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A Review of Secondary Utilization of Retired Power Battery

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Abstract. The exponential growth of the new energy vehicle industry has driven a surge in global battery installations, leading to a projected 900,000 tons of retired batteries by 2025. While secondary utilization theoretically extends lifecycles compared to direct disposal, persistent pack-level challenges remain. Specifically, issues such as capacity dispersion, resistance escalation, and aging-mode mismatches significantly impede rapid grading and reliable regrouping. Although current capabilities excel in data-driven sorting, critical gaps persist regarding standardization, cost realism, and large-scale safety validation. Consequently, this review compares the trade-offs of four end-of-life routes: pyrometallurgy offers robustness but entails high energy and lithium losses; hydrometallurgy achieves high purity yet relies on chemical additives; direct regeneration enables low-carbon structural restoration but is limited by feedstock cleanliness; and electro-regeneration facilitates cathode-to-cathode cycling pending specific modifications. Finally, by integrating material-level indicators with techno-economic and policy frameworks, we outline feasible pathways for sustainable secondary utilization.

Keywords: Secondary utilization of retired power battery, pyrometallurgy, hydrometallurgy, direct regeneration, electro-regeneration cycling

1. Introduction

Typically, power batteries possess a service life of approximately 5–7 years, after which their capacity declines to 70–80%, necessitating retirement [1]. Driven by the rapid expansion of the electric vehicle (EV) sector, this limited lifespan is currently generating an exponential surge in the volume of retired units [2]. If these batteries are subjected to direct disposal, the industry faces not only the leakage of hazardous electrolytes and heavy metals but also the squandering of strategic resources like lithium, cobalt, and nickel [3]. Consequently, the secondary utilization of retired power batteries (SURPB) has emerged as a fundamental strategy for fostering a low-carbon, resource-efficient circular economy [4,5].

Over the past four decades, battery recycling has undergone a significant evolution across Europe, North America, and China. The initial phase, spanning the 1990s to the 2000s, was characterized by the establishment of foundational infrastructures: while Western regions validated pyrometallurgical and hydrometallurgical processes [6], China focused on policy-driven collection networks under its "10th Five-Year Plan." Subsequently, the period between 2005 and 2010 marked a shift toward process optimization, where mechanical separation and acid leaching were prioritized to enhance metal extraction rates and minimize waste [7]. By 2015, the burgeoning EV market necessitated a fundamental transition from mere material recovery to functional reuse. Consequently, research

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frontiers expanded to include state-of-health (SOH) prediction and lifecycle modeling to support this new paradigm [8].

Around 2020, initiatives such as the Battery 2030+ program in Europe and China's Technical Roadmap for Battery Cascade Utilization advanced the field into the intelligent and standardized era [9]. Research priorities moved toward AI-assisted disassembly, residual value assessment, and module reconstruction, enabling real-world demonstrations in energy storage, peak-shaving, and low-speed vehicle applications. By 2025, attention has increasingly shifted to material-level regeneration, integrating direct relithiation, mechanochemical activation, and green hydrometallurgy, marking a new paradigm of closed-loop, high-value recovery [10].

Despite substantial progress, several challenges remain. Early work focused on feasibility without establishing systematic reuse standards. Mid-stage research advanced safety and energy management but overlooked economic and lifecycle assessments. Furthermore, recent innovations in low-carbon and green chemistry have yet to reach large-scale industrial deployment [11]. Key trade-offs persist among energy consumption, recovery efficiency, product consistency, and environmental impact, underscoring the need for integrated, scalable solutions.

This systematic examination of SURPB materials begins by tracing the trajectory of technological advancements across various regions and time periods. Following this historical overview, the paper shifts focus to the technical core, distinguishing the underlying mechanisms and trade-offs inherent in key recycling approaches such as pyrometallurgy, hydrometallurgy, direct regeneration, and electro-regeneration. These technical insights are subsequently integrated into a broader discussion on the performance of secondary utilization, covering economic, environmental, and resource metrics. Ultimately, this framework is intended to support the industry's transition toward sustainable power battery management.

The information sources considered in this study are limited to journal articles and conference papers. The method used in this paper for identifying, retrieving, classifying, and evaluating the literature is the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. The first step in the literature search process is to determine the review area and keywords. The keywords used in this paper include "power battery", "ladder utilization", "material regeneration", and "battery material". The selected literature search databases include Scopus, ProQuest, Elsevier, Web of Science, ACS Publications (American Chemical Society), and China National Knowledge Infrastructure (CNKI). Keyword combinations are used to search for literature in each database. The retrieved literature mainly includes publication titles, abstracts, and author keywords. According to the search criteria, the time range for literature search is set to the past five years, specifically from 2021 to 2025. Drawing upon an extensive analysis of 198 studies, this paper is structured to four detail methods as shown in Figure 1: pyrometallurgy, hydrometallurgy, direct regeneration, and electro-regeneration cycling. The review concludes with a summary and an outlook on future developments in this field.

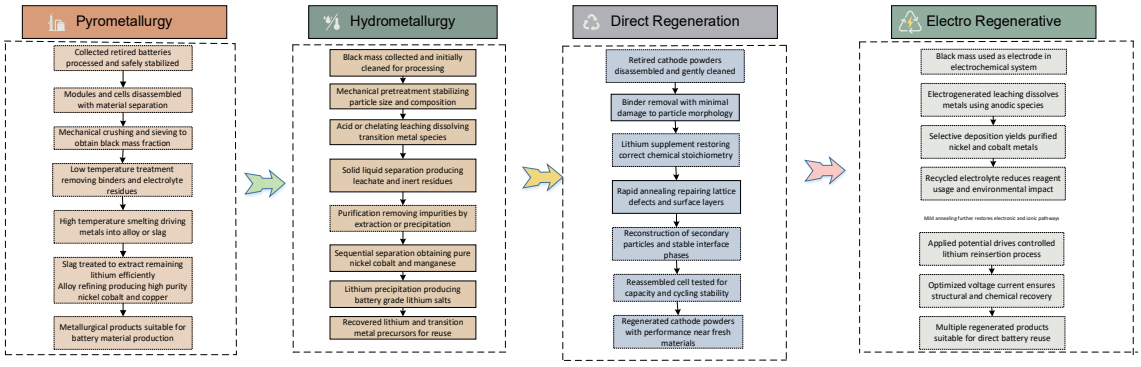

Figure 1. Flow chart of the four methods

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2. Related works

Over 2024–2025, supply risks for critical minerals and record-high CO_2 emissions strengthened the consensus that battery-grade materials must increasingly come from recycling and regeneration [12,13]. The International Energy Agency's (IEA) Global Critical Minerals Outlook 2025 classifies lithium, nickel, cobalt, and graphite as 'non-substitutable' elements in the energy transition. Furthermore, it advocates for specific policy levers to ease supply vulnerabilities. Recommended low-regret options include recycling targets, minimum recycled content, and extended producer responsibility (EPR). IEA's companion brief on recycling of critical minerals further calls for scaling recycling and harmonizing data and standards [14].

The European Union's Batteries Regulation was complemented on 4 July 2025 by implementing rules that standardize the calculation and verification of recycling efficiency and material recovery, with a focus on critical and strategic raw materials. The Regulation also introduces due diligence, carbon-footprint disclosure and the digital battery passport, creating an executable pathway for secondary materials to enter mainstream supply chains [15,16]. The European Environment Agency's 2025 circular-economy briefings echo this direction by underlining the role of higher Circular Material Use Rate (CMUR) and high-quality waste recycling to curb primary resource demand.

At the carbon-budget level, the latest Global Carbon Budget shows that fossil CO_2 emissions hit another record in 2024. This trend significantly heightens the urgency for supply-chain decarbonization and material circularity. Consequently, it creates a direct incentive to replace primary inputs with recycled ones. The World Bank's Climate-Smart Mining initiative, meanwhile, frames secondary recovery as a key lever for resource-rich developing countries to meet mineral demand with minimal environmental and climate footprints [17].

In terms of the regional SURPB. National and regional policies are moving in parallel. In the United States, Environmental Protection Agency (EPA) and Department of Energy (DOE) are advancing collection best practices and policy tools amid market uncertainty—ironically underscoring the anti-fragility of recycling and the value of regulatory clarity. India recently approved an incentive scheme for critical-mineral recycling (FY26–FY31), covering lithium batteries scrap and end-of-life vehicles, signaling proactive policy in emerging markets [18].

In terms of the corporate and industrial SURPB. The EU is driving industry implementation through recycling-rate metrics, mandates, and the 2025 implementing rules. This strategy is fostering capacity build-out and reporting standardization. Nevertheless, analyses suggest that Europe must speed up to meet 2030 demand. Ultimately, new requirements in 2031 will structurally integrate the recycling sector into primary value chains. Academic and think-tank work (e.g., UCL) suggests that, with aligned policies and viable business models, recycled lithium could materially offset primary demand by 2050—supporting direct regeneration and hydro/pyro-coupled routes from both demand and policy sides [19].

Taken together, the combined forces of regulatory obligations, market incentives, and climate targets are redefining the techno-economic boundaries of SURPB. Under this policy background, the following sections compare pyrometallurgy, hydrometallurgy, direct regeneration and electro-regenerative pathways in terms of principles, governing equations and their pros and cons. In section A, pyrometallurgy is examined for its robustness in handling mixed-chemistry feedstocks to recover valuable alloys, despite challenges regarding high energy consumption and lithium loss. In section B, hydrometallurgy is highlighted for its capability to achieve high-purity metal recovery and closed-loop precursor production through precise wet-chemical separation, though it relies heavily on chemical reagents. In section C, direct regeneration is discussed as a low-carbon strategy that restores electrochemical performance through non-destructive lattice repair and lithium supplementation, limiting its scope to specific feedstocks. In section D, electro-regeneration cycling is explored as an

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emerging green pathway that leverages selective electro-deposition and in-situ reagent generation to minimize secondary pollution.

Table 1. Overview of secondary utilization methods for power batteries

Approaches	Application Regions	Research Status	Principles	Advantages	Disadvantages
Pyrometallurgy [20-23]	Europe; North America	It has entered the mature stage of engineering	Under anaerobic or hypoxic high-temperature conditions, organic matter undergoes thermal cracking.	1. High levels of reduction and resource utilization. 2. Be capable of handling the mixed plastics and other hard-to-recycle organic solids in retired batteries. 3. Energy can be self-sustaining. 4. Compared with incineration, less pollutants such as carbon dioxide are produced.	1. The process control is complex. 2. The composition of the product is unstable. 3. The quality of the products needs to be improved. 4. The initial investment is relatively high.
Hydrometallurgy [24-27]	Europe, North America; China	It has entered the stage of engineering and large-scale application.	In a liquid phase environment, chemical reagents are used for leaching, dissolving, separation and purification.	1. High metal recovery rate 2. High product purity. 3. Suitable for processing low-grade materials 4. The reaction temperature is usually lower than that of pyrometallurgy.	1. Generate a large amount of waste liquid 2. High processing costs 3. Highly corrosive and pose environmental risks. 4. Long process flow.
Direct Regeneration[28-32]	North America; Europe; Asia	It is transitioning from theory-based material validation toward engineering implementation	Simple physical or chemical cleaning of used materials is carried out to restore their original functions, rather than complete decomposition.	1. The process flow is the simplest, with the lowest energy consumption and cost. 2. The original structure and value of the materials have been retained to the greatest extent.	1. The applicability is limited, as it is only suitable for specific types and certain degrees of degradation. 2. The performance after regeneration may be lower than that of new materials.
Electro-regenerative Cycling [32-35]	North America; Europe; China	From quantitative lithium supplementation to the coupling system of electro-generated acid, electro-generated oxidant and selective electro-deposition	Recovering the reversible capacity and kinetic performance of retired battery materials	1. The lithium supplementation amount can be precisely controlled. 2. Without damaging the morphology and structure of the material. 3. Low reagent consumption and environmentally friendly	1. Not suitable for materials with severe structural collapse or excessive by-products. 2. The regeneration efficiency is limited because the cycle takes a long time. 3. It is difficult to handle large-scale unevenly aged batteries.

2.1. Pyrometallurgy

This section provides a comprehensive review of the technological pathways for SURPB in regions with relatively mature technologies, such as Europe, the United States, Japan, and China. The primary objective is to analyze and summarize various pyrometallurgical techniques applied in the SURPB. Based on their application in the field of pyrometallurgy, the feasibility of secondary utilization is examined. The comparison overview of this method is shown in the Table 2.

In 2016, a dedicated lithium-SURPB processing line was completed in Germany by Accurec, configured as a thermal pretreatment/melting–selective separation route. In subsequent technical

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white papers, an operational "experience window" for maintaining stable performance under mixed-chemistry feedstock conditions was disclosed. In 2022, expansion of the lithium SURPB recovery unit was announced; Phase I was targeted to process 4,000 tons per year with battery-grade lithium salt output, and a roadmap was presented to raise the lithium SURPB recovery rate from about 50% to 80% [20].

In 2017, Ni recovered from used lithium-ion batteries (LIBs) was refined in Japan and converted into cathode materials, by which the nation's first "battery-to-battery" closed loop was achieved. In 2024, the construction of two new recycling plants in Ehime Prefecture was announced, with annual capacity planned to reach approximately 10,000 tons of equivalent LIBs by 2025 [21]. In Japan, responsibility for SURPB is assigned to manufacturers, and certain subsidies are provided by the government to strengthen producer participation. A range of residential and commercial energy-storage products with power capacities from 12 to 96 kW has been developed by Japanese enterprises specializing in SURPB.

From 2021 to 2025, it was noted in Glencore's North American reports that black powder can be processed by the Sudbury smelting system and that high-value metals such as Ni/Co/Cu can be recovered from alloys, whereas lithium is difficult to recover directly by traditional smelting. This challenge has been cited as a principal motivation for collaboration with hydrometallurgical enterprises [22]. In Europe, the black powder processing center in Portovesme, Italy, was jointly demonstrated by Glencore and Li-Cycle; Phase I is targeted to process 11,000 tons of black powder per year, with a long-term plan of 50,000–70,000 tons per year, as reported on glencore.com [23]. SURPB from Chevrolet vehicles have been repurposed through collaboration between General Motors and ABB, leading to the development of household and small-business backup power systems, as well as peak-shaving and valley-filling equipment integrated with clean-energy generation. The principles of metallurgical processes are shown below.

Table 2. Overview of secondary utilization pyrometallurgy methods for power batteries

Application Regions	Principles	Advantages	Disadvantages
Germany [20]	The raw materials are subjected to thermal pretreatment first, followed by smelting and selective separation	1. The process is mature and highly stable; 2. It has strong adaptability to mixed chemical systems; 3. Metals can be enriched to alloy phases; 4. The separation efficiency is relatively high.	1. High energy consumption; 2. Metals are prone to loss into the slag; 3. It is necessary to strictly control the oxygen potential and temperature to avoid sintering and volatilization.
Japan [21]	Recycling Ni through the pyrometallurgical route and remaking it into cathodes.	1. The closed-loop system is well-developed; 2. Some metals can be directly recycled to the material end.	1. Li recycling still requires additional steps; 2. The pre-treatment cost by pyrometallurgy is high; 3. It relies on supplementary hydrometallurgical processes.
North America [22,23]	The black mass is smelted, with Ni/Co/Cu entering the alloy phase; and the difficult-to-recycle Li is treated in collaboration with hydrometallurgical process.	1. The industrial equipment is large in scale and has high production capacity; 2. Strong adaptability to multi-metallic black powder; 3. The alloy phase can be further refined.	1. Li is difficult to be directly recycled in pyrometallurgical processes; 2. It has high energy consumption and carbon emissions; 3. It still relies on subsequent hydrometallurgical processes to complete the closed loop.
Italy [23]	The black powder is treated by pyrometallurgy and then the lithium salt is refined by hydrometallurgy.	1. High comprehensive recovery rate; 2. Suitable for large-scale centralized processing; 3. It can significantly reduce transportation and decentralized processing costs.	1. The process is complex and requires high investment; 2. The pyrometallurgical stage still brings energy consumption and Li loss.

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Low-temperature around 300-600℃, pyrolysis removes polyvinylidene difluoride (PVDF) binder and $LiPF_6$-based electrolyte and debonds active powders from current collectors; high-temperature smelting leverages controlled oxygen potential to partition metals between the alloy and slag phases: Ni/Co/Cu enrich in the alloy, whereas Li tends to form silico-aluminates in the slag. Non-isothermal kinetics are commonly analyzed by Arrhenius and Kissinger relations, this formula is as follows.

$$k(T) = Ae^{-\frac{E_a}{RT}} \tag{1}$$

$$\ln\left(\frac{\beta}{T_P^2}\right) = -\frac{E_a}{RT_P} + \mathrm{C} \tag{2}$$

In the Eq.1, A is the pre-exponential factor, R is the gas constant, T is the temperature, E_a is the activation energy, β is the heating rate, and T_P is the DTG peak temperature. To suppress particle sintering and Li volatilization, it is necessary to control the maximum temperature and oxygen partial pressure while ensuring debinding.

2.2. Hydrometallurgy

This section focuses on countries and regions with relatively mature technologies for the SURPB, such as North America, Europe, and China etc., providing a systematic review of their technical pathways. Centered on hydrometallurgy, it summarizes the key unit operations and process combinations for SURPB within this pathway, compares their adaptability and constraints across different application scenarios, and evaluates the engineering feasibility and boundaries of the hydrometallurgical route in supporting SURPB. Hydrometallurgy is inherently conducive to closed-loop recycling because it generates less waste and permits regeneration of high-value materials directly for battery manufacturing. These advantages not only enable high-value material regeneration for SURPB but also strengthen the sustainability and circularity of the entire battery supply chain [24]. The comparison overview of this method is shown in the Table 3.

Since 2019, Northern Europe has taken the lead in promoting hydrometallurgy to the engineering stage through cross-site collaboration. The system represented by Fortum in Finland has completed SURPB disassembly and mechanical pretreatment in Norway and Finland. In the final stage, lithium salts are recovered through carbonation precipitation and re-dissolution crystallization [25]. In 2020, the United States established hydrometallurgical refining and cathode material manufacturing units within the same industrial park. This system processes mixed feedstocks from consumer and SURPB through batch leaching and separation, directly feeding battery-grade lithium carbonate and nickel-cobalt precursors into the cathode production line, thereby significantly reducing the recycling cycle of regenerated materials [26]. During the same period, another significant approach in North America was Li-Cycle's distributed feedstock collection and centralized refining structure [26].

From 2020 to 2023, China's practices are characterized by the integration of high recovery rates with large-scale stable operations. A mature wet refining chain has been established for ternary and some lithium iron phosphate feedstocks. The lithium end flexibly switches between carbonate and phosphate routes based on downstream demand, while optimizing carbonation kinetics by controlling the salinity and pH of the mother liquor to stabilize particle grades. In East and Central China, GEM has established flexible lines designed for the parallel processing of ternary and lithium iron phosphate materials. Even with the rising proportion of lithium iron phosphate, these lines maintain high lithium recovery rates. Additionally, the process integrates wastewater reuse and salt management as critical units to meet operational constraints [27].

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Metals are transferred into solution via leaching with acids, complexants, or reductants, and are subsequently separated by solvent extraction, ion exchange, precipitation, or electrodeposition. For layered NMC in H_2SO_4–H_2O_2 media, the formula is as follows.

$$L_iMO_2 + (2+\delta)H^+ + \frac{\delta}{2}H_2O_2 \rightarrow L_i{}^+ + M^{2+} + (1+\delta)H_2O \quad (3)$$

Here, M represents Ni/Co/Mn, and δ reflects the reduction equivalent of the high valence state. while leaching kinetics are often modeled by the shrinking-core model (SCM), the reaction control formulation is as Eq.4 and the diffusion control formulation is as Eq.5.

$$1-(1-x)^{\frac{1}{3}} = k_r t \quad (4)$$

$$1-\frac{2}{3}x-(1-x)^{\frac{2}{3}} = k_d t \quad (5)$$

In these equations, x denotes the leaching fraction. For the subsequent separation stage, the cascade extraction of Ni/Co/Mn is governed by the distribution coefficient (D) and the separation factor ($\beta_{i/j}$).

$$D = C_{org}/C_{aq} \quad (6)$$

$$\beta_{i/j} = D_i/D_j \quad (7)$$

Table 3. Overview of secondary utilization hydrometallurgy methods for power batteries

Application Regions	Principles	Advantages	Disadvantages
Europe [25]	After mechanical pretreatment, acid leaching and lithium carbonate precipitation are carried out, and finally recrystallization is performed.	1. High recovery rate; 2. Well-engineered process with high maturity	1. High operating costs; 2. Require strict water quality management and mother liquor regulation.
The United States [26]	Complete the hydrometallurgical process and cathode material preparation within the same area.	1. Short recycling cycle; 2. High closed-loop degree; 3. Suitable for various mixed retired power batteries materials.	1. High investment in equipment and strict process control is required; 2. the complex composition of retired power batteries will increase the complexity of the extraction section.
China [27]	After acid leaching of the feedstock, extraction is carried out, followed by final precipitation.	1. High industrial maturity; 2. High and stable recovery rate; 3. Advanced wastewater reuse and salt management.	1. Impurities must be strictly controlled to prevent accumulation; 2. High requirements are placed on operational stability and mother liquor management.

Furthermore, the precipitation process is thermodynamically controlled by the solubility product to mitigate co-precipitation risks.

2.3. Direct regeneration

From 2018 to 2020, the academic community first established the theoretical foundation for direct regeneration. Multiple studies on layered oxides demonstrated that without converting cathode materials into metal salts, but maintaining their morphology at the SURPB, significant recovery of specific capacity, rate performance, and cycling stability could be achieved through lithium supplementation, defect repair, and controlled SURPB [28]. A notable work in this field employed

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solution-mediated lithium supplementation combined with short-time rapid annealing. This approach restored the capacity and coulombic efficiency of high-nickel ternary and lithium cobalt oxide to levels close to those of new materials. Additionally, electrochemical impedance spectroscopy revealed a significant decrease in interfacial charge transfer impedance.

From 2020 to 2021, the United States carried out a series of amplification and manufacturability evaluations on direct regeneration. The relevant technical route was based on the principle of maintaining the original particle size distribution and SURPB, introducing pyrolysis to remove binders and mild surface cleaning, followed by lithium replenishment at low temperatures, and then promoting lattice reconstruction through minute-level heat treatment [29].

From 2021 to 2024, China has been a hub for advancements in this field, with Tsinghua University and enterprises like CATL and BYD integrating direct regeneration strategies into the broader framework of SURPB. These researchers have systematically explored the direct regeneration system to satisfy the stringent performance requirements of secondary utilization. Specifically, for high-nickel ternary and LCO materials, advancements have focused on lithium replenishment and surface repair strategies. Furthermore, these innovations are backed by rigorous safety verification, ranging from laboratory testing to industrial scale-up. Consequently, this comprehensive evaluation provides the technical assurance necessary for the safe deployment of SURPB products [30].

From 2022 to 2024, the North American region entered a period of engineering exploration from pilot-scale to semi-pilot-scale, successively building demonstration lines centered on low-temperature plasma activation and mild lithium supplementation. The target materials expanded from production scraps to SURPB. Tests showed that the reversible capacity of high-nickel ternary materials could be restored to a range comparable to the original specifications without destroying the original SURPB, and the fluctuations in particle size and phase composition were controllable in consecutive batches [31].

From 2024 to 2025, Japan has concentrated on advancing surface treatment technologies to enhance the interfacial stability of high-nickel cathode materials [32]. A notable example involves plasma-activation strategies, which modify surface chemistry to suppress parasitic reactions, thereby significant improving long-term cycling. South Korea places greater emphasis on system-level electrode reconstruction, particularly for next-generation solid-state battery architectures. Research focuses on establishing continuous, scalable regeneration workflows that couple material-level recovery with electrode re-fabrication and full cell-level validation. This end-to-end framework highlights Korea's strategy of integrating process scalability with the practical requirements of commercial solid-state battery manufacturing. The comparison overview of this method is shown in the Table 4.

Direct routes preserve particle and secondary structures and restore functionality by re-lithiation, defect healing and controlled recrystallization. To evaluate the hydrogen evolution activity of the model catalysts, the Gibbs free energy for atomic hydrogen adsorption (ΔG_H^*) was calculated at equilibrium using following equation:

$$\Delta G_H^* = \Delta E + \Delta ZPE - T\Delta S + \Delta G_P H \tag{8}$$

where ΔE is the reaction energy change obtained from DFT calculation, ΔZPE is the difference of zero-point energy between adsorbed H^* and the gas phase hydrogen, ΔS is the change of entropy from the gas phase hydrogen to the adsorbed H^*. Using harmonic approximation calculations, ZPE and S are derived from vibrational frequencies of adsorbates and contributions from the basal plane are neglected. $\Delta G_P H$ is the correction of the free energy of H ions by the concentration dependence of the entropy:

$$\Delta G_P H = k_B T \times pH \times \ln 10 \tag{9}$$

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where k_B is the Boltzmann constant. pH = 13.8 and T = 298.15 K was used in this work.

The adsorption energy Eads is given by the following equation:

$$E_{ads} = E(X^*/slab) - E(slab) - E(X) \quad (10)$$

where $E(X^*/slab)$, $E(slab)$ and $E(X)$ are the total energies of X species adsorption on the slab, the clean slab and the X species. The formation energy (E_f) is given by the following equation:

$$E_f = \frac{\left(E_0 + nE(OH) - E(slab)\right)}{n} \quad (11)$$

Table 4. Overview of secondary utilization direct regeneration methods for power batteries

Application Regions	Principles	Advantages	Disadvantages
The United States [29]	The binder is removed by thermal treatment, followed by low-temperature lithium supplementation, and finally lattice reconstruction through annealing.	1. Significantly restore specific capacity, rate performance and cycle stability; 2. Suitable for high-nickel retired power batteries.	1. It is sensitive to the impurities; 2. There are still challenges to process stability when scaling up on a large scale.
China [31]	Multiple lithium supplementation media and surface phase repair strategies	1. The system is applicable to multiple types of materials (NMC, LFP); 2. It can significantly reduce the interfacial charge transfer impedance on high-nickel retired power batteries; 3. It has a complete evaluation path from the laboratory to large-scale production.	1. The control requirements for impurities are extremely high; 2. Large-scale commercial continuous production lines are still lacking.
Japan [32]	The plasma surface activation is used to suppress side reactions and enhance long-term cycling stability.	1. It can significantly improve surface side reactions and reduce the rate of impedance growth.	1. It mainly focuses on surface treatment of retired power batteries and has limited contribution to the overall structural reconstruction; 2. Its lithium replenishment and phase repair capabilities are relatively weak.
South Korea	Emphasizing system-level retired power batteries electrode reconstruction.	1. It is closely integrated with the solid-state battery industry chain; 2. It has engineering continuity; 3. It is suitable for the next-generation system.	1. It has limited compatibility with existing retired power batteries; 2. The technical path is still in its early stages of development;

Where E_0, $E(OH)$ and $E(slab)$ are the total energies of the slab containing vacancies, single hydroxyl and the clean slab, respectively, n is the number of vacancies.

2.4. Electro-regeneration cycling

In 2020, the United States conducted research on SURPB. To be specific, the manufacturability of the electrochemical lithium replenishment cycle on the material side. It adopted quantitative lithium intercalation combined with short-time thermal treatment to restore the stoichiometry and lattice integrity of layered cathodes, and verified the simultaneous improvement of capacity, rate, and impedance at both the half-cell and full-cell levels [32]. In 2021, a research team in the Illinois region of the United States made a key breakthrough in the collaborative design of interfaces and electrolytes. For the first time, it achieved selective electro-deposition of cobalt and nickel within a controlled potential window, demonstrating that high-selectivity separation of multi-metal systems could be accomplished through electrochemical processes without significantly increasing reagent consumption [32].

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From 2023 to 2024, studies in Europe and North America advanced electro-generated acid production, in-situ anode oxidant generation, cathode-selective electrodeposition, and hybrid schemes integrating electrodialysis and membrane separation. These electrochemical innovations directly support SURPB by providing cleaner and more controllable recovery routes for retired batteries. Recent reviews further identify current efficiency and unit energy consumption as key optimization variables for SURPB applications. Under moderate grid carbon intensity and electricity cost, such electrochemical units can markedly reduce inorganic acid and organic extractant usage while extending mother-liquor closed-loop cycles, improving both sustainability and process viability [33].

In 2024, Chinese university teams proposed a selective electrochemical lithium extraction scheme of prussian blue analogues for SURPB. In acidic or weakly acidic environments, lithium is preferentially dissolved into the solution through direct anode reactions or indirectly generated oxidants. Then, lithium salts are obtained through carbonation or solid-phase capture, thereby avoiding large-scale dissolution of iron and phosphorus and significantly reducing the subsequent separation burden [34].

From 2024 to 2025, the United States advanced two representative paths in demonstration lines and early commercialization. One enterprise of SURPB, with electrolytic extraction modules at its core, aimed to achieve targeted electro-deposition and metal transfer of black powder and nickel-cobalt intermediate solutions at room temperature or medium temperature; another enterprise of SURPB, centered on electrochemical metallurgy, constructed a closed-loop process, using electrolysis to replace high-temperature furnaces or high-dose chemicals. The main formulation is as follows (Eq.12-15) [35].

$$n_{L_i} = \frac{1}{F}\int_0^t I dt \tag{12}$$

Where I is current; t is time; n_{L_i} is moles of intercalated lithium; F is Faraday constant.

The electrode thermodynamics and kinetics follow the Nernst relation (Eq.13) and the Butler–Volmer expression (Eq.14), respectively, with the overpotential defined in Eq.15. Selective cobalt–nickel separation by electrodeposition can be realized by coordinating electrolyte composition with interfacial design under an appropriate potential window, as shown in recent studies [35].

$$E_{eq} = E^0 - \frac{RT}{nF}\ln Q \tag{13}$$

$$i = i_0\left[exp\left(\frac{\alpha_a F\eta}{RT}\right) - exp\left(-\frac{\alpha_c F\eta}{RT}\right)\right] \tag{14}$$

$$\eta = E - E_{eq} \tag{15}$$

In Eq.13, Eq.14 and Eq.15, E_{eq} represents equilibrium potential; E^0 is standard potential; R is gas constant; T is temperature; n is electrons transferred; Q is reaction quotient; i is current density; i_0 is exchange current density; α_a, α_c are transfer coefficients; η is overpotential; E is applied potential.

Table 5. Overview of secondary utilization electro-regeneration methods for power batteries

Application Regions	Principles	Advantages	Disadvantages
The United States [32,35]	Accurate lithium intercalation is achieved through electrochemical drive, followed by short-time heating to restore lattice integrity.	1. It can achieve precise lithium supplementation of retired power batteries; 2. The system is greener and uses less chemical reagents.	1. Sensitive to working voltage; 2. Uneven lithium supplementation may lead to interfacial side reactions; 3. Applicability is affected by the degree of retired power batteries aging.

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Table 5. (continued)

Europe [33]	Combining electro-generated acid, selective electro-deposition and electrodialysis	1. Significantly reduce the use of inorganic acids and organic extractants; 2. increase the number of closed-loop cycles of mother liquor; 3. be greener and lower in carbon emissions.	1. The process is complex and requires high-precision electrochemical control; 2. the equipment investment is large; 3. It is highly sensitive to the operating conditions of multi-metal retired power batteries systems.
China [35]	Under weakly acidic or acidic conditions, lithium is preferentially dissolved into the solution, and then lithium salts are obtained through carbonation or solid-phase capture.	1. Avoid large-scale dissolution of Fe 2. Reduce the burden of subsequent separation; 3. Retain the retired power batteries structure; 4. Be greener and use less chemicals.	1. Its compatibility with ternary retired power batteries materials is still limited; 2. It is necessary to strictly control electrode corrosion and side reactions.

The comparison overview of this method is shown in the Table 5.

3. Conclusion

Based on the recovery mechanism and process maturity, the existing approaches are categorized into conventional metallurgical routes, encompassing pyrometallurgy and hydrometallurgy, and emerging green regeneration routes, represented by direct regeneration and electro-regenerative cycling, and the review work of the technical characteristics, advantages, and limitations for these pathways is conducted separately.

Firstly, the application status of mature and emerging approaches is reviewed and compared. The applied approaches for industrial-scale recovery mainly include pyrometallurgy and hydrometallurgy. The former is robust in handling mixed-chemistry feedstocks but suffers from high energy consumption and significant lithium loss. The latter achieves high metal recovery rates and purity suitable for closed-loop systems, but it heavily relies on chemical reagents, leading to substantial wastewater and environmental burdens. In contrast, direct regeneration and electro-regenerative cycling are explored to address these environmental and cost challenges. Direct regeneration offers a low-carbon advantage by restoring the crystal structure without breaking down materials, yet it is strictly limited by feedstock cleanliness and consistency. Similarly, electro-regenerative cycling significantly reduces reagent consumption and secondary pollution through in-situ oxidant generation, but its engineering scalability and energy efficiency still need further optimization.

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