



How research & innovation ramp up Li-ion Battery recycling

Pietro Cattaneo^{a,c,1,*}, Lorenzo De Vita^{a,c,1}, Camilla Zanoni^{a,c,1}, Davide Ruzza^{b,1,**},
 Mariacristina Colantuono^{b,1}, Diana Di Cintio^{b,1}, Carmen Cavallo^b, Mark Copley^b,
 Eliana Quartarone^{a,c}

^a Department of Chemistry and R²BATT, University of Pavia, Via T. Taramelli 12, Pavia, 27100, PV, Italy

^b FAAM, FIB S.p.A., S.S. Appia 7 bis, Teverola, 81030, CE, Italy

^c INSTM Consortium, Via Giusti 9, 50121, Firenze, FI, Italy

ABSTRACT

The rapid growth of Li-ion Batteries (LIBs), especially in the automotive sector, raises urgent concerns regarding End-of-Life (EoL) management and the secure supply of Critical Raw Materials (CRMs), including lithium, cobalt, and nickel. To mitigate risks of resource scarcity and environmental impact, sustainable collection and recycling practices are essential to support the transition toward a circular economy, enabling the recovery of both metallic and non-metallic components. A zero-waste approach to LIB recycling is therefore emerging as a key priority. Industrial innovation and academic research are deeply interconnected in this field. Industry depends on scientific discoveries to scale up efficient recycling technologies, while academia is driven by challenges arising from industrial practice and regulatory demands. This reciprocal relationship accelerates the development of advanced recycling strategies capable of addressing technical and economic barriers. This review provides an overview of LIB recycling in Europe, focusing on the evolving legislative framework designed to regulate the proper management of spent batteries and promote the recovery of CRMs. Current industrial practices are discussed with particular attention to their limitations, alongside emerging academic solutions that could redefine the efficiency, sustainability, and economic viability of LIB recycling.

1. Introduction

It is now well established that in recent years the demand for Li-Ion Batteries (LIB) has increased significantly and with it the amount of waste generated, both from battery manufacturing and from End-of-Life (EoL) batteries. The rise in CO₂ emissions, the global warming, and the consequences of climate change have prompted European countries to take action toward achieving transport and mobility electrification across the continent. This is a long and demanding process, yet it is extremely necessary and requires careful planning and well-structured legislation to regulate every stage of the process [1–6].

Today, LIBs are employed in a wide range of applications, from the automotive sector to consumer electronics. To keep up with the high standards required, they make extensive use of elements classified as critical by the European Commission (e.g., Li, Ni, Co, Mn, P, natural graphite, Cu and Al) [7,8]. These materials are closely tied to a country's economy and, currently, Europe is entirely dependent on foreign countries for their supply; to reduce the environmental impact and the dependency on their imports, the European Union (EU) has begun to

focus on LIB recycling.

1.1. Regulatory framework and EU legislation

The establishment of a robust regulatory framework and coherent legislation constitutes a fundamental prerequisite for achieving the objectives set by the EU. The EU has consistently demonstrated a strong commitment to sustainability, circular economy, and the development of safe battery technologies. In this context, the European Commission adopted, in 2018, the Strategic Action Plan on Batteries, which outlines a comprehensive set of regulatory and non-regulatory measures aimed at supporting all segments of the battery value chain, including the recycling of LIBs [3,5].

Why is it important to have legislation that supports recycling regulations? According to studies conducted by the Centre for European Policy Studies, by 2030 the value of recycled materials, including Co, Al, Ni, and Li, is expected to grow up to €555 million and subsequently increasing to €2.6 billion by 2040. It has also been estimated that recycled materials will be used in 1.3–2.4 million electric vehicles (EVs)

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* Corresponding author. Department of Chemistry and R²BATT, University of Pavia, Via T. Taramelli 12, Pavia, 27100, PV, Italy.

** Corresponding author.

E-mail addresses: pietro.cattaneo01@universitadipavia.it (P. Cattaneo), davide.ruzza@faam.com (D. Ruzza).

¹ These authors contributed equally to the work.

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by 2030 and 15 million by 2040 [6]. The impact of this market is expected to lead to an increase in employment, across the battery supply chain, since battery recycling processes are estimated to generate 15 additional jobs per kt of battery waste, culminating in 15.000 new positions by 2040 (roughly 80 % allocated to collection and dismantling activities and 20 % to recycling operations) [6,7].

1.1.1. The new European Battery Regulation

The new European Battery Regulation 2023/1542 (in force since February 2024) outlines the rules to be followed to achieve an ecological transition in Europe regarding battery waste recycling and management, with a particular focus on critical materials. The Battery Regulation transforms the logistics of battery waste from a voluntary, often unprofitable, activity into a legal obligation. It prohibits the landfilling of waste batteries and requires that economic operators, which include manufacturers and distributors, provide end-users with free collection services [4]. The regulation forces the creation of a comprehensive collection infrastructure and emphasizes key aspects such as environmental sustainability, safety, traceability, responsibilities, and recovery and recycling goals [3,5,9].

Also, the Regulation dedicates a specific section to the obligations of producers, who are responsible both financially and operationally for the management of EoL-LIBs. Extended Producer Responsibility (EPR) is a policy mechanism designed to operationalize EoL responsibility by placing the financial and/or physical burden of post-consumer product management directly on producers [4]. This approach shifts the responsibility “upstream” to the producers, encouraging them to design products that are more durable, repairable, and recyclable, thereby reducing waste and environmental impact. By internalizing the costs of disposal into the production process, EPR schemes incentivize a fundamental re-evaluation of product design and manufacturing from the outset [10]. Also the regulation establishes limits for Hg, Cd, and Pb content in batteries (5, 20, 40 ppm on the battery's total weight, respectively) [4].

The EU has been a leader in implementing EPR schemes through landmark legislation (although the approach differs from that of the Battery Regulation). The Waste Electrical and Electronic Equipment (WEEE) Directive (entered into force in 2003 and amended in 2012) and the End-of-Life Vehicles (ELV) Directive (entered into force on September 2000) require producers to finance the collection, treatment, and recycling of components, with mandatory recycling quotas expressed as overall recovery/recycling rates by weight (65 % of the average weight of electrical and electronic equipment placed on the market in the previous three years for the WEEE and 85 % of the collected wastes for ELV), rather than specific elemental recovery targets [11–13]. They also include restrictions, limiting the presence of Cd, Hg, Pb, polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs) in new electrical and electronic equipment, and Pb and Hg in new vehicles. Between 2012 and 2020, the EU collection rate of WEEE increased from 38 % to 46 % as a result of the Directive, though this value remained below the target specified by the document [12,13]. However, beyond collection, the Directive has also stimulated technological innovations in e-waste treatment, material recovery, and closed-loop recycling processes, particularly for metals such as Cu, Au, and critical materials. These directives and regulations exemplify how policy can drive industry-wide change by creating a legal framework for accountability and sustainability [13,14].

While EPR schemes provide the regulatory incentive for a circular economy, traceability serves as the essential data engine that makes it all possible. Beyond its traditional role in ensuring product safety and mitigating risk, traceability is now a fundamental enabler of circularity [15]. For this reason, producers will be required to start compiling a Digital Battery Passport (DBP, effective from February 2027), a record of the complete lifecycle of a battery including detailed specifications of all constituent materials, providing critical data to all supply chain stakeholders, facilitating efficient management, recycling, and material

recovery of batteries.

A major logistical challenge in LIB recycling is their classification as Class 9 hazardous materials, which significantly increases transportation costs due to the need for specialized containers and safety protocols. The DBP will provide the necessary data for efficient sorting and logistics, helping to mitigate safety risks during transport and ensuring compliance with the stringent recycled content mandates.

The analyses of historical data also allow for sustainability reporting and continuous improvement; in this sense, traceability is not merely a “nice-to-have” feature but a fundamental prerequisite for a functional circular economy. The challenge is not a lack of technical capacity since the technology for digital identifiers and data capture exists; the true hurdle is a systemic failure of collaboration and data integration across the supply chain. Critical information is often scattered across multiple platforms and disconnected systems, preventing businesses from forming a complete view of a product's journey. This disconnect underscores a central problem: the technology is ready, but the governance and operational ecosystems required to support it are not [16].

1.1.2. Critical Raw Materials and strategic autonomy

A huge issue regarding the growth of battery market is posed by supply shortages that can have implications on both economic and geopolitical level. In 2011, the European Commission made a list of Critical Raw Materials (CRMs), defined as ‘raw materials (...) which most consumer countries are dependent on importing, and whose supply is dominated by one or a few producers’ [8,17].

In 2023, following the fifth update of this list (bringing the total number of CRMs to 37) the European Commission adopted the CRM Act (in force since May 2024), which establishes specific targets for the EU: 10 %, 40 % and 15 % of the annual consumed CRMs should be, respectively, extracted, processed and recycled in Europe and, in order to reduce dependence on single external suppliers and mitigate supply shortages due to geopolitical events, the CRM Act sets a limit of 65 % for CRM imports from any single non-EU country [18–20]. In fact, geopolitical instabilities and environmental and ethical issues worldwide are favouring the soaring of the price of CRMs for LIBs manufacturing since most of them are extracted and refined by few countries (Table 1) [21–26].

The new EU batteries regulation clearly put into evidence the need to recycle CRMs in a safe and sustainable way; additionally, the regulation covers the contents of recycled materials requested in manufacturing (16 % for Co and Cu, 6 % for Li and Ni by 2031), the recycling efficiency targets (70 % for LIBs by 2030) and the material recovery targets (95 % for Co, Cu, Ni and 80 % for Li by 2031) [4]. According to the market analyst, a combined total of about 180 kt of Li, Co, Ni, and Mn could be recovered by 2030 by LIBs and re-introduced in the production chain, partially making up for raw materials shortages [30]; some of the CRMs (Co, Al and Cu) are already recycled with a satisfying End-of-Life Recycling Input Rate (EoL-RIR, reported in Table 1), which is the

Table 1

LIBs main CRMs mining and refining countries (average produced quantities are expressed as % of the global extracted or refined materials in the period 2021–2023)[27–29]; EoL-RIR are referred to the year 2023 [21].

CRM	Main Miners [% of global]	Main Refiners [% of global]	EoL-RIR [%]
Lithium	Australia (52 %) Chile (22 %)	China (58 %) Chile (29 %)	0
Cobalt	DRC (63 %)	China (60 %)	22
Nickel	Indonesia (33 %)	China (35 %)	16
Manganese	South Africa (29 %)	China (55 %)	9
Aluminium	Australia (28 %)	China (59 %)	32
Natural Graphite	China (67 %)	n.a.	3
Copper	Chile (28 %)	China (40 %)	55

n.a. = not available.

percentage of overall demand that can be satisfied through secondary raw materials, considering that (as of 2018) an EoL-RIR of 30 % was considered high [31,32]. Battery recycling would also have a substantial benign environmental impact on the reduction of mining activities, causing a subsequent projected abatement of CO₂ emission by 1 Mt by 2040 as well as the reduction of labour under potentially unsafe conditions.

1.1.3. Global perspectives on LIBs recycling

In the previous paragraphs, we extensively discussed Europe's approach to LIB recycling; here, we briefly examine how other major global powers are addressing this challenge. The United States does not yet have a regulatory framework comparable to the European Battery Regulation, but awareness of the vulnerability of CRMs supply chains is growing. To address this, strategic programs and initiatives have been established, such as the Lithium-Ion Battery Recycling Prize organized by the U.S. Department of Energy or the launch of the ReCell battery recycling Research & Development (R&D) centre. These programs aim at promoting sustainable material recovery from batteries and to develop direct recycling processes, ultimately reducing dependence on foreign suppliers [33,34].

China is the global leader in the battery sector, dominating both manufacturing and raw material refining. The Chinese government has implemented an EPR framework, requiring manufacturers to ensure product traceability and to establish comprehensive recycling systems [35].

The global mobilization in this sector highlights the critical importance of achieving a circular economy for LIBs. To realize this goal, effective policies and regulatory frameworks are essential, guiding industrial practices toward sustainable and efficient recycling approaches. The combined international efforts underscore that technological capacity alone is insufficient; coordinated strategies and policy-driven incentives are key to creating a truly sustainable LIB recycling ecosystem.

1.2. Scheme of a Li-ion battery

To complete the context in which this work is set, an overview on what is a LIB is needed. LIBs operation relies on the reversible Li⁺ intercalation/deintercalation in two host materials (anode and cathode), between which Li⁺ migrates back and forth through a separator soaked with an electrolyte. The optimization of the performance of the LIBs has been the focus for R&D on batteries over the last decades, leading to a plethora of new materials, geometries, sizes and compositions that can make recycling difficult for a potential company, which must carefully assess what type of battery has been collected, and act accordingly. An examination of the internal scheme of a LIB and the main material that can be found therein (Fig. 1) is briefly discussed hereafter.

1.2.1. Cathode

Within a LIB, the cathodes account for about 40 wt% of the cell mass and 65–70 % of its price; it consists of a composite material cast on an Al foil acting as the current collector. The cathode composite material is a mixture of 88–95 wt% cathode active material (CAM), 2–4 wt% polymeric binder (mainly Polyvinylidene Fluoride, PVDF) and 2–3 wt% conductive carbon black filler (CB, to enhance electrical conductivity) [36].

The CAM is a material that can store Li⁺ ions; several CAM families can be used and they differ in terms of composition and crystal structure that determine their performance [37]; the choice of the chemistry of a LIB represents a compromise between cost, energy density, safety, and lifetime. The most widespread CAMs on the market nowadays (reported in Table 2) are part of one of three main families with different crystal structures: layered, spinel-like and olivine-like [38–40].

The polymeric binder must have strong affinity for the CAM, the CB and the Al foil in order to create a conductive matrix around the particles and to keep the material attached to the collector [43]. PVDF is usually used in cathodes for several reasons, including hydrophobicity, electrochemical and chemical stabilities and compatibility with the solvents used in cathode manufacturing (chiefly, N-Methyl-2-Pyrrolidone, NMP)

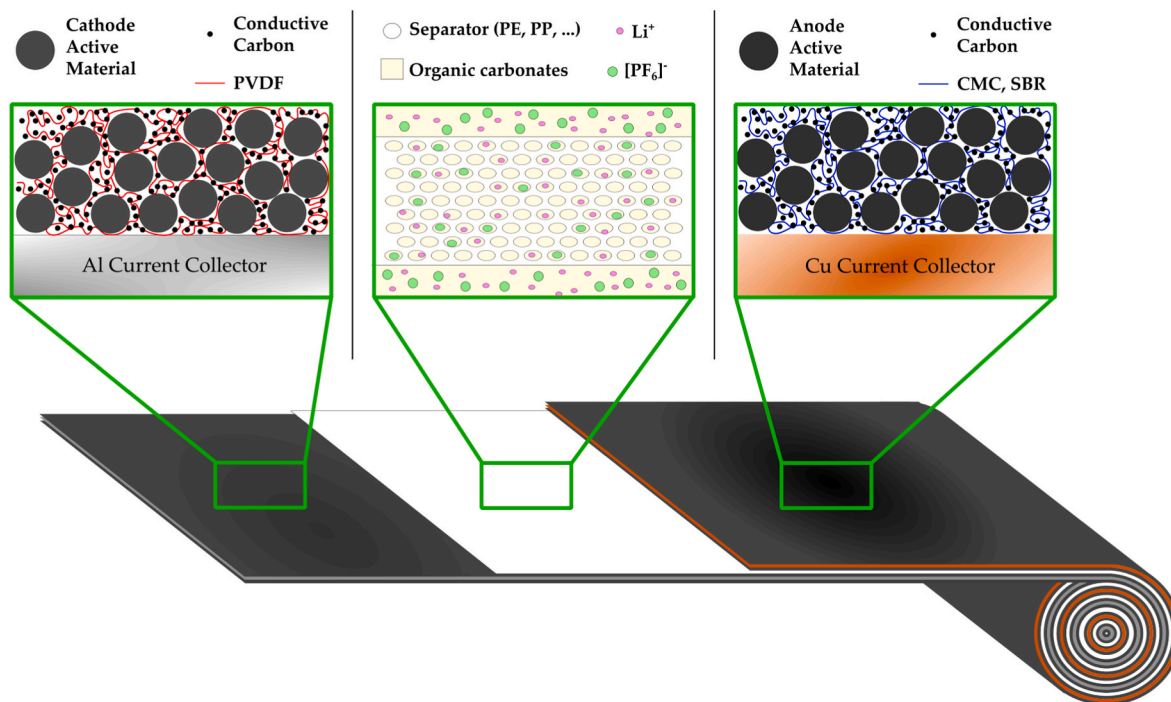


Fig. 1. Scheme of a cylindrical LIB jelly roll. From left to right: cathode (composed by CAM and C held together by PVDF and cast on an Al current collector); separator (constituted by a microporous membrane of PE or PP imbibed with an electrolyte solution composed by LiPF₆ dissolved in an organic carbonate mixture); anode (composed by AAM and C held together by SBR, CMC or SBR/CMC and cast on a Cu current collector).

Table 2
Main chemistries on the market, their share and typical use [41,42].

Chemistry	Formula	Structure	Market share	Use
LCO	LiCoO ₂	Layered	Dumped	Consumable electronics
LMO	LiMn ₂ O ₄	Spinel-like	Small	Power Tools, E-bikes
LFP	LiFePO ₄	Olivine-like	Growing	E-bikes, EVs, power tools
NCA	LiNi _x Co _y Al _z O ₂	Layered	Steady	Tesla EVs
NMC	LiNi _x Mn _y Co _z O ₂	Layered	Main force	Consumable electronics, EVs

[44].

1.2.2. Anode

Anode account for about 30 wt% of the cell mass and, similarly to the cathode, consist of a composite material made of: (i) 95–98 wt% anode active material (AAM); (ii) 1–3 wt% polymeric binder; (iii) 1–2 wt% conductive carbon. The composite material is cast on a Cu foil acting as the current collector.

Concerning the AAM, anodes usually rely on graphite that can intercalate Li⁺ ions between layers. As for the binder, the use of Carboxymethyl Cellulose (CMC) and Styrene-Butadiene Rubber (SBR) or a mixture of them is preferred mainly for: (i) processability in water; (ii) graphite affinity, as the carboxyl groups of CMC promote strong bonding with graphite particles; (iii) higher elasticity, as graphite tend to expand/contract more than CAMs when Li intercalates between layers [45,46].

1.2.3. Electrolyte

The electrolyte is a solution acting as a medium for Li⁺ ions to move back and forth between the electrodes, thus it must exhibit high ionic conductivity to Li⁺ while acting as an electronic insulator. It critically influences battery performance by promoting ion movement, reducing internal resistance and enabling faster charging and discharging. Also, it significantly impacts battery safety and longevity as Li dendrites, Solid Electrolyte Interphase (SEI) and Cathode Electrolyte Interphase (CEI) formations are closely tied to the electrolyte behaviour. Li dendrites are prone to form on the surface of the anode when the ionic conductivity of the electrolyte is low; they can pierce the separator causing a short-circuit, thus they must be avoided. SEI and CEI are formed, respectively, by electrolyte reduction at the anode and electrolyte oxidation at the cathode and they prevent the continuous consumption of the electrolyte while allowing for Li transport at the anode and avoiding metal dissolution at the cathode; their formation is physiological and can be favoured or disadvantaged by modifying the electrolyte in order to obtain the desired characteristics.

In most commercial cells, the electrolyte consists of a highly soluble Li salt (e.g., LiPF₆, LiBF₄, LiClO₄, Lithium bis(trifluoromethanesulfonyl) imide LiTFSI, ...) dissolved in a mixture of organic carbonates (ethylene carbonate EC, diethyl carbonate DEC, dimethyl carbonate DMC, ...). The presence of organic volatile carbonates can cause pressure build-ups in case of malfunction, leading to explosions and fires; to mitigate these risks, alternative solutions (e.g., solid electrolytes) are being actively explored [47].

1.2.4. Separator

The separator is a thin membrane that prevents the direct contact between the electrodes; it has to be thermally and chemically stable to maintain its mechanical properties within the temperature range in which cells operate and with the chemicals therein [48]. To this aim, a microporous separator made of polyethylene (PE), polypropylene (PP) or a composite of both, is often used since they offer high chemical mechanical and thermal stabilities as well as a great ability to form

porous structure [49]. Separator porosity has to be carefully tuned: if too high, it can cause a mechanical weakening of the separator; if too low, it can cause a poor wetting of the separator and insufficient ionic conductivity [50].

2. Industrial overview on LIB recycling: current practices

The global transition to a clean energy future and the rapid growth of e-mobility are fundamentally reliant on LIBs; as the number of EVs and energy storage systems (ESSs) increases exponentially, so does the impending wave of EoL-LIBs, whose management is not only an environmental obligation but a strategic imperative.

2.1. Major and emerging industrial players in Europe

The European LIBs recycling ecosystem is characterized by a mix of established industrial and innovative startups, all supported by a network of research institutions. This landscape is currently experiencing a massive surge in planned capacity, a direct response to a strategic need for a circular value chain.

Umicore is a well-established leader in LIB recycling, widely recognized as one of the early pioneers in the industry. Its long-running facility in Hoboken (Belgium) operates at an annual capacity of about 7 kt of EoL batteries and production scrap—equivalent to roughly 35000 EV battery packs [51]. This plant is notable not only for its scale but also for its ability to process mixed chemistries safely and efficiently, giving Umicore valuable technological and operational experience. Over the years, this has helped the company build strong relationships with automakers and battery producers, positioning it as a key player as global demand for recycling capacity continues to grow.

Among the emerging leaders, established in 2023, Fortum Battery Recycling is offering a comprehensive *end-to-end* solution, from initial waste collection and pre-treatment to the final refining of materials. The company utilizes a combination of low-CO₂ mechanical and hydrometallurgical processes to achieve a recovery rate of up to 95 % for valuable metals [52]. Its facility in Harjavalta (Finland) is noted as Europe's largest closed-loop hydrometallurgical plant, currently processing 3 kt of black mass per year, with an announced plan for a significant expansion to 28 kt annually. In addition, its mechanical plant in Ikaalinen (Finland) can recycle approximately 3 kt of used batteries per year, an equivalent of about 10000 EV batteries [53].

SNAM, originally focused on nickel-cadmium and other industrial batteries, has expanded its capabilities to include LIBs as electric mobility and portable electronics have grown. SNAM operates collection and recycling facilities in France and works closely with automotive original equipment manufacturers (OEMs) and energy-storage providers. Its processes focus on safe dismantling, material recovery, and compliance with European environmental standards, making SNAM a reliable and recognized actor in the evolving LIB recycling value chain.

Other significant players contributing to the ecosystem include: i) Stena Recycling, specialized in industrial-scale recycling and reuse; ii) Veolia, which has entered a strategic partnership with Renault to manage EoL-LIBs; iii) Ecobat that has a notable presence with facilities in Europe and a focus on recovering all materials, including those from low-value LFP chemistries [54–56].

The market is also being reshaped by a new wave of innovative startups. Cylib, a groundbreaking company born out of RWTH Aachen University in 2022, has rapidly gained prominence by developing a proprietary holistic and water-based technology designed to recover all elements within a LIB, claiming a 90 % recycling efficiency and an 80 % reduced carbon footprint compared to traditional raw material extraction. With over €90 million in funding for its first-of-a-kind (FOAK) industrial plant in Dormagen (Germany), Cylib exemplifies the rapid scaling potential of research-backed innovators [57].

While projections from institutions like Fraunhofer-Institut für System-und Innovationsforschung (ISI) indicate that planned recycling

capacities will exceed the supply of EoL-LIBs in the near-term, this is no sign of market failure [58]. Instead, it reflects a calculated race to capture market share and secure a dominant position in a newly born but rapidly growing industry. Apart from the already mentioned EU Battery Regulation, the market's dynamism is mainly stimulated by the proliferation of new gigafactories across Europe, which generate a significant volume of valuable production scrap that can be recycled in the short term. Companies are responding by clustering their recycling facilities near these production hubs to create short scrap loops, thereby de-risking their investments and building the necessary infrastructure ahead of the anticipated surge in EoL-LIBs after 2030 [59].

Beyond Europe, significant LIB recycling activity is also advancing globally. In the United States, companies such as Redwood Materials, Li-Cycle, and Ascend Elements are rapidly scaling hydrometallurgical and closed-loop processes supported by strong federal incentives. China remains the world's largest and most mature LIB recycling market, driven by extensive industrial capacity and strict producer-responsibility regulations, with major players including GEM, Brunp (CATL), and Huayou. Efforts are also emerging in other regions—such as South Korea (LG Energy Solution, SungEel), Japan (JX Nippon, reflecting a broad global push to establish circular supply chains for critical battery materials).

2.2. Existing commercial recycling technologies

The commercial landscape of LIBs recycling in Europe is defined by the technical and economic characteristics of two primary processes: pyrometallurgy and hydrometallurgy (Fig. 2). While each has a distinct role, the industry is increasingly moving towards more advanced and combined approaches to meet rising demand and stringent environmental targets.

2.2.1. Efficiency and economic viability

The choice of the recycling technology to be exploited has profound implications on recovered material quality, environmental impact, and economic viability.

Pyrometallurgical (Fig. 2a) processes use high temperatures to recover and purify valuable metals in the battery's materials. This process usually involves two stages. The battery is initially subjected to combustion within a smelting furnace operating under a vacuum or an inert atmosphere. The constituents present in LIBs undergo a heating process exceeding their respective melting points, facilitating the separation of metallic components in the molten state by reduction reactions and the subsequent generation of distinct immiscible molten strata. The main outputs of the smelting procedure include metal alloys and slag.

Valuable elements such as Co, Ni, and Cu are typically found in the metal alloy, whereas the slag fraction commonly contains Li, Mn, and Al [60].

Hydrometallurgy (Fig. 2b) is a widely adopted recycling technique that uses aqueous solutions to recover valuable metals from EoL-LIBs. Its key strengths are a high recovery rate and a better yield of high-purity metals. In the leaching process, various chemical reagents, such as acids or alkalis, are used to dissolve the metal ions from the battery waste. Acid leaching is a commonly used method for recovering valuable metals from spent LIBs, where sulfuric or hydrochloric acid is used to dissolve the metal ions [61]. Alkali leaching, on the other hand, uses a basic solution, typically sodium hydroxide or potassium hydroxide, to extract the metal ions [61,62]. After leaching, separation and purification techniques are used to remove impurities and isolate the metal ions for further processing. Solvent extraction is a process that separates metal ions from impurities in a two-phase system by using solubility differences between the metal ions and the solvent. Chemical precipitation is another method used for metal separation and impurity removal. The process involves adjusting the pH of the solution to precipitate different metals.

Recovery rates can exceed 98 % for metals like Cu, Ni, and Li and the process is also more energy-efficient and has a lower carbon footprint than pyrometallurgical processing, achieving a 39 % decrease in emissions from battery cell production in a lifecycle analysis [59,63]. However, it is important to note that Life Cycle Assessment (LCA) outcomes depend strongly on regional energy mixes and process-specific assumptions; therefore, these comparisons should be interpreted within the context of the study boundaries and energy sources used. Potential disadvantages of hydrometallurgy are the generation of large amounts of wastewater containing chemical reagents and impurities, and the evolution of gases potentially harmful (e.g., Cl_2 , NO_x , SO_x , ...).

2.3. Challenges in treating different battery chemistries

The diversity and constant evolution of battery chemistries present one of the most significant technical and economic challenges to the recycling industry. The market is shifting from Co-rich chemistries (e.g., LCO) to Ni-rich variants and low-value LFP batteries. This means that recycling processes must remain flexible and adaptable, as legacy systems optimized for one type of input are becoming obsolete.

The most pressing challenge is the treatment of the low-value stream: LFP batteries. These batteries are increasingly popular due to their lower cost and higher safety, but they lack the high-value metals like Ni and Co that have traditionally made recycling economically viable [59]. Consequently, the recovered value from LFP batteries often fails to offset

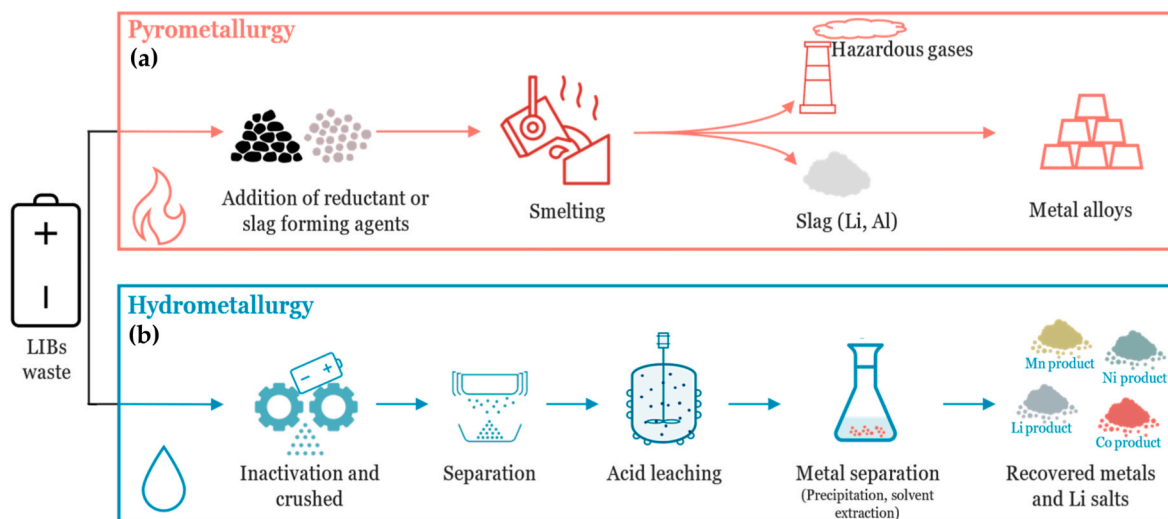


Fig. 2. (a) Pyrometallurgy and (b) Hydrometallurgy flow charts of the processes. Adapted from Ref. [60] under the terms of CC BY 4.0 license.

the costs of collection, transport, and processing, leading them to be sold at negligible value or disposed of as hazardous waste. This is a major sustainability concern, which is being addressed by the EU Regulation by setting recycling targets for Li, thus forcing the industry to find a commercially viable solution.

Conversely, NMC and LCO batteries are economically attractive due to their high content of Ni and Co. However, they present their own set of technical complexities: the existence of various NMC formulations, ranging from NMC111 to newer high-nickel NMC811 variants, complicates recycling, as each requires a tailored approach to maximise recovery and purity. High-Ni NMCs such as NMC 811 are particularly problematic: their lower cobalt content reduces the economic incentive for recovery, while their Ni-rich chemistry is thermally less stable and far more sensitive to impurities introduced during processing. Even trace levels of copper, iron, or aluminium can degrade electrochemical performance when the cathode is resynthesized. These materials also demand tighter control of leaching, purification, and calcination conditions to prevent oxygen loss and structural degradation. In practice, this means that recycling NMC 811 requires cleaner feedstocks, more precise process control, and more complex lithiation or resynthesis steps—factors that raise both cost and technical difficulty [64].

2.4. Industry-Academia Collaborations and EU projects

Industry-Academia Collaboration (IAC) refers to a formal partnership between companies and academic or research institutions, such as universities and research centres. Its principal aim is to reconcile the theoretical knowledge produced within academia with the practical demands of industry in terms of innovation and application. Such collaboration operates as a bidirectional mechanism, fostering the mutual exchange of ideas, expertise, and resources that ultimately advance both domains [65].

This form of collaboration is multifaceted rather than linear, encompassing a wide spectrum of institutionalised activities. A central element is represented by joint research initiatives, in which academic scholars and industry practitioners collectively address defined challenges. Another critical dimension involves technology and knowledge transfer, frequently facilitated through licensing arrangements or the establishment of university spin-offs. In addition, IAC plays a pivotal role in talent development by aligning curricula with evolving industry requirements and by offering internships and placements that provide students with practical experience while simultaneously cultivating a highly skilled graduate workforce. This elevated definition reflects a fundamental strategic shift in how the EU and its stakeholders perceive these relationships [65]. It is a progression from a linear model, where knowledge was seen as flowing in a single direction from academia to industry, toward a more non-linear model that emphasizes frequent, iterative, and interactive co-creation between universities, the private sector, and public institutions. The structural design of EU programs like Horizon Europe is a direct result of this evolution, demonstrating a deliberate policy to foster this intricate, co-creative ecosystem.

Horizon Europe serves as the EU's key funding program for research and innovation (R&I), acting as a strategic framework to facilitate and amplify IAC. With an allocated budget of €93.5 billion for the 2021–2027 framework, the program exemplifies an unparalleled financial commitment to R&I as a central instrument for advancing the EU's strategic objectives. These encompass not only the acceleration of climate action and the pursuit of sustainable development, but also the reinforcement of long-term economic resilience and growth, thereby underscoring R&I as a foundational pillar of the EU's policy [66,67].

Horizon Europe is organised around three interconnected pillars, each addressing distinct yet complementary dimensions of the R&I ecosystem: i) *Excellent Science* strengthens the foundations of European research by supporting frontier science and talent development (notably through the Marie Skłodowska-Curie Actions); ii) *Global Challenges and European Industrial Competitiveness* constitutes the core arena for IAC by

financing collaborative research across six thematic clusters that align academic and industrial actors in tackling pressing societal and technological issues; iii) *Innovative Europe* focuses on fostering breakthrough innovations and their market deployment, primarily through instruments such as the European Innovation Council and the European Institute of Innovation and Technology [66,67].

Beyond the Horizon Europe framework, the EU utilizes other strategic instruments to foster innovation and strengthen its position in the battery value chain and the circular economy. This includes Important Projects of Common European Interest (IPCEI) and other targeted initiatives. IPCEI represent a class of large-scale, transnational initiatives that mobilise both public and private resources to generate substantial economic and societal benefits for the EU. Funded through state aid mechanisms, these projects are designed to boost European industrial growth, employment, and global competitiveness. Within the battery sector, the IPCEI framework has been operationalised through two complementary initiatives: the IPCEI on Batteries and the IPCEI European Battery Innovation (EuBatIn). Both initiatives share a common objective of building a complete, competitive European battery value chain, with participants representing the full lifecycle, from raw materials and cell development to recycling and repurposing. This includes developing new, sustainable processes for raw material extraction and refining, improving advanced materials for battery cells, and creating innovative battery systems and management software.

In this context, the Batteries Europe R&I Roadmap 2025 serves as a strategic guide for advancing Europe's leadership in the rapidly evolving battery sector [68]. Building on insights from experts across thematic working groups and task forces, this updated roadmap (first versions were from 2021 to 2023) outlines key research areas that span the entire battery value chain and highlights the need for skills development, social awareness, and sustainable innovation. Aligned with Horizon Europe, the roadmap provides a foundation for prioritizing EU R&I projects, ensuring that they address the most pressing scientific and industrial challenges. It also complements the IPCEI on Batteries by guiding the strategic direction of large-scale industrial projects, fostering cross-border collaboration, and accelerating the deployment of cutting-edge technologies across Europe.

3. Academic research on LIBs recycling

3.1. Sorting & deactivation of batteries

Collected spent LIBs have to be sorted prior to recycling, to select the proper recycling process; sorting can be difficult due to the lack of a DBP for the batteries manufactured in the past (that are now in need of recycling). From a research lab perspective, the best way to sort LIBs is to read the labels (if present) or to open the cell and characterize it.

Some sort of deactivation process must be performed before battery disassembly and dismantling opening to guarantee safe handling and avoid uncontrolled release of residual capacity, that can lead to local overheating and fires. The most traditional way to deactivate batteries is by immersion in salt-saturated solutions, to short-circuit the electrodes in a controlled, cost-effective and straightforward way [69,70]. However, chemical side-reactions may compromise the cell casing, causing the leakage of the electrolyte in the solution and the infiltration of the solution inside the cells.

A finer approach is their electrical discharge using an electronic load [71,72]. Despite the instruments being expensive, only few studies being published by now, this could be a great opportunity to recover energy from EVs battery packs on industrial scale, although the lack of information on the State of Health (SoH) and the residual capacity of the batteries makes the process even harder [71,72].

In recent years, new investigated methods have been explored to improve the identification and sorting of spent LIBs before recycling. Among these, Machine Learning (ML) and Artificial Intelligence (AI) approaches have shown promising results in recognizing battery

chemistries and estimating their SoH based on measurable parameters such as voltage profiles, impedance spectra, and elemental composition. Supervised algorithms trained on large datasets can classify different cathode materials (e.g., NMC, LFP, LCO) from limited input data, even when the original labelling or design information is missing [73–75].

3.2. Shredding vs dismantling

Deactivated battery packs and modules can be separated into cells to be subsequently opened to recover the single components. Manual disassembly (i.e., the tear-down of battery packs/modules to cell level) and dismantling (i.e., the opening of the cells) aim at reducing the complexity of the LIBs by removing plastics, papers and casings. An effective manual disassembly/dismantling process results in minimal subsequent separation steps, positively affecting the recycling cost [70]. Table 3 reports the generic composition of an NMC EV battery pack considering also the material in the pack and modules peripheries that can be eliminated manually [76].

Manual dismantling is a relatively simple method but it is associated with low efficiency (due to the absence of a standard battery configuration and the possible different joining systems), severe safety hazards (e.g., HF evolution from the electrolyte, Li reaction with humid air that can lead to fires, ...) and it requires higher manpower, making it one of the most cost-intensive steps during LIB recycling; nevertheless, it has been partly adopted in some recycling facilities, such as in the LithoRec process [76,77]. Recently, the adoption of a hybrid-human workstation has been proposed, in which the robot would conduct more superficial and repetitive tasks whereas the human works on more demanding activities and can react to possible unusual circumstances [78,79].

Modern recycling facilities, on the other hand, prefer to mechanically disintegrate packs, modules and cells by crushing them and then eliminate unnecessary materials to obtain a black mass (BM) to be subsequently recycled. Compared to a manual disassembly/dismantling, crushing has a much higher processing capacity and can be done in several ways: dry crushing and inert crushing are the go-to choice for industries but they suffer from safety or economic issues; wet crushing and cryo crushing are present mainly as pilot-scale processes still requiring optimization [80–86].

After crushing, the mixture is often subjected to a magnetic separation of the metallic components and a sieving process, to separate the different size fractions generated in the crushing due to the different

Table 3

Mass composition of an NMC EV battery pack, referred to the whole battery pack (adapted from Ref. [76]) and to the single cells.

	Component	Material	wt.% (referred to pack)	wt.% (referred to cell)	
Battery Pack Periphery		Steel	5.7	–	
		Electronics	2.7	–	
		Al	18.0	–	
		Plastics	5.7	–	
		Cu	2.3	–	
Modules Periphery		Al	5.3	–	
		Plastics	1.5	–	
Cell	Cathode	Steel	3.3	–	
		Al foil	5.5	9.9	
		Li	1.0	1.8	
		Ni	3.1	5.6	
		Co	3.1	5.6	
		Mn	2.8	5.0	
		O	4.8	8.6	
	Anode	Cu	9.2	16.5	
		Graphite	8.2	14.7	
	Housing	Al	5.8	10.4	
	Electrolyte	Volatile Components		8.3	14.9
	Separator	Plastics	3.8	6.8	

mechanical properties of the LIB components [87].

3.2.1. Black mass separation techniques

The term black mass denotes the powder fraction obtained from the mechanical shredding and sifting of spent batteries, composed by a mixture of cathode and anode materials in which current collectors, separators, and electrolyte residues can be found. The separation of individual components from the BM represents a significant issue, for which various methodologies have been developed. Particularly challenging is the separation of graphite from CAM, since both fractions exhibit comparable particle size distributions and conventional size-based separation methods result ineffective.

Among the most effective approaches is froth flotation, a technique historically employed in the mining industry for mineral beneficiation, where separation is driven by differences in surface hydrophobicity [88]. Froth flotation has then been adapted to the treatment of BM since graphite displays inherently higher hydrophobicity than the metal oxides typically constituting cathode materials [89]. Froth flotation is generally performed in a specific reactor equipped with a high-shear mixer and compressed air injection to promote the formation of the froth [90]. The use of additives such as a collector (to enhance target particles hydrophobicity) and a frother (to stabilize the formed froth) helps improving the flotation efficiency [91]. Kerosene and methyl isobutyl carbinol (MIBC) are commonly employed as collector and frother, respectively, and have been shown to promote efficient graphite separation, but greener alternatives have also been reported [90–92]. This technique has been shown to yield high separation efficiencies between graphite and nickel, manganese, and cobalt oxides. In contrast, the separation of LFP is more challenging, as LiFePO₄ particles are often coated with carbon, which imparts a hydrophobicity similar to that of graphite [90].

Due to the challenges associated with separating graphite from LFP via froth flotation, primarily caused by the amorphous carbon coating on LFP particles, alternative methods have been developed that exploit the electronic and magnetic properties of the materials [93–95]. For example, high-intensity magnetic separation (HIMS) has proven to be a highly effective technique for separating paramagnetic and diamagnetic materials [96]. In this case, LFP behaves as paramagnetic due to the presence of Fe(II) in its structure, while graphite is diamagnetic. When BM containing LFP is introduced into a strong magnetic field, the paramagnetic CAM is strongly attracted to the magnets, whereas diamagnetic particles, such as graphite, can be collected separately. Other approaches rely on electrostatic separation, which applies an electric field to the particle mixture. Conductive particles, such as graphite, are attracted toward an electrode, while less conductive or insulating particles, such as cathode metal oxides, are deflected and collected separately. These methods are particularly valuable in cases where conventional flotation is insufficient, enabling higher recovery rates and improved purity of the separated fractions.

3.3. Binders & current collectors

The recovery of current collectors and binders strictly relates to the delamination of the electrode materials from the metallic foils by removing the binder. For electrodes containing water-based binders (e.g., CMC, SBR) this can be easily achieved by treating them with water to liberate the CAM/AAM particles [97]. As for PVDF-containing electrodes, the process is harder and may involve hydro/solvometallurgical, thermal or mechanical treatments.

Hydro- and solvometallurgical delamination of cathodes can be achieved: (i) by dissolution of the binder (possibly assisted by ultrasound or supercritical fluids) with organic solvents (e.g., NMP, Dimethylsulfoxide DMSO, ...) and its subsequent recovery by anti-solvent precipitation (chiefly, H₂O) [70,98–101]; (ii) by leaching of the CAM with acids causing its disintegration and detachment from the current collector [43,102]; (iii) by weakening of the adhesion forces between

the electrode material and the current collector through competitive interactions with Al between PVDF and a competing substance (e.g., Ethylene Glycole EG) [103].

As for thermal treatments, despite being energy-demanding and potentially hazardous for the environment, it is the most used technique in industries for its effectiveness in delaminating electrodes by thermally degrading the binder (which is obviously not recovered) [104]; the literature reports temperatures in the range 500–800 °C kept for 5–90 min in order to have a drop in the adhesion strength between the electrode material and the collector and achieve delamination, possibly assisted by an air-jet that also breaks down the electrode material to a fine powder (Adhesion Neutralisation Via Incineration and Impact Liberation process, or ANVIL) and/or using additives that either form gas bubbles (helping in the detachment process) or limit the evolution of toxic and hazardous by-products [104–109].

Finally, mechanical delamination involves the physical separation of the electrode material from the current collector. To the best of our knowledge, besides the manual scratching of the electrode material using a blade, few successful treatments has been reported in the literature. One easily scalable and green method is based on ice-stripping and it involves spraying water onto electrodes and putting them into contact with a cold surface to rapidly freeze the water; after freezing, the collector is ripped off by taking advantage of the adhesion between the frozen water within the electrode material and the cold surface [110]. Additionally, supercritical fluid extraction (SFE) using CO₂ and a co-solvent in which PVDF is soluble (e.g. DMSO, Dimethylformamide DMF, NMP, Dimethylacetamide DMAc, ...) has been also reported; the technique, applied to spent cathodes from LIBs and scraps, successfully led to the delamination of the cathodes due to removal of the binder by means of mild conditions, namely 38–120 °C, 80–100 bar and 13–20 min, and lead to a reduction by 6.7x of the solvent volumes required (with respect to classical solvometallurgical methods) [111–116].

3.4. Cathode active material (CAM) recycling

From an academic point of view, two main approaches are used for the recycling of cathodes, hydro-/solvometallurgy and direct recycling [117]. Direct recycling is cheaper, easier and allows to maintain the morphology and the structure of the treated CAM but it has limitations concerning the amount of Li that can be reintegrated in the structure and the applicability on different cathode chemistries. Hydro-/solvometallurgy consists in a deeper treatment involving the dissolution of the spent CAM and the recovery of the metals in form of precursors, then available to resynthesise fresh CAM (or for other purposes). The leaching step plays the most important role in solvometallurgy, consisting in the solubilization of valuable metals from the CAM matrix. This can be achieved using various leaching agents and approaches that have been explored over several decades, each offering distinct advantages and challenges (summarized in Table 4).

3.4.1. Hydrometallurgy

If water is used as main component of the leaching system, the technique takes the name of hydrometallurgy. Hydrometallurgy includes the leaching of CAMs using two main classes of leaching agents: inorganic acids (already covered in this work) and organic acids.

The already discussed challenges posed by the leaching with inorganic acids paved the way for the research on new leaching agents. Organic acids (e.g., Citric Acid CA, Lactic Acid LA, Acetic Acid AA, ...) are in the spotlight for their biodegradability, lower toxicity, and ability to act as complexing agents, thus promoting valuable metals dissolution even under mild conditions with satisfying yields [118–123]; these are further improvable either by using a reductant (H₂O₂, glucose, ascorbic acid, ...) or by treatment with ultrasound or microwave [124–126]. However, the kinetics is generally slower than that of inorganic mineral acids and the selectivity of metal dissolution can vary depending on several parameters (e.g., acid and reductant concentration,

Table 4

– Pros and Cons of the mentioned approaches for CAM solvometallurgical recycling

Technique	Examples of leaching agents	Pros	Cons
Inorganic Acid Leaching	H ₂ SO ₄ , HNO ₃ , HCl	High efficiency Well-established Cost-effective	Environmental impacting Safety hazards
Organic Acid Leaching	CA, AA, LA, ...	Eco-friendly Cost-effective Safe handling	Lower efficiencies
Bioleaching	Bacteria: <i>A. ferroxidans</i> , <i>A. thiooxidans</i> Fungi: <i>A. niger</i> , <i>P. simplicissimum</i>	Costs can be lowered Eco-friendly Safe handling	Lower efficiencies Environment-sensitive microorganisms Slow kinetics (microorganisms' metabolism) Time-consuming (need to grow cultures)
ILs and DESs leaching	Choline Chloride + LA Choline Chloride + EG ...	Solvents can be reused Eco-friendly Safe handling	Lower efficiencies High viscosity of solvents Higher cost Hygroscopicity

solid-to-liquid ratio, temperature, ...).

3.4.2. Bioleaching

Bioleaching exploits the metabolic activity of microorganisms to directly leach transition metals or to create the environmental conditions promoting metal solubilization (*indirect leaching*) from ores and from e-wastes (at a lab scale) [127–132].

For bacterial bioleaching, microorganisms from the *Acidithiobacillus* genus (*A. ferroxidans* and *A. thiooxidans*) are mainly used together with elemental sulphur and FeS₂. Their metabolic pathways comprise the oxidation of S to produce an acidic environment in which Fe²⁺ is oxidized to Fe³⁺, that acts as indirect leaching agent for other transition metals in the system [133–135]. The process is inherently slow and sensitive to operational parameters such as pH, the presence of magnetic fields, contaminants or catalytic species, pulp density, and oxygen and nutrients availability [136–141].

As for fungal bioleaching, *Aspergillus niger* and *Penicillium simplicissimum* are mainly used for their metabolic pathways that involve the production of organic acids mixtures (e.g., gluconic acid, citric acid, ...) whose composition depends on the species and the conditions in which the fungi are grown [142–147]. Unfortunately, fungal bioleaching shows lower leaching efficiencies compared to bacterial bioleaching, although effort are being made to: i) further optimize the conditions in which fungi are grown to tune the organic acid cocktail; ii) study the synergistic effect between different species; iii) find new more efficient microorganisms [148–155].

3.4.3. Solvometallurgy with ionic liquids and Deep Eutectic Solvents

Ionic liquids (ILs) are mixtures of ions that are liquid in standard conditions and represented a frontier in solvometallurgical recycling due to their tuneable physicochemical properties (through the combination of various ions) and high dissolving power [156–158]. ILs based on imidazolium, pyridinium, or phosphonium cations, paired with halides or organophosphate anions, despite being expensive, have been shown to leach Li and transition metals effectively by disrupting the oxide lattice of the CAM and solubilizing Co and Ni through complexation and redox reactions, sometimes even under ambient conditions [159–164].

Deep Eutectic Solvents (DESS) offer a cost-effective and biodegradable alternative to conventional ILs; they are binary or ternary mixtures of at least one hydrogen-bond acceptor (HBA) and one hydrogen-bond

donor (HBD) featuring a melting point lower than that of the pure components. HBA and HBD concentrations, mole ratios and intermolecular interactions can be tuned to obtain a DES properly tailored for LIBs recycling, though most of them are prone to absorb humidity (that can decrease in the leaching properties and the degradation of the components) and are highly viscous (making simple operations more difficult than with an aqueous solution) [70,165–167]. Despite promising lab-scale results, the challenges in metal separation and solvent regeneration must be addressed for practical deployment.

3.4.4. Transition metal recovery: co-precipitation vs. selective precipitation

After dissolution, transition metal ions have to be recovered in form of precursors for the synthesis of new CAM or for other purposes. The easiest way to recover them is through co-precipitation, a widely used technique that leads to a mixture of transition metals salts. Common anions used for co-precipitation are OH^- , CO_3^{2-} and S^{2-} although, recently, an eco-friendlier approach using oxalic acid has been actively explored [165,168]. Although co-precipitation does not allow the separation of pure salts, it remains the go-to choice for transition metal reclamation, especially if the mixture is reused to resynthesise a CAM with the same composition of the original one.

To obtain pure transition metals salts, selective precipitation can be an alternative though, due to the similar properties of Co, Ni and Mn, their separation remains a hard task, so co-precipitation is still the preferred way. An interesting selective precipitation approach relies on the combined use of peroxydisulfate $\text{S}_2\text{O}_8^{2-}$ as an oxidizing agent and OH^- to control pH and obtain metals precipitation [169]. Another approach widely reported in the literature is the use of liquid extractant or extractant-imbibed PVDF membranes/beads to selectively separate metal ions: Ni-loaded Mextral®272P, Cyanex 272 and PC-88A and Cyanex 272-PVDF membranes and beads were successfully used to separate Co from Ni and other metals [170–173]. As can be deduced, selective precipitation is difficult due to the need for strong oxidants (e.g., $\text{S}_2\text{O}_8^{2-}$) whose production is energy-intensive and can be hazardous for the operators; also, the use of liquid extractants is cost-intensive, especially when used to manufacture membranes and beads to adsorb transition metals. These techniques have been explored only in the lab and they will hardly be scaled up for green industrial purposes.

3.4.5. Lithium recovery

Lithium is often left in the leaching solution until every other metal has been extracted since a lot of the salts it forms have high solubility. As precipitating agents, CO_3^{2-} and PO_4^{3-} are the go-to choice and are added usually as sodium salts [174,175]; due to the huge quantities of Na salts required, the recovered Li salt can be heavily contaminated by the precipitating agent, thus needing further purification.

Another green technique has been explored relying on carbonation by bubbling CO_2 inside the solution [176]. The pH of the solution has to be controlled taking into account the acid-base equilibria of the carbonate system generated by the dissolution of CO_2 in water. When the pH value equals the negative logarithmic value of a dissociation constant (pK_a), there is an equimolar equilibrium between the acid and its conjugate base. In the specific case, pK_{a1} (=6.3) is referred to the $[\text{H}_2\text{CO}_3]/\text{HCO}_3^-$ equilibrium and pK_{a2} (=10.3) to the $\text{HCO}_3^-/\text{CO}_3^{2-}$ equilibrium. A pH value between 8.3 and 10.3 allows to set the equilibrium in favour of HCO_3^- that binds to Li^+ and precipitates, avoiding excessive loss of CO_2 or the formation of the highly soluble Li_2CO_3 .

3.4.6. Direct recycling

Despite the advances in the development of more sustainable hydro/solvometallurgical recycling processes, these always imply the disruption of the CAM structure. Instead, direct recycling approaches have the great advantage of renewing the CAMs functionalities while preserving their structural integrity at the same time [177]. This allows to minimize the required steps for the recycling process as well as the waste production, leading in turn to a major economic benefit and reduced

environmental impact [178].

Direct recycling aims at regenerating the structure of spent CAMs and restore their pristine composition. In particular, it focuses on the restoration of the lithium content to the original stoichiometry in the different CAMs. Indeed, the main problem in spent CAMs is the loss of active lithium given by the prolonged cell cycling. Also, structural defects (e.g. antisite Fe_{Li} in LFP, the substitution of a Li atom with a Fe atom in the crystal structure) can occur upon long-term battery use [179].

Different relithiation strategies have been explored so far to compensate for this Li^+ loss and proved to efficiently restore the structure and performance of various CAMs such as LCO, NMC, LMO and LFP [178–182]. Despite some variations in the experimental conditions, all types of approaches can generally be applied to the different cathode chemistries. In the case of LFP, for instance, a reducing agent is typically needed for the relithiation to counteract iron oxidation to Fe^{3+} and favour Li^+ insertion in the olivine structure [180,181].

The ideal application of direct recycling would be on spent cathode materials directly recovered from disassembly of EoL cells, as they present much less impurities from AAM and other cell components, which could hinder the efficiency of the direct regeneration process [183].

Direct recycling methods can generally be divided into different categories according to the relithiation approach adopted: i) solid-state sintering; ii) eutectic/molten salts; iii) hydrothermal methods; iv) electrochemical methods; v) others (e.g. aqueous, ionothermal) [182,184,185].

Solid-state sintering consists in the high-temperature treatment of spent cathode materials with a lithium salt as relithiation agent. Most commonly used salts are LiOH and Li_2CO_3 , but also organic Li salts are finding use to this purpose [186,187]. Despite the simplicity of this route, often involving a single regeneration step, the high temperatures – generally above 600 °C – and long times required for the treatment make it high-energy demanding. Moreover, the formation of spurious phases at high-T conditions is another concern for these solid-state regeneration methods.

Eutectic/molten salts methods involve the use of lithium salts or their mixtures showing low melting point. The treatment above these temperatures allows to obtain a melt as lithium source, i.e. a liquid environment where Li^+ diffusion is greatly enhanced compared to solid-state systems. LiNO_3 has been used as molten salt alone or in combination with LiOH , Li_2CO_3 and other salts which are able to provide a low eutectic point. Different binary or ternary mixtures have been explored [188–190]. The lower temperatures needed for this kind of regeneration process – generally between 200 °C and 500 °C, depending on the salt mixture employed – reduce the energy consumption of the relithiation step with respect to solid-state sintering. However, an extra washing step to remove the excess salts and/or an annealing step at higher temperatures to restore the crystal structure of the CAM and remove possible phase impurities are often needed.

Hydrothermal methods are based on the treatment of spent CAM with an aqueous solution of a lithium salt such as LiOH at moderate temperature (150°C–250 °C) and high pressure in a sealed container. Also in this case, an annealing step at higher temperatures to regenerate the structure is often needed. These methods allow for a fast relithiation step in a low-cost and low-impact medium without the need of elevated temperatures. The main limitation is the high-pressure operations involved, which make the scalability of this strategy more challenging [191–193].

In electrochemical relithiation, spent cathode materials can be regenerated directly on the current collector, eliminating the need for physical separation and simplifying the overall process. Typically, the cathode is assembled in a two- or three-electrode configuration, with the spent cathode serving as the working electrode and lithium metal, prelithiated graphite, or a solvated Li^+ source acting as the Li-supplying counter electrode. A controlled cathodic current is applied to the

working electrode at a potential tailored to the specific cathode chemistry, driving the migration of Li^+ ions and restoring the CAM to its original stoichiometric composition [194,195].

With this strategy, the recovery of the cathode material from the current collector can be avoided and the usage of reactants is reduced. Nonetheless, the electrochemical cell setup is not straightforward and limits the applicability of the process at larger scale.

Other direct recycling approaches include solution-based regeneration and ionothermal methods. The first relies on the relithiation of CAM in water or other solvents at ambient/low temperature, thus reducing the energy demand and avoiding high-pressure systems required in hydrothermal methods [196]. The second exploits the advantages of ILs, such as low volatility, good thermal stability and reusability, to provide a high-diffusion environment which can facilitate the relithiation of the spent material [197]. However, the high cost of the IL reagents needed is a major drawback of this approach.

3.5. Anode active material recycling

The most largely used AAM for LIB anodes is graphite, either natural or synthetic, due to its high conductivity with good capacity and low working voltage along with exceptional thermal and mechanical stability [198]. Given its lower economic value compared to transition metals-containing CAMs, recycling of graphite in spent LIBs has always received much less interest. In traditional recycling processes anodic graphite, together with other carbon materials contained in LIBs as additives such as conductive carbon, have generally been discarded or in the best case downcycled to be reemployed in different lower-value applications [199]. For example, in pyrometallurgical methods graphite is usually burned together with the CAM so as to exploit its reducing ability at high temperatures towards transition metals and thus facilitate their recovery. However, the huge demand for graphite-based materials as well as the presence of Li and other metals residues in spent anodes make their recovery much more valuable and strategic in terms of supply of resources and environmental impact [200–202].

Spent graphite from EoL batteries can be recovered through various separation techniques, based on different density, hydrophobicity or morphological properties compared to cathode materials, as previously mentioned [202–207]. Depending on the specific separation efficiency of the method adopted, the purity of the recovered graphite can be variable, but hardly close to the high-quality standards required for battery remanufacturing. Moreover, the formation of a SEI on the anode upon cell cycling is often observed [205]. Therefore, a purification step is typically performed to remove all the impurities from the other battery components, with a specific focus on residual metals from CAM and possibly from Al and Cu current collectors. A chemical leaching with strong mineral acids is commonly employed for this purpose, often assisted by a reducing agent which improves the solubility of transition metal ions impurities, but alternative leaching procedures based on milder chemicals like organic acids have been reported to effectively obtain purified graphite [202–204,208]. Long-term cycling of LIBs, with continuous intercalation/deintercalation of Li^+ in the anodic material, can also lead to surface defects as well as increase the disorder degree of the graphite. This issue is usually tackled by a thermal annealing process above 900 °C which could restore the pristine graphitic structure [208–210].

3.6. Electrolyte recovery

The electrolyte is a key component of LIBs, enabling Li^+ transport between the anode and cathode and thus completing the electrochemical circuit [211–214]. Over prolonged cycling, electrolyte decomposition occurs, involving both solvent and salt degradation, which leads to the evolution of a plethora of by-products and hazardous gases [215]. Within this context, electrolyte recycling is often considered under two distinct scenarios: i) production scrap and ii) EoL-LIBs. In

the case of production scrap, the electrolyte is only marginally degraded, enabling its recovery in a form suitable for reuse in the assembly of new cells. Conversely, for EoL-LIBs, the recovery of pristine carbonate solvents and Li salts is not achievable; nonetheless, the recovered fractions retain significant value since Li salts represent a critical secondary source of Li, while solvent degradation by-products can serve as precursors or feedstocks for the synthesis of alternative chemical compounds [216].

Though the electrolyte is currently pyrolyzed from an industrial point of view, there has been some academic development in their sustainable recycling, for example: (i) a two-step method exploiting a toluene-assisted precipitation of the $\text{LiPF}_6\text{-EC}$ complex, followed by distillation to separate the three components; (ii) a low-temperature thermal treatment (about 130 °C) to recover electrolyte solvents while preventing excessive evaporation or decomposition [216,217]. However, due to the risks linked to toluene use and the inevitable degradation of the electrolyte at 130 °C, currently the most promising technique for the recovery of electrolyte in terms of salt and solvents, is SFE with CO_2 (the most used fluid due to the cheapness and eco-friendliness) [218–220]. Its adaptability and efficiency suggest significant potential for the extraction of carbonates, positioning it as a compelling solution for next-generation recovery processes with preliminary overall solvent extraction yields reaching 66 % when a supercritical CO_2 density above 700 kg m^{-3} is used (density is the main variable in SFE and can be tuned by changing pressure and temperature) [221]. These results are highly encouraging, although further investigations are needed to optimize the extraction efficiency of each component, including the lithium salt.

4. Challenges and opportunities for industrial scale-up

4.1. Technical barriers and process optimization

The large-scale implementation of LIBs recycling is constrained by several technical barriers, many of which stem from the absence of industry-wide standardization. The broad spectrum of battery chemistries combined with the heterogeneity of physical designs, including cylindrical, prismatic, and pouch cells and the hierarchical structure going from battery packs to modules to cells (Fig. 3), pose a considerable obstacle to the establishment of uniform recycling processes.

Each design introduces distinct challenges; for instance, cylindrical cells contain densely wound layers that complicate material separation, whereas prismatic cells incorporate compact plates that heighten the likelihood of short-circuiting during disassembly. This variability necessitates tailored recycling strategies for different battery types, ultimately reducing process efficiency and elevating safety risks when mixed chemistry and formats are handled together [222]. The solution to this problem lies in the ongoing shift from labour-intensive, hazardous manual sorting to automated, AI-powered disassembly systems [223]. AI-powered vision systems are used at the initial stage to categorize batteries by chemistry, size, and form factor, routing them to the correct processing stream to prevent contamination and dangerous reactions. Once sorted, robotic arms equipped with specialized tools can precisely unscrew casings, cut through housings, and separate components without damaging valuable materials [224]. This surgical precision is critical for preserving the integrity of materials like the cathode, which can then be directly recycled. These robotic systems transform the slow and dangerous process of manual disassembly into a precise and automated one, enabling higher throughput and greater material purity.

Nevertheless, the increasing diversity of battery designs, coupled with the tendency of automated recycling systems to be optimized for only a limited number of dominant formats, presents a profound systemic challenge. This situation generates a stream of so-called *orphan batteries* that are frequently excluded from automated sorting processes.

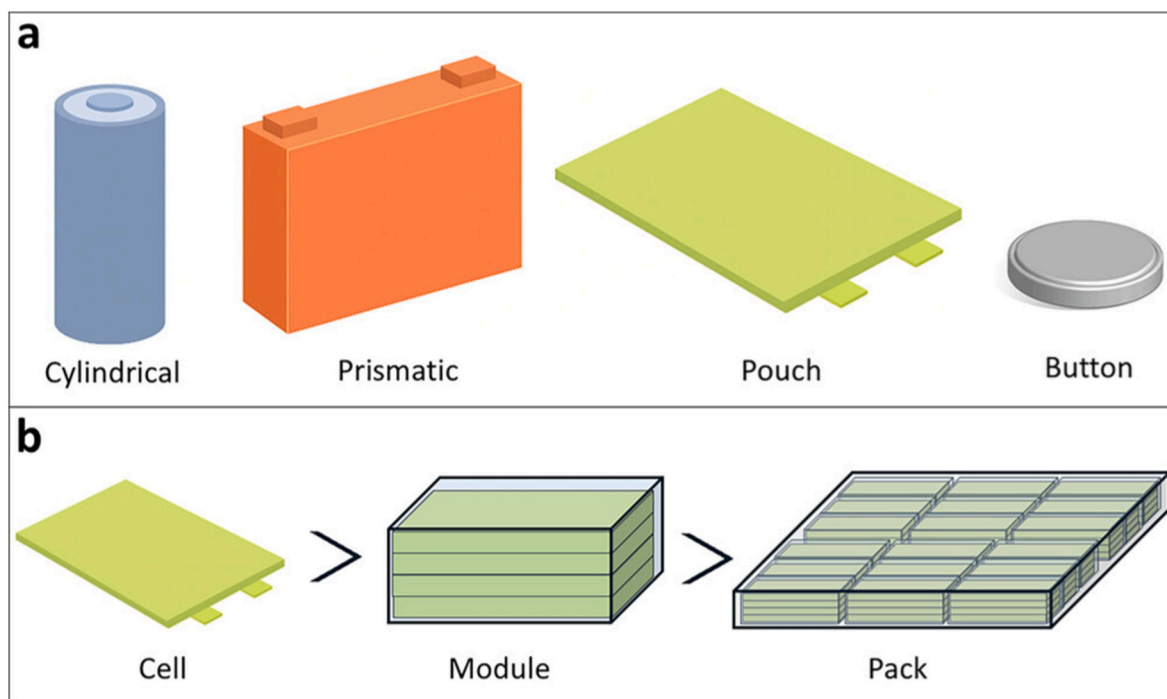


Fig. 3. (a) Battery cell shapes and (b) the formation of battery pack. Reproduced from Ref. [222] with permission. Copyright 2025, John Wiley and Sons.

4.2. Advancing LIBs recycling through automation and AI

The rapid growth of the LIB market, particularly for EVs, has exposed the limitations of traditional recycling methods, which are energy-intensive, inefficient, and not well-suited to the diverse and heterogeneous EoL battery stream. Academic research has addressed these systemic challenges by developing intelligent, adaptable solutions that overcome technical and institutional barriers. Universities have laid the groundwork for combining ML and Deep Learning (DL) with advanced sensing technologies, such as computer vision and spectroscopy, to automate battery identification and material characterization. This integration enables precise processing of different cathode chemistries (e.g., NMC vs. LFP) and positions AI as a specialized analytical tool rather than just a routine automation system. Accurate material characterization is a crucial first step for maximizing recovery rates and optimizing recycling strategies [225].

The physical dismantling of LIB packs presents technical barriers related to complex physical configurations, high cell density, and catastrophic safety risks. To handle the physical variability inherent in EV battery designs, research developed sophisticated software controls, introducing intelligent hybrid task planners and utilizing hybrid Visual Servoing (VS) methods to provide the necessary agility for automated disassembly. These vision-based systems integrate real-time component tracking via cameras mounted on the robotic end-effectors, allowing the robotic manipulators to dynamically adjust their trajectories and orchestrate coordinated pick-and-place operations in response to non-standardized battery geometries [226].

4.3. Safety and environmental concerns

Safety and environmental concerns are present at every stage of the battery recycling process. Spent LIBs can retain a significant charge, posing a risk of thermal runaway, fires, and explosions during collection, transport, and processing. These batteries are legally classified as hazardous waste due to their ignitable and reactive properties, requiring specialized handling and transport under strict regulations [227].

A critical safety challenge within the broader waste management sector is the improper disposal of LIBs in household trash or curb side

recycling streams. Such practices are a leading cause of fires in Material Recovery Facilities (MRFs) and garbage collection vehicles [228]. When batteries are damaged or compressed by compactors or sorting equipment, they may short-circuit, producing heat and sparks that can readily ignite nearby combustible materials such as paper, cardboard, and plastics.

A further consideration is the location of the recycling facility. The environmental footprint of recycling is heavily dependent on the electricity source of the processing plant. For example, recycling in regions that rely on a high percentage of coal-fired power will have a higher carbon footprint than in regions with a cleaner energy mix, such as those that use hydropower or geothermal energy. This indicates that the environmental benefits of LIB recycling are not a standalone attribute; they are amplified by the decarbonization of the energy grid. This creates a powerful synergy between the clean energy transition and the development of a circular battery economy, suggesting that investments in one area directly bolster the sustainability of the other [229].

4.4. Economic constraints and market dynamics

The economic landscape for industrial-scale LIB recycling is one of significant growth potential coupled with substantial constraints and uncertainties. The global market for battery recycling is projected to reach \$13 billion by 2030 [230]. This growth is directly tied to the rapid expansion of the EV and energy storage markets, which are creating a clear and growing supply of EoL and manufacturing waste.

The fundamental economic driver for recycling is the value of the materials contained within the batteries. Spent LIBs contain valuable metals such as Co, Ni, and Li in higher concentrations than can be found in natural ores. Recovering these materials can provide a domestic, secondary supply that helps to moderate the price of virgin materials and reduce reliance on geopolitically concentrated primary sources [230].

The profitability of recycling is highly sensitive to the volatile prices of virgin materials. When the cost of mined metals is low, the economic case for recycling diminishes, which can undermine private investment and make it difficult to secure consistent long-term returns. A further uncertainty is the unpredictable supply of EoL batteries. In this regard,

second-life applications (e.g., the repurposing of retired EV batteries for stationary energy storage) can extend the useful life of battery systems. While this contributes to resource efficiency, it also delays EoL availability and introduces uncertainty in the timing and quantity of materials entering recycling streams (a 10-year battery lifespan can potentially reach over 20 years with second-life applications), creating a logistical challenge for recyclers who require a consistent feedstock to operate efficiently [231]. Nevertheless, second-life use remains the preferred option according to the waste management hierarchy, as it maximizes value retention before recycling. However, repurposing is not always feasible, since many batteries reach EoL in damaged or degraded conditions, making the development of efficient and scalable recycling processes still essential.

This combination of uncertain material prices, variable battery availability, and extended second-life use contributes to a phenomenon akin to a *J-curve effect* (used in financial analysis and in this case applied to the battery recycling industry), where early stages involve high investment, low and unpredictable EoL battery volumes, and high operational costs, followed by improvements in efficiency and profitability as the industry matures. This leads to a period of financial instability before EoL volumes from the EV boom (post-2030) become substantial enough to make large-scale recycling consistently profitable [223]. This dynamic highlights the need for government-funded research, incentives, and strong regulatory frameworks to bridge this financial gap and de-risk the market for private investment. Second-Life repurposing has also an effective role in decreasing the EoL battery volume further enhancing this phenomenon.

5. Conclusions

The recycling of LIBs still faces critical industrial barriers that stand in the way of true sustainability. Crucial, among them, are the loss of technological value (since organic components are often burned off), the high energy demands of pyrometallurgical routes, the reliance on hazardous reagents in traditional hydrometallurgy, and the poor economic viability of recycling chemistries such as LFP, which contain fewer high-value elements.

In response, Europe is taking the lead through regulations, directives, and collaborative initiatives that are pushing research toward robust, sustainable solutions. These efforts target the full spectrum of LIB chemistries and formats, from cobalt-rich to LFP and from cylindrical to prismatic cells.

The roadmaps set out by European programs (e.g., Batteries Europe, Battery 2030+, ...) envision a fully integrated life-cycle approach: designing batteries with recyclability in mind, ensuring traceability through DBPs, and ultimately enabling collection and recycling via environmentally responsible and economically feasible processes. Looking ahead, the success of DBPs will hinge less on technical limitations (since digital identifiers and data capture technologies already exist) and more on overcoming systemic fragmentation of data across the supply chain. Meanwhile, academia faces the challenge of translating laboratory-scale breakthroughs into industrial recycling processes that can rival the efficiency and cost-effectiveness of conventional pyrometallurgical and hydrometallurgical pathways.

CRedit authorship contribution statement

Pietro Cattaneo: Writing – review & editing, Writing – original draft, Conceptualization. **Lorenzo De Vita:** Writing – review & editing, Writing – original draft, Conceptualization. **Camilla Zanoni:** Writing – review & editing, Writing – original draft, Conceptualization. **Davide Ruzza:** Writing – review & editing, Writing – original draft, Conceptualization. **Mariacristina Colantuono:** Writing – review & editing, Writing – original draft, Conceptualization. **Diana Di Cintio:** Writing – review & editing, Writing – original draft, Conceptualization. **Carmen Cavallo:** Writing – review & editing, Supervision, Conceptualization.

Mark Copley: Writing – review & editing, Supervision, Conceptualization. **Eliana Quartarone:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing 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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Data availability

No data was used for the research described in the article.

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