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# Recycling and Circularity of Li-Ion Batteries

## White Paper 162

Version 1


Energy Management Research Center

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## Executive summary

Recycling of Li-ion batteries is important from an environmental and economic perspective. Not only is it necessary for preventing serious environmental damage, it is also pivotal for securing a resilient supply chain of critical materials for batteries. The volume of retiring batteries brings a huge potential from recycling, promoting local re-industrialization by establishing a strong circular economy. In this paper we discuss the current state of recycling, highlighting challenges and opportunities posed by integrating the Li-ion battery value chain in a circular model to address sustainability needs. While Asia leads the sector, we review the growing efforts from governments and private companies around the world to improve their participation; reset critical materials supply chains; and promote local economies. Finally, we provide insights on the critical working areas for advancing Li-ion battery recycling and circularity, toward realizing the full potential of this technology.


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# Introduction

Li-ion batteries (LIBs) are deployed worldwide as part of electric vehicles (EVs), stationary energy storage systems (ESS)[1], and consumer electronics. As these batteries approach their end-of-life (i.e., retire), issues with their disposal become apparent. This is due to the potential damage to the environment if not properly handled, and increasingly compelling because of their high volume. Hence, their integration into a circular model is imperative.

Currently China leads the recycling market of LIBs[2]. However, increasing efforts to gain participation from other countries exist with a vision of a profitable business that helps secure the supply chain of critical materials worldwide. In addition to the environmental benefits, recycling LIBs brings important economic opportunities including:

- reduced foreign dependence for critical materials for battery re-manufacturing;
- resetting and securing supply chains of critical materials[3];
- local industrialization around recycling, refining, & extraction processes, etc.
- profitable businesses and employment creation.




**Figure 1**

*Circular model of the Li-ion battery life cycle*

*Green bubbles detail the battery life cycle stages, curved arrows indicate the material flows in a closed loop of a circular approach*

[1] ESS systems are critical for continued operation of facilities including hospitals, data centers, industrial complexes including the energy sector, etc. See Schneider Electric White Paper 71, *Understanding the Total Sustainability Impact of Li-ion UPS Batteries*, for more information on the sustainable aspects of LIBs used in ESSs.

[2] *Global EV Outlook 2024*, Apr. 2024, International Energy Agency – IEA

[3] In the context discussed here, securing of supply chains refers to ensuring the continuous and sufficient sourcing of materials needed for Li-ion battery manufacturing. Resetting supply chains refers to the establishment of supply chains where the traditionally involved parties, routes, and trade conditions are changed to fit the new needs of the customer.

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**Figure 1** details the stages in a circular[4] product life cycle model of LIBs. These include:

- Mining/minerals – raw materials are mined from natural reserves.
- Manufacturing – fabrication of battery cells and battery packs.
- Use – batteries are used in various applications (OEMs, commercialization as part of mobile and stationary devices).
- Collection – recovery of end-of-life batteries for distribution to earlier stages of the product life cycle (manufacturing and use) via reuse and recycling processes.
- Disposal – non-recyclable materials are discarded (usually in landfills).

Recycling feeds recovered materials back into new battery manufacturing, and partially contributes to addressing the growing demand for precursor materials.

This paper reviews the importance and current status of LIB recycling and examines how a circular approach can benefit all participants in the LIB value chain. This paper also discusses the technical challenges and advancements in recycling; the business opportunities; and the governmental efforts from Europe, the United States, and other countries to improve their participation.

## Recycling importance and environmental benefits

Recycling of LIB materials is important to recover useful materials from retired batteries and manufacturing scrap, that otherwise would end up as hazardous waste in landfills. Key environmental benefits of LIB recycling include:

- **Reduced impact on ecosystems** – because the needed materials are sourced from scrap/waste batteries instead of mines, there is less destruction of ecosystems. This also slows the depletion of mineral and metal resources[5].
- **Decreased energy use**[6,7,8] – the concentration of materials of interest in the recycled/recovered products is usually higher than that of mined ores, therefore reducing the energy associated to extract/refine the precursors.
- **Reduced use of hazardous substances**[8,9] – some extraction and refinement processes of raw materials require harmful chemicals. By sourcing the materials from waste batteries, the use of these harmful substances is also reduced or avoided.
- **Improved land use** – recycling reduces landfill use, along with the potential risks from harmful substances leaching into the soil and underground water sources.
- **Improved waste management and reduced risk of fire** – when LIB are wrongfully disposed of with municipal waste, risk of fire increases. Recycling

[4] In a circular business model resources used for manufacturing are returned to production to form a closed loop. Circular economy seeks to minimize the environmental footprint and maximize utilization of resources and profitability. **Figure 1** shows the circular model integrated with the life cycle of LIBs.

[5] Tankou *et al.*, *Scaling Up Reuse and Recycling of Electric Vehicle Batteries: Assessing Challenges and Policy Approaches*, Feb. 2023, ICCT White Paper

[6] Jacoby, *It's time to get serious about recycling lithium-ion batteries*, Jul. 2019, ACS Chemical & Engineering News

[7] Steward, *et al.*, *Economics and Challenges of Li-Ion Battery Recycling from End-of-Life Vehicles*, Jan. 2019, Procedia Manufacturing

[8] Lv *et al.*, *A Critical Review and Analysis on the Recycling of Spent Lithium-Ion Batteries*, Feb. 2018, ACS Sustainable Chemistry and Engineering

[9] Baum *et al.*, *Supplemental Information* *Lithium-Ion Battery Recycling – Overview of Techniques and Trends*, Jan. 2022, ACS Energy Letters

greatly reduces this concern, preventing safety issues for workers and the contamination of landfill designated areas.

- **Reduced GHG emissions**[7,8] – developing local recycling and LIB remanufacture facilities reduces the GHG emissions associated with their transportation. Recovered materials from LIB recycling are usually highly concentrated and of higher quality. As a result, the emissions associated with their processing into new batteries are also reduced. Savings of 0.7 tonnes of $CO_{2\text{-eq}}$ per tonne of LIB recycled have been reported, excluding the gains from the potential recovery of lithium[10].

## Circularity and business opportunities

The different factors involved in the circular LIB recycling value chain and the outcomes possible from an approach centered in sustainability are illustrated in **Figure 2**. Retired LIBs as a materials source cycle through various segments in the value chain. Notice that manufacturing feeds both battery "application markets" and "recycling". As batteries in service retire, they can be serviced or repurposed for a second or third life, or alternatively sent to recycling. When the battery life can no longer be extended via reuse/refurbishment, recycling recovers the materials and feeds back to manufacturing, where they are made into new batteries to start the following cycle. The reverse logistics[11] segment is critical in making this loop safe and efficient. Regulations, incentives, and multisector/industry collaborations facilitate the implementation and proper functioning of this circular system. As a result, important positive outcomes emerge, including improvement of local economies; workforce development; reduced environmental impact; market transparency, and securing the LIB supply chain.

The reuse and repurposing segment extends the useful life of LIBs, recovering manufacturing value otherwise wasted. Often, reuse is implemented in applications with less demanding requirements as they enter successive lives. For example, EV batteries would enter the ESS market in a second life, where energy density as well cycling intensity requirements are not as high. This represents an important business opportunity because second-life batteries can cost 30 to 70% less than first-life batteries for ESS applications[12].

The forecasted demand of materials for LIB manufacturing exceeds the current supply available[13]. Moreover, it exceeds the growing forecasted supply from the recycling and mining sectors together[14,15].Thus, a collective effort between the different players is necessary to realize the targeted capacities of planned recycling and mining facilities that feed into LIB manufacturing.

[10] Process considers pyrometallurgical recycling and reuse of recovered materials for new battery manufacturing. Source: *Commission Staff Working Document on the Evaluation of the Directive 2006/66/EC on Batteries and Accumulators and Repelling Directive 91/157/EEC*, Section 3.2.4.5. End-of-life: recycling, Sep. 2019. European Commission

[11] Reverse logistics processes include all tasks involved in the collecting, sorting, storing, and distributing retiring LIBs, into the reuse/recycling stream (i.e., recyclers and manufacturers).

[12] *Second-Life EV Batteries: The Newest Value Pool in Energy Storage*, Apr. 2019, McKinsey & Company

[13] *Achieving Resiliency and Sustainability for the EV Battery Supply Chain*, Sep. 2022. Arthur D. Little

[14] *Battery 2030: Resilient, Sustainable, and Circular*, Jan. 2023, McKinsey & Company and Global Battery Alliance

[15] Bae & Kim, "*Technologies of Lithium Recycling from Waste Lithium Ion Batteries: A Review*, May 2021, Materials Advances




**Figure 2**

*Circular Li-ion battery economy model*

*Incentives, regulations, and multisector collaborations facilitate overcoming challenges in all value chain segments, producing beneficial outcomes. Mining and disposal segments are also part of the LIB value chain, although not the focus of this work*

A sustainable circular model would target three main objectives: (1) profitability without dependence on governmental subsidies; (2) meeting demand at appropriate scale; and (3) minimization of environmental impacts[16]. For this to occur, all segments in the battery recycling value chain need to work in concert.

The following work areas are essential to realize a sustainable recycling system:

- the coordinated work of collection and transportation of used batteries to recycling facilities;
- the recycling and distribution of recovered materials;
- and the development of efficient synthesis[17] methods for cathode materials from recovered precursors.

[16] Vinayak *et al.*, *Circular Economies for Lithium-Ion Batteries and Challenges to their Implementation*, Oct. 2024, Next Materials

[17] Material synthesis refers to the sequence and group of methods to fabricate or artificially produce a material with specific desired properties. For example, LFP cathode materials ($LiFePO_4$) are usually prepared from lithium carbonate ($Li_2CO_3$), and iron phosphate ($FePO_4$) precursors, by using a solid-state reaction in which the precursors are combined in appropriate ratios, ground-mixed and subjected to a temperature of ~ 650 °C for several hours. All these parameters (choice of precursor and ratios, mixing speed and pressure, temperature and duration of the heat treatment, etc.) influence the final properties of the cathode material, and therefore the performance of the battery that contains it. The described is the solid-state synthesis process for LFP, yet there may be alternative synthesis processes including sol-gel synthesis.

Making processes safer and more efficient, with continuous improvements in the technologies around each of these activities, will increase the opportunities for thriving businesses.

## Market size and business opportunities

The emerging recycling market is mainly driven by the demand for LIBs, tied to the growing adoption of EVs and ESS, and the resultant feedstock of batteries to be disposed of.

The global LIB demand is estimated to grow from ~700 GWh in 2022, to about 4700 GWh by 2030, split approximately as 90.5% for mobility, 6.2% for grid storage, and 3.3% for consumer applications[14] (see **Table 1)**.

Following a similar trend, worldwide EV sales (EVs and plug-in hybrid EVs) reached over 10 million units in 2022, representing 14% of all new car sales, and are projected to grow to 35% by 2030[18].The ESS contribution is also expected to increase from the broader adoption of stationary storage to support data centers and microgrid applications, accounting for about 12% of the EV battery demand by 2030[2]. For more information on the drivers and advantages of adopting battery energy storage systems, see our White Paper 185, *Understanding BESS: Battery Energy Storage Systems for Data Centers.*

**Table 1**

*Global trends in EV sales, LIB demand, and revenues from recycling and manufacturing segments of the LIB value chain*

| Year | Global LIB demand[14] | Global EV sales[18] | | Recycling revenue[14,19] | Manufacturing revenue[14] |
|---|---|---|---|---|---|
| | [GWh] | [Million units] | % New car sales | [Billion $ USD] | [Billion $ USD] |
| 2022 | 700 | 10 | 14 | 2.55 | 40.8 |
| 2030 | 4700 | 25 | 35 | 13-18 | 195 |

The stakes are high, with expected global revenues from recycling representing between 13 to 18 Billion USD[14,19] by 2030 (3% of the total revenue for all LIB market segments), and projected to more than double to ~40 Billion by 2040.[14] The main driver is the use of all recovered materials as input for new battery manufacturing in an ideal closed loop.

To put it in perspective, global revenues for the LIB manufacturing segment (cell and pack manufacturing) are expected to reach ~195 Billion by 2030[14], representing 48% of the total LIB value chain segments[20].

The global estimate for feedstock[21] entering the recycling stream amounts to about 250 tons in 2020, where the largest contributing sources are retired batteries

[18] *Global EV Outlook 2023: Catching up with Climate Ambitions*, Apr. 2023, International Energy Agency - IEA

[19] Meng *et al.*, *Intelligent Disassembly of Electric-Vehicle Batteries: A Forward-Looking Overview*, Jul. 2022, Resources, Conservation and Recycling

[20] LIB value chain segments in the revenue projections include: mining; refining; active materials; cell manufacturing; pack manufacturing; reuse and recycling. Source: *Battery 2030: Resilient, Sustainable, and Circular*, Jan. 2023, McKinsey & Company and Global Battery Alliance

[21] The share between type of retiring LIBs, in Europe between 2019 and 2020, is roughly divided as: consumer electronics ~77%; EVs ~18%, and other applications 5% (including ESS and E-bikes). Sources:
*Recycling of Lithium-Ion Batteries Will Increase Strongly in Europe*, Jan 2023, Fraunhofer ISI
*Commission Staff Working Document on the Evaluation of the Directive 2006/66/EC on Batteries and Accumulators and Repelling Directive 91/157/EEC*, Use of lithium batteries placed on the EU market (Table 5), Sep. 2019, European Commission

together with the scrap[22] material generated during the LIB manufacturing processes.[23] This is projected to grow at an approximate CAGR of 25% by 2040, see **Table 2**. As we transition to electric mobility and its infrastructure grows, the relative shares between the feedstock categories (scrap from production, EVs, ESS, and consumer electronics) are expected to shift. EVs will represent a larger contribution, as these batteries reach their end-of-life.

**Table 2**

*Global feedstock entering the recycling stream*

| Global supply of LIB recycling feedstock[23] | | | | | |
|---|---|---|---|---|---|
| Year | Category | [kiloton] | % | Total [kiloton] | CAGR* [%] |
| 2020 | Production scrap | 120 | 48 | 250 | |
| | Retiring batteries (all types) | 130 | 52 | | |
| 2030 | Production scrap | 860 | 43 | 2,000 | 23.1% |
| | Retiring batteries (all types) | 1,140 | 57 | | |
| 2040 | Production scrap | 1,230 | 6 | 20,500 | 26.2% |
| | Retiring batteries (all types) | 19,270 | 94 | | |

* CAGR % is calculated for year ranges 2020 – 2030 and 2030 – 2040.

The opportunities brought by this circular economy extend beyond the expected revenues and environmental benefits. New jobs created at each of the stages in the LIB value chain are an important driver for social prosperity. Indeed, it is estimated that with each GWh/year of new battery factory capacity, around 80 new jobs are created. This represents between 220,000 to 290,000 total new jobs in manufacturing, considering the creation of about 90 gigafactories each with an annual capacity of 30 to 40 GWh within the next decade[24].

Extrapolating this to other segments of the battery value-chain, one can see how the net effect is attractive for the re-industrialization[25] and development of local economies. Even peripheral businesses such as construction, supply chain, food services etc. benefit. The development areas potentially span across logistics, recycling, research & science, education, and advanced battery manufacturing.

## Countries leading LIB manufacturing and recycling

The largest LIB manufacturers are in China and South Korea, where they have established control over the supply chain of critical precursor materials. Some of these manufacturers have expanded their operations to European and North American countries, motivated by the booming markets, incentives, and policies adopted to promote sustainable economies including the U.S. Inflation Reduction Act[26] and the E.U. Green Deal Industrial Plan[27].

[22] Scrap from LIB manufacturing is projected to reach ~ 60% of the total feedstock entering the recycling stream by 2030 in Europe.
Sources:
*UK's Biggest Opportunity from Battery Waste Is to Feed Its Cathode Manufacturing Industry*, Feb. 2022, Advanced Propulsion Centre UK
*Recycling of Lithium-Ion Batteries Will Increase Strongly in Europe*, Jan. 2023, Fraunhofer ISI

[23] *Battery Recycling Takes the Driver's Seat*, Mar. 2023, McKinsey & Company

[24] *Capturing the Battery Value-Chain Opportunity*, Jan. 2022, McKinsey & Company

[25] Industry reactivation and economic growth by the modernization of aging industries or the establishment of new ones.

[26] *Inflation Reduction Act of 2022*, Aug. 2022, US Congress

[27] *Green Deal Industrial Plan*, Feb. 2023, European Commission

China and South Korea also lead the recycling business[2,28]. Emerging players include Canada, the US, India, Norway, Australia, Japan, and Argentina[29]. Aligning with this, intellectual property records also point to China's lead. China dominates with nearly 2,600 total publications between 2010 and 2021; followed by Japan with ~250, South Korea with ~110, and the US with ~100 publications[30].

## Government incentives and policies for LIB manufacturing and recycling

Governments worldwide have been launching ambitious development programs capitalizing on the opportunities offered by the growing LIB value chain, particularly in Europe, the United States, and India.[29] These include incentives and regulations[31,32] across different activities:

- promoting manufacturing and recycling;
- setting strategies and targets for end-of-life battery collection rates and recycled materials content in new batteries;
- labelling and identification of batteries (i.e. battery passports);
- and commercialization rules including extended producer responsibility guidelines.

**Table 3** shows the targets in recycled content in new LIBs. The U.S. has not yet established recycled content targets. However, estimations indicate feasible targets similar to those of Europe, considering the cost, available technology, and recycling capacity[33].

**Table 3**

*Target minimum recycled content in new batteries*

*Top: Europe*
*Bottom: India (targets per battery type)*

| Region | Year | Cobalt | Lead | Lithium | Nickel |
|---|---|---|---|---|---|
| Europe[31] | 2031 | 16% | 85% | 6% | 6% |
| | 2036 | 26% | 85% | 12% | 15% |

| Region | Year | Portable | Electric vehicle* | Automotive** | Industrial |
|---|---|---|---|---|---|
| India[32] | 2027 | 5% | 5% | 40% | 40% |
| | 2030+ | 20% | 20% | 40% | 40% |

* Any battery specifically designed to provide traction to hybrid and electric vehicles for road transport.

** Any battery used only for automotive starter, lighting, or ignition power.

Aligning with the E.U. Green Deal Industrial Plan[27], the new EU Battery Directive[34] includes (among other aspects):

- targets for recycling and use of recovered materials in new battery manufacturing;

[28] *Lithium-Ion Recycling Rates Far Higher than Some Statistics Suggest*, Jul. 2023, PV Magazine

[29] *Global EV Outlook 2023 – Policy Developments*, Apr. 2023, International Energy Agency - IEA

[30] *CAS Lithium Ion Battery Recycling: A Review of the Current Methods and Global Developments*, Sep. 2022, American Chemical Society

[31] *Regulation (EU) 2023/1542 of the European Parliament and of the Council*, Jul. 2023, European Union

[32] *India's Battery Waste Management Rules 2022*. Aug. 2022, Government of India – Ministry of Environment, Forest and Climate Change

[33] Dunn *et al.*, *Electric Vehicle Lithium-Ion Battery Recycled Content Standards for the US – Targets, Costs, and Environmental Impacts*, Oct. 2022, Resources Conservation and Recycling

[34] One of the purposes of this regulation update is to harmonize the standards regarding the LIB value chain activities across all EU member states, promote transparency, reduce environmental and social impacts and encourage a circular economy. Source: *Council Adopts New Regulation on Batteries and Waste Batteries*, Jul. 2023, European Council

- battery passport and labeling guidelines (including disclosure of carbon footprint);
- and rules favoring repurposing for reuse over recycling[31].

The U.S. has rolled out a combination of regulations and incentive plans including the 2022 Inflation Reduction Act, the Bipartisan Infrastructure Law, and the Defense Production Act. Together, these programs add a stimulus to the "advanced batteries" value chain of over $8 U.S. Billion. They target advances for battery manufacturing; reverse logistics and collection programs; new manufacturing and recycling capabilities; and research in recycling and advanced energy storage technologies.

In India, the Production Linked Incentives (PLI) on Advanced Chemistry Cell (ACC) Battery Storage, launched in 2021 with a budget of ₹181 Billion INR. This initiative seeks to accelerate local battery manufacturing for both mobility and stationary storage applications, develop a domestic supply chain and attract foreign investment. The initiative is connected with the PLI for the automotive sector (₹259.38 Billion INR), and the Faster Adoption of Manufacturing of Electric Vehicles (FAME) program (₹100 Billion INR), in its transition from a fossil-fuel based transportation system to an EV-based system.[35]

Some other initiatives include:

- the Australian Made Battery Plan[36] aiming to boost domestic battery manufacturing and develop Australian industry and job security around renewable technologies;
- the Argentinian proposed law for the promotion of sustainable mobility[37];
- Japan's Green Growth Strategy[38];
- the creation of Lithium for Mexico[39];
- Russia's Kolmozerskoye project[40].

## Multisector collaborations

Important pioneering efforts from governments, academia, and industry help bridge the gaps in technology, logistics, and financing; toward a profitable, sustainable recycling market. In the U.S., the ReCell Center[41], Li-Bridge[42], and Lithium-Ion Battery Recycling Prize Competition[43] are exemplary collaboration hubs for the development of a circular economy, strongly encouraged by the U.S. government. The ReCell Center's areas of research include direct recycling of materials; advanced resource recovery; modeling and analysis; and design for sustainability.

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[35] *Three Companies Signed Program Agreement under PLI Scheme for Advanced Chemistry Cell Battery Storage*, Jul. 2022, Indian Ministry of Heavy Industries

[36] *National Battery Strategy*, Feb. 2023, Department of Industry, Science and Resources, Australian Government

[37] *Proyecto de Ley de Promoción de la Movilidad Sustentable*, Oct. 2021, Ministerio de Desarrollo Productivo Argentina

[38] *Green Growth Strategy through Achieving Carbon Neutrality in 2050*, Oct. 2022, Ministry of Economy, Trade and Industry, Government of Japan

[39] *Decreto por el que se Crea el Organismo Publico Descentralizado Denominado Litio para Mexico*, Aug. 2022, Diario Official de la Federacion, Secretaria de Gobernacion, Gobierno de Mexico

[40] *Polar Lithium, a Joint Venture of Nornickel and Rosatom, Receives Right to Develop Kolmozerskoye Project*, Feb. 2023, Nornickel

[41] ReCell Center, <https://recellcenter.org/>

[42] Li-Bridge, <https://www.anl.gov/li-bridge>

[43] Lithium-Ion Battery Recycling Prize, <https://www.herox.com/BatteryRecyclingPrize>

The Li-Bridge initiative seeks to "accelerate the development of a robust and secure domestic supply chain for LIBs"[42].

In the U.K., the Reuse and Recycling of Lithium Ion Batteries (ReLib) project leverages the efforts from seven academic institutions, the Diamond Light Source, and over 20 industrial partners. [44] This initiative concentrates efforts in three key areas including gateway testing and dismantling; characterization and recycling; and business and regulation. The industrial partners participate in sectors ranging from recycling and disposal; mining and materials extraction; water filtration; chemical; and life cycle analysis (LCA).

With the European Union's support and gathering the efforts from Germany, Belgium, and France, the RecyLIB project was launched in 2022. This project includes 6 partners across universities and industry, and a budget of €1.1 Million. The focus areas include: new battery materials; solventless electrode fabrication; cell manufacturing; electrochemical benchmarking of recovered materials vs virgin materials; cell dismantling; black mass[45] separation; active material regeneration and repairing; and advanced centrifuge technologies.[46] Their purpose is to explore direct recycling technologies and establish sustainable, low-energy, and highly efficient manufacturing and recycling chains for LIBs.

Beyond government mediated initiatives, multisector-industry collaborations can leverage partners' strengths and expertise along the circular value chain, giving them an advantageous business position by streamlining parts of the circular model.

Examples of relevant business partnerships in Europe include Renault-Veolia-Solvay, Valmet-Fortum-Nornickel-BASF, and Volkswagen-Northvolt-Hydro. In the U.S., notable examples are Tesla-Redwood Materials and Honda-Jaguar-Land Rover-Orvia-Ascend Elements cooperations.

## Challenges

While a circular model and LIB recycling help maximize the benefits of mined materials and prevent needed materials entering landfills, there remain some challenges. These are discussed in relation to the following areas:

- Circularity implementation
- Reverse logistics
- Safety and training of workforce
- Recovery processes and material yields

### Circularity implementation

**Challenge 1: the wide breadth of available Li-battery chemistries drives a lack of standardization in processes and expected products**.

Despite being a challenge, the variety of chemistries is a feature of a constantly evolving technology, where improvement necessarily produces new chemistries. The wide breadth of chemistries, cell sizes, and formats (cylindrical, prismatic, and pouch), increases the complexity in the reuse/refurbishment of second- and third-life batteries.

[44] ReLib, <https://www.faraday.ac.uk/research/lithium-ion/recycle-reuse/>

[45] Black mass is a black powdered material composed of the mixture of LIB anode and cathode active materials. Black mass is produced as part of the LIB recycling process.

[46] RecyLIB Project, <https://recylib.eu/>

Next, revenues from recovered materials are subject to fluctuation, because the type of batteries available for recycling at a specific point in time determines the profitability.

Recycling of batteries with high cobalt and nickel content such as NMC (nickel-manganese-cobalt-oxide) and LCO (lithium-cobalt-oxide) has been favored over recycling batteries with chemistries containing materials of lesser value such as LFP (lithium-iron-phosphate).[47] Looking forward, recycling of LIBs regardless of their chemistry is of paramount importance. NMC, NCA (nickel-cobalt-aluminum-oxide), and LFP are expected to dominate the LIB markets[14,48]. Thus, inclusive (i.e., all chemistries) recycling strategies must be implemented. Failure to implement cost-effective strategies to include recycling of "lower-value" LIBs will result in:

- large waste of lithium resources;
- significant landfill deposits;
- increased environmental impact from the potential leaching of hazardous chemicals into the soil and water streams;
- and risk of explosions and wildfires.

This also requires the personnel involved in recycling to be highly trained and detail oriented. Under a standard handling procedure, differences in the cathode materials may represent risks in the workplace.

**Challenge 2: variable feedstock entering the recycling system**

Timing for feedstock entering the recycling system is tied to the LIB value chain development and functioning. Today, manufacturing scrap is the primary source of battery stock for recycling. At a manufacturing facility, depending on the complexity of the production processes and operation maturity, scrap can range between 10 to 30% [49]. Another important source are batteries from consumer products such as appliances, computers, and mobile devices. In the longer term (8-15 years), retiring batteries from EVs are expected to become the primary source, not only for recycling but also for repurposing/reuse in applications such as stationary energy storage. This average time of 8 to 15 years could even extend to ~20 years depending on the application, battery type, and actual use profile[50]. This would delay an important segment of the input to the recycling stream.

**Challenge 3: limited and immature regional recycling capabilities**

Forecasts of the recycling demand and capability typically include capacity of planned facilities and the expected retiring quantity of batteries. These forecasts help assess the preparedness of a region to process the volume of waste batteries that otherwise would end as landfill.

Lack of regional recycling capabilities has been identified as a major challenge in the U.S.[51] Therefore, promoting the expansion of recycling capabilities is one of the main strategies to realize a truly circular value chain. This challenge is exacerbated

[47] *EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model*, Apr. 2019, Argonne National Laboratory, U.S. Department of Energy

[48] *Analysis of Global Battery Production: Production Locations and Quantities of Cells with LFP and NMC/NCA Cathode Material*, Jun. 2023, Fraunhofer ISI

[49] *European Battery Recycling: An Emerging Cross-Industry Convergence*, Jun 2022, Arthur D. Little

[50] Use profile refers to the operational conditions of a battery including charging and discharging speeds and loads, the frequency and number of charge-discharge cycles, and the operating temperatures.

[51] *EPA LIB Disposal and Recycling Stakeholder Workshop Summary Report*, Oct. 2021, U.S. Environmental Protection Agency

by the difficulties in establishing new capabilities including lengthy and complex permit processes, gaining the support of local communities, and availability of sites with access to sufficient clean-energy and key transportation resources (e.g., ports and railways)[52]. Recent reports on the installed and announced recycling capacity in the U.S. show optimistic results indicating a positive response to governmental stimulus connected to the increasing EV adoption[53].

Contrasting the available regional recycling capabilities, China is highlighted as having a marked recycling overcapacity[2]. This in turn represents a challenge for implementing a local circular model as centralized recycling may be preferred.

**Challenge 4: lack of official statistics**

The lack of official and rigorous reporting and accounting of the collection rates; recycling and reuse rates; and recycling capabilities, prevents assessing the effectiveness of current practices and timely decision making, bringing additional uncertainty.

**Challenge 5: competent trading of recovered materials**

Another pressing challenge connected with the insufficient amount of battery manufacturing capabilities within the U.S., is the lack of a significant local market for black mass. Therefore, most recovered materials are exported for refining and battery remanufacturing abroad, missing the benefits of local battery manufacturing[33,51]. Similar concerns exist for retiring battery materials being exported from Europe to recyclers in Asia[54].

**Challenge 6: current centralized overproduction of LIBs**

Overproduction of Chinese LIBs is another area that threatens the realization of this circular model. China has ramped up the manufacturing of new batteries leveraging the great maturity of its manufacturing sector and the reduction in materials pricing during 2023-2024[55]. This has led to a steady reduction in battery prices over the same period.

**Challenge 7: fluctuating prices and gaps in regulations**

Tied to the previous challenge, price reduction for new batteries represents a challenge to the reuse/refurbishment segment, because implementation of new batteries may be favored over second-life batteries[12]. Another challenge is the lack of clear standards regarding liability in case of failure or malfunction of repurposed batteries.

The implementation of an identification system (battery passport) is proposed as a solution to these challenges. A battery passport would provide a traceable history of the battery along with information on the chemistry and configuration, and facilitate the refurbishment process. The implementation of extended producer responsibility (EPR) policies[56] in concert with landfill bans, and targets for minimum recycled content in new LIBs, are expected to encourage reuse and recycling[51].

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[52] *Building a Robust and Resilient U.S. Lithium Battery Supply Chain*, Feb. 2023, Li-Bridge

[53] *Will the U.S. EV Battery Recycling Industry be Ready for Millions of End-of-Life Batteries?*, Sep. 2023, The International Council on Clean Transportation

[54] *Lithium-Ion Battery Recycling Goes Large*, Nov. 2023, ACS, Chemical & Engineering News

[55] *China's Low-Cost Lithium-Ion Battery Push*, Jun. 2024, BloombergNEF

[56] Extended producer responsibility policies are set by governments.

## Reverse logistics

Most reverse logistic challenges are related to user awareness and behavior, limited removability of batteries from devices, and safe transportation and storage options[51].

**Challenge 8: insufficient partnerships between manufacturers, vendors, collectors, and recyclers**

A strong distributed system to recover deployed batteries reaching their end-of-life starts from the producer or vendor. Extended producer responsibility policies for LIBs are important because they demand recycling considerations in the product design and business models of manufacturers and distributors. This strengthens the circular approach and motivates the recovery of LIBs at their end-of-life. A connected circular system implies that manufacturers and vendors establish partnerships with collectors and recycling parties to ensure a responsible (and profitable) end-of-life for batteries in their products.

**Challenge 9: unclear, burdensome collection schemes limit recycling**

Reducing requirements from consumers by developing convenient, local, and easy-access collection systems, is expected to improve used battery recovery rates[57]. Offering incentives and subsidies has also been proposed to encourage participation from all involved parties[51]. Proper labeling of LIBs facilitates the reverse logistics processes. This labeling informs all related actors (users, collectors, and recyclers) of the type of batteries and therefore the precautions and best ways to manipulate them.

The collection system needs to address both businesses and individual users. For example, LIBs used in uninterruptible power supply (UPS) systems are collected through various channels established by the UPS vendor, including collaboration with third-party collectors or through direct return of retiring equipment.

**Challenge 10: safety risks lead to strict transportation requirements**

LIBs are sensitive to extreme temperatures, humidity, and mechanical impact, resulting in a potential fire hazard if improperly handled. Therefore, LIBs are cataloged as UN Class 9 (miscellaneous dangerous goods), and their transportation is strictly regulated by applicable authorities depending on the type of transport and transportation route. This results in increased cost for transportation, impacting recycling profitability.

A strategy to facilitate the recycling and reverse logistics processes is the differentiation of recycling facilities in “hubs” and “spokes”, depending on the recycling processing capabilities of the plants.[58] In spokes, the first steps in battery recycling: discharging, disassembly, and mechanical processing are carried out to produce black mass. Hubs have the additional capabilities to transform black mass into refined battery materials via pyrometallurgy, electrochemical hydrometallurgy, or a combination of these. Hubs and spokes work in synergy. Spokes are distributed while hubs are centrally located within a business region. Such an arrangement facilitates the logistics and reduces transportation costs. Another factor contributing

[57] Improvement of collection rates is a major issue since improper handling has serious environmental consequences. Reported collection rates in Europe seem to be improving from a 25% in 2012, and 45% in 2016, targeting 65% by 2025. Collection rates for other regions remain unclear, as no official or rigorous statistics are available. Source: J. Neumann *et al.*, *Recycling of Lithium-Ion Batteries - Current State of the Art, Circular Economy, and Next Generation Recycling*, Jan. 2022, Advanced Energy Materials

[58] Terminology adopted from Li-Cycle, <https://li-cycle.com/technology/>

in localizing recycling facilities is their proximity to LIB manufacturing plants. This enables the large amounts of scrap from LIB manufacturing, to move rapidly into recycling stream.[22,23]

## Safety and training of workforce

**Challenge 11: keeping up with constant evolution of procedures and ensuring workforce safety**

The constant development and improvement of the recycling processes require updating the training of involved personnel at an equivalent pace. This, added to the advances (and therefore changes) in LIB technologies, represent a challenge as employees need to frequently update and incorporate new procedures. Given the importance of safe work practices, workforce training must always be a priority. Automation and implementation of engineering controls at all stages of the recycling value chain (emphasizing process simplification and safer operation) is a central strategy to improve efficiency and minimize risk for employees.

Moreover, using machine learning (ML) and artificial intelligence (AI) has been identified as an essential toolkit, and applied to sorting[59], discharging[60], and disassembly processes, to help prevent issues such as electrical shock to employees.[19]

Incentives from governmental funds have been proposed to improve the workforce training related to LIB recycling, of particular importance for small collectors and transportation segments[51].

## Recovery processes and material yields

**Challenge 12: prevalence of manual and risky pretreatment steps in recycling**

Regardless of the recycling approach (pyrometallurgy, hydrometallurgy or direct recycling), multiple pretreatment steps are needed (see **Figure 3**). These may include battery sorting, discharging, pyrolysis (deactivation of the batteries by heating them in a vacuum at ~600 °C), disassembly, and mechanical separation[61]. These processes are highly manual, dependent on battery characteristics and involve safety risks for operators. Automation stands out as a potential solution.

**Challenge 13: low yields, lithium waste, high energy intensity, and production of toxic gases in pyrometallurgy**

In the pyrometallurgy approach, the batteries are subjected to very high temperatures (smelting), up to ~1450 °C,[62] producing a high volume of toxic gases that needs to be treated before they can be released to the environment.

The metals are molten into an alloy, while the remaining materials form a mixture of oxides that can be used as filler for construction materials or disposed to landfill.

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[59] Sloop, *Distinguishing Batteries in a Recycling Stream US10014562B2*

[60] Sloop, *Discharging of Batteries US8823329B2*

[61] Mechanical separation consists of the shredding of batteries under a specific environment that varies depending on the recycler's technology. Common environments include water, inert gas atmospheres, and vacuum. Electrolyte evaporation is promoted by using heat during the shredding process (not suitable when using water); subsequently the electrolyte is recovered using condensation. When using water as a medium for the shredding process, the polymers and graphite stay on the surface, the black mass is suspended in the water, and the metals (mostly aluminum and copper) sink to the bottom of the container. The black mass is then separated from the water via centrifugation and drying, and later refined to extract valuable materials for cathode fabrication.

[62] *Comparison of Different Methods for Recycling LIBs*, Oct. 2023, Duesenfeld

The alloy containing iron, nickel, cobalt, and copper should be further refined before it forms a feedstock for new battery manufacturing.

This process has the advantage of being suitable for all types of LIBs, minimizing the dismantling/disassembly requirements, and eliminating the need of sorting LIBs. However, it carries a disadvantage of low yields (~32-50%), especially when compared to hydrothermal methods.[62]

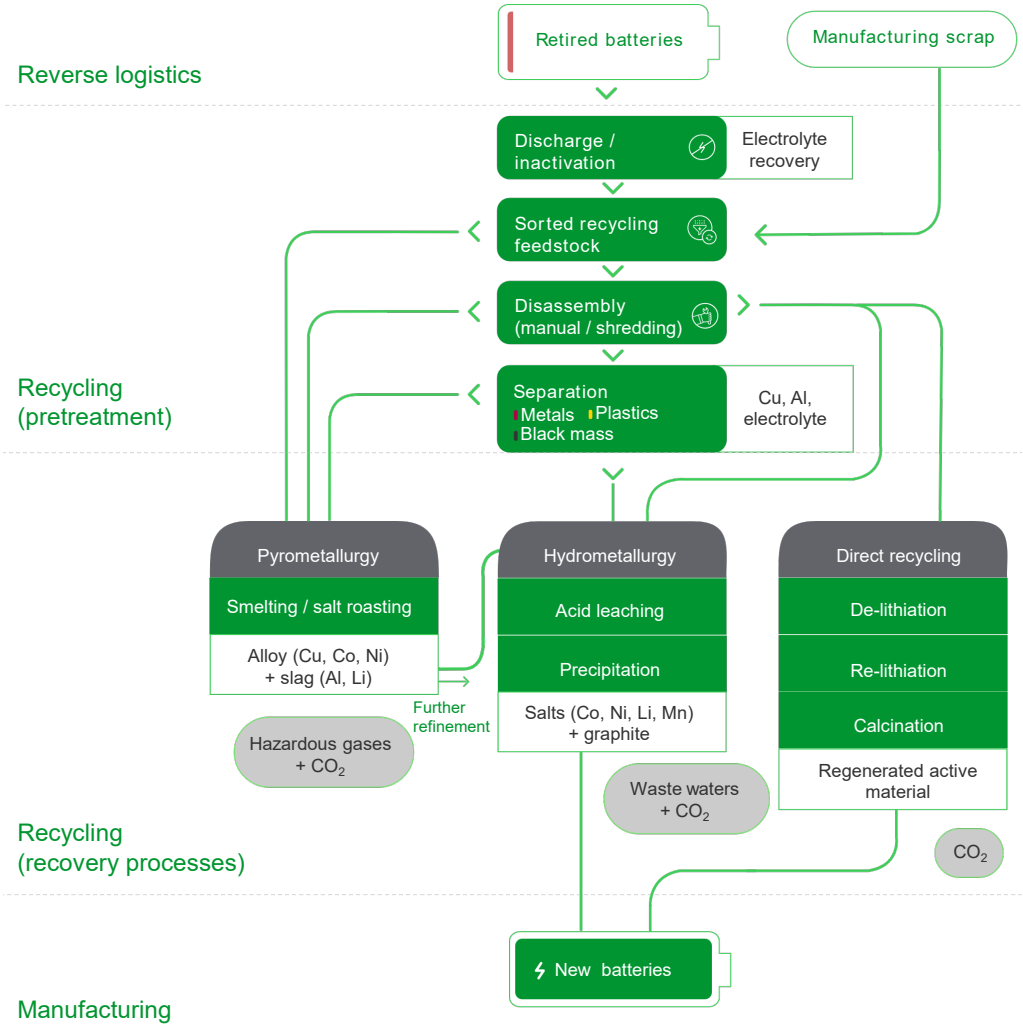



**Figure 3**

*Overview of main LIB recycling approaches (pyrometallurgy, hydrometallurgy and direct recycling), and processes involved*

*Recovered materials are shown at the respective processing steps, byproducts are indicated in light-grey boxes at end of the respective approaches. Some processing steps have been omitted for brevity. Actual recycling methods in industry may incorporate variations and combination of processes from different approaches*

**Challenge 14: production of dangerous waste waters in hydrometallurgy**

For the hydrometallurgical approach, a necessary mechanical pre-treatment subjects the batteries to shredding through a series of rotary mills. This produces a mixture of plastics, black mass[63] and metallic chips. Bulk separation of these materials is usually done by using their differences in density.

Hydrometallurgy implements a series of chemical reactions using highly acidic/alkaline aqueous solutions to extract metal salts (containing cobalt, nickel, lithium, manganese, etc.) from the black mass. Advantages of this process include low-energy and high yield (~95%); however, there are issues regarding the use of large amounts of water and the water purification processes needed.

[63] Alternatively, black mass can also be processed using pyrometallurgy, with the limitations in recovery of lighter materials previously described.

Increasingly, strategies to recycle the water within the processes are being implemented, therefore producing a net-zero effect and preventing pollution.

Advances in the recovery processes target increasing materials yield while implementing low energy, neutral water-based technologies (as opposed to highly acidic/alkaline solutions and/or using organic solvents). These show great promise toward more sustainable and economic extraction/recovery processes. These are possible with a better understanding of the recycling process, the materials, and their interactions with substances. Two notable examples are highlighted here.

The first is the recovery of ~75% Li using water-based mechano-chemical processes. This approach can be implemented for black mass regardless of the differences in battery chemistry[64]. And can further be coupled with hydrometallurgical processes to increase the recovered materials yield. The second example is the aqueous electro-extraction process developed by Nth Cycle, where materials are selectively recovered materials by using different voltages[65].

**Challenge 15: direct recycling dependence on pretreatment steps efficiency improvements**

Another approach under continuous development is direct recycling, where the cathode materials are separated from other battery components in the early pretreatment stages; and treated without going through dissolution or purification processes.[66] I.e., the cathode materials from the retiring batteries are treated to restore their original performance without destroying their chemical structure. This is achieved by using a combination of processes including re-lithiation[67] and annealing[68]. Also, other active materials within the batteries are recovered and upcycled, including the electrolyte and graphite.[69]

Direct recycling however depends on efficient pretreatment steps. Namely, sorting, discharging, disassembly and cathode material separation from its conducting substrate. Moreover, for this type of recycling, the huge breadth of battery chemistries, sizes and form factors (cylindrical, prismatic, or pouch) is problematic because the processes would need to be adjusted on-the-fly depending on the available LIB feedstock.

## Solutions and vector trends looking forward

As recyclability and recycling markets move forward, there are technical and business trends that should help increase LIB recycling rates and improve recycling economics. Strategies to simplify, automate, and streamline tasks; aiming to establish profitable business models and bring resiliency to the recycling value chain become crucial for success.

Recycling technologies are advancing, and recycling companies craft their own combination of processes to improve the materials yields. By coupling traditional

[64] Dolotko *et al.*, *Universal and Efficient Extraction of Lithium for Lithium-Ion Battery Recycling Using Mechanochemistry*, Mar. 2023, Communications Chemistry

[65] Nth Cycle OYSTER™ technology, <https://nthcycle.com/technology/>

[66] Montoya *et al.*, *Direct Recycling of Lithium-Ion Battery Cathodes: A Multi-Stage Annealing Process to Recover the Pristine Structure and Performance*, Sep. 2022, ACS Sustainable Chemistry & Engineering

[67] Re-lithiation is the process of restoring the Li content in reclaimed cathode material from retired Li-ion batteries to match the Li content of new Li-ion batteries with optimum electrochemical performance.

[68] Annealing is the process to heat up a material and cool it at a slow controlled rate to release internal stresses the material may have. The temperature and cooling rate depend on the type of material and desired material properties.

[69] *Direct Recycling of Materials*, ReCell Center

approaches, pyro- and hydro-metallurgy, with more recent ones such as electro-hydraulic extraction, additional advantages emerge. These include recovery yields of ~ 95%; and net-zero water consumption effect: water is used in a closed loop, minimizing the environmental impact.

Advances in direct recycling will have an enormous effect in minimizing the energy, emissions, and cost compared to the full recycling and battery re-manufacturing process. If refurbishment of cathode materials could be streamlined, other areas in the circularity model including recovery rates and profitability would improve. Used batteries would be considered items of high value, motivating participation from consumers, and collection and logistics partners.

Designing batteries with a circular perspective offers the potential to extend the life of LIBs through reuse in subsequent lives while facilitating the recycling processes. Circular design principles for batteries include: proper labeling and identification of battery chemistry and hazards; preference for bolted versus welded battery modules to ease disassembly; and standardization of modules and cells.

Reverse logistics requires clear policies, and guidance on transportation and safe handling of LIBs. Reverse logistics can be viewed as a fabric, as the cohesive element necessary to realize a resilient circular economy. It connects the LIB collection and distribution processes from manufacturers, vendors, and users to the recycling and remanufacturing partners. Given their importance, more effort should be spent to include collectors and transporters as essential partners via fair businesses and long-term agreements. This helps to further formalize their role and bring attention to issues in this area. In doing so, recovery rates of retiring batteries may be greatly improved by streamlining the recovery processes. Furthermore, safe and efficient logistics are put in place for all partners.

Frequent and open communication between LIB recycling stakeholders (local authorities, manufacturers, distributors, recyclers, etc.) to identify and address challenges is key for a functioning circular chain. Capitalizing on the newer technologies and sharing of information greatly helps coordinate efforts to overcome such challenges.

Another aspect that progresses local circular models around LIBs is centralized operations reporting. This delivers an official consolidated view of the impacts at scale. Such reporting could include the amounts of retired batteries entering the reuse or recycling streams, and the yields of repurposed batteries or recovered materials respectively. Similarly, other segments of the circular model could report their contribution to the system. Motivations for adopting a reporting system could include visibility and recognition, facilitating further partnerships. For governments, such a system facilitates decision making, and policy discussion and implementation.

## How artificial intelligence can help

ML/AI applied to collection, storage, distribution systems, and dismantling of waste LIBs, is already being researched and implemented[19,70]. AI is also applied to predicting recovered materials availability for trade from networks sharing recycling information, which greatly improves the profit potential.

[70] Yuan *et al.*, *A New Heuristic Algorithm Based on Multi-Criteria Resilience Assessment of Human–Robot Collaboration Disassembly for Supporting Spent Lithium-Ion Battery Recycling*, Nov. 2023, Engineering Applications of Artificial Intelligence

Looking forward, a larger AI system could predict the materials availability based on the implementation of battery IDs and their status update from different players in the battery supply chain. Another potential application of AI is in the optimization of new battery design. This includes standardization of battery chemistries and configurations for efficient handling at their end-of-life, whether reused/repurposed or recycled.

Furthermore, as new partners emerge and more data on operations becomes available, AI could be applied to run simulations of recycling models to forecast local systems capacity and resiliency. These simulations would help visualize the impact of the projects and identify potential issues before they have a negative effect in local economies.

## Conclusion

The strategic and environmental importance of EVs and reliable energy management at scale, motivates establishing a circular, resilient, and independent economy around energy storage systems and specifically LIBs. This is a worldwide phenomenon.

As new battery manufacturing plants are established, local recycling is expected to help secure the supply chain, mitigate materials price volatility, and reduce the environmental impact associated with mining of new materials and extensive landfill from waste batteries.

This paper discussed the ecosystem of partners working together in the circular business model to overcome the current challenges and capitalize on the opportunities. Partners involved in this circular economy work to improve the recyclability of LIB with better processes and systems. This allows users to have confidence in procuring products where recycling is central, ensuring a sustainable development of economies.

As a customer using LIBs, consider these five points:

- What are your organization's environmental goals and targets? How can your choices support achieving those goals?
- What is your position in the ecosystem, what is your role, and in which areas could you innovate?
- What are your reverse logistics considerations for collection, recycling, and reclamation? Are there potential partnerships to explore?
- What resources are currently available at various points in the LIB recycling value chain? And how can you leverage your expertise to benefit from these?
- What regulations, incentives, and/or penalties drive your participation and that of your ecosystem?

## About the author

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