Faraday Insights - Issue 20: July 2024

THE FARADAY INSTITUTION

Developing a UK lithium-ion battery recycling industry

Jonathan Leong, Business Intelligence Manager, Faraday Institution

Establishing a battery recycling industry in the UK will enhance the security of the supply chain for the raw materials needed for EV battery production, while also ensuring the sustainable treatment and management of used materials. At present, recycling is a labour-intensive process, with costs heavily dependent on factors such as battery chemistry, commodity prices and recovery efficiency. Developing and implementing advanced recycling technologies and processes should increase efficiency, reduce costs and help foster a circular domestic battery economy.

Introduction

The transition to electric vehicles (EVs) requires large amounts of raw materials, such as lithium, nickel, cobalt, copper and graphite, to manufacture the batteries that power them. When these batteries reach end-of-life (EOL), it is important that the materials they contain are appropriately managed and their value maintained.[1]

The recycling industry will become a substantial global and UK economic opportunity in the 2030s as EV batteries manufactured in the early 2020s reach their EOL. Creating a circular battery economy through recycling in the UK would not only reduce the UK's dependency on importing critical materials, such as lithium, graphite and cobalt, but also reduce carbon emissions, environmental costs and the need for mining virgin raw materials around the world. As such, and as recognised in the UK Battery Strategy, recycling will be a vital part of the development of a more secure and resilient battery supply chain.[2] The need for this has been exposed by disruptions in global trade as a result of the pandemic and energy crisis. It is also an issue that the UK will find difficult to sidestep as battery recycling will be a necessary component of the EOL waste management of EVs.

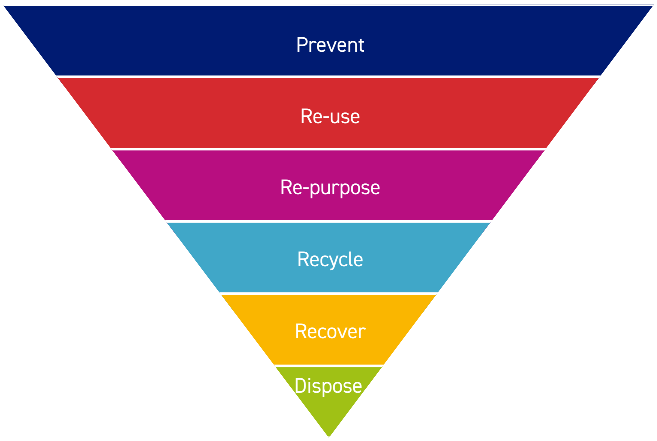
Recycling is not the only possible option for EOL lithium-ion batteries but part of a waste management hierarchy (Figure 1) also involving re-use, re-purposing, recovery and disposal. Before recycling and the recovery of materials is undertaken, in many cases cells will be re-used or re-purposed. Re-use involves using the cell again for its initial purpose, such as an EV, after undergoing refurbishment or repair. It is often viewed as the preferred first option as it retains the prior processing value by utilising the cell in another automotive application. Re-purposing involves utilising the cell in an alternative, less demanding application, such as stationary storage, with minimal changes to the cell itself. A potential downside of this approach is that high-specification battery materials are used in lower-grade applications that they are neither needed for, nor best suited to (delaying recovery of materials that could be used for the remanufacture of future batteries). Disposal is the least attractive option, as ecological and environmental damage is of concern due to the potential leaching of toxic materials, as well as the loss of valuable minerals. Batteries are banned from being incinerated or dumped into landfill in the UK under the Waste Batteries and Accumulators Regulation 2009.

Image: Shredded battery feedstock. Courtesy of ReLiB project, University of Birmingham.

1 Nature (January 2019). Recycling lithium-ion batteries from electric vehicles.

2 Department for Business and Trade (2023). UK Battery Strategy.

Figure 1: Waste management hierarchy



Source: Faraday Insight 9 (September 2020).

This insight outlines the size of the global recycling market, the key recycling processes and the economics of battery recycling, particularly the challenges involved in retaining the value of recycled materials. Developments in the UK and European recycling industry along with the opportunities and challenges for the UK to establish itself as a leading battery recycling location are also highlighted. The Insight complements Insight 9: The importance of coherent regulatory and policy strategies for the recycling of EV batteries.[3]

Establishing a UK-based lithium-ion battery recycling industry is crucial for creating a resilient, sustainable and secure supply chain. Cost-effective and efficient recycling in the UK will not only encourage parts of the battery supply chain and manufacturing to locate in the UK but also spur innovation and enhance the UK's position in the global battery economy.

Global and UK Battery Recycling Market Size

Volumes of EOL battery material available for recycling are anticipated to be fairly modest throughout the 2020s. EV battery life is currently around 10-15 years, so EVs sold before 2020 would mostly not be ready for recycling until after 2030, and then only if battery recycling occurred at the end of first use. Given the potential for second-life applications,[4] material availability for recycling may be delayed even further, perhaps by another five years or so. This means EOL recycling volumes are not expected to increase sharply until the mid-2030s.

Recycling opportunities will, however, occur much earlier through the need to recycle manufacturing scrap generated during the battery production process itself. Production scrap originates in many different areas, such as cells that fail to meet quality control standards, defective cells and modules or unused excess electrode material. Production scrappage could be as much as 20-30% during the initial scale up and optimisation phase, before falling back to about 5-10%.[5] Production scrappage is expected to be the primary source of recycling material throughout the 2020s.[6] In the 2030s, the proportion of recycling from EOL batteries increases significantly and by 2040 around 83% of recycled battery material is expected to originate from EOL batteries.[7] In addition, there is also a small but significant proportion of EVs written off by insurers each year due to the inability to repair or assess damaged EV battery packs after, for example, vehicle collisions.[8] Such damaged batteries are often deemed as unsuitable for reuse and need to be recycled.[9]

Around 3.7 million metric tonnes of battery material are expected to be available globally for recycling in 2035, supplying 10% of the lithium and 18% of the cobalt and nickel metals required for battery manufacturing.[10] China leads the world in battery recycling and is set to have around 430 GWh of batteries available for recycling by 2035, compared to a global total of 770 GWh (Figure 2). This is due to early EV adoption, substantial EV sales and established networks for collecting, disassembling and recycling used batteries. Europe and the US somewhat lag behind China, with estimates of 140 GWh and 120 GWh respectively available for recycling by 2035.

3.7 million tonnes of battery material available globally for recycling in 2035

10% of Li needed for battery manufacturing could be supplied from recycled material

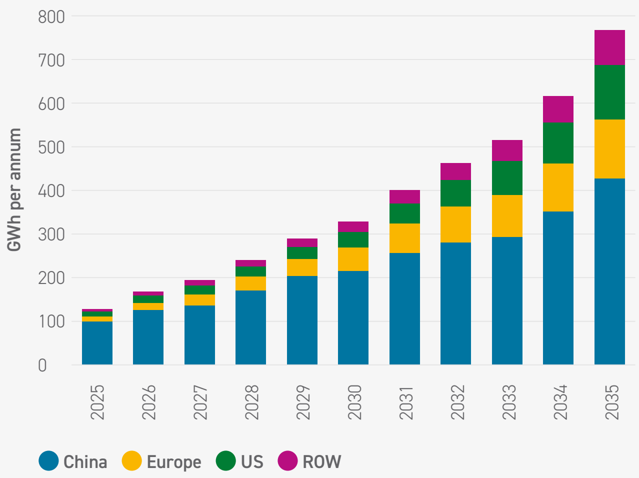
18% of Co and Ni needed for battery manufacturing could be supplied from recycled material

Recycling Processes

Current battery recycling processes are focused on the recovery of high-value metals and are split into three main technological methods: pyrometallurgy, hydrometallurgy and direct recycling. A simplified process flow diagram highlighting these battery recycling routes is given in Figure 3. While the initial logistics (e.g., steps such as transportation and handling) are common across these processes, the procedures deviate from the disassembly stage onward.

[3] Faraday Insight 9 (September 2020). The importance of coherent regulatory and policy strategies for the recycling of EV batteries.
[4] Office for Product Safety and Standards (January 2023). A Study on the Safety of Second-life Batteries in Battery Energy Storage Systems.
[5] BNEF (February 2024). Lithium-Ion Battery Recycling Market Outlook.
[6] Benchmark Mineral Intelligence (September 2022). Battery production scrap to be main source of recyclable material this decade.
[7] McKinsey (January 2023). Battery 2030: Resilient, sustainable, and circular.
[8] Reuters (March 2023). Scratched EV battery?
[9] Carwow (October 2022). Electric Car Battery Recycling.
[10] BNEF (March 2024). Lithium-Ion Battery Recycling Market Outlook.

Figure 2: Battery recycling availability by region



Due to early EV adoption, substantial EV sales and established networks for collecting, disassembling and recycling used batteries, China leads the world in battery recycling.

Source: BNEF (March 2024). Lithium-Ion Battery Recycling Market Outlook

Pyrometallurgy and hydrometallurgy are currently used in industry whereas direct recycling is still at the research stage.

For EOL lithium-ion batteries, recycling processes are focused on the recovery of the cathode materials, as they contain the majority of valuable materials. Some of the first commercially available lithium-ion batteries were lithium cobalt oxide (LCO) chemistries used in consumer electronics, where the valuable cobalt was prioritised for recovery. The introduction of new cell chemistries into the market, such as cobalt- and nickel-free lithium iron phosphate (LFP), affects the profitability of recycling.

Box 1: Key recycling technologies

Battery recycling processes cover three main technologies – pyrometallurgy, hydrometallurgy and direct recycling – which differ by complexity, efficiency and cost-effectiveness.

- Pyrometallurgy offers simplicity and high capacity but has a relatively low lithium recovery rate and high energy requirements.
- Hydrometallurgy provides higher recovery rates with less energy use but involves complex chemical processes and potential environmental risks.
- Although direct recycling promises high material recovery with minimal environmental impacts, it is still in the early stages of development. It faces challenges in scaling and integration into existing processes, as well as adapting to a variety of different cell chemistries and designs.

Pyrometallurgy

Pyrometallurgy was the first recycling process used at an industrial scale and involves using high temperatures to purify valuable metals. Metals recovered through this process require further treatment to achieve battery-grade purity. The pyrometallurgy process does not necessarily require pre-treatment of the materials to be recycled, but pre-treatment shredding is often conducted to allow separation of some of the lithium before combustion so avoiding a major loss in lithium inventory, therefore increasing economic viability of the process.

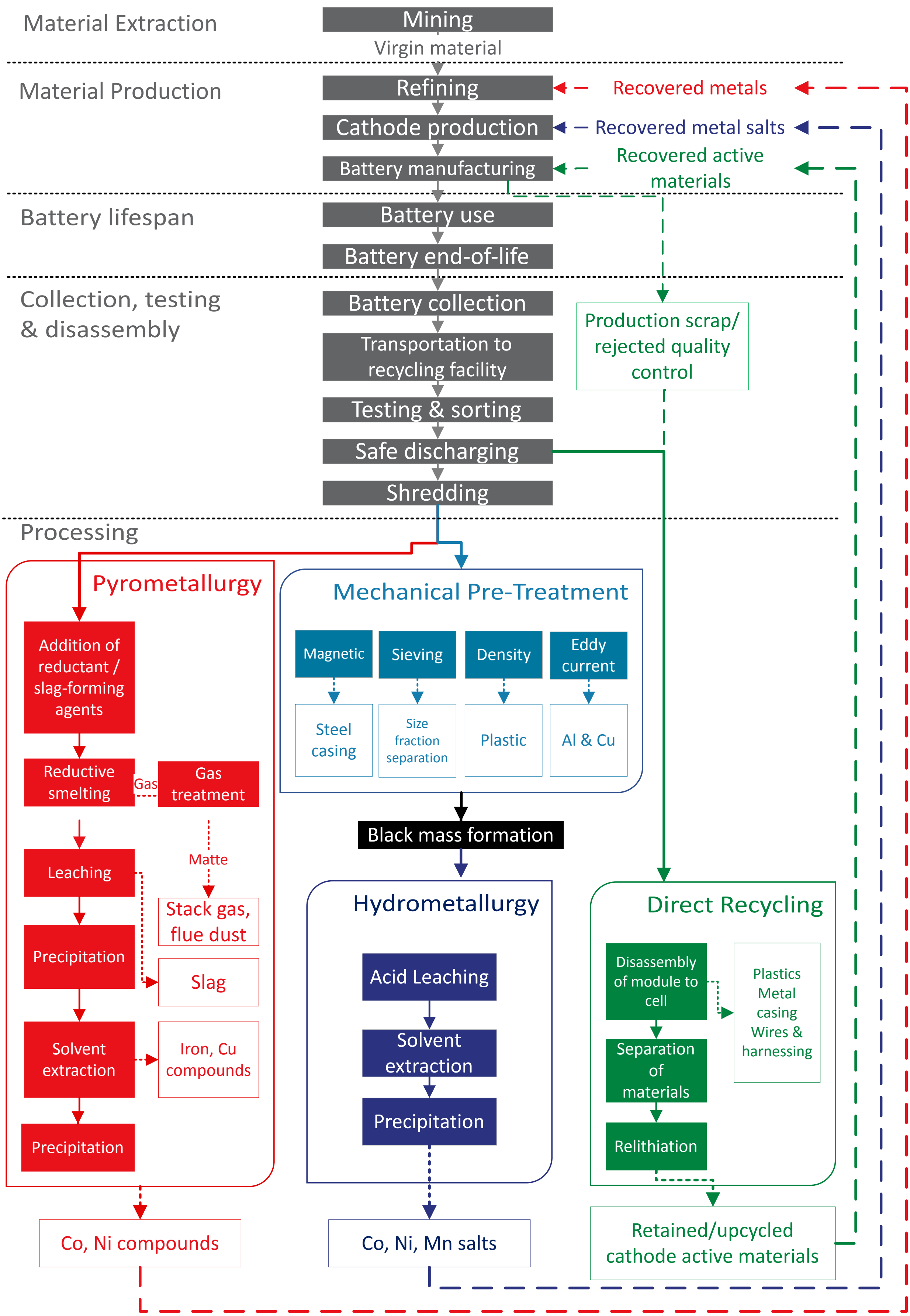
In the pyrometallurgical recycling process, an initial thermal treatment (140°C to 500°C) is employed to remove volatile electrolytes and organic solvents prior to the main smelting processes (1400°C to 1700°C).[11] The first temperature zone, called the "pyrolysis zone", generates energy from the combustion of these organic materials that can be used to reduce overall energy demand. These processes yield alloys (which include cobalt, copper and nickel) and an oxide slag (containing lithium and aluminium), which can be reduced and further purified via leaching and solvent extraction methods.[12] Some battery components, such as the plastics and graphite, combust and release energy, thereby contributing to and reducing the electrical energy required to generate the high temperatures required. The key advantage of pyrometallurgy is the ability to process mixed waste streams and the low sensitivity to cell provenance and composition.

Pyrometallurgy is a relatively simple process with short reaction times and a lower consumption of concentrated acids than hydrometallurgy.[13] Given the high rate of chemical reaction, coupled with a large treatment capacity and scalability, it has matured into a widely adopted recycling process. European companies such as Umicore (Belgium), Glencore (Switzerland) and Accurec (Germany) have implemented this process. Pyrometallurgical technologies are also predominant in countries such as Japan and Korea and remain extensively utilised in China, reflecting a current global preference for these established recycling methods.

The main drawback of pyrometallurgy is the material loss, including loss of the electrolyte and graphite anode, leading to a low recovery rate and loss of a critical material. Another drawback is that pyrometallurgy results in significant carbon dioxide and toxic gas emissions.[14] However, over the last decade, pyrometallurgical technologies have matured to the point where toxic gases produced are captured and treated, significantly decreasing the impact on the environment. In addition, the high temperatures needed require substantial capital expenditure on equipment and high energy consumption during operation.

[11] Energy Fuels (October 2021). Comprehensive Review on Concept and Recycling Evolution of Lithium-Ion Batteries (LIBs).
[12] Joule (2019). Recycling end-of-life electric vehicle lithium-ion batteries.
[13] Journal of Power Sources (April 2021). Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review.
[14] Engineering (June 2018). A Mini-Review on Metal Recycling from Spent Lithium-Ion Batteries.

Figure 3: A simplified flowsheet of pyrometallurgy, hydrometallurgy and direct recycling



Only cobalt, nickel and copper can be recovered as alloys during the pyrometallurgy process. To extract the lithium that would otherwise be lost in the slag, a combined approach using pyrometallurgy and hydrometallurgy has been proposed, where the lithium is leached from the slag via hydrometallurgical processes.[15] Other techniques, such as vacuum evaporation, which utilises reduced atmospheric pressure to facilitate evaporation to recover lithium have also been proposed.[16] These hybrid approaches not only ensure the safe containment of hazardous battery components but have also increased industrial-scale recovery rates to 95% for cobalt, copper and nickel from mixed battery sources, as demonstrated by Umicore.[17] Increasing the recovery rate of lithium and graphite would further increase the sustainability of this process.

Hydrometallurgy

Whilst pyrometallurgy is a mature and dominant recycling process, recent literature and commercial interest have shifted towards hydrometallurgy. This process involves the use of leaching agents, such as inorganic or organic acids, to dissolve the metals in EOL batteries into a solution, which can then be separated and recovered. Different reagents can be employed to selectively extract a particular metal, producing a purer waste stream than is possible using pyrometallurgy, which requires less downstream refinement to reach the quality required for battery remanufacture. The increased recovery rate and yield of metals, combined with fewer purification steps and a lower energy and CO_2 emissions footprint, have resulted in growing industrial interest in hydrometallurgy. In Asia, for example, South Korean recycler SungEel HiTech operates with a hydrometallurgical focus while GEM and Brunp in China apply hydrometallurgical methods.

The process of hydrometallurgy delivers a high recovery rate of over 98% for copper, nickel and lithium. The first step in the process is a compulsory pre-treatment step, where the cells are discharged and undergo comminution - a process to reduce the material particle size. This typically involves crushing, shredding and other processing steps to allow the separation of the valuable metals from other materials (including plastics and steel casings). The process is not without risks. The release of volatile organic compounds and highly corrosive hydrogen fluoride poses a significant safety challenge. These risks can prove a hurdle to industrial development due to the potential for secondary pollution.[18]

The output of the shredding and pre-treatment stage is a valuable mixed metal waste referred to as 'black mass' (see Box 2). At this point, it can be bought and sold as a commodity for further treatment.

Further treatment of the black mass uses acids or solutions to selectively react to dissolve and precipitate metal salts. Various parameters such as temperature, pH level and acid concentrations can affect the metal extraction efficiency and purity.

The substantial consumption of chemical reagents in this process induces environmental hazards. These include the potential for chemicals to percolate into the ground, which can result in wastewater pollution, hazardous residue and ecotoxicity concerns. Moreover, the multiple chemical interactions required to leach and separate the materials is a long and complex process that is highly dependent upon the reagent selectivity (the ability of an acid to target one particular metal to react with).

The central focus of academic and industrial hydrometallurgy

Box 2: Black mass as a commodity

After the shredding process, the intermediate product, black mass, contains valuable metals including cobalt, nickel, manganese and lithium. The value and price of this commodity are determined by battery-grade mineral spot prices, where each valuable mineral contributes to the total black mass price. The black mass price differs from the virgin material spot price to account for the recycler processing costs and margins, and will also differ by region and by individual offtake agreements.

The purity of the black mass, which significantly affects further processing and overall economics, is dependent upon the type of feedstock. Production scrap from a battery facility is typically derived from a known single source, thus resulting in higher recovery and purity rates. Conversely, when multiple battery chemistries and waste streams are combined and shredded, additional separation processes are needed to remove impurities. The unwanted impurities, such as aluminium, iron and copper, originate from battery components such as foils and casings. Removing these impurities requires additional processing steps, with an associated economic cost.

Variations in purity and composition contribute to different gradings and prices for both the black mass and the extracted metals, as higher purity levels typically command higher prices. However, there is currently not a consistent market benchmark for this commodity. Most is currently exported to Asia to undergo hydrometallurgy, as this attracts the most competitive prices.[19]

Currently, the UK does not have any operational commercial-scale hydrometallurgy capacity or cathode active material production. Establishing and aligning both of these would allow for a retained domestic supply that can onshore material processing and production.

[15] Journal of Power Sources (2012). Development of a recycling process for Li-ion batteries.
[16] Chemie Ingenieur Technik (October 2015). Recovery Concept of Value Metals from Automotive Lithium-Ion Batteries.
[17] Umicore: Capturing profitable growth and enabling a circular and low-carbon battery value chain.
[18] WMG & Advanced Propulsion Centre UK (2022). Considerations in Lithium-ion Battery Recycling.
[19] Advanced Propulsion Centre (2023). Automotive Battery End-of-Life Value Chain.

research is to further improve the material recovery rate and to achieve the purity required in battery manufacturing in the most economic and environmentally friendly manner. Materials need to have a high purity (greater than 99%) to qualify as battery-grade quality. However, components within the battery, such as copper and aluminium foils, can significantly affect the performance of the precious material if not adequately removed before the leaching stage. Improved mechanical separation techniques and the effective segregation of cathode and anode waste streams can help improve this purity.

Increasing the recovery rate further could involve recovering materials where it might not be economically viable to do so, or where there is plenty of market supply. These materials include graphite, polymers (including binders), electrolytes and separators. Other challenges will arise with the shredding of larger pack sizes and the accommodation of new structures, such as cell-to-pack where the battery is integrated into the car's chassis or frame. Appropriate design of the latter could potentially make pack dismantling significantly easier than current models.[20]

The release of toxic gases or residual wastewater during hydrometallurgical processes has led to research focusing on the use of alternative reagents with a lower ecological footprint. These include using organic acids (e.g., citric, succinic and ascorbic acids) for leaching to avoid the generation of carbon dioxide and chlorine gases, which are produced when using inorganic acids.[11] A more novel alternative is bioleaching, which utilises bacteria or fungi to produce inorganic or organic acids that can be used for leaching.[21] The industrial application of bioleaching is challenging and currently slow due to long treatment periods, slow microbial culturing and the use of low concentrations of metal ions. However, it offers significant advantages such as energy savings and reduced environmental impact.[22] Another alternative is the use of a class of solvents called deep-eutectic solvents,[23] which provide a highly selective, efficient and readily reusable alternative.[24] There is also the potential for graphite to be recovered via water delamination,[25] a simple, all-in-one delamination and washing process that could minimise hazards encountered by using alternative solvents. Challenges remain over the performance of the recovered material as it is affected by local contamination and air exposure.

Direct recycling

Direct recycling involves repairing and maintaining the functional cathode structure with minimal changes by supplementing lithium salts into the structure of lithium-deficient cathode materials. This could potentially yield a high value product stream with a low energy consumption and few post-processing steps.[26] Unlike pyrometallurgy and hydrometallurgy, the cells require disassembly to physically separate and recover battery components, with a focus on the cathode material, which holds around 50% of the battery's value.

Direct recycling has numerous benefits such as retention of economic value, lower environmental impact due to the absence of harsh chemicals used for leaching, and the need for fewer downstream processing steps. In particular, the pre-existing crystal structure of the recycled cell is retained, instead of a metal ore or salt that has to be processed and refined, which reduces the energy requirements of the recycling process. The reduction in intermediate steps also reduces yield loss, resulting in an overall higher recovery rate. Furthermore, this approach reduces the likelihood of impurities contaminating the material, producing a higher-quality material. Ideally, direct recycling could be integrated into battery manufacturing itself, enabling the recovery of production scrap without altering their composition or undergoing extensive processes to breakdown, refine and remanufacture the component materials.

Direct recycling is a less mature technology than pyrometallurgy and hydrometallurgy with no commercially established industry. Scale-up optimisation is required to identify roadblocks and cost-intensive steps to ensure commercial viability. The disassembly step is currently performed manually, requiring skilled labour and specialist equipment. Automating the physical disassembly could provide a quicker, safer and more accurate method for scaling this promising approach, thereby optimising the recovery of valuable material.

During battery use, around 20% of the useable lithium is lost due to undesired parasitic reactions and the formation of interface layers.[24] These side reactions consume some of the active lithium available, leading to increasing internal resistance, worsening electrochemical performance and early cell failure. As such, batteries being manufactured from recycled cathodes using direct recycling methods would require additional lithium to replenish the original cathode capacity. The process of lithium addition would have to be conducted in a way that does not hinder the reaction pathways that could impact the performance of batteries remanufactured from the recovered material. Research is being conducted to improve processes that restore the lithium ratios and microstructure, including optimising coating methods or sintering.[27]

[20] Green Chemistry (2020). The importance of design in lithium-ion battery recycling – a critical review.
[21] Metalurgija (2015). Biohydrometallurgical methods for metals recovery from waste materials.
[22] ACS Sustainable Chemistry & Engineering (September 2018). Hydrometallurgical processes for recycling spent lithium-ion batteries: a critical review.
[23] Deep eutectic solvents (DES), are a type of ionic solvent that is generally composed of two or three substances capable of self-association to form a mixture with a melting point lower than each substance. The solubility and selectivity of DES make it a promising green alternative for the extraction of transition metal oxides, including Co, Ni, and Mn oxides.
[24] Resources, Conservation and Recycling (January 2023). The application of deep eutectic solvents in lithium-ion battery recycling: A comprehensive review.
[25] Journal of Materials Chemistry (2023). Reclamation and reuse of graphite from electric vehicle lithium-ion battery anodes via water delamination.
[26] ACS Sustainable Chemistry & Engineering (2022). Direct Recycling of Lithium-Ion Battery Cathodes.
[27] Materials Today Energy (2023). Direct recycling of degraded lithium-ion batteries of an electric vehicle using hydrothermal relithiation.

Box 3: Performance of recycled materials

Slight deviations in the composition of battery cathode materials can compromise battery performance, meaning that incorporating recycled materials into existing material streams adds additional risk to battery manufacturing.

In-use, battery materials degrade over time due to a variety of factors including chemical, electrochemical and mechanical processes. Consequently, there is a pressing need for the development of treatment and assessment methods that can ensure recycled materials are comparable with virgin materials. Given these challenges, many battery manufacturing companies consider recycled material as inferior to virgin commercial material.

However, some studies[28] have concluded that recycled materials have similar performance to virgin materials, with some evidence that recycled cathode material might even outperform their virgin counterparts. One mechanism behind this superior performance is an increase in porosity, which allows lithium ions to be better accommodated into the cathode resulting in less straining and cracking and reduced battery degradation. The increased exposed surface area also provides more sites for lithium to penetrate the cathode structure, potentially enabling faster charging.

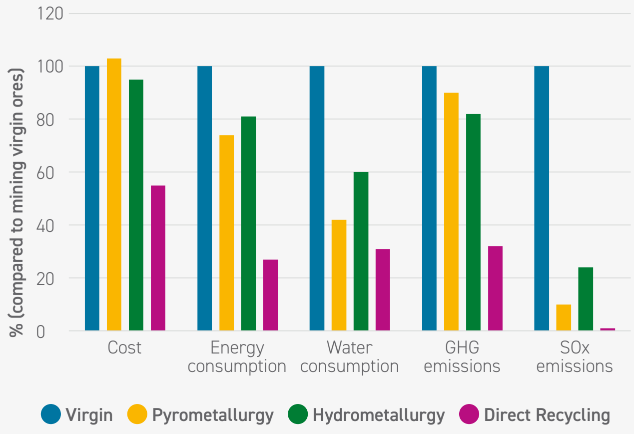
Any promising performance benefit from recycling could positively contribute to the economic viability of direct recycling and battery remanufacturing. This is particularly relevant in a market with increasing demand for low-cost batteries and security of critical material supply.

Upcycling is a variation to direct recycling. Upcycling involves altering the cell chemistry to update it to a more commercially relevant and desired composition compared to direct recycling, which allows the cathode material to be replenished to the same previous composition. For example, the Faraday Institution ReLiB project is exploring upcycling lithium-titanate (LTO) anodes into more desirable niobium-based anodes that can offer a higher energy density.

Environmental Performance of Recycling Methods

The choice of recycling methods has a significant impact on energy and environmental sustainability. In Figure 4, key environmental metrics, including greenhouse gas (GHG) and sulfur oxide (SO_x) emissions, and water and energy consumption, are compared against mining virgin ores for lithium nickel manganese cobalt oxide (NMC) batteries. This analysis from Argonne's EverBatt model compares performance metrics for a 50,000 tonnes per year recycling capacity, and at this potential scale shows direct recycling having the lowest impact across all categories.

Figure 4: Environmental and economic costs of producing NMC111 utilising virgin ores or recycling methods



If adopted at scale, direct recycling would have lower environmental impact than pyrometallurgical and hydrometallurgical processes.

Source: Recycling (May 2021). Direct recycling R&D at the ReCell Centre. Numerical data for figures.

Economics of Lithium Battery Recycling

The turnover of the global lithium-ion battery recycling market is expected to reach US$ 40.6 billion by 2030, with hydrometallurgical process recycling accounting for 65% of the total.[29] The commercial viability of recycling depends on a range of factors, including process efficiency, disassembly costs, the battery chemistry being recycled, the market price for recovered materials, energy costs and the cost of collection. As recycling material availability increases, economies of scale will also play an increasingly important role in shaping the industry. These are discussed in turn.

$ **US$ 40.6** billion battery recycling market by 2030

Recycling recovery rate

To date, lithium-ion battery recycling has mainly focused on the recovery of valuable materials such as cobalt, nickel, lithium, copper and aluminium, while lower-cost components such as binders and separators are often not recovered. The recovery rate depends on which process is used (Table 1), along with commodity prices, the specific battery chemistry, manufacturing scale and the level of standardisation. Current recovery by weight at a pack level for pyrometallurgy is between 55-70% and between 60-80% for hydrometallurgy of shredded modules.[30]

[28] Joule (November 2021). Recycled cathode materials enabled superior performance for lithium-ion batteries.
[29] Allied Market Research (2022). Lithium-Ion Battery Recycling Market Outlook - 2030.
[30] CET Journal (2022). Recycling of Lithium-Ion Batteries: Overview of Existing Processes, Analysis and Performance.

Current recovery by weight at pack level:

55-70% pyrometallurgy

60-80% hydrometallurgy

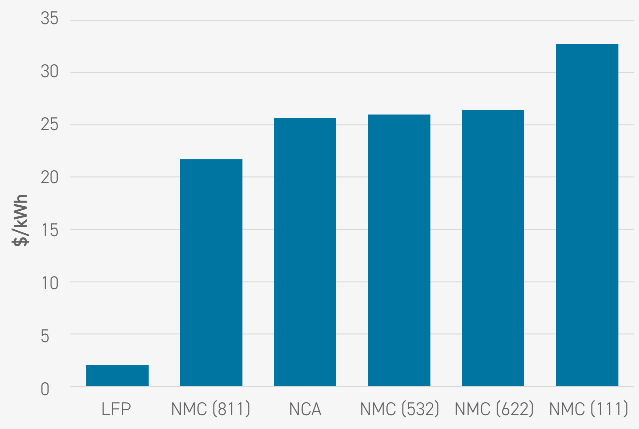
The operation of the recycling process, including energy, labour, materials and facilities, contributes to 75-90% of total recycling costs, with the remainder largely due to transportation. Pyrometallurgy is a more expensive process because of higher utility and labour costs, whilst hydrometallurgy has higher material costs due to the use of leaching chemicals.[37]

Maximising recycling efficiency is critical to retain as much value as possible and to minimise the environmental impact. As efficiencies begin to plateau, attention will turn to recovering components that may have lower economic value or for which there is little current commercial interest in recycling. Graphite, for example, is a material that may soon have a supply deficit. Predominantly serving as an anode material, graphite contributes between 50-100 kg to the weight of the battery pack. The surge in EV demand is anticipated to account for more than half of mined graphite demand, the majority of which is currently produced in China. This poses a considerable challenge for countries aiming to cut reliance on critical minerals from China. It also highlights the potential benefit of research being conducted on scaling graphite recycling processes, which has previously been seen as a high-effort and low-reward endeavour.

Battery chemistry, materials and suitability for second-life applications

The battery chemistry of the waste stream being recycled, such as NMC, LFP, lithium nickel cobalt aluminium (NCA) and lithium manganese oxide (LMO), significantly influences the profitability of recycling (Figure 5). The recycling of LFP batteries is not as profitable as that of NMC and NCA batteries, largely because lithium, cobalt and nickel are recovered from NMC and NCA batteries while only lithium is recoverable from LFP. Despite lithium being the only recovered element in LFP batteries, new extraction techniques that achieve recovery of over 99.5% purity in lithium salts may increase recycling profitability, boosting it beyond its current marginal profitability.[38]

Figure 5: Battery recycling profitability by battery chemistry



The battery chemistry of the waste stream being recycled significantly influences the profitability of recycling, with LFP significantly less profitable than early generations of NMC.

Source: BNEF (June 2021). Second-Life Batteries Part 1: Technology and Applications

The economics of EV battery recycling are also affected by the price of raw materials. With high raw materials

Table 1: Recycling recovery rate by material and recycling processes

Process	Pyrometallurgical		Hydrometallurgical			Hybrid pyrometallurgical and hydrometallurgical
Material	**Mixed[31]**	**LCO[32]**	**LCO[33]**	**NMC[34]**	**LFP[35]**	**NMC[36]**
Lithium	0%	0%	98%	99%	97%	85%
Nickel	99%	98%	0%	98%	n/a	99%
Manganese	0%	n/a	0%	98%	n/a	99%
Cobalt	99%	99%	96%	98%	n/a	99%
Iron	0%	0%	0%	n/a	98%	0%
Copper	99%	94%	0%	0%	0%	0%

[31] Journal of Sustainable Metallurgy (2017). Recovery of Valuable Metals from Spent Lithium-Ion Batteries by Smelting Reduction Process Based on MnO–SiO2–Al2O3 Slag System.
[32] Transactions of Nonferrous Metals (2017). Recovery of valuable metals from spent lithium ion batteries by smelting reduction process based on FeO–SiO2–Al2O3 slag system.
[33] Waste Management (2018). Organic reductants based leaching: A sustainable process for the recovery of valuable metals from spent lithium ion batteries.
[34] Journal of Power Sources (2018). Economical recycling process for spent lithium-ion batteries and macro- and micro-scale mechanistic study.
[35] RSC Advances (2016). Optimized Li and Fe recovery from spent lithium-ion batteries via a solution-precipitation method.
[36] Journal of Power Sources (2017). A promising approach for the recovery of high value-added metals from spent lithium-ion batteries.
[37] iScience (July 2021). Financial viability of electric vehicle lithium-ion battery recycling.
[38] Resources, Conservation and Recycling (May 2023). Priority Lithium recovery from spent Li-ion batteries via carbothermal reduction with water leaching.

prices, recycling used batteries is more profitable, as the value of the recovered materials is worth more than the costs of recycling. Indeed, the profitability of recycling markets has previously increased during spikes in the prices of lithium, cobalt and nickel due to supply disruption and increasing demand.[39] On the other hand, markets such as lithium are subject to increasing price volatility, driven by their dependency on a small number of major producers, thus creating inherent risks and uncertainties for recycler profitability. Comparing current industrial processes, the hydrometallurgical route is less susceptible to price fluctuations and changes in cell chemistry than pyrometallurgy, but is widely expected to be the more profitable process at scale.[40]

Next-generation low-cost battery chemistries, such as sodium-ion batteries, will pose a particular challenge for recycling economics. Not only are they free of lithium, cobalt and nickel, but they also use lower-cost materials including sodium, manganese and iron oxides. Further considerations are outlined in Box 4.

In the case of LFP, the iron ores and phosphates used to synthesise the cathode material are relatively inexpensive compared to LFP itself, owing to the energy intensive nature of the synthesis steps. If LFP could be directly recovered and refurbished for reuse, significant additional value could be captured. Direct recovery of LFP is an emerging and promising area of research.[41]

More generally, to prevent low-cost batteries from becoming waste products rather than recyclable assets, it is crucial to capture additional value beyond the recovery of the base metal salts. This is a driving force behind the development of new recycling technologies (including direct recycling), a challenge actively addressed[42,43] in the Faraday Institution's ReLiB project.[44]

Another avenue for capturing additional value could come from the repurposing of batteries in second-life applications. However, this approach is not without risk, as cells with unknown histories that are damaged or significantly degraded could be repurposed, potentially leading to unacceptable performance or catastrophic failure. Repurposing would require each cell, at its EOL, to be tested and assessed before a decision is taken on its suitability for reuse; a non-trivial logistical challenge given the variety of cell chemistries, designs and sizes.

Battery chemistries with superior safety characteristics, durability and longer life are better suited to second-life applications. This could favour LFP batteries, as they offer a longer lifespan and are less prone to overheating compared to some other chemistries. Furthermore, utilising LFP chemistries for second-life applications enables the critical minerals required for high-performance batteries to be recycled back into the circular supply chain, avoiding the tying up of valuable materials that could otherwise be used profitably.

Box 4: Recycling next generation chemistries

The recycling industry will need flexibility in accommodating waste streams from both current and next generation battery technology. Differing compatibilities may require different recycling methods and cost considerations. The large volume of identical cells that will eventually arise from popular EV models offers the possibility of bespoke recycling processes optimised for efficiency and tailored to specific feedstocks.

Some next generation chemistries, like those utilising new materials, offer significant potential for direct recycling profitability. For example, the hydrometallurgical recovery of lanthanum and zirconium from lithium lanthanum zirconate (LLZO) type ion conductors in certain solid-state batteries could be more lucrative than recycling current generation liquid electrolytes.

High-performance next-generation batteries, such as lithium-sulfur and lithium-metal-solid-state-batteries, often incorporate lithium metal. Recycling these batteries presents unique challenges and opportunities. Handling large volumes of lithium metal can be hazardous due to its flammability and the potential release of hydrogen upon contact with water. This challenge is particularly pronounced when recycling very large battery packs due to the heightened risks of chemical reactions and the complexity of safely dismantling these structures. As a result, developing safer battery disassembly techniques will be crucial to accommodate the recycling of these next generation batteries.

While lithium metal constitutes a significant portion of the material costs in lithium-sulfur and lithium-metal-solid-state-batteries, direct recycling of lithium metal is not currently commercially viable. This is due to its high reactivity, virtually no availability of EOL batteries, and the safety risks associated with handling batteries in a charged state. Consequently, lithium metal is typically processed into lithium salts, a less efficient but safer recycling method. However, the direct recovery of lithium metal could become a significant cost driver for next-generation battery recycling, necessitating disassembly in a charged state, which adds complexity due to safety considerations.

[39] McKinsey (October 2022). Power spike: How battery makers can respond to surging demand from EVs.
[40] Applied Energy (2024). A techno-economic assessment of two recycling processes for black mass from end-of-life lithium-ion batteries.
[41] CS Energy (2022). Lithium-Ion Battery Recycling - Overview of Techniques and Trends.
[42] Nature (January 2019). Recycling lithium-ion batteries from electric vehicles.
[43] J. Phys. Energy (February 2023). Roadmap for a sustainable circular economy in lithium-ion and future battery technologies.
[44] ReLiB: Recycling and Reuse of EV Lithium-ion Batteries.

For second life to become a meaningful market, improved understanding and warranty guidance will be required. This necessitates the development of methods that can reliably predict residual life before the failure of the battery, prior to their approval for second-life applications. The EU Battery Passport will also ensure that only batteries meeting specific safety, durability and performance criteria are used for second-life applications.[45]

Pack disassembly

Another factor influencing the cost of recycling is the number of processes needed to dismantle the pack and access the cell material. This may not be economically feasible if manual labour is used, as trained high voltage technicians would be required. The situation is further complicated by the variability in pack designs and the number of different parts used by different manufacturers. These differences not only impact disassembly costs but also impede the transition to automated processes for recycling.

Automating the dismantling of batteries could offer substantial cost benefits. For instance, manual disassembly of EV battery packs from Renault, Nissan, Peugeot, Tesla, BAIC and BYD incurs costs ranging from US$ 47 to US$ 197 per pack. This cost variability is mainly due to differences in the number of modules, screws, fasteners and welded parts.[46] Transitioning from manual to semi-automated or automated recycling could significantly reduce costs, with total recycling costs for a Nissan Leaf decreasing from US$ 0.64 per kg to US$ 0.02 per kg.[46] Current research is exploring the possibility of automation and advancements in artificial intelligence and is rapidly progressing to enable batteries to be sorted based on visual characteristics including size, colour and geometry.[47]

'Design for recycling' refers to the strategy of designing battery packs, modules and cells to optimise recyclability and minimise waste. This provides automakers, manufacturers and recyclers with a consistent framework to simplify and safely dismantle cells at their EOL. This focus on consistency in pack design across manufacturers and countries could significantly reduce the time and costs of recycling, thereby improving throughput and profitability. This would allow recycling plants to cater to multiple automotive companies and different EV models. While widespread standardisation is unlikely to happen in the short term, some progress can be made to accelerate the move to automation.

One option to potentially improve the ease of disassembly is to use glues or resins[48] instead of mechanical fastenings. This needs to be balanced against the need for durability and robustness in first life as well as the increased complication in separating these adhesives and the knock-on effect it could have upon purity.

Furthermore, universal labelling could enable the automatic sorting of batteries into distinct groups based on structure or chemistry. Currently, the International Dismantling Information System (IDIS) database provides manufacturer-specific safety information and EOL dismantling information.[49] This could be expanded beyond conventional lead-acid batteries to encompass lithium-ion battery testing, discharging and dismantling for recycling. Integration of an IDIS-like database within a battery passport system could further enhance transparency by disclosing the batteries history, composition, origin and guidelines for safe handling and recycling. In the future, real-time analysis of in-use battery data could, in principle, remove the need for additional EOL testing entirely.

Energy, logistics and transportation costs

The cost of energy is one of the main factors affecting the economic feasibility of various recycling process, with energy costs comprising 45% of the total operating cost for pyrometallurgy and 32% for hydrometallurgy. The former exhibits significantly more sensitivity to electricity price than hydrometallurgy.[40]

The costs of transporting EOL batteries to recycling facilities are also significant, accounting for almost half the disposal costs. This is primarily due to safety considerations and the classification of batteries as hazardous waste.[46]

Transport costs and logistics significantly influence the extent to which the UK battery recycling industry can best develop economically and sustainably, whether through a centralised operation or a decentralised network.[50] In the EU, a decentralised system is expected to be the most advantageous as it minimises distance travelled, resulting in lower transportation costs and reduced safety risks associated with transporting batteries.[51]

While a decentralised model requires higher capital expenditure, the significantly lower transportation costs - about half that of a centralised alternative - more than offset the lower capital plant costs associated with a centralised model. The decentralised model also reduces safety risks and carbon emissions associated with transporting batteries long distances.[51] In the UK context, these factors indicate that establishing a separate UK recycling industry will be commercially optimal over exporting recycling material to Europe. The optimal location for UK recycling facilities is discussed in the next section. Transport costs can also be substantially mitigated if vehicles are dismantled at or near the recycling facility, with less hazardous parts transported elsewhere.

[45] European Commission. Ecodesign for Sustainable Products Regulation.
[46] Applied Energy (December 2022). Breaking it down: A techno-economic assessment of the impact of battery pack design on disassembly costs.
[47] Nature (January 2019). Recycling lithium-ion batteries from electric vehicles.
[48] Green Chemistry (2022). Debondable adhesives and their use in recycling.
[49] The International Dismantling Information System.
[50] Applied Energy (September 2022). Optimising the geospatial configuration of a future lithium-ion battery recycling industry in the transition to electric vehicles and a circular economy.
[51] Resources, Conservation & Recycling Advances (May 2022). Battery dismantling centre in Europe: A centralized vs decentralized analysis.

Developments in the UK and European Recycling Industry

Lithium battery recycling plants around the world utilise a range of technologies to extract valuable material from EOL batteries. Some recycling facilities specialise in pre-treatment processes, which involve shredding and separating the battery components, while others focus on black mass treatment. Only a limited number of recycling plants globally are equipped to perform both processes.

UK recycling industry

The UK has begun to develop a battery recycling industry featuring pilot-scale plants, pre-treatment and black mass facilities as integral parts of this evolving sector. However, most capabilities within the UK are still either in the planning stages or operating on a pilot-scale. Currently, the UK has seven publicly announced pre-treatment plants and three black mass treatment plants (Figure 6).[52] Given the substantial amount of capital equipment required for recycling operations, companies typically have prior experience in similar industrial processes such as electronic waste recycling or precious metal recovery. Start-ups entering the sector tend to specialise in specific niches, such as second-life applications or fast-discharging processes. Innovative research projects, such as ReLiB or RECOVAS,[53] are actively working towards scaling up and demonstrating the commercial viability of novel recycling processes and technologies.

Figure 6: Geographic location of announced UK battery manufacturing and recycling facilities

Battery Production

1 UKBIC
2 AESC
3 Agratas
4 West Midlands Gigafactory (Proposed)

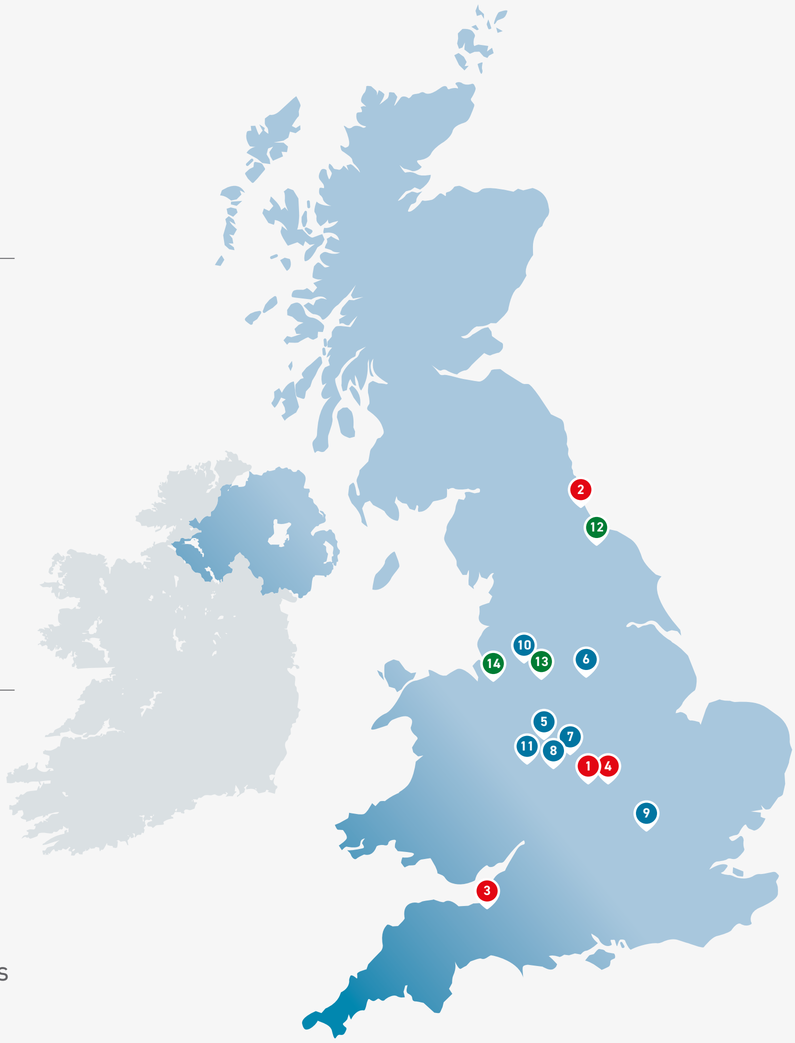
Recyclers – Pre-Treatment

5 Ecobat
6 RS Bruce (operational)
7 Veolia
8 EMR (Birmingham)
9 Lithium Battery Recycling Solutions (Suez UK)
10 Ecoshred
11 Recyclus

Recyclers - Black Mass Treatment

12 Altilium Technology Group
13 CellCycle
14 ICoNiChem

Recycling facilities are all in planning stages unless otherwise stated.



The map is illustrative. It is not intended to be exhaustive or comprehensive.

[52] Although there are no recycling plants in the UK that are dual use, this is consistent with the global picture where there are only five dual sites that are able to conduct pre-treatment and black mass treatment at scale.
[53] RECOVAS.

UK battery recycling plants are often concentrated near or within manufacturing facilities to utilise the benefits of co-location. These benefits include reduced transportation costs, knowledge of the exact origin and composition of the feedstock (which allows for the selection of the most appropriate recycling methods), and the consistent availability of production scrap for the recycler to process. In the event that recycling centres are established to handle a variety of waste types from numerous customers, it is essential to identify potential sites in the UK as quickly as possible in order to speed up the planning and permitting process.

A study by the University of Birmingham examined the optimal geographic locations for the UK's future recycling industry, based on a comprehensive analysis of likely supply chains and transportation costs.[50] If pyrometallurgical technology is used, the study concluded there will be enough demand for three recycling plants located in the West Midlands, London, and Yorkshire and the Humber by 2040. Should hydrometallurgical technology be adopted, seven recycling plants would be needed by 2040.

Number of UK recycling plants needed by 2040

3 using pyrometallurgy

7 using hydrometallurgy

One characteristic of the electrification of the automotive industry is the formation of key collaborations between battery makers and automotive OEMs. These collaborations may take the form of partnerships, joint ventures or vertical integration within the business. To reinforce closed-loop supply chains, joint-development agreements or offtake agreements are now emerging between automotive Tier 1s and recyclers.[54,55,56] This is mutually beneficial as battery manufacturers can maintain control over their proprietary cell formulations, while simultaneously ensuring a consistent supply of feedstock for the recycler.

The European and global battery recycling industry

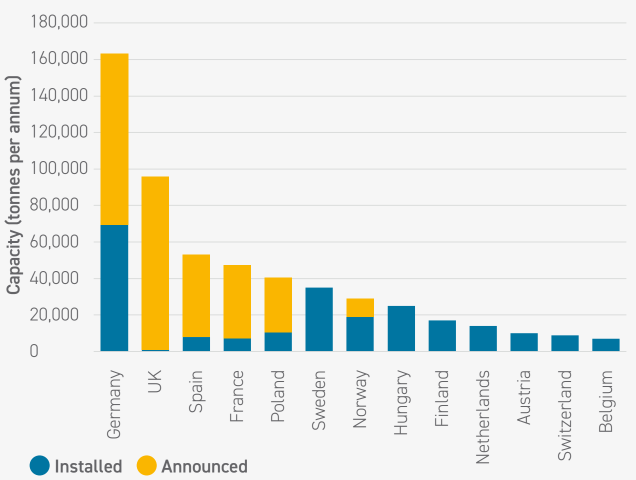
As of 2021, there were 32 established or planned lithium-ion battery recycling facilities worldwide with around 400,000 tonnes of recycling capacity. This consists of 322,500 tonnes of existing operational capacity, with an additional 70,000 tonnes in planned capacity.[57] Currently, over two-thirds of recycling capacity resides in China. In Europe, companies such as Umicore, BASF and Veolia have the capacity and supply agreements to recycle batteries at scale; European recycling capacity is expected to 400,000 tonnes per annum by 2025.[58] In the UK, new entrants such as Altilium Clean Technology and Recyclus are making their presence felt. Competition includes cell manufacturers, automotive OEMs, existing waste disposal and recycling entities as well as new entrants.

32 established or planed Li-ion battery recycling facilities globally

Two thirds of global capacity is in China

European countries are expected to significantly increase lithium-ion battery recycling capacity (Figure 7). Recycling capacity is currently highest in Germany at around 160,000 tonnes per annum with significant proposed expansion expected in UK, Spain and France.

Figure 7: Existing and announced lithium battery recycling capacity across Europe



In Europe, recycling capacity is currently highest in Germany, with significant proposed expansion expected in the UK, Spain and France.

Source: Fraunhofer Institute (July 2023). Battery Update. Numerical data for figures

[54] Ascend Elements (February 2023). Ascend Elements and Honda Reach Basic Agreement to Collaborate on Procurement of Recycled Lithium-ion Battery Materials in North America.
[55] Redwood Materials (June 2022). Redwood Materials and Toyota collaborate on electric vehicle battery collection, remanufacturing, recycling, and battery materials supply.
[56] Veolia (March 2021). Groupe Renault, Veolia & Solvay join forces to recycle end-of-life EV battery metals in a closed loop.
[57] ACS Energy (2022). Lithium-Ion Battery Recycling Overview of Techniques and Trends.
[58] Fraunhofer ISI battery update (2023).

Table 2: Examples of the size and type of major battery recycling centres in Europe

Country	Company / plant name	Current capacity (tonnes per annum) [planned capacity]	Description of process	Example products
Belgium	Umicore	7,000 [150,000]	High temperature pyrometallurgical process, with hydrometallurgical capabilities	Co, Ni, Cu chemicals
France	Euro Dieuze Industrie / Veolia	30,000	Cells are shredded in a closed system, including battery collection and diagnostics	Recovered black mass, metal salts
France	Valdi (Eramet)	20,000	Pyrometallurgical process produces a metal alloy	Ferro-nickel/ferro-manganese alloy
Germany	BASF	15,000	Mechanical shredding and hydrometallurgy	Recovered metals as metal salts, black mass (Co, Ni, Cu, Mn)
Germany	Accurec Recycling	4,000	Cells placed in a pyrolysis chamber and heated to 250°C	Co alloy, Li_2CO_3
Germany	Primobius	2,500	Mechanical shredding and hydrometallurgy	Recovered metals as metal salts, black mass (Co, Ni, Cu, Mn)
Germany	Duesenfeld	3,000	Two-stage crushing in inert physical conditions	Co, Ni, Mn as active materials
Germany	Li-Cycle	10,000 [30,000]	Shredding without discharging or dismantling	Black mass
Norway	Li-Cycle	10,000	Shredding without discharging or dismantling	Black mass
Norway	Northvolt	12,000 [125,000]	Gigascale recycling under development at Revolt Ett	Co, Ni, Mn as active materials
Finland	AkkuSer and Boliden	4,000	Mechanical for copper refining by Boliden	Copper, black mass
UK	Altilium Clean Technology	10,000 [50,000]	Hydrometallurgy	Recovered metal salts
UK	EMR	[30,000]	Pre-treatment and shredding	Black mass

Source: ACS Energy (2022).Lithium-Ion Battery Recycling Overview of Techniques and Trends, Company Websites (BASF, Veolia, Accurec, Primobius, Altilium Metals)

Opportunities for UK Growth

The UK Government is working to develop a domestic EV battery supply chain, which includes the recycling of lithium batteries. The initiative is reinforced by the UK Critical Minerals Strategy, which highlights the role of recycling in facilitating urban mining to create a closed-loop system, where recycled materials are reused in the production of new EV batteries.[59] Identified minerals of particular importance for current lithium-ion cell production include lithium, cobalt, graphite as well as niobium and silicon, which are proposed as alternative anode chemistries.

The UK government has recognised the importance of battery recycling in the recent UK Battery Strategy and supported a number of R&D initiatives. These include the £4.4 million grant from the Advanced Propulsion Centre for the RECOVAS project, over £11 million of mid-technology readiness level (TRL) investment from the Faraday Battery Challenge on second life and recycling projects, and £18.5 million of funding from the Faraday Institution for the ReLiB project to improve recycling technologies and establish new recycling routes. Attention should turn towards scaling up these technologies given that the UK is at risk of remaining reliant upon and vulnerable to other countries for critical materials. Indeed, recycling as a form of urban mining, and the retention of these key metals could supply 39-57% of lithium, cobalt and nickel demand for batteries by 2040.[60]

Key advantages of establishing domestic battery recycling include ensuring critical material supply, reduced economic and environmental costs from transportation and reduced safety risks. Going forward, priorities should include streamlining the environmental permitting process, including obtaining planning permission, battery treatment operator permits and approved battery exporter permits. With the growing demand, the permitting process risks becoming a

[59] BEIS (July 2022). Resilience for the Future: The UK's critical minerals strategy.
[60] Goldman Sachs (March 2022). Batteries: The Greenflation Challenge.

bottleneck in scaling up recycling infrastructure. Improved alignment and understanding between industry and permitting agencies could expedite this process, ensuring that safety standards are upheld while efficiency is improved.

Whilst there is extensive UK legislation, the UK Government needs to develop additional policies for EV battery recycling in order to match Europe and global initiatives (see Box 5). These include regulation on extended producer responsibility, re-use and re-purposing, chemistry labelling and a coherent waste hierarchy strategy.[3] Given the UK's relatively small market compared to the US, China and Europe, a bespoke approach is probably needed, balancing environmental standards with ensuring sufficient flexibility for innovation and growth.

Policies on managing second life applications are also needed including definitions on universal systems, standards and EOL waste protocols. For example, determining if UK-manufactured cells used in European exported cars should capture the same information needed for an EU-battery passport. There also needs to be alignment on data covering the origin, composition and manufacturing history of cells, together with how data would be stored and accessed. Controlling access from different stakeholders may be achieved by using blockchain platforms to treat batteries as unique digital assets that can be traced and monitored through multiple uses.

For recycling facilities to achieve financial and technological viability, a sufficient volume of feedstock is needed. However, developing recycling facilities without a guaranteed supply of batteries can lead to unprofitability. This also leads to the increased bargaining power of suppliers, who are predominately cell manufacturers that generate production scrap. The UK Government should consider offering grants, tax credits and subsidies to encourage battery recycling, impose regulations that make it mandatory to recycle batteries and invest in research and development to further improve recycling efficiencies.

The development of the UK recycling industry should also be integrated into a wider battery manufacturing strategy. Without a large and sustainable UK battery manufacturing industry, it would be difficult to create a circular economy, though it is important to stress that onshore recycling would still be necessary as a pillar of an EOL waste management strategy. Infrastructure and policy interventions have been discussed previously,[61] and other linked initiatives and activities to develop the UK recycling industry include:

- Investment to establish the UK's processing capability for battery precursor materials (e.g., mixed-metal hydroxide precursor cathode active materials). It is this midstream processing capability rather than primary resources that currently provide China with its dominant position in the global supply chain for many battery materials.
- Development of an integrated battery supply chain: The UK needs to work towards creating an integrated supply chain and collaborate with other countries to ensure the wider global supply chain is more resilient to unforeseen disruptions and events.
- Increased training and education on handling and management of lithium-ion waste streams. To include the safe handling of batteries from household disposal of battery waste, kerbside collection, after-market facilities and operation at recycling centres.

Continued overleaf

[61] Innovate UK KTN (2023), The 2035 UK battery recycling industry vision.

Box 5: UK, European and global policy context

The primary UK legislation governing battery recycling is the 2009 Waste Batteries and Accumulators Regulations,[62] which place obligations on battery producers and distributors to recycle or dispose of batteries responsibly, explicitly prohibiting incineration or landfill disposal. Under the Hazardous Waste Regulations 2005, lithium batteries must be handled, stored, transported and disposed of safely. Other relevant legislation includes the Waste Electrical and Electronic Equipment Regulations 2013 and the Environment Act 1995, which contains provisions related to waste control and environmental protection.

The first European Union legislation on batteries and waste batteries came into effect in 2006 and emphasises recycling as a crucial element of the European Battery Directive. Manufacturers of EV batteries and accumulators are required to cover the costs of battery collection, treatment and recycling, as well as the establishment of systems for the separate collection of batteries.[63] The disposal of EV batteries in landfill or incineration without proper treatment is prohibited, a regulation that is mirrored in the UK.

In August 2023, the new EU Battery Regulation[64] came into force, promoting the circularity, sustainability and traceability of batteries through digital labelling, QR codes and a Battery Passport.[65] The Battery Passport is designed to enhance transparency and accountability in the lifecycle of a battery, from manufacturing and usage to recycling and disposal. The passport comprises seven content clusters: general information, labels and certifications, carbon footprint, supply chain due diligence, materials and composition, circularity and resource efficiency, and performance and durability.[64] For battery producers, there is also an obligation to be accountable for the environmental impacts of their products across the lifecycle via an extended producer responsibility (EPR).

Sustainability topics introduced include encouraging the use of low-carbon manufacturing techniques, declarations of carbon footprint and the promotion of ethically and responsibly sourced materials by supply chain due diligence disclosures. Provisions also set minimum recovery rates for 2027 and 2031, along with minimum recycled content requirements in new batteries to be met by 2031 and 2036.[66]

On the global stage, China has already established a comprehensive regulatory framework for lithium battery recycling, holding automotive manufacturers accountable for battery recycling[67] and enforcing recovery rates.[68] In particular, China requires at least 98% recovery for nickel, cobalt and manganese, and 85% or more for lithium.[69]

In the US, the Inflation Reduction Act of 2022 allocated US$ 400 billion of support towards promoting and commercialising clean energy technologies, with US$ 335 million designated for lithium-ion battery recycling.[70] Incentives aimed at scaling up domestic battery recycling include tax credits where automakers can qualify if they source a minimum amount of recycled battery materials from domestic suppliers or countries with free trade agreements.

Continued overleaf

[62] The Waste Batteries and Accumulators Regulations 2009.
[63] Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006.
[64] Regulation 2023//1542 of the European Parliament and of the Council of 12 July 2023.
[65] European Commission (December 2022). EU agrees new law on more sustainable and circular batteries.
[66] European Parliament, Making batteries more sustainable, more durable and better-performing, June 2023.
[67] ACS Energy (2022). The Regulatory Environment for Lithium-Ion Battery Recycling.
[68] State Council of China (2018). China unveils policy for NEV battery recycling.
[69] Argus Media (January 2020). China launches NEV battery recycling regulation.
[70] Department of Energy (August 2022). Biden-Harris Administration Establishes Bipartisan Infrastructure Law.

Conclusions

As a result of the rapid growth in EV sales from the early 2020s, the volumes of recycled EV batteries are set to increase sharply in the mid-2030s, with retired EV batteries increasingly dominating the recycling market. The transition towards more affordable and battery chemistries containing more abundant elements, such as LFP, will influence the future economic viability of battery recycling. These batteries yield less valuable material and contain lower quantities of expensive metals such as cobalt and manganese.

Research is ongoing into the recycling of lithium batteries, including understanding the commercial viability of recycling other components such as graphite anodes or electrolytes.[71] However, additional research is needed, along with comprehensive changes to regulation and policy strategy, to overcome the current challenges and maximise the potential of these technologies for the UK.

In particular, to strengthen the UK's position in the global recycling market and enhance the resilience of the UK supply chain, requires:

- Further research to improve recycling technologies, with a focus on new methods for direct recycling and enhancing material recovery from diverse battery chemistries.
- Further research to improve recycling processes focused on more efficient recovery rates and reduced environmental impacts.
- Expanding research on second-life applications, particularly the feasibility and safety of second-life applications for EV batteries.
- Embracing design for recycling principles to standardise and simplify battery designs, including more efficient and cost-effective disassembly at scale.
- Developing initiatives that encourage the reuse and repurposing of batteries.
- Providing financial support to recycling facilities to help then reach commercially viable levels of operation along with incentives for SMEs and startups in the sector.
- Developing strategy and policy to reduce reliance on primary raw materials, particularly imported materials, to spur innovation and investment in the UK battery supply chain.
- Strengthening domestic capabilities and capacity to handle future EOL EV battery designs and chemistries.

Increasing the recycling of battery materials contributes to a more resilient and stable supply chain while also promoting the efficient use of resources. Consistent and focused policies, along with the delivery of improvements in recycling technologies, will be essential to achieving these objectives. The effort will enhance the UK's competitive advantage in the global battery market.

About the Faraday Institution and Faraday Insights

The Faraday Institution is the UK's independent institute for electrochemical energy storage research, skills development, market analysis, and early-stage commercialisation. We bring together academics and industry partners in a way that is fundamentally changing how basic research is carried out at scale to address industry-defined goals.

Our 'Faraday Insights' provide an evidence-based assessment of the market, economics, technology and capabilities for energy storage technologies and the transition to a fully electric UK. The insights are concise briefings that aim to help bridge knowledge gaps across industry, academia and government. If you would like to discuss any issues raised by this "Faraday Insight" or suggest a subject for a future Insight, please contact Stephen Gifford.

Sign up today to be added to the distribution list for future "Faraday Insights" www.faraday.ac.uk/subscribe.

The Faraday Institution is a key delivery partner for the Faraday Battery Challenge at UK Research and Innovation, which is delivered by Innovate UK. The Challenge is making the UK a science and innovation superpower for batteries, supporting the UK's world-class battery facilities along with growing innovative businesses that are developing the battery supply chain for our future prosperity. Its aim is to build a high-tech, high-value, high-skill battery industry in the UK.

[71] Energies (October 2022). Literature Review, Recycling of Lithium-Ion Batteries from Electric Vehicles, Part II: Environmental and Economic Perspective.

CONTACT
Stephen Gifford
Chief Economist
stephen.gifford@faraday.ac.uk
www.faraday.ac.uk
01235 425125
07741 853068

THE FARADAY INSTITUTION

Faraday Battery Challenge

Delivered by Innovate UK