this technological domain.

4.1.1. Analysis of patent application trends

Figure 3 illustrates the developmental trajectory of global spent power battery recycling technologies, as analyzed from the trend of the 2623 patent applications, and the trajectory can be broadly categorized into three stages. The first stage, spanning from 2004 to 2009, witnessed the nascent phase of spent power battery recycling technologies worldwide. During this period, many countries began to consider the management and disposal of spent power batteries, recognizing that improper handling could lead to environmental pollution and resource waste. As a result, they started developing and patenting technologies and equipment for recycling spent power batteries. The second stage is the period from 2010 to 2017, characterized by a gradual increase in patent applications in the field of spent power battery recycling. This phase witnessed a growing number of inventors dedicating their efforts to this domain, thereby making significant contributions towards environmental sustainability and resource conservation. The third stage, from 2018 to the present, represents the period of rapid development, during which the field of spent power battery recycling has witnessed a pronounced trend towards advancement. Notably, there has been an exponential increase in the number of patents filed annually, indicating significant technological breakthroughs and widespread attention for research in this domain. The growing involvement of countries, regions, enterprises, universities, and research institutes further signifies a heightened focus on environmental protection and spent power battery recycling. This reflects the dynamic progress of innovative activities and accelerated advancements in global science and technology.

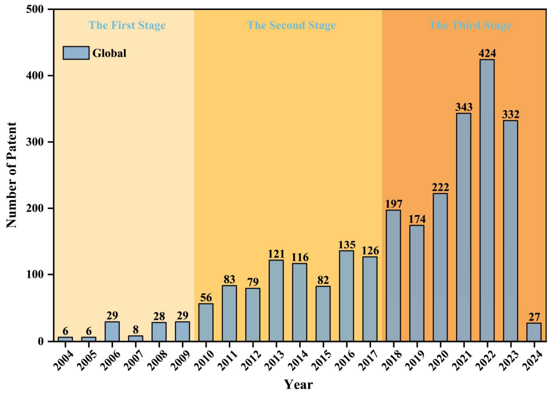


Figure 3. Trend of global patent applications related to spent power battery recycling technologies.

4.1.2. Analysis of global distribution of patent applications

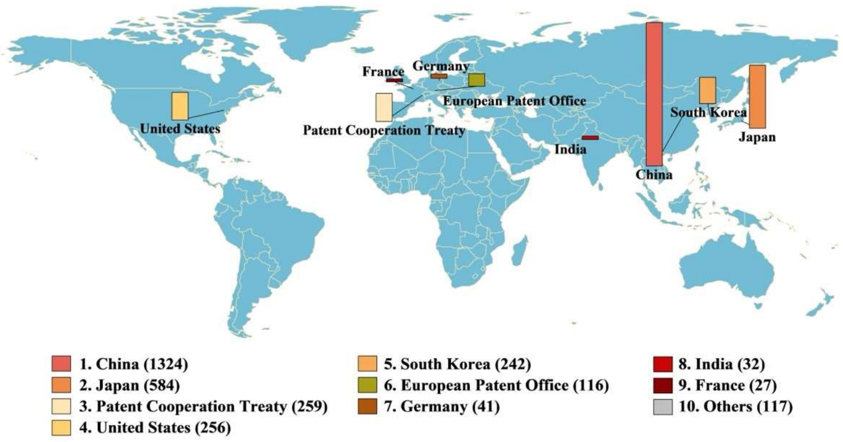


Figure 4. Distribution of patent applications related to spent power battery recycling technologies.

The geographical distribution of patent applications provides profound insights into the vitality of research and development, serving as a crucial indicator of technological progress and the strategic patent landscape across different countries and regions. It not only reflects the dynamic changes in the global innovation landscape but also signifies the competitive environment of future technology markets, offering invaluable guidance for nations, enterprises, investors, and researchers. **Figure 4** illustrates the global distribution of patent applications related to spent power battery recycling technologies over the past two decades.

Regarding the countries where these applications were filed, a majority of the patent applications originated from China, Japan, the United States, and South Korea. Specifically, China accounted for 1324 applications, followed by Japan with 584 applications, the United States with 256 applications, and South Korea with 242 applications. In contrast, other countries, such as Germany, India, and France, exhibited relatively lower numbers of patent filings. This distribution reflects the geographical concentration of global technological innovation and the varying levels of emphasis placed on patent protection by different nations. China, Japan, the United States, and South Korea emerge as leading producers in power battery manufacturing. In recent years, China’s rapid development in the new-energy automobile industry, coupled with its increasing focus on resource conservation and environmental protection, has propelled significant advancements in spent power battery recycling technologies, positioning related patent applications at the forefront globally. As a traditional science and technology powerhouse, Japan boasts profound expertise and a cutting-edge advantage in the realm of spent power battery recycling technologies, making it the pioneering nation to implement technological patent protection. Both the United States and South Korea have witnessed a gradual surge in their respective numbers of relevant patent applications on spent power battery recycling technologies, which serves as tangible evidence of their steadfast dedication to fostering technological advancement and their diligent upholding of intellectual property protection measures. Conversely, countries with relatively lower volumes of patent applications may be influenced by various factors, such as limited capabilities for technological innovation, insufficient research and development investments, or less pronounced market demands.

Regarding the filing of patent applications, 116 patents were filed through the European Patent Office (EPO), while 259 patents were filed through the Patent Cooperation Treaty (PCT). As a regional patent authority, the EPO granted patents with a legal effect in its member countries. Filing via the EPO saves both time and cost, as compared with via the PCT. Patent application filing through PCT is a more globalized strategy, involving an initial international examination phase and national examination phases in each country or region. This approach aims to streamline the cumbersome process and reduce the high costs associated with filing separate applications in multiple countries. The larger number of PCT applications indicates a broader global interest in spent power battery recycling technologies, suggesting that this field is not only promising in Europe but also holds significant potential in major markets like China, Japan, the United States, and South Korea. This trend reflects the flexibility to choose an appropriate filing strategy based on specific needs and market focus, with the EPO being a cost-effective option for targeted protection within Europe, and the PCT providing a streamlined approach for seeking broader international market opportunities.

4.1.3. Analysis of technology patent applicants

The distribution of patent applicants reveals the level of concern, depth of expertise, and research capabilities exhibited by the key players in technological innovation. The ranking of patent applications directly reflects the technological investment and emphasis of different companies or research institutions in this field, and the top-ranked applicants tend to have more research and development resources and stronger technological strength. By analyzing the composition of patent applicants, it was possible to gain insights into the competition pattern in the field of spent power battery recycling technologies, the proportion of applicants from different countries and regions, and the cooperation and competition among them, which are important bases for judging the competition situation in international markets. In addition, the emergence of new applicants may also signal new market entrants or potential technological changes. **Figure 5** shows the top 20 patent applicants for spent power battery recycling technologies. Notably, Toyota Motor Corporation of Japan leads the pack with 171 patent applications, which not only demonstrates its continuous investment in technology research and development but also reflects its leading position in technological innovation in the battery industry. Following closely is LG Chem, Ltd., of South Korea with 159 applications, indicating that chemical methods for spent battery recycling are currently the mainstream approach. Next is Contemporary Amperex Technology Co., Ltd., of China with 73 patent applications. Particularly noteworthy is that its subsidiary, Brunp Recycling Technology Co., Ltd., is a leading enterprise in China for the recycling of spent batteries. Twelve of the top 20 patent applicants are companies from Japan, indicating that Japan has an advantage in spent power battery recycling technologies. There are six from China, including two universities, namely Central South University and Harbin University of Science and Technology, reflecting the in-depth integration of industry, academia, and research in the field of spent power battery recycling in China, which provides constant intellectual support for technological innovation.

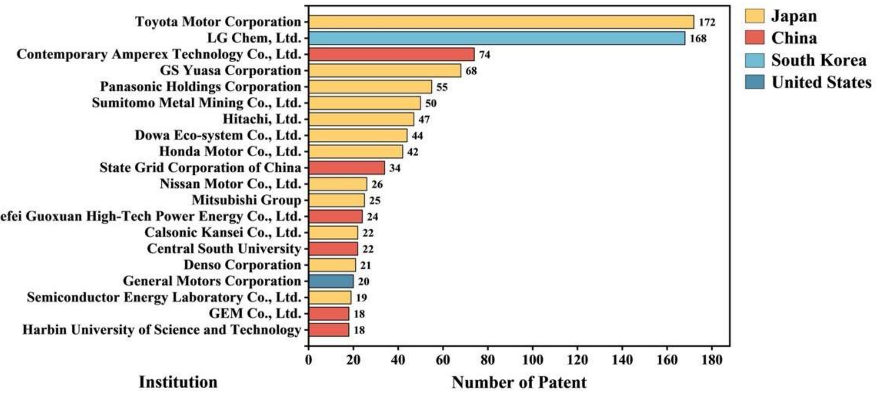


Figure 5. Top 20 patent applicants in spent power battery recycling technologies.

4.2. Analysis of technology fields

Analysis of technology fields is an important part of the formulation of science and technology policy, the strategic planning of enterprises, and the choice of scientific research direction. It aims to reveal the global research and development hotspots, technological evolution paths, and cross-field integration trends of a particular technology through in-depth analysis of the distribution of the technology in different International Patent Classifications (IPCs). The IPC is a standardized patent classification method developed by the World Intellectual Property Organization to provide a uniform and systematic classification framework to facilitate the search, management, and analysis of patent documents. The IPC divides technologies into eight sectors, which are further subdivided into classes, subclasses, groups, and subgroups, forming a multi-level, fine-grained classification system. This classification allows research activities in different technical fields to be clearly distinguished and categorized.

Figure 6 provides the major IPC distribution of spent power battery recycling technologies in the past 20 years, listing the main technical fields involved as H (electrical), G (physical), C (chemistry and metallurgy), and B (operation and transportation). The main classes are H01M (methods or devices for the direct conversion of chemical energy into electrical energy, such as battery packs), G01R (measurement of electrical variables and measurement of magnetic variables), H02J (circuit installations or systems for the supply or distribution of electricity, as well as electrical energy storage systems), C22B (production or refining of metals and pretreatment of raw materials), B60L (power units for electric vehicles, power supply for auxiliary equipment for vehicles, electric braking systems for vehicles in general, magnetic suspension or levitation for vehicles, monitoring and control of operating variables for electric vehicles, and electric traction), B09B (solid waste treatment), and G06F (electric digital data processing). It can be seen that most patent filings related to spent power battery recycling technologies are in the fields of H01M and G01R, mainly due to the rapid development of the power battery industry, and the first step of spent power battery recycling is to carry out the assessment and detection. In recent years, with the wide application of advanced technologies, such as artificial intelligence and machine learning, the recycling process of decommissioned power batteries has been significantly optimized and improved. These technologies have injected new vitality into the key aspect of battery assessment and detection, making the recycling process more efficient, accurate, and sustainable. To maximize the utilization of spent power batteries, the concept of echelon utilization has gradually entered the field related to power systems, so the research in the field of H02J has also increased. In the field of C22B, battery recycling is more about the application of chemical metallurgy technology, such as hydrometallurgy and pyrometallurgy, to extract and refine precious metals. The volumes of patent filings in the fields of B60L, B09B, G06F, and other fields indicate that the technology areas involved in spent power battery recycling technologies show an expanding trend.

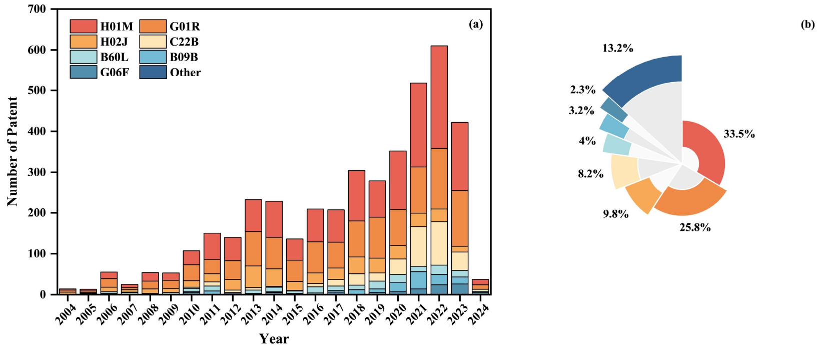


Figure 6. (a) Proportion of IPC classes per year related to spent power battery recycling technologies; **(b)** Total proportion of IPC classes related to spent power battery recycling technologies.

The IPC classification of the technology fields was adjusted to refine theme labels, and a patent application clustering map was created based on the search results, as depicted in **Figure 7**. The peaks piled up by the dots of each patent application represent different technical directions, and the higher the peaks, the more patent applications in the relevant directions are represented. It is evident that spent battery recycling technologies are widely distributed and show a clear development trend. The most concentrated areas of technology include algorithms, neural networks, state estimation, dismantling and sorting of battery cells, electrode active materials, valuable metals, and electrolytes.

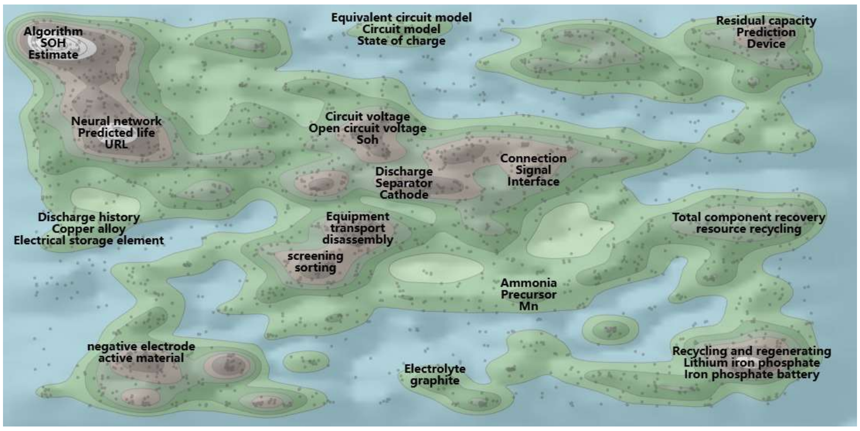
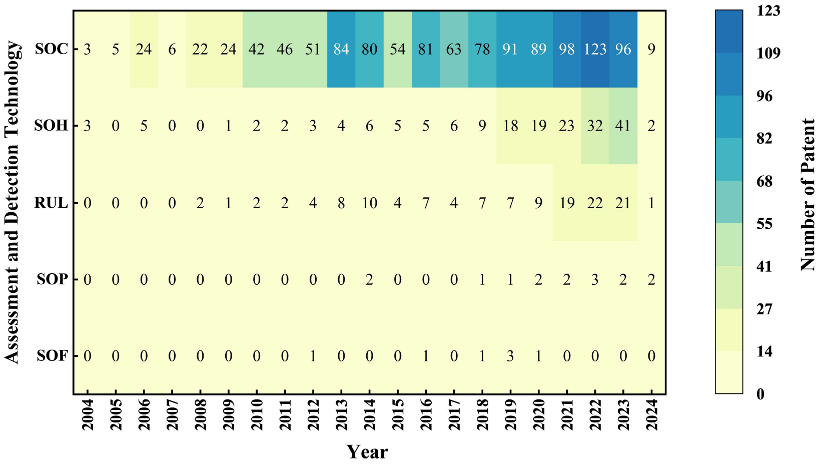


Figure 7. Clustering map of patent applications related to spent power battery recycling technologies.

A technical route analysis was conducted on the 2623 patent applications retrieved from the Derwent Innovation database, combined with the main technical direction of the IPC. The research situation in each stage of the recovery process was statistically classified and summarized, as presented in **Table 3**. The process flow of recovery technology primarily consists of the fields of echelon utilization, pretreatment, extraction and separation of valuable metals, regeneration preparation, and recycling of other materials. In the field of echelon utilization, there are 1477 patent applications related to battery pack evaluation and detection, which highlights its significance and rapid technological evolution. **Figure 8** reveals the development trends of assessment and detection technologies. SOC evaluation technology exhibits the most significant growth, with a steady upward trend from 2010 to 2023, reflecting its critical role in real-time capacity estimation for battery management systems, particularly in EVs and energy storage applications. Although the data in 2024 show a decline, this is likely due to incomplete patent filings for the second half of the year, as patent filings are typically concentrated later in the year. SOH evaluation technology has seen consistent growth since 2015, accelerating notably after 2018, driven by the increasing demand for health monitoring to extend battery lifespan and ensure safety in second-life applications, such as stationary energy storage. RUL detection technology shows slower growth, gaining momentum after 2020, which indicates a growing but niche interest in predictive lifecycle management. In contrast, SOP and SOF detection technologies show limited growth, likely due to their unclear role in battery management systems. Across all categories, patent filings have increased significantly since 2015, corresponding to the rapid growth of the EV market and the integration of renewable energy systems. As the volume of spent power batteries increases, relying solely on disassembly and recycling proves insufficient to meet the demand. Given that a significant portion of spent power batteries can still be utilized in intelligent grids, wind power generation, photovoltaic power generation, and energy storage under specific usage conditions, there has been a notable surge in patent applications related to evaluation and testing in recent years.

Table 3. Analysis of technical routes of spent power battery patent applications.

Recycling technology	**Specific technologies**	**Number of filed patents**
Echelon utilization	Transport and screening	15
	Assessment and detection	1477
	Sorting and regrouping	62
Pretreatment	Discharge	39
	Dismantling	102
	Crushing segregation	130
Metal extraction and separation	Pyrometallurgy	107
	Hydrometallurgy	326
	Biological method	8
	Integrated method	20
	Other methods	12
Regenerative preparation	Solid-state reaction	51
	Hydrothermal treatment	2
	Co-precipitation	39
	Sol-gel	4
	Carbothermal reduction	7
Direct recycling	-	152
Recycling of other materials	Graphite, electrolyte, diaphragm	70



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
SOC	3	5	24	6	22	24	42	46	51	84	80	54	81	63	78	91	89	98	123	96	9
SOH	3	0	5	0	0	1	2	2	3	4	6	5	5	6	9	18	19	23	32	41	2
RUL	0	0	0	0	2	1	2	2	4	8	10	4	7	4	7	7	9	19	22	21	1
SOP	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	1	2	2	3	2	2
SOF	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	3	1	0	0	0	0

Figure 8. Heatmap of assessment and detection technologies.

Regarding pretreatment technology, battery disassembly and crushing separation hold a relatively higher proportion. The pretreatment process for spent batteries is generally similar. A small percentage of the patent applications involve preprocessing procedures for batch processing in a single integrated operation. Therefore, the implementation of large-scale automated batch processing is currently a technical hotspot. In the field of metal extraction, hydrometallurgy continues to dominate as the mainstream recycling technology due to its high efficiency and applicability across various materials. However, emerging technologies, including hybrid methods that integrate hydrometallurgy and pyrometallurgy, along with innovative approaches, such as photocatalytic technology, membrane separation technology, and anaerobic thermal decomposition, are gaining traction for their potential to enhance recovery rates and reduce environmental impacts. Furthermore, biological methods, though currently representing a smaller proportion of patent applications, offer an environmentally friendly and sustainable alternative for metal recovery. These methods hold significant promise for further research and industrial adoption, particularly in addressing challenges, such as high energy consumption and chemical waste. The trends depicted in **Figure 9** illustrate the evolution of annual patent filings related to spent power battery recycling technologies.

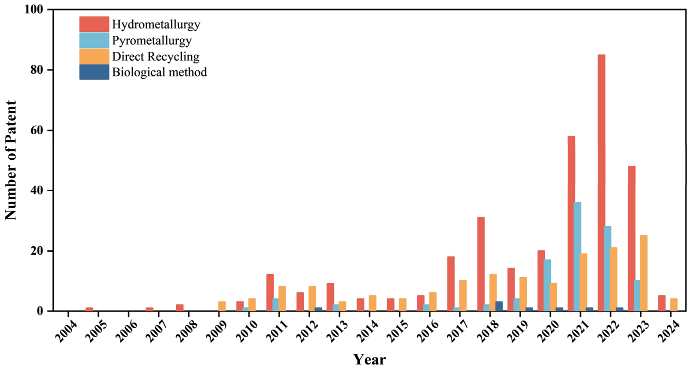


Figure 9. Evolution of annual patent filings related to spent power battery recycling technologies.

The treatment of waste gases and wastewater generated during the recycling of spent battery power has received limited attention and importance, as evidenced by the scarcity of patent applications. This represents a notable weakness that warrants further consideration. Solid-phase sintering and co-precipitation are widely used technologies in battery manufacturing regeneration. Direct repair technology for spent power batteries has progressively matured and achieved industrialization. Owing to the technology's remarkable efficiency, environmental-friendliness, and cost-effectiveness, an increasing number of companies are adopting it as a replacement for traditional hydrometallurgy and pyrometallurgy methods, which is a current research focus. In addition, the recovery technology for specific battery components, such as graphite, electrolyte, and separators, is also a research hotspot, with 70 patent applications, indicating research input and technological accumulation.

5. Policies and regulations for power battery recycling

In recent years, numerous countries have enacted a lot of policies and regulations on the recycling of spent power batteries to establish comprehensive battery life cycle management. These measures aim to facilitate resource recovery, mitigate environmental pollution, and actively foster sustainable development in related industries.

5.1. European Union

Regulation (EU) 2023/1542 was enacted by the European Parliament and the Council of the European Union on 12 July, 2023, and has been in effect since 18 February, 2024. This regulation comprises fourteen chapters primarily addressing battery labeling and marking, battery compliance assessment, operator responsibility and liability, spent battery management, and digital battery passport, among other aspects. Notably, in terms of spent battery management, the regulation does the following: (1) enforces a system with extended producer responsibility by mandating battery producers to assume accountability for recycling and reusing spent batteries; (2) establishes a categorized system for the recycling and collection of batteries; (3) specifies the obligations for distributors, operators, users, and regulators; (4) sets material recycling rates, as well as material recycling targets, to enhance the recycling efficiency of spent batteries; (5) necessitates that battery producers provide information regarding battery composition, environmental impacts, and recycling practices; and (6) introduces a preventive management and reporting system for ensuring transparency and traceability of relevant information.

5.2. The United States

The management and development of spent power battery recycling and reuse have become a growing focus for both federal and state governments in the United States. They are actively establishing and enhancing legal and regulatory frameworks to effectively govern and promote the recycling and utilization of spent power batteries across different levels. At the federal government level, the United States Congress enacted the bipartisan Infrastructure Investment and Jobs Act in 2021. This legislation provides financial support and incentives for research, development, and innovation in battery recycling technologies across multiple projects. Additionally, it mandates that spent batteries must be collected using methods that are both technically and economically feasible, ensuring the safety of waste management workers, while optimizing the value and utilization of recycled battery materials. The United States Inflation Reduction Act of 2022, which not only fosters the growth of the domestic battery recycling industry but also enhances resource recycling efficiency, offers the following: (1) automatic recognition of EV battery materials recycled in the United States as "made in the USA"; (2) provision of tax credits or subsidies for investments in clean energy projects, such as battery recycling facilities; and (3) economic incentives and market access advantages to bolster the battery recycling sector. At the state government level, New York's Rechargeable Battery Recycling Act mandates that retailers or manufacturers of rechargeable batteries assume responsibility for recycling used rechargeable batteries returned by consumers. Under California's Rechargeable Battery Recycling Act, used rechargeable batteries returned by consumers are to be recycled by all retailers of rechargeable batteries in California at no cost to the consumers.

5.3. China

China has implemented a series of policies and regulations concerning the recycling of used power batteries in recent years. For instance, the Implementation Plan for the Extended Producer Responsibility System was enacted in 2017, mandating EV and power battery manufacturers to establish an extensive network for recycling used power batteries and to assume complete responsibility for resource utilization and environmental impact throughout the power batteries' entire life cycle. It emphasizes comprehensive traceability management of power batteries across all stages. Issued in 2018, the Interim Measures for the Recycling and Utilization of New-Energy Vehicle Power Batteries clarified the primary responsibility of automobile manufacturers in power battery recycling and outlined the responsibilities of relevant enterprises across all stages of recycling. A well-established recycling system encompassing collection, storage, transportation, echelon utilization, and final disposal was implemented. Additionally, specific construction and operational requirements were formulated for power battery recycling service outlets, while a unified traceability information system was established. The Interim Measures for the Administration of Industry Norms for the Comprehensive Utilization of Used Power Batteries for New-Energy Vehicles, released in 2019, proposed specific requirements regarding the production scale, technical equipment, and environmental protection standards for enterprises engaged in the comprehensive utilization of used power batteries. These measures aim to guide the industry towards standardized development. The Administrative Measures for the Echelon Utilization of Power Batteries for New-Energy Vehicles, issued in 2021, emphasizes the primary responsibility of enterprises engaged in the echelon utilization of spent power batteries from new-energy vehicles and also requires the establishment of standardized recycling service points, collaborative construction of recycling systems, and stringent management of end-of-life echelon products, all of which to ensure standardization and efficiency throughout the echelon utilization process. The Industrial Structure

Adjustment Guidance Catalogue (2024), issued by the National Development and Reform Commission, promotes the recycling and reuse of used power batteries through automated disassembly, rapid sorting and grouping, the assessment of battery residual life and consistency, the comprehensive recovery of valuable components, echelon utilization, as well as the development and application of regeneration technologies and equipment.

5.4. Other countries

In Germany, the implementation of the Batteries Act (BattG2) in 2021, a revision of the 2009 Batteries Act (BattG), requires the following: (1) manufacturers or sellers assume responsibility for ensuring the recycling and proper disposal of used lithium-ion batteries, as well as covering the associated costs and adhering to environmental regulations; (2) manufacturers or sellers are required to actively engage in public awareness campaigns regarding lithium-ion battery recycling, provide accurate information on appropriate disposal methods, and facilitate access to suitable recycling facilities; and (3) batteries must be labeled with a recycling logo to guide consumers in the correct disposal.

The Power Battery Industry Strategy released by Japan in 2022 underscores the significance of recycling and utilizing used power batteries, positioning them as a crucial element of sustainable development. It puts forth a range of measures, including piloting carbon footprint regulations, establishing robust recycling and utilization systems, and promoting battery echelon utilization. These initiatives aim to enhance the recycling and utilization rate of used power batteries and to achieve resource circularity and environmental protection goals.

South Korea actively advocates for the enactment of legislations concerning the recycling and comprehensive management of used batteries. On 10 July, 2024, the government issued the Legislation, System, and Infrastructure Development Plan for Promoting the Used Battery Industry. The plan outlines a series of measures for recycling and disposing used batteries: (1) enact a comprehensive bill within one year to support plans for the used battery industry, (2) implement a battery lifecycle tracking system by 2027, (3) introduce a certification system for recycled materials and a performance evaluation system for EV batteries prior to disposal, and (4) formulate a code for the fair trade of used batteries and implement a business registration system. **Table 4** lists the main policies and regulations related to power battery recycling in various representative countries.

Table 4. Policies and regulations on power battery recycling in select countries.

Policy/regulation title	Year	Country	Details on battery recycling
Regulation (EU) 2023/1542	2023	European Union	• Implements system for extended producer responsibility • Requires battery manufacturers to be responsible for recycling and reusing spent batteries • Establishes recycling collection classification system • Sets material recovery targets • Clarifies obligations of each participant • Requires manufacturers to provide information on battery composition and recycling practices

Table 4. (*Continued*).

Policy/regulation title	**Year**	**Country**	**Details on battery recycling**
Infrastructure Investment and Jobs Act	2021	USA	• Provides technical and financial support for battery recycling projects • Requires use of feasible methods to collect used batteries • Ensures safety of waste management workers • Optimizes value and utilization of recovered battery materials
Inflation Reduction Act	2022	USA	• Requires EV battery materials recycled in the United States to be considered “made in the USA” • Provides subsidies or tax credits for battery recycling programs • Provides economic incentives and market access advantages
Rechargeable Battery Recycling Act	2005	California, USA	• Rechargeable battery retailers to offer free collection services for used rechargeable batteries returned by consumers
Rechargeable Battery Recycling Act	2010	New York, USA	• Rechargeable battery retailers to assume responsibility for recycling used rechargeable batteries returned by consumers
Implementation Plan for the Extended Producer Responsibility System	2017	China	• EV and power battery manufacturers to be responsible for establishing spent battery recycling network, utilizing after-sales service networks to recycle spent batteries, and implementing product coding to establish full-life-cycle traceability system
Interim Measures for the Recycling and Utilization of New-Energy Vehicle Power Batteries	2018	China	• Clarifies main responsibility of automobile production enterprises in power battery recycling • Establishes a comprehensive recycling system • Formulates specific construction and operation requirements for power battery recycling service outlets • Establishes unified traceability information system
Interim Measures for the Administration of Industry Norms for the Comprehensive Utilization of Used Power Batteries for New-Energy Vehicles	2019	China	• Presents specific requirements regarding production scale, technical equipment, and environmental protection standards for comprehensive utilization enterprises engaged in spent power battery management
Administrative Measures for the Echelon Utilization of Power Batteries for New-Energy Vehicles	2021	China	• Clarifies main responsibility of enterprises using echelon utilization of spent power batteries for new-energy vehicles • Requires establishment of standardized recycling service points • Collaborates in construction of recycling systems • Strictly manages scrapped echelon products
Industrial Structure Adjustment Guidance Catalogue	2024	China	• Recycling of spent power batteries via automated dismantling of spent power batteries, automated rapid sorting into groups, battery residual life and consistency assessment, integrated recovery of valuable components, echelon utilization, recycling technologies, equipment development and application, etc.
Battery Act (BattG2)	2021	Germany	• Requires manufacturers or sellers to be responsible for undertaking recycling and disposal of spent power batteries, hence ensuring environmentally sound handling and recycling of valuable materials
Power Battery Industry Strategy	2022	Japan	• Emphasizes importance of recycling and utilizing used power batteries • Puts forward measures that pilot carbon footprint regulations, establish robust recycling and utilization system, and promote battery echelon utilization
Legislation, System, and Infrastructure Development Plan for Promoting the Used Battery Industry	2024	South Korea	• Enacts comprehensive bill within one year • Establishes a battery lifecycle tracking system by 2027 • Introduces certification and evaluation systems • Formulate code for fair trade and implement business registration system

As countries pursue economic and environmental sustainability, the role of intellectual property in promoting innovation in the battery recycling industry has gained attention. Intellectual property not only drives research and development but also protects and incentivizes innovation in advanced recycling processes [136]. It is crucial in ensuring breakthroughs in battery recycling technologies and motivating inventors and research institutions to invest in new solutions. Major global economies, including the EU, the USA, China, and Japan, have established intellectual property systems for battery recycling to encourage innovation. These systems are particularly important in the capital-intensive and high-tech recycling sector, where developing effective recycling technologies requires significant upfront investment. For example, the US Inflation Reduction Act of 2022 and China's Extended Producer Responsibility System have boosted patent filings for advanced recycling technologies, highlighting the positive impact of supportive policy frameworks on innovation. While patent protection promotes innovation, sharing and transferring patented technologies are essential for the global adoption of sustainable recycling practices. Similar to the patent pool model in the pharmaceutical industry, where multiple patent holders share technologies, such a model has proven effective in accelerating technology diffusion [137]. This approach provides small businesses and emerging markets with access to cutting-edge technologies, reducing redundant R&D costs and accelerating the adoption of best practices. In addition, technology transfer agreements play a crucial role in bridging the technological gap between developed and developing countries. By enabling emerging markets to access patented recycling technologies, these agreements can accelerate the spread of environmental technologies and support the economic development of in developing countries [138]. However, ensuring equitable access to these technologies, while maintaining the incentive structure of patent systems, requires careful regulation and international cooperation [38]. If not managed properly, stringent patent protections could limit the access of low- and middle-income countries to green technologies, hindering global collaboration.

6. Conclusion

Recycling technologies of spent power batteries, as clean technologies that save resources, have become a research hotspot globally. In recent years, with the support of policies in various countries and the joint efforts of scientific research institutions and enterprises, the technology of spent battery recycling has opened up a good prospect. The following conclusion can be drawn from the analysis of relevant policies and regulations, as well as from the analysis of global patent applications related to the technologies of spent power battery recycling:

(1) In recent years, Europe, the United States, and China have been continuously enhancing and implementing diverse policies and regulations in the domain of spent battery recycling to address environmental pollution and resource wastage issues caused by used batteries. By incorporating government bodies, battery manufacturers, EV manufacturers, distributors, users, and recycling enterprises into upstream and downstream supervision and management processes, while strengthening responsibility awareness and communication across all stakeholders involved, comprehensive life cycle management systems for the

battery industry have been established. These policies and regulations have played a pivotal role in promoting the eco-friendly transformation of the battery industry, hence enhancing resource utilization efficiency and fostering advancements in battery recycling technologies.

(2) From the trend of patent applications related to spent power battery recycling technologies over the past two decades, it is evident that the technologies underwent three distinct stages: the nascent stage, the gradual growth stage, and the current rapid expansion stage. This signifies that spent power battery recycling and utilization have garnered significant attention globally and emerged as a burgeoning industry. The focus of development has shifted from being predominantly led by Japan and South Korea to China taking the lead, with close pursuit from the United States and Europe. Enterprises constitute the majority of applicants, while research institutions and universities contribute to a smaller extent. The leading companies in this field are primarily Japanese automobile enterprises and Chinese battery manufacturers. In terms of recycling processes, there is a predominant research direction towards echelon utilization, as well as extraction and separation of valuable metals. The number of patent applications related to evaluation and detection technologies continues to grow annually, and the technologies are progressing towards more intelligent systems capable of batch processing. This approach aims to maximize battery value, while assessing battery condition for subsequent processing. Valuable metal extraction and separation methods mainly rely on hydrometallurgy and pyrometallurgy techniques; however, emerging technologies also play a role in this domain. Biotechnology research, along with wastewater treatment technology, have received relatively less attention compared with other areas. The number of patent applications related to direct recycling methods is also increasing due to the methods' environmental-friendliness, cost-effectiveness, and technical feasibility. Recycling enterprises increasingly employ these methods, which enable the direct repairment, recharging, and activation of spent power battery cells. Additionally, there is growing popularity in recovering materials, such as the anode, electrolytes, separator, and electrodes, from spent power batteries.

(3) China holds a significant advantage in terms of the volume of patent applications related to spent power battery recycling technologies compared with Europe, the United States, Japan, South Korea, and other nations. Furthermore, with the increasing popularity and promotion of new-energy electric vehicles, China's lithium-ion battery industry and spent battery recycling industry are expected to witness continuous growth. Consequently, a substantial portion of the exchange and development of spent power battery recycling technologies is anticipated to occur in China in the near future. In terms of patent applicants, both domestically and internationally, Japanese and South Korean enterprises exhibit complex research and development cooperation relationships involving corporations, individual experts, and universities. Conversely, there are relatively fewer collaborations among patent applicants in China, which places China at a disadvantage in international competition. The primary focus of spent power battery recycling technologies development lies in echelon utilization,

pretreatment, metal extraction, and direct recycling technologies. Echelon utilization technology is a relatively novel field with a substantial number of patent applications, and its overall technological advancement has been bolstered by the progress in various artificial intelligence technologies, rendering it a prominent research and development area. In the realm of echelon utilization technology, battery performance evaluation and assessment, as well as computer simulation, are key areas of investigation. Assessment and detection techniques play an indispensable role in the echelon utilization of spent power batteries due to their diverse specifications and parameters. Current developmental directions encompass the creation of battery management systems tailored for spent power batteries, along with more intelligent evaluation and monitoring technologies and low-cost auxiliary components. In terms of pretreatment procedures, material screening through battery crushing stands out as a pivotal technological domain. Metallurgy technology for precious metal extraction, alongside other physical approaches, takes center stage in the metal extraction segment, while repair processes, lithium replacement methods, and activation techniques constitute crucial research areas for direct recycling endeavors. Recycling preparation technology has a larger technical bottleneck and the development conditions are strict, resulting in unsatisfactory technical effects. The technology of the recycling of other materials, due to its high cost and low profit, which are the two major weaknesses at present, is rarely studied.

The future prospects of recycling technologies for spent power batteries are promising. However, in order to fully realize the potential and overcome existing challenges, multifaceted efforts are still required. Based on the current situation and characteristics, the following suggestions are proposed.

Firstly, in the management of recycling spent power batteries, it is imperative to clarify the responsibilities of relevant entities, enhance industry entry requirements, and implement a robust traceability system for battery information. In addition, an efficient cooperative recycling system and a comprehensive life-cycle management framework for spent power batteries should be established. Furthermore, there is a need to refine process and technology specifications and requirements and to foster close collaboration between upstream and downstream enterprises in order to establish an integrated industrial chain encompassing the collection, transportation, treatment, and resource utilization of spent batteries. Moreover, incentive mechanisms must be implemented to raise awareness among users regarding the importance of recycling end-of-life batteries, as well as stimulate innovative thinking among enterprises towards environmentally-friendly approaches for handling spent power batteries. Also, policy support should be strengthened, particularly for technologies that require further development.

Secondly, in terms of collaborative research, it is imperative to enhance cooperation and exchanges between international organizations, enterprises, research institutes, and individual experts. By leveraging each other's advanced experiences and technologies, university research can be combined with practical projects undertaken by enterprises to facilitate the successful translation of technological achievements. This process should gradually establish a joint innovation platform comprising both enterprises and research units. Guided by market forces, this platform will integrate production, learning, and research activities and promote the sustainable and robust development of spent battery recycling technologies through policy guidance and market-oriented approaches.

Thirdly, in the realm of recycling technologies, it is crucial to strike a balance between advancements across various technical domains and effectively coordinate the entire technical chain. Emphasis should be placed on fostering breakthroughs in pivotal technical fields and on the collaborative exploration of emerging areas of interest, thereby fortifying weaker technical domains. Furthermore, proactive efforts must be made to facilitate interdisciplinary field innovation.

Acknowledgments: This work was supported by the Science and Technology Commission of Shanghai Municipality (grant number 21DZ1209700).

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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