Recharging the Future:

The Benefits of Battery Disassembly

INDUSTRY REPORT

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Introduction – The need for Electric Vehicles Battery Circularity

By 2035, millions of electric vehicles will reach their end of life, creating a massive wave of batteries that need to be responsibly managed. Studies estimate that that over 7.5 million EV batteries containing 2.3 million tons of high value material will need to be recycled in Europe alone with an expected tenfold increase of recyclable material between 2030 and 2040[1]. The lack of efficient recycling processes for EV batteries poses a significant challenge to the sustainability of the electric vehicle industry.

Improving the circularity rate of materials for EV batteries is becoming more and more important for multiple reasons:

1. **To decrease cost of EV vehicles and batteries to enhance European competitiveness**
2. **To develop local sources of raw materials and increase supply chain resilience**
3. **To comply with regulatory obligations**
4. **To achieve OEMs corporate sustainability goals**

Western OEMs need to reduce EV and battery prices to compete with Chinese entrants which have largely superior cost positions. With the battery contributing up to 40% of vehicle production cost[2], improving residual value and reducing raw material cost, which accounts for up to 65% of the total battery pack production cost, are key strategies to provide a more competitive pricing.

- Sourcing cheap material becomes more difficult. New mining projects have become increasingly expensive and geopolitically sensitive with China dominating refining capacities for all five key metals (Lithium, Cobalt, Nickel, Copper, Aluminium)[3]. Risk of resource and reserve depletion is top of mind for mining CXOs[4]. Copper ore grade, for example, has been declining from >1% to less than 0.6% since the late nineties[5]. This, combined with fewer discoveries (only 14 major discoveries since 2014 compared to 75 the decade prior), make developing quality mining assets at low costs challenging.

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[1] Strategy& 2023 for tonnage, one battery pack assumed at 350kg
[2] Deloitte, Study: The key role of battery costs in Automotive, 2023
[3] McKinsey Global Materials Perspective 2024
[4] S&P Global Market Intelligence exploration data
[5] BHP, 2024; using data from S&P Global Materials (1990 – 2000) and Wood McKenzie (2000 – 2030)

- Battery production cost on a EUR/ kWh basis are almost double in Europe vs. China. The investment required for a battery gigafactory, is almost double in Europe (106 MEUR per GWh/a) vs. China (55 MEUR per GWh/a)[6].

Given the challenge of finding competitive mining assets with an attractive risk-return profile, recycling material locally can create a steady flow of readily available material at a more predictable cost. Especially in tight copper and battery metal markets, high quality secondary material presents valuable flow at already competitive cost. This can also strengthen Europe's supply chain resilience by diversifying its sources of raw material and reducing its dependency on single suppliers, as pointed out as a strategic priority by the Draghi report on the future of European competitiveness.

From a regulatory point of view, the EU has set strict recycled content obligations for batteries sold on its market, with the required recycled content rising for lithium from 6% by 2031 to 12% by 2036, for cobalt from 16% to 26%, and for nickel from 6% to 15%. In addition to the battery-specific regulation, the wider 2023 Critical Raw Material Act (CRMA) mandates better control of supply chains and sets ambitious targets for origins of critical raw material (e.g., Lithium, Nickel, and Manganese): less than 65% of the consumption of those metals is supposed to come from countries outside of the EU. Considering Europe's dearth of raw materials and developed mining projects, a considerable portion of that material must, therefore, originate from recycled contents internal to the European market.

Finally, automotive OEMs have publicly committed to an increased use of recycled content, not only in batteries but in the entire vehicle structure, responding to some demand of the public opinion. For example, BMW set a 50% target, Stellantis (by 2030) and Mercedes-Benz 40%, and Renault 33%, while Northvolt, the Volkswagen-backed battery producer, set its ambition at 50%.

Current Challenges with EV Battery Circularity

While different alternatives exist to create "circularity" for EV batteries and their raw materials, recycling is the most appropriate choice for end-of-life ('EoL') batteries of EVs. The other options, retrofit and reuse, are costlier and more difficult to implement. The retrofit option raises numerous questions in terms of certification, safety, and warranty risk with OEMs shying away from implementing repair schemes, or even not planning for it in some Tesla models[7]. Also, the lifetime of new batteries is increasingly matching the useful vehicle lifetime[8] which decreases the need and attractiveness for replacement or

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[6] RWTH, Roland Berger Battery Monitor 2023

[7] Business Insider, Alexa St. John, Sept 4 2023, Tesla's Model Y Battery Has 'Zero Repairability'

[8] Kastanaki, E. & Giannis, A., 2023, Dynamic estimation of end-of-life electric vehicle batteries in the EU-27 considering reuse, remanufacturing and recycling options, *Journal of Cleaner Production,* Vol. 393

repair. On the other hand, the reuse option through e.g. battery energy storage systems, is conceptually attractive but the tangible economic benefits on a 'Levelized cost of storage' basis (i.e. calculated over lifetime) are uncertain[9]. Currently, actors in the market largely use near-pristine modules from overproduction or production scrap.

Therefore, the focus should be on increasing the efficiency and effectiveness of the recycling process through technologies that help reduce the process cost and increase the purity of the recycled output. One of these enabling technologies is automated disassembly, where innovative solutions are being developed. The implementation of these solutions would also answer the European needs identified in the Draghi reports, where it is critical that the region invest in new technologies and innovation to improve efficiency and sustainability of raw material extraction and processing.

The Recycling Process: From Collection to Refining

In order how to increase the efficiency and effectiveness of the battery recycling process, it is important to understand the main steps involved in this "resource recovery". The process described in Figure 1 below is focused on the hydrometallurgical road, in opposition to pyrometallurgical process, of which use is decreasing. It is already widely used today as it is especially more effective to recover Lithium; most announced future deployments in Europe follow that route.

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[9] Steckel et al., 2021, Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems, *Applied Energy*, Vol 300,

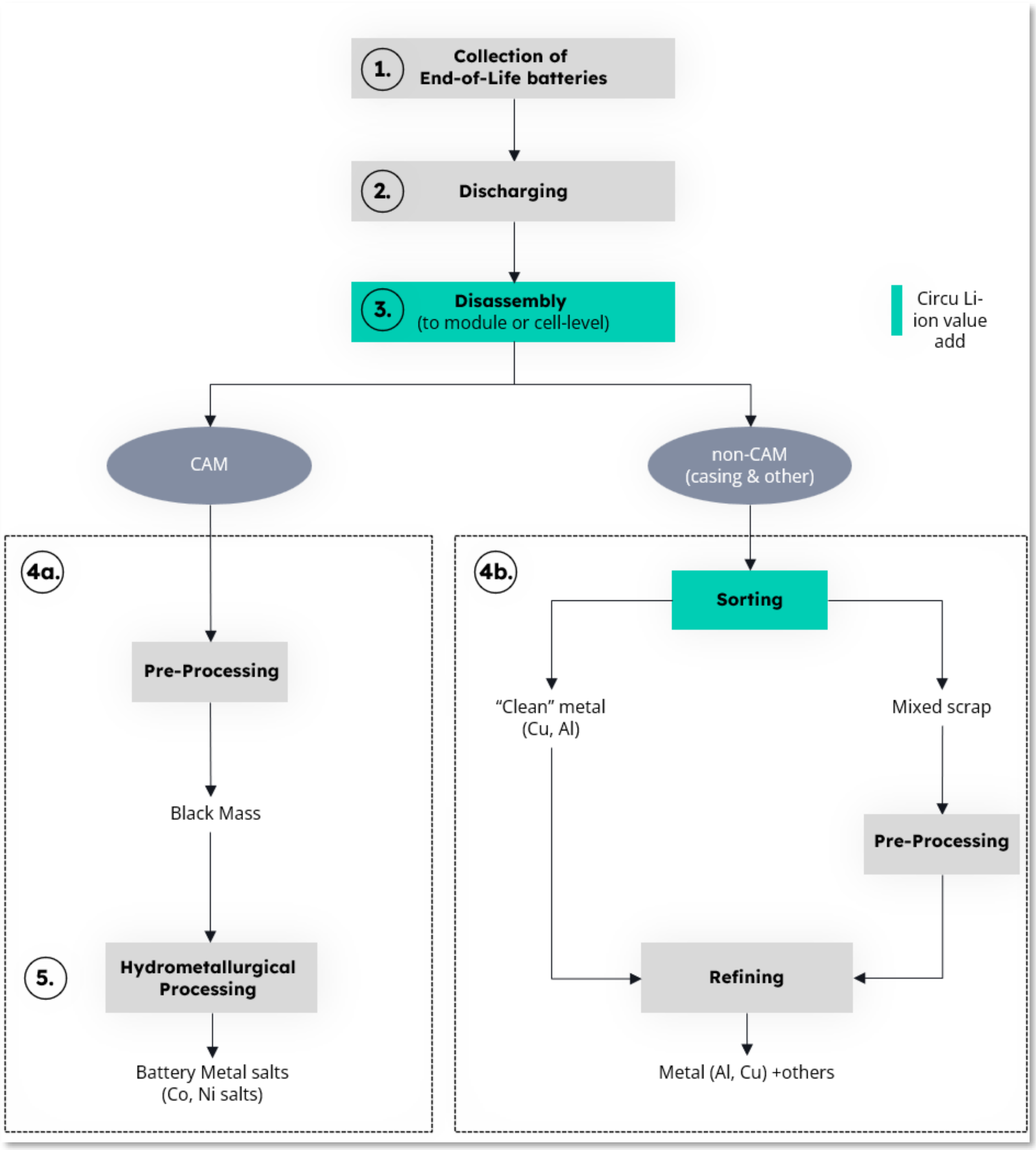

Figure 1. Recycling process and material flow for EV's Batteries

- Step 1 – **Collection**. Once the battery in an EV reaches its end of life, the battery pack is removed from the vehicle and collected through diverse collection schemes (scrap car dismantlers, independent collectors or service shops, logistics companies, OEMs in case of warranty)
- Step 2 – (Deep) **Discharge**. This is a critical step to allow the future handling of the battery. Given the safety issues, this requires specific procedures and highly qualified personnel

- Step 3 – **Disassemble**. As in the previous step, this activity must be accomplished by high-voltage-certified-operators manually opening battery packs and disassembling to module or cell level[10], which represent high operating costs. The outcome of this activity will create two streams of material:
    a. The first, which is made of modules and cells, contains the cathode active materials (“CAM”)– Nickel, Lithium, Cobalt, and, depending on the process, graphite[11]. After pre-processing, typically via shredding and material separation, this material yields ‘black mass’ with a high concentration of critical high value metals.
    b. The second is constituted of the casing material, typically made of aluminium, cables and electronic connectors (“non-CAM material”). The battery management system which contains rare earth material is also included
- Steps 4 & 5 are the actual **recycling** steps, which typically require both preprocessing (step 4) and refining (step 5)
    a. For the **CAM material**, the process flow is already well established based on creating a “black mass” which is then refined (most capacity today is live in Asia and black mass is usually shipped). The actual value chain enables the recovery of more than 85% of the original raw materials, that can then be reused in new batteries. The black mass is created through shredding and is then treated via a hydrometallurgical process. This allows to recover the material in the form of battery metallic salts (mostly cobalt, nickel). The black mass should amount to more than 1 million tons by 2035 (representing ~40-50% of pack weight)
    b. For the **non CAM material** (casing, other), the first step is a potential additional sorting and disassembly, which allows for some metal to be recovered and treated directly through the traditional refining path (e.g. “clean” copper or aluminium). Most of the time, the non-CAM material is simply shredded and the output separated into the different components, which are then refined following the traditional processes. This non CAM material could represent more than 0.6 million tons by 2035, of which 0.13 million tons of Copper and 0.47 million tons of Aluminium by 2035.

In regards to the black mass treatment for the CAM material (step 5 in Figure 1) hydrometallurgical processing, with or without a prior pyrolysis step, has gained mainstream adoption across Asia and attracted investment around Europe and North America.

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[10] Cell-level disassembly is not currently common practice in the industry but the increasing shift to cell-to-pack architecture pack design will require novel ways of disassembly while production scrap is often on cell-/ module-level rather than with finished packs

[11] It also still contains significant amount of Aluminium (in the module housing), Copper (as foils in the cell), and other material to be separated from CAM in subsequent steps.

Although the hydrometallurgical refining route is more effective for lithium recovery and in principle adaptable to different feedstock input, the process is sensitive to impurities, most notably Aluminium, Copper, and Fluorine, which complicates pre-processing and increases the need for clean and uniform black mass input. Aluminium and copper content beyond levels of around 1% in weight percentage is desirable, levels above 2% make the process economically challenging. Payables in the thinly traded spot market for black mass show a steep discount beyond that threshold[12] . Today, according to industry experts, this low level of impurity is unattainable for most commercial black mass producers in the market.

The scaling of the refining process with diverse feedstock is thus not yet a trivial task given the complicated flowsheets. In addition, metallurgical processes have a significant GHG footprint: while scope 1 emissions are usually substantially higher for pyrometallurgy, scope 2 and 3 emissions typically lift the GHG intensity of hydrometallurgy to elevated levels, even more when the CAM material is "dirty" and requires a lot of pre-processing.

Emerging Technologies – Direct Recycling

Responding to these challenges, 'direct recycling' has recently gathered increased industry and research interest as a possible paradigm shift to the utilization of purely metallurgical procedures used today. Some recent studies expect this technology to be up to 45% more efficient on a unit-economic basis against established metallurgical pathways, once commercially exploited. Compared to pyro- and hydro-recycling routes, direct recycling may also offer significant advantages in terms of energy consumption, safety and environmental benefits[13].

The core idea behind 'direct recycling' is to keep intact the chemical structures and 'rejuvenates' cathode and anode materials directly, instead of extracting material from black mass. This emerging process increases the recycling yields and shorten the required process to reintroduce the material into new cells[14]. The technology relies on separating, delaminating and washing the different elements after extracting the cells inner components, e.g., the 'jelly roll', and rejuvenating that material through a variety of techniques as seen in Figure 2.

In order to industrialize this new approach, scalable solutions to disassemble and separate cell components into foils will need to be developed. These will need to be adaptable to all the cathode designs.

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[12] Fastmarkets. 2024. CIF South Korea, CIF Southeast Asia and EXW Europe black mass payable indicators

[13] Wei, Gaolei et al.. 2023. Direct recycling of spent Li-ion batteries: Challenges and opportunities toward practical applications, *iScience*. Vol. 26 (9). 107676

[14] Jiawei Wu, Mengting Zheng, Tiefeng Liu, Yao Wang, Yujing Liu, Jianwei Nai, Liang Zhang, Shanqing Zhang, Xinyong Tao, Direct recovery: A sustainable recycling technology for spent lithium-ion battery, *Energy Storage Materials*, Volume 54,2023, Pages 120-134 https://doi.org/10.1016/j.ensm.2022.09.029.

By 2035, a combined ecosystem with hydrometallurgical and direct approaches is likely to be established to optimize the recycling for each feedstock input. In the meantime, the industry players are focusing on improving the economics of the current recycling routes, and automating processes is one of the key levers to do that.

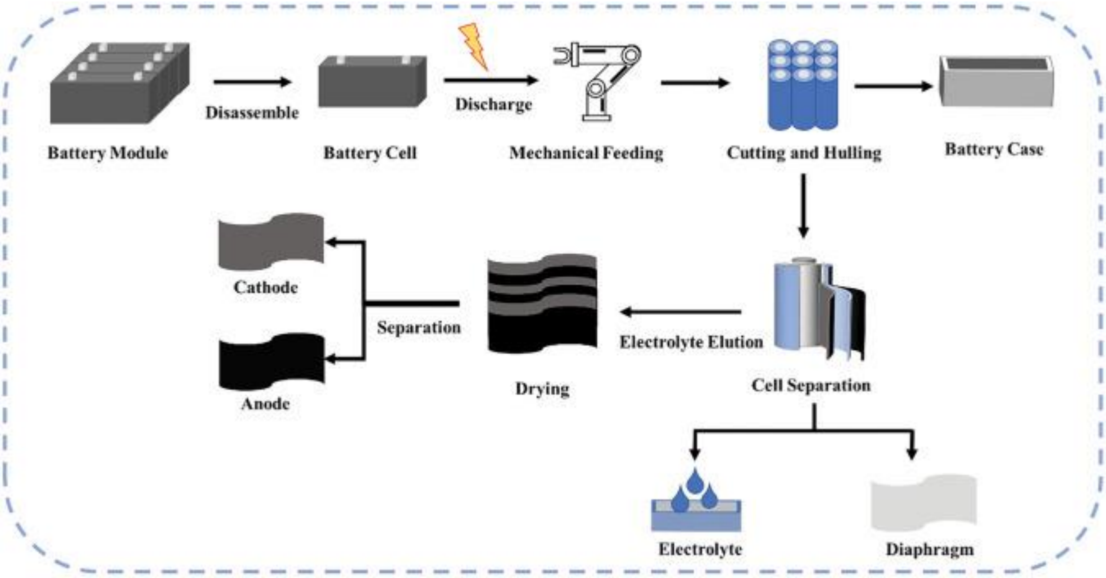

Figure 2. Direct Recycling Pre-Treatment[15]

Economic Benefits of Automated Disassembly

Current recycling business models are costly and heavily dependent on multiple factors, notably the diversity of battery design, the expensive labour cost, the inefficient operational processes and the high level of capex required. As described in the previous chapter, disassembly steps are crucial for battery recycling. Given the very manual nature of this process in today's operations, one estimates that significant value can be created by automating this step to lower cost and build a process flow that allows to recover higher value metals[16].

Cathode Active Materials (CAM)

For CAM, one estimates that robotization of the disassembly process can create a cost benefit of up to 195 EUR/ton of feedstock going to pre-processing (i.e. material after disassembly) and a potential additional value of 250-300 EUR/ ton of black mass in case

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[15] Huang, M., Wang, M., Yang, L. *et al.* 2024. Direct Regeneration of Spent Lithium-Ion Battery Cathodes: From Theoretical Study to Production Practice. *Nano-Micro Lett.* **16**, 225. https://doi.org/10.1007/s40820-024-01459-5

[16] Lander et al. 2023. Breaking it down: A techno-economic assessment of the impact of battery pack design on disassembly costs. *Applied Energy*, Vol 331

of cell-level disassembly. This represents a value pool of ~690mn EUR in 2035 for Europe alone, and double together with North America.

By automating the disassembly of the EV batteries, the following benefits are created in the commercialized recycling pathways:

1) The disassembly process becomes more efficient, and not reliant on highly qualified personnel. This represents a decrease from 200 EUR/ ton in operational expenses today to <70 EUR/ton in directly attributable labour expenses for disassembly
2) The pre-processing of material improves, creating two benefits:
    a. Reduce the weight of CAM to be further processed (i.e. having a better “quality” CAM with less irrelevant material and reducing wear-and-tear of machinery, esp. to separate Al content). Our first estimate is that by lowering the feedstock weight by ~25% for module-level disassembly, 37% for cell-level disassembly[17], this would decrease the attributable cost per kg output proportionally, i.e. going from ~260 EUR/ ton (including operational expenses and maintenance required) to ~195 EUR/ ton
    b. Reduce the impurity level in the black mass, especially in terms of Aluminium content. The target is to get 1% of Al content for commercially viable black mass, but it is usually substantially higher in operations today. The higher the Aluminium content, the more cost prohibitive it becomes to treat the black mass. Achieving lower level of Aluminium impurities can represent a reduction in treatment, which is significant since that the average OpEx per ton is 1,440 EUR/ ton for a plant in Germany[18]. Additional benefits are the reduction of other impurities such as copper, which impact less the refining costs but are more a safety concern.[19]

Automated disassembly is also a critical enabler to the direct recycling route, which is expected to decrease processing costs by up to 40% compared to hydrometallurgical pathways[20]. This should represent an expansion of the profit pool by ~1bn EUR over conventional metallurgical pathways, if NMC feedstock accounts for 80% of returning packs in Europe[21].

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[17] Based on VW MEB battery pack design analyzed by Circu Li-ion

[18] Lima et. al. for Neometals. 2022. Econommic Aspects for Recycling of Used Lithium-ion batteries from Electric vehicles. DOI:https://doi.org/10.3390/en15062203

[19] Expert interviews European and Asian Hydromet refiners and integrated recyclers (n = 4)

[20] Lander L, Cleaver T, Rajaeifar MA, Nguyen-Tien V, Elliott RJR, Heidrich O, Kendrick E, Edge JS, Offer G. Financial viability of electric vehicle lithium-ion battery recycling. iScience. 2021 Jun 25;24(7):102787. doi: 10.1016/j.isci.2021.102787.

[21] While empirical data is not readily available and no best practice process has been established, a hydrometallurgical process analysis from China suggests a hydrometallurgical profit of 1.50 USD (1.39 EUR) per kg battery feedstock for NMC622 batteries. Source: Vu, Thang Toan and Seo, Junhyung and Song, Daesung. 2024. A Comprehensive Techno-Economic Analysis of the Full Project for Recycling Valuable Metals from Waste Lithium-Ion Battery. Available at SSRN: https://ssrn.com/abstract=4820323 or http://dx.doi.org/10.2139/ssrn.4820323

Non CAM material (casing and other materials)

For other materials, the value created through automated disassembly relies mostly in lower operating costs since the current upcycling/refining processes to separate the different metals after shredding are already set-up as they are the same as those used for the recycling of metallic scrap (from internal combustion engine vehicles, from metallic structures, electric devices, etc). One estimates a potential reduction of operating costs of 30 EUR/ton, which would represent 70 million EUR in 2035 for Europe.

Total economic value of automation

As described in the previous section, the value creation potential of automating disassembly activities in the EV battery recycling process is significant. It is estimated at close to 700 MEUR by 2035 for Europe based on the current metallurgical routes (and would almost be double together with North America) and would require limited capex (current estimates at 100 MEUR for Europe, with expectations that equipment prices will go down in the future given scale and standardization).

Additionally, the shift towards the direct recycling route and its high upside value (1BEUR in Europe and double with North America) will only be possible through the implementation of automation for the “delayering” of CAM. The value will be created through the reduction in the operating costs of black mass material preparation (i.e. less/no shredding), the reduction of energy consumption in the hydro metallurgical process and the reduction in gas emissions (which could have an additional cash benefit in the future).

The increase in automation levels throughout the value chain will also offer additional advantages, that have not yet been quantified. For example, it will permit to set-up more local recycling centres, lowering logistics costs. These centres will no longer require highly trained workforce and will guarantee higher safety conditions for the remaining human operators. The automation of processes will create more data, that can be used to improve not only the tracking process and support the monitoring of regulatory requirements, but also influence the design of future EV batteries (“Design to cost”) .

Finally, once an automation unit is installed in a recycling centre, it will become much easier to expand its range of activities to the entire vehicle, allowing for example a better recovery rate of rare earth material from electronics components.

Investing in EV recycling automation solutions – A strategic imperative

Strategic investment rationale

Increasing the efficiency and effectiveness of EV battery recycling processes through automation is economically viable and will become an imperative for Europe to strengthen its supply chain resilience and sustainability objectives. Several actors can act to capture the potential value at stake through lucrative business opportunities:

- **"Scrap collectors and processors"** i.e. End of Life Battery Collectors (e.g. LKQ corp) and Pre-processors (e.g. Derichebourg Environnement, Celsa group, Radius Recycling), vehicle dealers and dismantlers, battery collection centres. These players are at the heart of the vehicle recycling process today and will continue to do so in the future. Through automated smart solutions, they can lower their operating costs and resell the scrap at a higher value, taking out some steps out of the operations and potentially removing intermediaries in the full value chain.
- **Refined metal producers** (e.g. Umicore). Today, these companies focus their business model on purifying extracted metals to meet the required specifications for use in batteries. By integrating urban mining solutions through automation technology, they could move up the value chain and allow them to allow them to control better their supply of key materials for their operations.
- **Mining companies** (e.g. Glencore, US Strategic Metals, Galp). In addition to their traditional extraction and beneficiation sites, the mining conglomerates want to add new local sources of supply, in order to meet the objectives and regulatory requirements defined by the European institutions, but also to add lower cost assets to their portfolio, given the degradation of the ground ore, and the increase in capex and risk to develop new extraction projects.
- **Automotive OEMs.** These players are currently investing heavily in sustainable solutions, in order to lower the lifetime cost of their EV products and meet the expectations from the market and their customers in terms of sustainability. OEMs look for solutions that maximize the recovery of valuable materials from EVs thus lowering the total cost of the vehicle. They also investigate alternatives to secure their sourcing of critical material to lower the risk of disruption in their supply chains. Additionally, in the future, an efficient disassembly process should allow them to reuse/repair more components and facilitate the aftermarket support.
- **Technology solution providers** (e.g. Tomra, Metso, Andritz) who develop and manufacture machines such as scrap crushers and cutters, where an automated sorting process could reduce operating cost of their solutions.

Case Example on mining houses – Glencore & Li-Cycle partnership

Glencore, a leading producer, recycler and marketer of nickel and cobalt, and Li-Cycle, a leading battery recycling company, announced in 2022 a strategic partnership to strengthen their influence on the worldwide battery raw material supply chains.
Through this partnership, Glencore aims to provide Li-Cycle's facilities with a constant flow of EoL battery feedstock. In return, the mining conglomerate will offtake the end-products from the recycling process, namely the battery grade materials and the byproducts. The agreement includes an LOI to jointly develop a feasibility study for building up the biggest European hydrometallurgical plant in Italy at an existing Glencore site. With the development of the new hub, both parties are aiming to process up to 70,000 tons of black mass per year to produce battery grade material. The feasibility study is currently under review and the hub is expected to go into operations in 2027.
With this, Glencore aims to become a key automotive OEM supplier of battery grade materials coming from recycled raw materials to help EV OEMs meet their regulatory requirements related to recycled content in new EV batteries.

Case example of automotive OEMs - Volkswagen

In Germany, Volkswagen has invested significant resources and attention into shaping a recycling flow with its in-house cell producer PowerCo.
In its home country, the company has built a pre-processing battery recycling plant to improve the circularity of their EV batteries. The recycling plant employs the hydrometallurgy process to recover metals out of black mass produced from its own VW EoL batteries. The company expects to process 1,500 tons of batteries per year in a pilot phase designed to gain meaningful insights to scale-up at a later stage and secure raw materials for their supply chain.
Besides the piloting initiative in Germany, the company has also forged direct partnerships with battery recyclers, including Redwood Materials in the US, and has also invested in CAM-production through a joint venture with materials company Umicore, called Ionway.

Investment imperative

Projections for the volumes of end-of-life EV batteries forecast exponential growth in the coming years. Finding the right solutions to optimize the full value chain of EVs throughout their lifecycle and secure the required raw materials is becoming an urgent topic. To secure a winning position in the recycling flow, early movers will gain competitive advantages thanks to:

1. The establishment of a **scalable value chain**: As the demand for critical raw materials intensifies, building a robust and scalable value chain is essential. This

enables the efficient recapture of valuable resources, ensuring long-term sustainability and profitability.

2. The anticipation and adaptation to the **regulatory dynamics**: The regulatory landscape is subject to rapid changes driven by geopolitical shifts and evolving climate policies. Companies must not only react swiftly to these changes but also proactively influence future regulations to create a favourable operating environment.
3. The creation of an **optimized ecosystem** with committed partners: Developing a comprehensive ecosystem to optimize all the steps of the value chain is crucial. This will enable the reduction of carbon footprints, enhanced resource security, and foster innovation in recycling technologies, while enabling a wider adoption of EVs.

Companies should invest today in the burgeoning market for EV battery recycling. This will put them in a leading position to approach a future where sustainability and resource efficiency will become paramount. This proactive approach will not only yield significant financial returns and secure supply chain, but also contribute to the global environmental goals.

Recommendations

With the current EV market expected to grow exponentially, and the first batches of EV coming end-of-life, the issue of EV battery recycling is becoming critical.

Current recycling solutions are inadequate, being both costly and inefficient in recovering materials in their original form. Automating the disassembly process can revolutionize this sector and create a genuine urban mining resource. This also paves the way to recycling alternatives in the future, such as retrofitting or repair.

With its proven solutions, Circu Li-Ion stands as your ideal partner in transforming the recycling sector for EV and create urban mining solutions. We are committed to “creating” the resources of the future, all while minimizing capital expenditure and safety and environmental risks.