PRESCOUTER

MARKET REPORT 2022

# STATE OF BATTERY RECYCLING

CAN WE MEET OUR LIB RECYCLING OBLIGATIONS BY 2030?

# CONTENTS



# EXECUTIVE SUMMARY


The following report provides a thorough overview of the current and upcoming lithium-ion battery recycling targets and illustrates what it will take to meet these targets by all parties involved. We are not only asking if we can meet our LIB recycling obligations; we are also asking if these recycling obligations are too ambitious for 2030, and what it will take to meet these obligations.

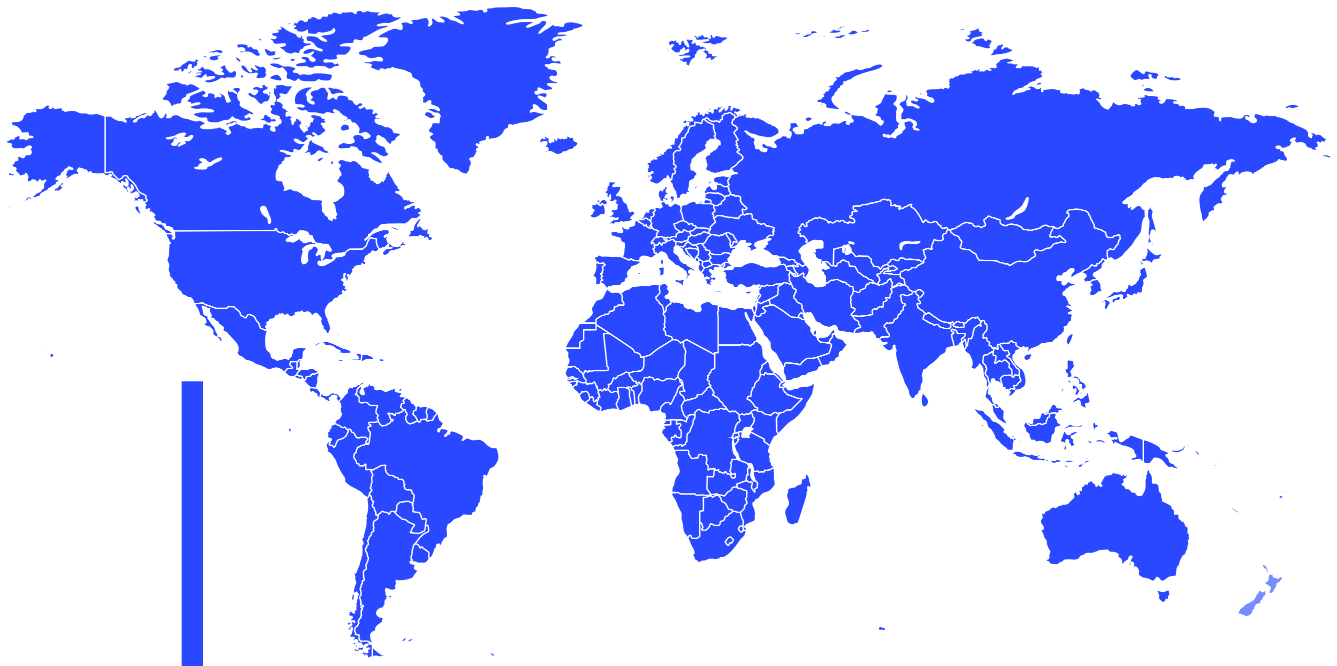
In the European Union, the draft of the new Battery Directive sets EV batteries as a new battery classification, with a set of requirements to minimize their carbon footprint. The average LIB recycling target will be approximately 70% by 2030, with the aim to recover 70% of lithium and 95% of nickel, copper, and cobalt in end-of-life batteries.

The updated proposals in the amended Regulation (EU) No 2019/1020 also has provisions for recycled materials that must be used in new cells. These figures are 4% for lithium and nickel and 12% for cobalt by 2030.

Taking the UK as an example, with EU battery legislation demanding that 4% of lithium comes from recycled sources, more than 87,000 Tesla Model 3 battery packs would need to be recycled annually to meet this demand. Using this same logic for the EU, over half a million Tesla Model 3 battery packs need to be recycled by 2030 to meet that same demand of 4%. This means that the UK demand for lithium in 2030 will be 11.4K tonnes, from which 456 tonnes must come from recycled sources. For the EU, the lithium demand will be nearly 60K tonnes, with approximately 2.8K tonnes needing to be from recycled sources.

Obtaining that much recycled material from end-of-life vehicles will be difficult, as a significant percentage will also be going to second-life uses. So, another source to obtain recycled materials for re-use in new batteries (and to meet obligations) can be the scrap from gigafactories. In fact, manufacturing scrap could become the main source of recycling material as well as the ideal starting point.

In North America, the USA and Canada are not as advanced as the EU in setting up a proper body of regulatory framework. The adoption of more stringent measures for LIB recycling must come from the federal level rather than leaving it to the states or provincial governments. This will be vital, because if the laws are not consistent throughout the country, original equipment manufacturers (OEMs) will likely dump waste where regulations are most relaxed.



# ABOUT THE AUTHORS

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Sofiane leads the high-tech, aerospace & defense, and automotive & logistics practices at PreScouter. For nearly a decade, he has worked with hundreds of F500 and G1000 clients across multiple industries, through which he has developed an expertise in key emerging technologies (such as 5G, IoT, AI/ML, blockchain, energy storage and generation, quantum sensing, and others) and a strong understanding of the associated business ecosystem and drivers pushing these sectors forward (e.g., key players and trends, roadblocks to commercialization, etc.). Sofiane's strategic insights have ranged from technical due diligence for acquisition targets to identifying relevant markets for newly developed products based on emerging technologies and assessing market penetration strategies. Sofiane holds a PhD in Materials Science and Engineering from the Georgia Institute of Technology, where his research focused on nanotechnology and energy storage.

### Athan Fox

Dr Fox is a PhD graduate in Chemistry from the University of Cambridge and Founder of Ever Resource Ltd – a UK-based company developing solutions for end-of-life products. Dr Fox is experienced in battery-related circular economy innovations and has led a team which developed and scaled up a novel hydrometallurgical process for the recycling of lead-acid batteries. His expertise includes the recycling of alkaline batteries, lithium-ion batteries, end-of-life plastics and municipal solid waste. Dr Fox currently sits on the Board of ALGOLiON, an Israeli start-up which has developed ground-breaking solutions for the detection of defects in lithium-ion batteries. He has also co-founded battery recycling plants in the UK and in Europe, and has worked with publicly listed companies to bring next-generation circular economy innovation into the UK and European markets.

### Jorge Hurtado

Jorge has a broad interest in development, sustainability, and the environment. He performs research on the translational effects of the adoption of green technologies in developing countries and offers high-quality information and analysis about the latest insights into disruptive technologies. Jorge holds an MA in Conservation and development, a Ph.D. in Biology and Statistics, and a diploma in Green Economy from the University of Florida, Syracuse University, and Ryerson University; respectively.

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### Mahmoud Mostafa

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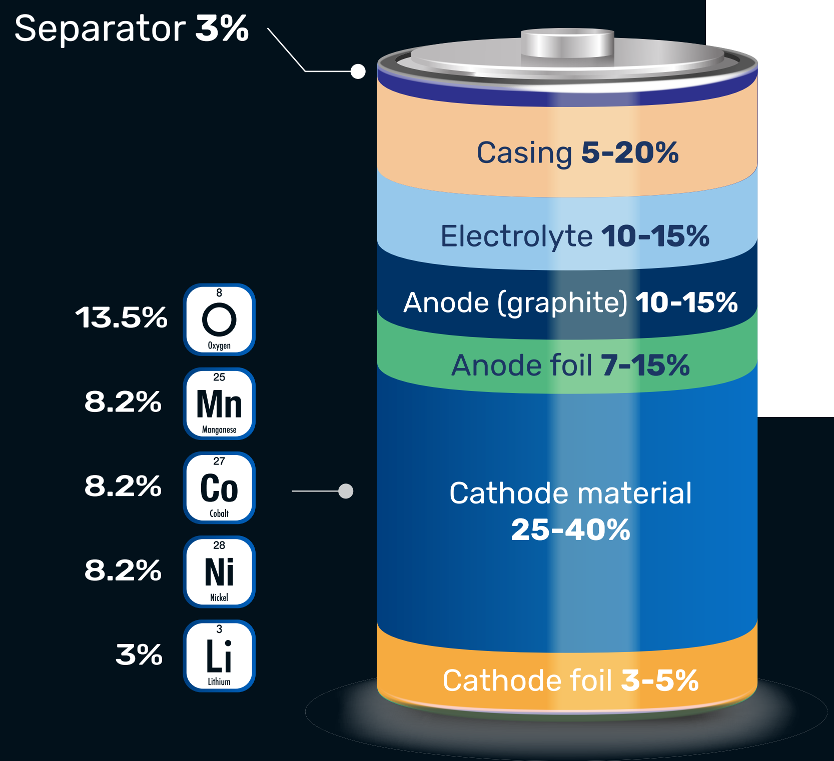
### Anwar Sattar

Anwar is a Chemical Engineer who specializes in electric vehicle and lithium ion battery recycling. Anwar Sattar is one of the leading figures in battery recycling in the UK. His main area of interest is the development of next generation battery recycling technologies.

# Current status of regulatory frameworks addressing end of life market for automotive LIBs




## EUROPEAN UNION

To manage the end of life of batteries, The European Union (EU) enacted, in 2006, Battery Directive 2006/66/EC. This set of policies replaced the 1991 Battery Directive to include more regulations to minimize the environmental harms associated with waste batteries. Under the Battery Directive, all batteries used to power electric vehicles (EVs) that are high-performance batteries fall within the category of industrial batteries.

Under this Directive, producers of batteries and other products that incorporate a battery are responsible for the waste management of batteries that they placed on the market, in particular, the financing of collection and recycling schemes.

Currently, the EU is seeking to repeal Directive 2006/66/EC and amend the Regulation (EU) No 2019/1020 with a new regulatory framework for batteries setting sustainability requirements. The new Battery Directive is expected to mandate strict requirements for end-of-life management of LIBs for EVs. The proposal also includes obligations for operators that source raw materials. The draft report was discussed during the EU Council's meeting held in Brussels in December 2021, as part of the EU's Strategy on Adaption to Climate Change.

The draft of the new Battery Directive has three intertwined aims to improve the functioning of the internal market by considering all value chain processes to ensure fair competition through a set of rules that everyone must adhere to, provide incentive for a circular economy, and reduce the potential environmental and social effects across all stages of the battery life cycle.

In the draft, EV batteries are a new battery classification with a set of requirements to minimize their carbon footprint.

By 2027, producers should present a declaration of recycled content of battery metals with mandatory minimum levels of recycled content to be set at 12% cobalt, 4% lithium and 4% nickel for 2030. The 2035 targets are set at 20% cobalt, 10% lithium and 12% nickel.

New obligations will be put in place for economic operators that place rechargeable industrial batteries and EV batteries on the market, with increased collection targets for waste portable batteries.

Considering recycling efficiencies, expected targets for lithium-based batteries are suggested as 65% by 2025, and 70% by 2030. It also suggests specific material recovery targets of 35% for lithium by 2025, and 70% for lithium by 2035.

All EV batteries should be labelled with identification and main characteristics. It also would include lifetime, charging capacity, separate collection requirements, hazardous substances and safety risks.

**By 2027, battery producers must present a declaration of their content of recycled cobalt, lead, lithium and nickel.**

# GERMANY

As a member state, Germany adheres to Battery Directive 2006/66/EC. The Directive forms part of the German National Legislation and was implemented into national law by the Batteries Act (BattG or Batteriegesetz). A corrected version, BattG-2, came into effect in January 2021.

BattG applies to any type of battery and accumulator (i.e., applied to all batteries used to power EVs), and has governed the disposal of used disposable and rechargeable batteries since 2009. The law makes importers/distributors and battery producers/manufacturers accountable to finance the collection of waste batteries and provides the needed framework for the establishment of organizations that will be responsible for battery collection.

BattG2 introduces a compulsory registration of manufacturers and distributors with Stiftung Elektro-Altgeräte Register (Stiftung EAR), instead of reporting to the German Environment Agency (Umweltbundesamt, UBA).

“Producers of EV batteries are the main responsible party for financing the collection, treatment and recycling of waste batteries” is stated in paragraphs 8 and 9 of the Battery Act.

The handling, storage, and transportation of EVs is regulated by the (i) AltfahrzeugV, an ordinance that provides procedural instructions for EVs, including some interim storage of EV batteries; (ii) GGVSEB regulates the transportation of dangerous goods regarding the carrier, vehicle driver and the consignee; (iii) Allgemeinverfügung für beschädigte Lithiumbatterien regulates the handling of damaged EVBs; and (iv) AbfVerbrG regulates national and transnational transportations of waste, dealing with the obligation for labelling transportation vehicles.

# FRANCE

The French law in Articles R.543-124 to R.543-132 of the Environmental Code emphasizes that the principle of responsibility has extended to include manufacturers of any type of battery marketed in France. It also extends the collection of all used batteries independently of whether they contain hazardous substances or not. Likewise, the French law established a national registration of battery and accumulator manufacturers and introduced recycling yields (50 - 75%).

Producers of electric vehicle batteries will carry the expenses of collection, treatment, and recycling of waste batteries. “Professional users of batteries or automotive and industrial batteries” can legally agree with producers to accept the responsibility of end-of-life battery management (Article R.543-130 Environment Code). These responsibilities include both financial and technical to allow the proper management of waste batteries.

# UNITED KINGDOM

The Waste Batteries and Accumulators Regulations 2009 is the primary law that applies in the UK and is currently experiencing changes and modifications. Together with Scotland’s Waste Batteries Regulations 2009 (SSI 2009 No. 247), The Batteries and Accumulators (Placing on the Market) Regulations 2008 (SI 2008/2164), The Batteries and Accumulators (Placing on the Market) (Amendment) Regulations 2012 (SI 2012/1139), and The Environmental Permitting (England and Wales) Regulations 2010 (SI 2010/675) establish rules for UK manufacturers/ producers and their obligations in terms of battery collection and recycling, collection and take-back programs and financing.

The UK Waste Batteries and Accumulators offer an initial detail of the regulation to handle the take-back of industrial batteries, with manufacturers/producers being the financiers for the collection and recycling. Manufacturers’/producers’ responsibility is to ensure that all collected batteries are delivered and accepted by an approved battery treatment operator for treatment and recycling. This responsibility is extended to producers of EVBs to manage the end of life and recycling under the amendments in the Waste batteries: Producer responsibility, 2018. The producer responsibility indicates a complete prohibition of EV batteries waste disposal in landfills.

As of 2020, the BSI, the UK’s National Standards Body, has published PAS 7061, which is the new standard for batteries for the propulsion of EVs. This describes the best practice to handle battery packs without environmental risks from sourcing material, manufacturing, use and disposal.

# ITALY

The Italian regulatory framework is based on Directive 2006/66/EC and was implemented with Legislative Decree No. 188/2008. The Directive makes producers responsible for proper collection management, procedures to guarantee battery treatment before recycling and recycling for any portable battery used in motor and industrial vehicles.

Producers of batteries are required to:

- Organize and finance the collection of waste batteries, treatment and recycling;
- Register with the National Register of Batteries and Accumulators producers;
- Annually report to the National Register the quantities of batteries and accumulators placed on the national market in the previous year;
- Include the information on the type of incorporated Batteries and Accumulators, methods to follow for removal and disposal, potential environmental and health impact, and any penalties associated with illegal disposal.

# UNITED STATES

In contrast to the EU, the United States does not legally dictate or promote recycling of LIBs. Existent regulation such as the Mercury-Containing and Rechargeable Battery Management Act of 1996 categorizes only mercury, nickel cadmium and small Pb-acid batteries as hazardous waste. The Act does not cover LIBs because LIBs are not considered as toxic or hazardous waste.

The U.S. Environmental Protection Agency has likewise not introduced recycling regulations for LIBs; however, California, Minnesota, and New York have developed legislation and incorporated LIBs into their waste management and Extended Producer Responsibilities regulations.

California introduced the Rechargeable Battery Recycling Act of 2006; New York implemented the Rechargeable Battery Recycling Act in 2010; and Minnesota created the Rechargeable Battery and Products Law of 1994. These states allow the free return of batteries and prohibit disposal of LIBs in municipal landfills. For LIBs, Minnesota requires manufacturers of vehicles and batteries to co-manage waste batteries.

According to California Bill AB-2832 Recycling and Reuse, the auto manufacturer establishes proper mechanisms and structures to handle the disposal of LIBs from EVs, with no cost to owners.

**The United States does not legally dictate or promote recycling of LIBs.**



# CANADA

In Canada, LIBs for EV battery packs are not classified as dangerous goods or hazardous waste. There is not an existent federal policy in Canada that relates to management of used EV batteries.

To regulate battery recycling, in general, Canada makes use of waste management and hazardous material policies. For instance, the transportation of EV batteries is regulated by the Export and Import of Hazardous Waste and Hazardous Recyclable Material Regulations, the Interprovincial Movement of Hazardous Waste Regulations, and the Transportation of Dangerous Goods Regulations.

End-of-life LIB management is mostly regulated at the provincial rather than federal level. Ontario, Quebec, British Columbia, and Manitoba are the only provinces with some form of battery policy. The Extended Producer Responsibility Policies transfer the responsibility to manufacturers to have a collection system for used LIBs that they have placed on the market.

**BRITISH COLUMBIA**

Recycling Regulations delegate producers the responsibility for developing a collection system in place and managing waste batteries.

**MANITOBA**

The Waste Reduction and Pollution Prevention Act regulates waste diversion, including LIBs, through a third-party recycle center, but there is no regulatory framework in Manitoba to handle EV waste.

**ONTARIO**

The Waste-Free Ontario Act in 2016 enacted the Resource Recovery and Circular Economy Act and the Waste Diversion Transition Act. The Act focuses on batteries but does not mention LIBs. However, the Act makes producers responsible for the development of collection systems and requires them to register with a producer responsibility organization.

**QUÉBEC**

The Environment Quality Act provides the abilities to the government to develop policies and frameworks related to waste management, which include LIBs.

**In Canada, there is not an existent federal policy that relates to management of used EV batteries. End-of-life LIB management is mostly regulated at the provincial level.**

# CHINA

China is one of the countries that has started making significant efforts to implement policy management and science and technology investment of waste LIB recovery.

The Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution (1995) considered waste batteries as dangerous solid waste and pleaded for implementing a recycling process for batteries.

In 2003, Chinese government agencies issued the Policy of the Policy Pollution Prevention Techniques from Waste Batteries. The policy required battery industries to take responsibility for collecting waste batteries and for proper labelling. The 2016 version on Pollution Prevention Techniques of Waste Batteries includes pollution prevention and control technologies for waste collection, transportation, storage, utilization, and disposal.

In 2016, the General Office of the State Council issued the Implementation Plan of the Extended Producer Responsibility System for batteries and set recycling targets of 40% for battery waste, which includes LIBs, by 2020 and 50% by 2025.

In 2018, the Interim Measures for The Management of Power Battery Recovery and Utilization of New Energy Vehicles assigned automobile manufacturers the primary responsibility for power battery recovery and carrying out the full life cycle management of power batteries.

This legislation was followed by the Interim Provisions on The Traceability Management of Power Battery Recovery and Utilization of New Energy Vehicles (2018) that require the establishment of a comprehensive management platform. This platform will include traceability management along the Chinese value chain (i.e., from battery production, sales, use, scrap, recovery, and utilization).

With the notice on the Pilot Work of Power Battery Recycling of New Energy Vehicles (2018) allowing independent companies to carry out pilot programs aiming to battery recycling, by 2021, this program is being implemented at a large scale across major cities. The process allowed major cities to introduce additional regulations, aiming to standardize the power battery recycling program.

In 2020, The Law of the People's Republic of China on The Prevention and Control of Solid Waste Pollution was amended. Among major amendments is the establishment of a credit record system for the prevention and control of waste LIB pollution. The law poses strict legal liability for unauthorized dumping, stacking, and discarding of industrial solid waste (including waste LIBs).

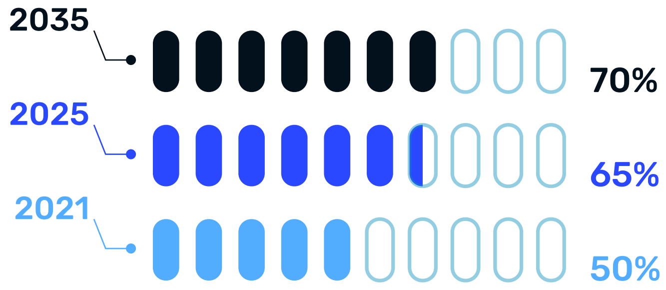
In January 2021, China implemented the revised contents of the import management of solid waste through The Notice on Matters Related to the Total Ban on Solid Waste Import. This law prohibits the importing of solid waste.

**The 2020 amendment of the Prevention and Control of Solid Waste Pollution law established a credit record system for the prevention and control of waste LIB pollution, posing strict legal liability for unauthorized dumping, stacking, and discarding of industrial solid waste (including waste LIBs).**

# Battery recycling targets

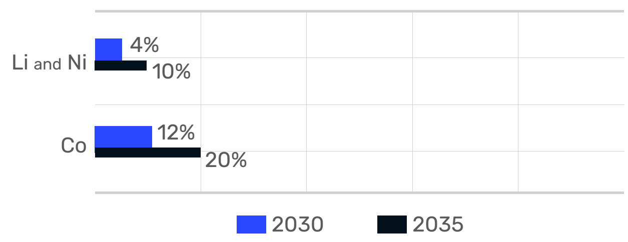
## EUROPEAN UNION

### AVERAGE LITHIUM-ION BATTERY RECYCLING TARGET*



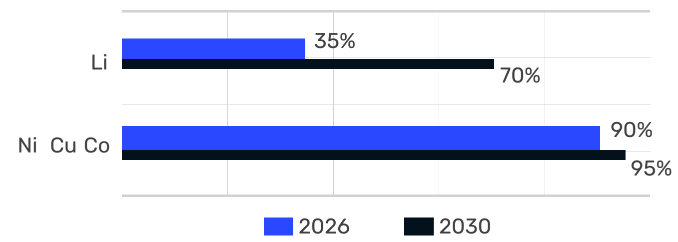

* Average refers to the % of material recycled in one calendar year
A material can only be counted as recycled if it is no longer considered waste i.e., it is used in another application.

### RECYCLED MATERIAL PER CELL




The updated Proposals in the amended *Regulation (EU) No 2019/1020* also has provisions for recycled materials that must be used in new cells.

### LEVELS OF RECOVERED MATERIAL




The updated Proposals in the amended *Regulation (EU) No 2019/1020* has minimum efficiencies that recyclers must achieve.

## CHINA

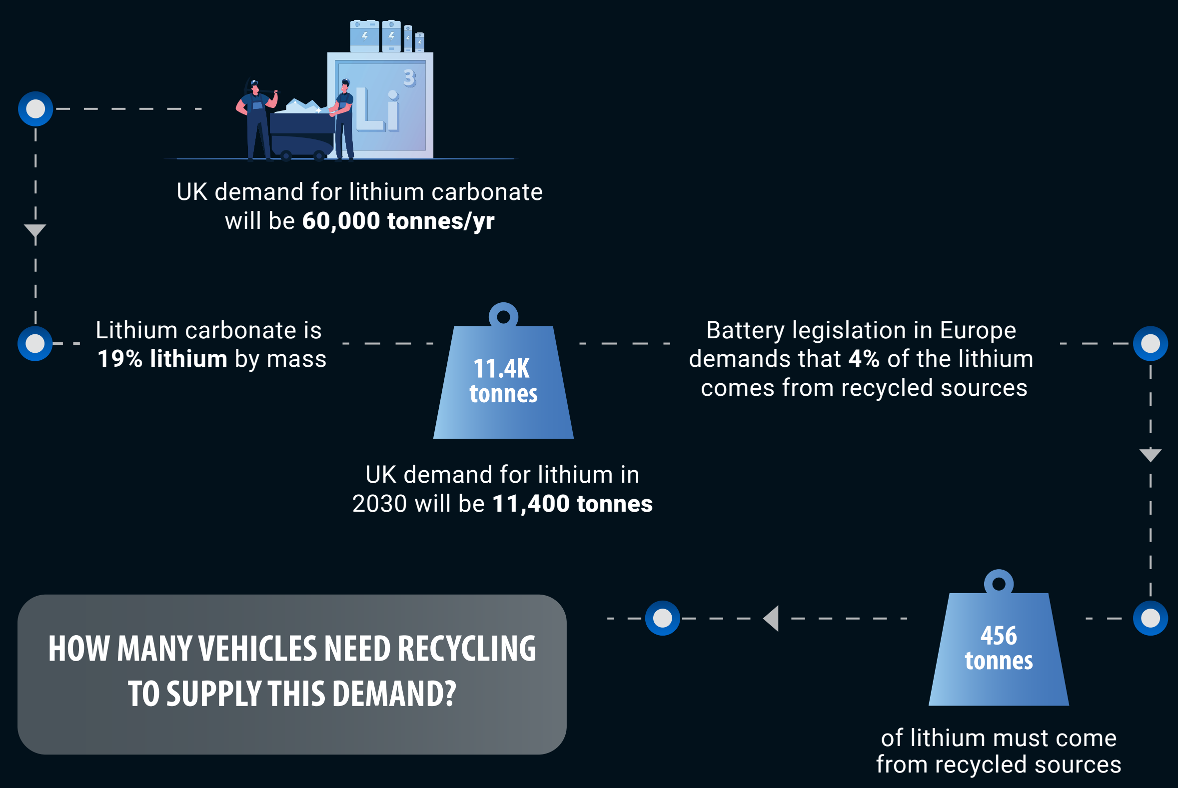
### LEVEL OF RECOVERED MATERIAL IN 2021

| 3 Li Lithium | 28 Ni Nickel | 27 Co Cobalt | 25 Mn Manganese | Rare Earth Elements |
|---|---|---|---|---|
| >85% | ≥ 98% | ≥ 98% | ≥ 98% | ≥ 97% |

The Implementation Plan of the Extended Producer Responsibility System, which determined to implement the extended producer responsibility system for four categories of products, including electrical appliances and electronics, automobiles, lead-acid batteries, and packaging materials. The Implementation Plan also set specific recycling targets to achieve a recovery rate of 40% for major waste products (including waste LIBs) by 2020 and 50% by 2025.

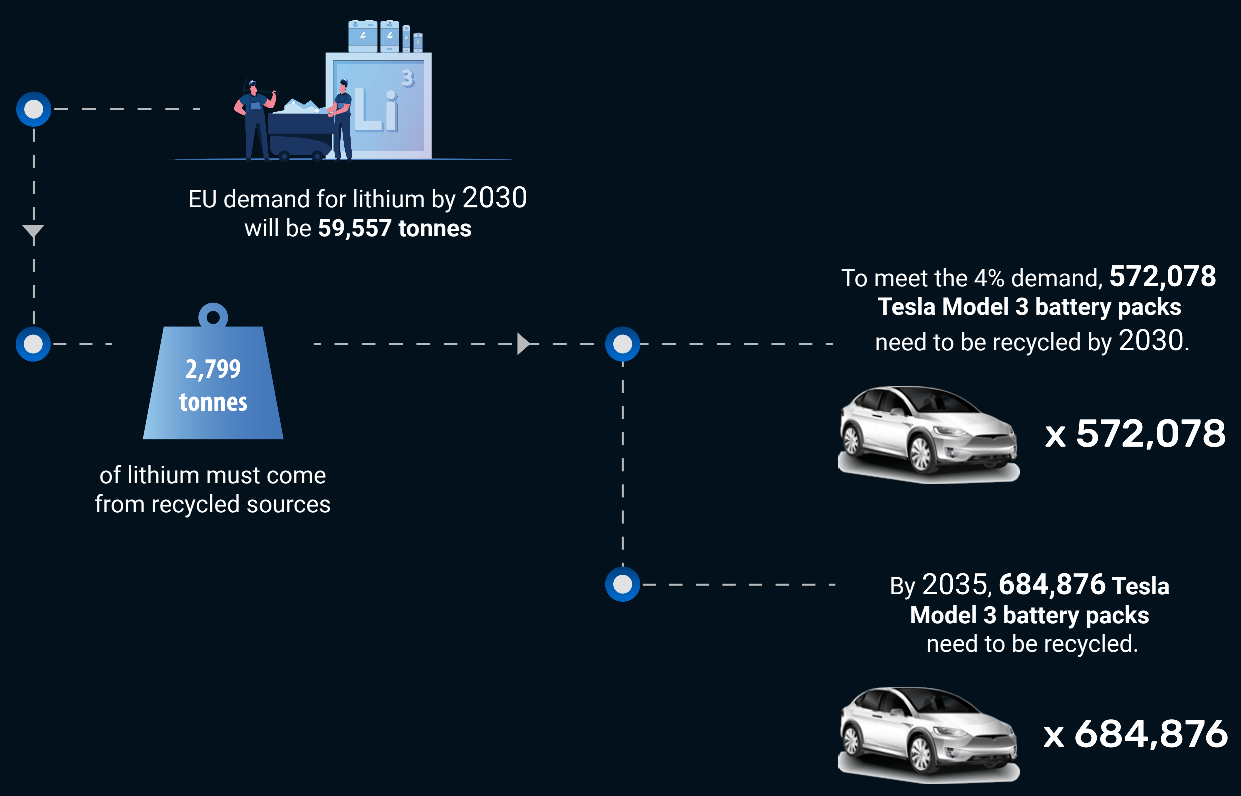
## UNITED KINGDOM

Taking the UK as an example, with EU battery legislations demanding that 4% of lithium comes from recycled sources, over 87,000 Tesla Model 3 battery packs would need to be recycled annually to meet this demand.

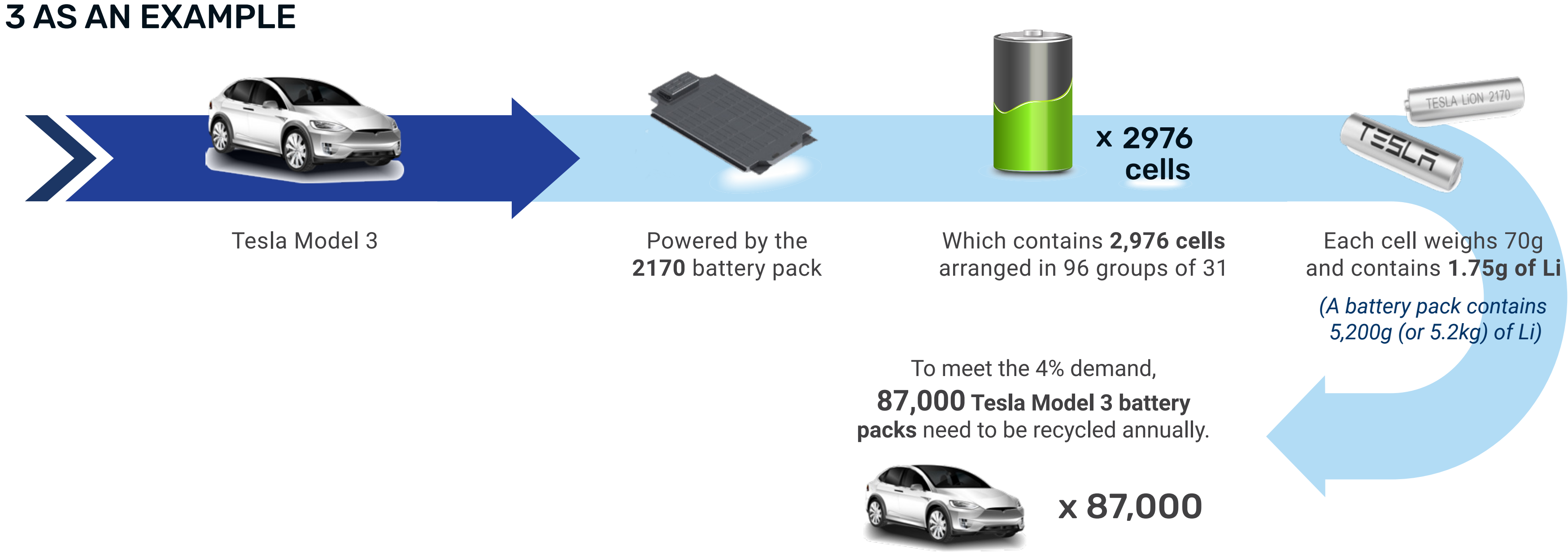



## EUROPEAN UNION

Using this same logic for the EU, on a per annum basis, over half a million Tesla Model 3 battery packs need to be recycled by 2030 to meet that same demand of 4%.




### USING THE TESLA MODEL 3 AS AN EXAMPLE



# Where will the recycled material come from?

Manufacturing scraps can be seen as the ideal starting point for sourcing recycled materials.

## Types of waste produced and quantities

Current LIB manufacturing processes may result in production scraps of 5% to 30% (typically 10%), depending on the stage of the company and level of expertise1 (note that this is based on expert estimates). Scraps can be generated from electrodes and other trimmings or rejected products (e.g., products that fail quality control) from several steps in the manufacturing line.

Given the lifetime of batteries and the current availability of manufacturing scraps, this material is seen as an ideal starting point for recycling.

According to Yole, a 2019 estimate for 2021, approximately 50% of the recycling market would be composed of manufacturing scrap (the remaining is end-of-life EV batteries), which is believed to drop to approximately 40% (148,788 tons) by 2025. As a comparison, one company (Li-cycle, Canada) mentioned that the share of manufacturing scrap in their waste sources currently is 29% and in 2025 is estimated to be 68%.

In terms of types of wastes produced, each unit in the production line may generate a different type of manufacturing scrap. The figure below presents the general production steps in a manufacturing line as well as the general yield and potential combination of recycling methods.

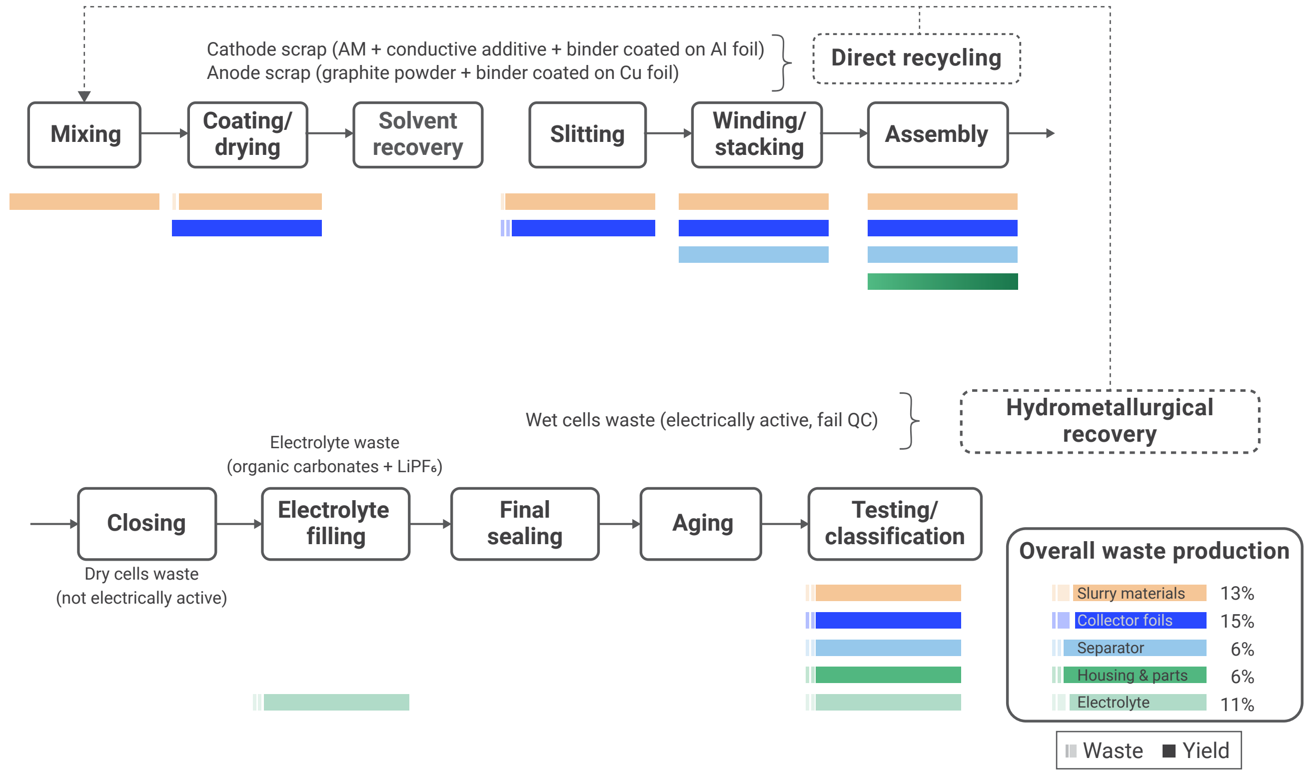



**Figure.** Generalized manufacturing process of LIBs. Under each unit, the estimated waste generated is presented. Above each unit, the type of waste generated and potential route for recycling is also shown. (adapted from Hanisch *et al.*, 2015).

In the figure above, a potential combination of two recycling methods is presented. In the upper portion of the figure, the scraps generated may be recycled by direct recycling, while in the bottom portion of the figure, the scraps may be recycled by hydrometallurgical methods. Using only the direct recycling method, for NMC and LFP pouch cells for example, the GHG emissions may be up to 10% and 14% (for NMC and LFP respectively) lower than using hydrometallurgical methods.

Therefore, a combined route would result in lower GHG emissions of up to 10-14%, with the more scraps that are processes by direct recycling, the closer to 10-14% savings in GHG. The combination may present economic benefits as well, given that the operating cost of direct recycling is higher than hydrometallurgical recycling (as shown in Figure 1); however, a more detailed techno-economic analysis is required. Pyrometallurgy was not included in this exercise because it likely leads to higher GHG emissions than both hydrometallurgy and direct recycling.

**The combination of direct recycling and hydrometallurgical methods in processing manufacturing scraps could result in a 10-14% reduction in GHG emissions.**

## Comparison between East and West - who is producing more of what?

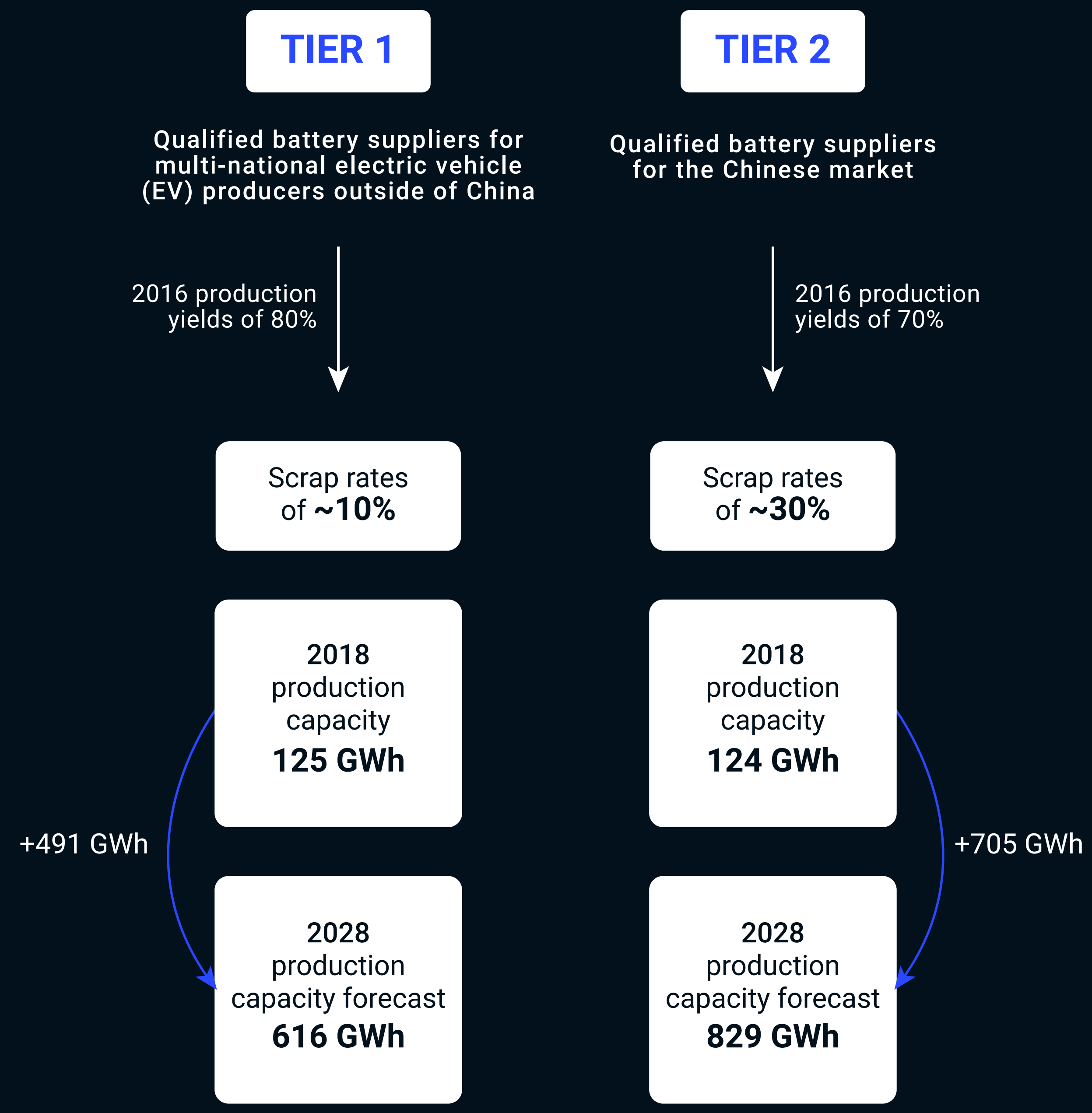
Producers are classified as tier 1 and 2. Tier 1 producers are qualified EV battery suppliers at the multi-national level while Tier 2 suppliers are qualified suppliers for the Chinese market. Precise figures about wastes and yields are difficult to obtain because most companies keep this information confidential. However, considering:

a) The previously mentioned estimates for the overall industry of manufacturing scraps ranging between 5-30%;

b) The study from Chung *et al.* that considered two production yields in a 2016 study: 80% for tier 1 and 70% for tier 2.

It can be estimated that tier 1 producers would have scrap rates of approximately 10% (the typical value as reported by Gaines et al.1), and tier 2 producers would be at the high end of the range (30%).

Also, the production capacities of tiers 1 and 2 for 2018 are reported as 125 GWh (tier 1) and 124 GWh (tier 2), and for 2028 as 616 GWh (tier 1) and 829 GWh (tier 2) (a 2018 estimate). Therefore, given the capacity of tier 2 producers for the Chinese market only, and the lower production yield, Chinese producers generate more manufacturing scrap currently and will likely continue in the near future.



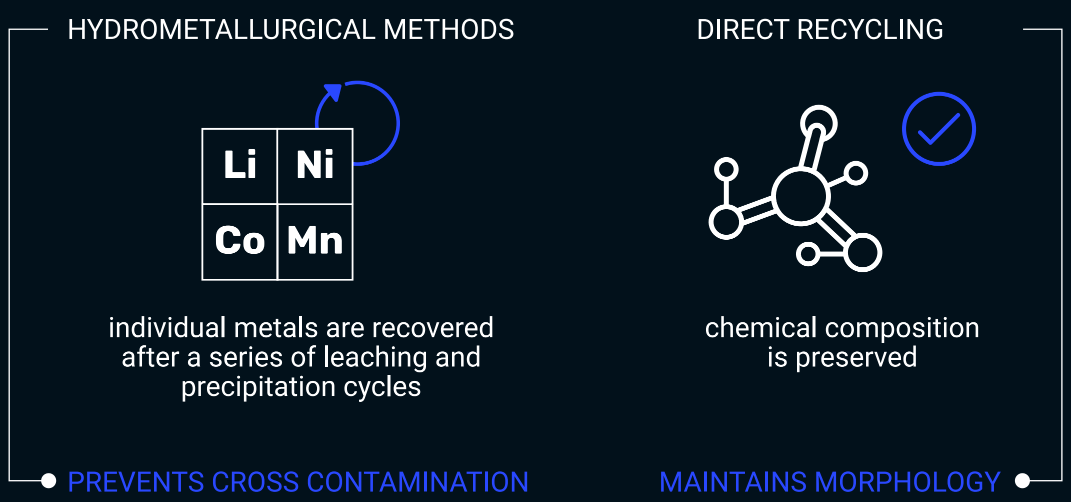

Given the capacity of tier 2 producers (for Chinese market only) and the lower production yield, Chinese producers generate more manufacturing scrap currently and will likely continue in the near future.

**Chinese producers are generating more manufacturing scrap than their Western counterparts and will likely continue to do so in the near future.**

# Cathode recovery - might have a much better application within giga factories

The recycling process of cathode manufacturing scrap could be optimized by segregating this material from other wastes, such as anode scrap. Therefore, cross contamination is avoided (in hydrometallurgical methods) and the morphology may also be maintained (in direct recycling method). In hydrometallurgical methods, the individual metals are recovered after a series of leaching and precipitation cycles, whereas in the direct recycling method, the crystal morphology of the cathode is preserved and the material can be reincorporated in the manufacturing line with almost no changes since the chemical composition is preserved. Gaines *et al.* argue that direct recycling could be used at present to process manufacturing scrap. The authors also present a third-party estimate that manufacturing scrap could become the main source of recycling material.

### CATHODE RECOVERY BETWEEN HYDROMETALLURGICAL AND DIRECT RECYCLING METHODS



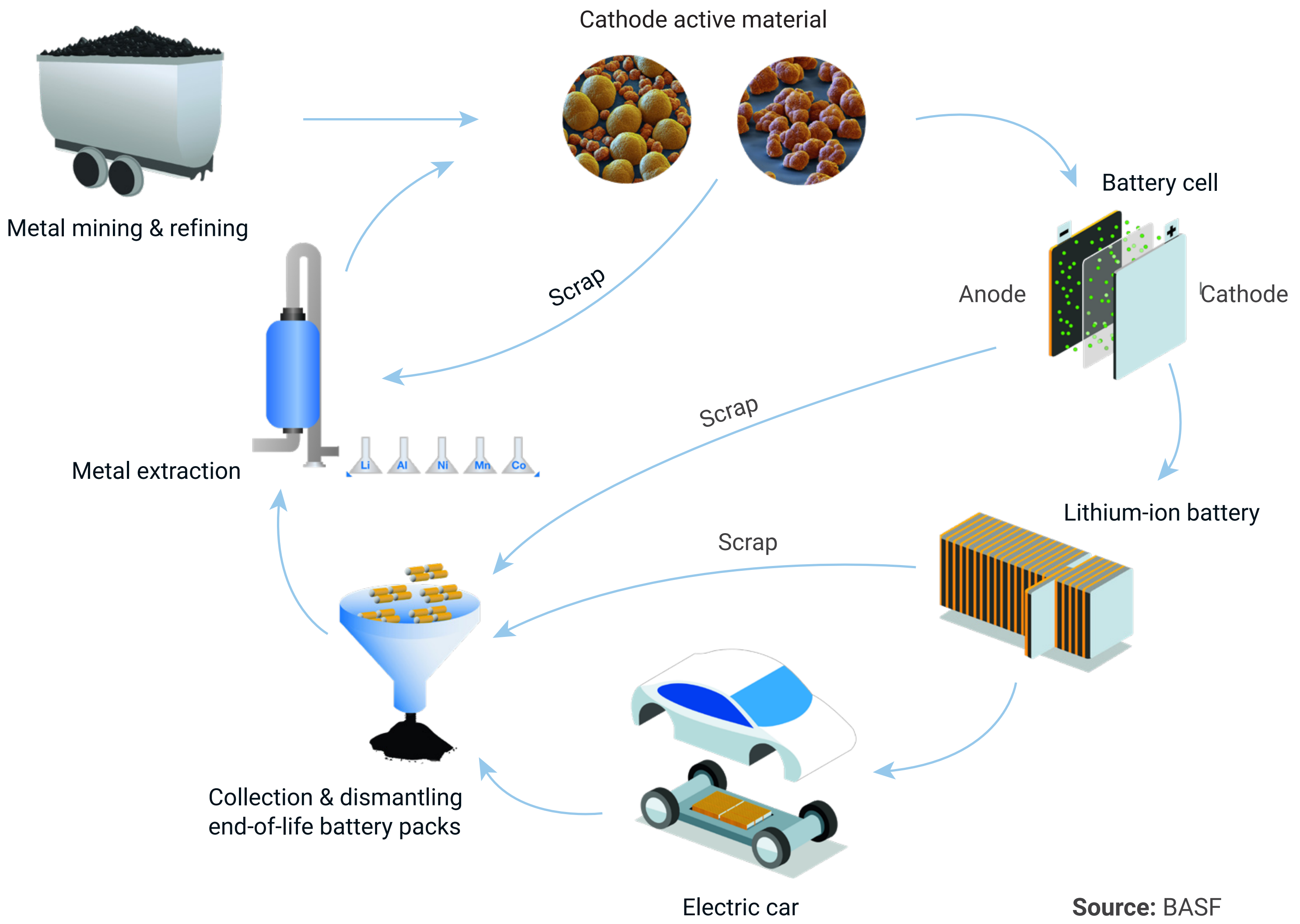

**Cathode recycling is the key to viability for LIB recycling in general, as the cathode is the most energy- and water-intensive component to produce. It also contains the most expensive materials that need to be recovered.**

# Processes that allow delamination of electrodes and repairing of materials

Processes for delamination described in the literature include the use of heat that can decompose the binder, use of solvents to remove the aluminum current collector, or use of sonication. The first two processes have as disadvantages the time (approximately 3 hours) and high temperatures needed.

The sonication alternative was first reported with low-power ultrasound, which can take up to 1.5 hours. A more recent study used high-energy ultrasound to allow delamination in a matter of seconds. A sonotrode that can deliver a high-energy wave, strong enough to break the adhesive bonds between the current collectors and the active materials, is used, and in the best configuration, the process can last less than 10 seconds. However, this process is at a very early stage of development. A different approach involves the development of alternative binders that are easier to remove, for instance carboxymethyl cellulose (CMC) in the anode, which is soluble in water. According to Harper *et al.* for cathodes, developing water-based binders is more technically complex because cathode materials are usually degraded in contact with water. This would require the manufacturers to design for recycling but can ultimately simplify the loop.

### BATTERY MATERIALS CIRCULAR ECONOMY




**Source:** BASF

# What would be the optimum way to recycle LIBs?

The recycling processes can be classified in 3 groups: pyrometallurgical, hydrometallurgical, and direct recycling. These processes can also be mixed (e.g., a pyrometallurgical process needs a hydrometallurgical step). Each option has advantages and disadvantages, but in broad terms:

- **Pyrometallurgical:** This type of recovery involves using furnaces at high temperatures to "smelt" the LIBs, generating metal alloy (containing cobalt, nickel, and copper, which can be further processed by hydrometallurgy), slag (containing aluminum, manganese, and lithium, are typically not recovered due to poor economics), and gases (volatile organics from the electrolyte and binders).

- **Hydrometallurgical:** Although hydrometallurgical refers to the acid leaching part, processes that involve mechanical shredding and material separation have been incorrectly referred to as hydrometallurgical in the literature to distinguish them from pyrometallurgical processes. In such processes, battery materials are first processed using mechanical means to enable access to the components that make up the cells. These components are then separated into concentrated individual streams using a combination of processes that make use of the material's physical and chemical properties such as density, magnetism, etc.

  Physical-mechanical separation techniques make recycling more circular. They are not essential for pyrometallurgy, but do reduce waste; but for hydrometallurgy, they are essential. For instance, how would you process the black mass if you have not first separated it from other components?

  The most valuable components – contained in the cathode material – are then leached in acid and other aqueous solutions to get the metal ions into solution, which then can be recovered by solvent extraction (to concentrate the metal ions into individual streams), followed by precipitation. Metals can be recovered in different forms such as sulfate, oxalate, carbonate, and hydroxide, depending on the reagents used. The economic incentive for this process is mainly related to the recovery of cobalt and nickel. For Co-rich batteries, hydrometallurgical and pyrometallurgical can recover approximately 70% of the cathode value (which is lower for cathodes with lower Co content).

- **Direct recycling:** This process maintains the chemical structure of the cathode, avoiding complex purification steps. The recovery of both anode and cathode components were demonstrated (although the anode is of low value). This is the least developed process and several issues still exist, such as the low flexibility in terms of composition (which given the lifetime of a few decades, may result in new and varied formulations that this process may struggle to adapt to). Theoretically, the direct recycling process would be able to recover practically all the components (except the separators).

Harper *et al*. compared the three general recycling processes considering several parameters qualitatively, as shown in the figure below. In terms of best-worst scale, hydrometallurgy processes usually fall in the middle (yellow in their scale), while pyrometallurgy and direct recycling result in worst cases in certain parameters. It is worth noting that the most suitable process may differ depending on specific conditions. For example, if a facility cannot manage large volumes of strong acidic wastes, hydrometallurgy may not be the best choice.

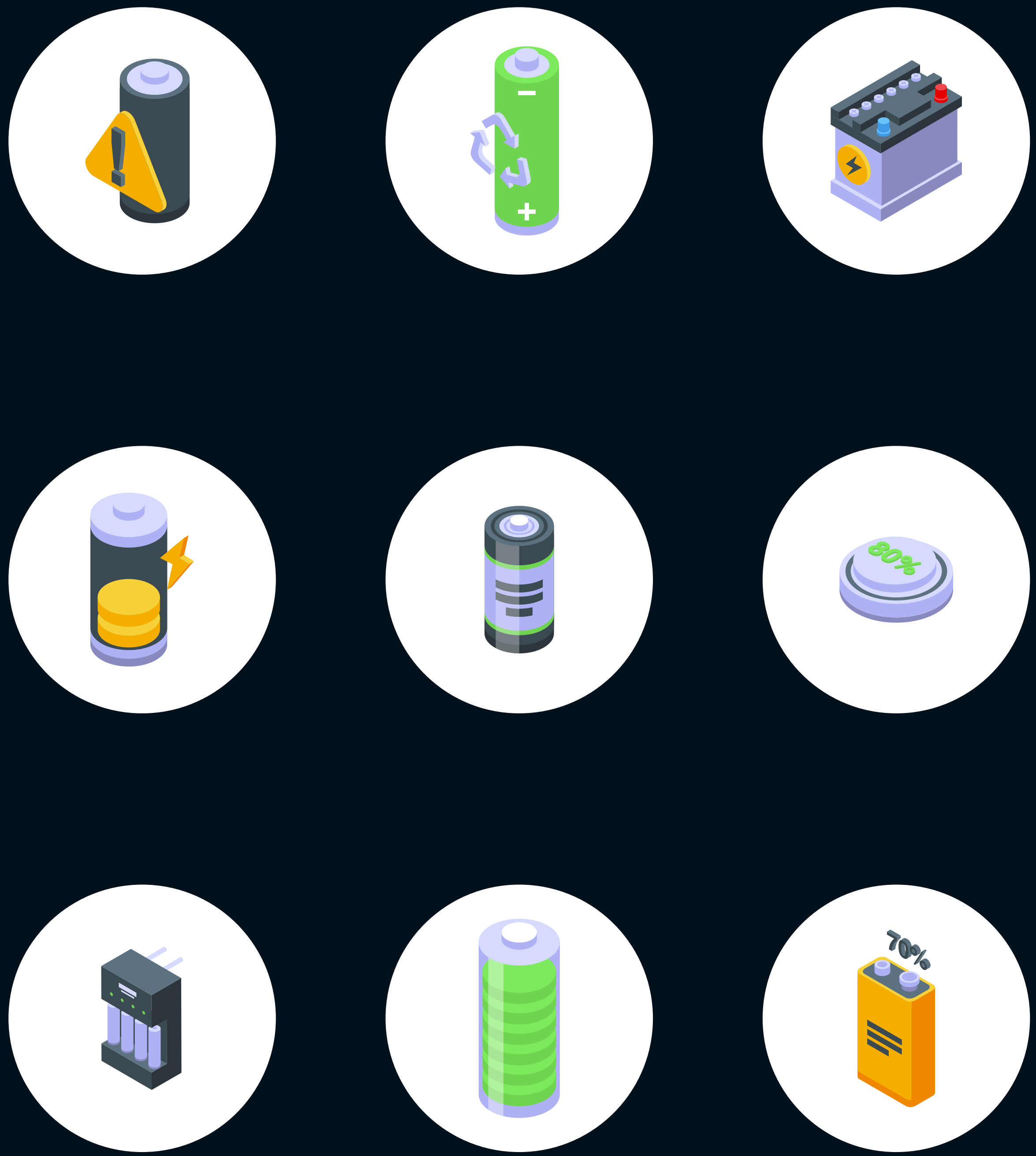
| | Pyrometallurgy | Hydrometallurgy | Direct recycling |
|---|---|---|---|
| Complexity | + | ○ | ⊖ |
| Energy usage | ⊖ | ○ | ○ |
| Capital cost | ⊖ | ○ | ○ |
| Production cost | + | ○ | ⊖ |
| Cathode morphology preserved | No | No | + |

+ ○ ⊖

Best <<<<< Worst

**Figure.** Qualitative comparison of LIB recycling processes (adapted from Harper *et al*., 2019).

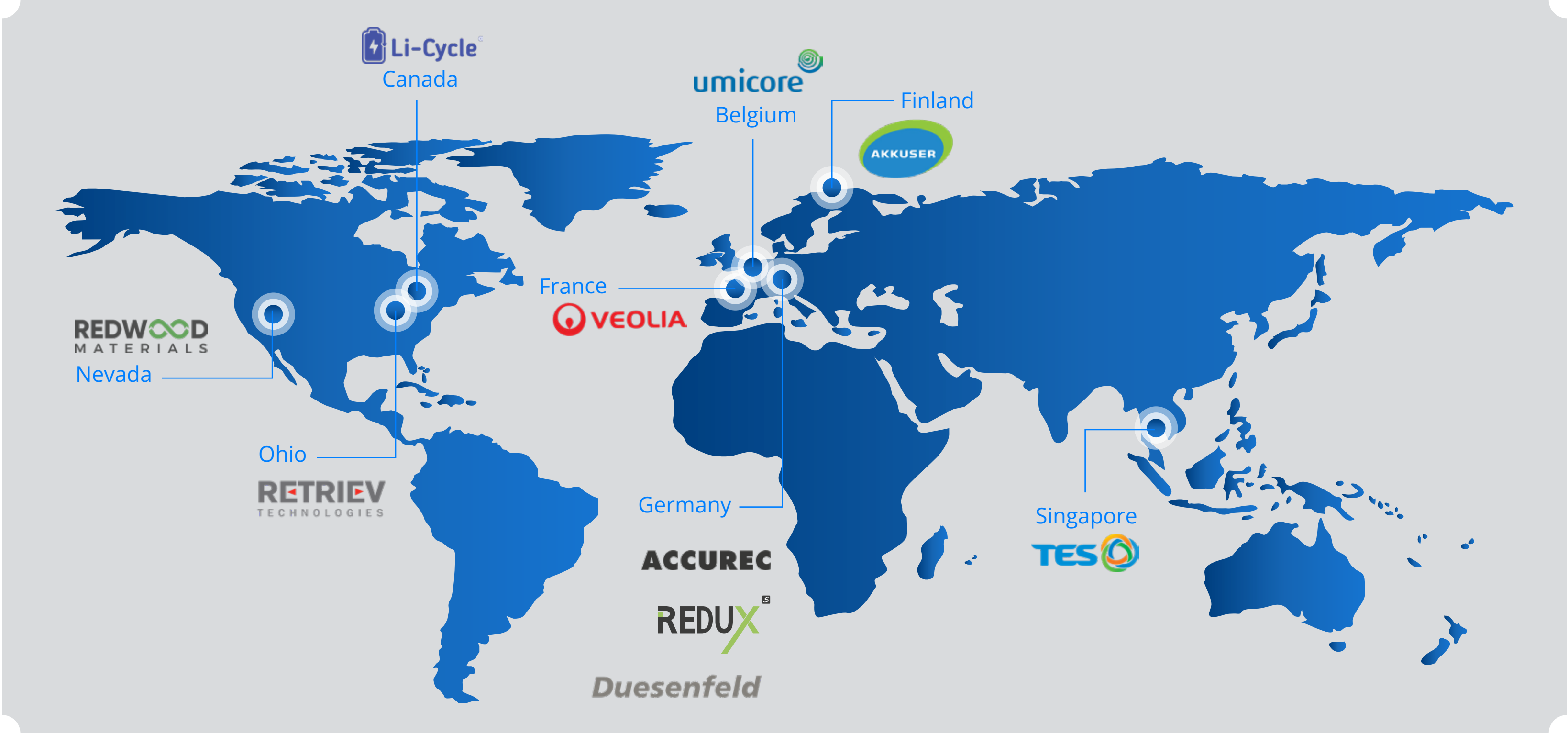
Another important point is that not all recycling methods are suited to process all different chemistries. Pyrometallurgical and hydrometallurgical methods may result in more GHG emissions than not using any recycling method for LFP batteries, and pyrometallurgical methods also often lead to downcycling (i.e., producing less valuable products). In addition, it may also not be feasible to employ hydrometallurgical or direct recycling due to the low cost of the cathode materials in the LFP case. New separation methods could improve the economics and the GHG emissions, such as the sonication method (as discussed below). By refining the electrode separation, the purity of products may be increased, as well as the economic performance of the process.




# Recyclable materials in different lithium-ion battery types

| Material | Material Value USD/kg | % content in a cylindrical cell | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | NMC111 | NMC523 | NMC622 | NMC811 | NCA | LFP | LMO | LCO |
| **Casing** | | | | | | | | | |
| Steel* | 1 | 15% | 15% | 15% | 15% | 15% | 15% | 15% | 15% |
| Aluminum | 2.5 | 5% | 5% | 5% | 5% | 5% | 5% | 5% | 5% |
| Copper | 10 | 7% | 7% | 7% | 7% | 7% | 7% | 7% | 7% |
| **Anode Material** | | | | | | | | | |
| Graphite | 3.2 | 18.1% | 18.1% | 18.1% | 18.1% | 18.1% | 18.1% | 18.1% | 18.1% |
| **Cathode Material** | | | | | | | | | |
| Manganese | 2.5 | 6.1% | 5.5% | 3.6% | 1.8% | | | 19.4% | |
| Lithium | 400 | 2.3% | 2.3% | 2.3% | 2.3% | 2.3% | 1.4% | 2.3% | 2.3% |
| Cobalt | 80 | 6.5% | 3.9% | 3.9% | 1.9% | 2.9% | | | 19.3% |
| Nickel | 30 | 6.5% | 9.7% | 11.6% | 15.4% | 15.6% | | | |
| Aluminum | 2.5 | | | | | 0.4% | | | |
| Iron | 0.5 | | | | | | 11.3% | | |
| **Total Value per kg (USD)** | | **$18.06** | **$16.92** | **$17.44** | **$16.94** | **$9.87** | **$7.21** | **$11.24** | **$26.19** |

# Key players in the battery recycling space




## LI-CYCLE: Spoke and Hub recycling with no landfilled waste

Li-Cycle, a Canadian startup, uses their proprietary Spoke and Hub technologies, which combine mechanical safe size reduction and hydrometallurgical resource recovery specifically designed for lithium-ion battery recycling. The company's process uses only leaching (bypassing the smelting process) to recover more than 95% of all raw materials found in LIBs, according to Li-Cycle. Hence, Li-Cycle's proprietary technology allows for safe processing of all LIBs without any landfilled waste and minimal GHGs, enabling a more sustainable end-of-life pathway for LIBs. Recent partnerships include New Flyer (a subsidiary of NFI Group) and Atlis Motor Vehicles.

## REDWOOD MATERIALS: Closing the loop for end-of-life batteries

Redwood Materials is a Nevada-based battery recycling company aiming to create a circular or 'closed loop' supply chain and become one of the world's top battery recycling companies. Redwood recycles scrap from battery cell production and consumer electronics through a combination of pyrometallurgy and hydrometallurgy to remove organic materials and plastics and to dissolve metals into a solution, respectively. Retrieved materials include lithium, cobalt, copper and nickel that are supplied back to customers. Recent partnerships include Panasonic and Amazon.

## RETRIEV TECHNOLOGIES: A pioneer in end-of-life battery management

With headquarters in Lancaster, Ohio, Retriev offers custom recycling solutions for consumer, industrial and EV vehicle batteries. Retriev utilizes its patented hydrometallurgical process to recover critical materials necessary for manufacturing lithium-ion batteries. In late 2021, Retriev Technologies allied with Heritage Battery Recycling to create a large lithium-ion battery recycler under the Retriev Technologies brand. The company operates battery recycling and sorting facilities in Lancaster, Ohio, Baltimore, and Train, BC.

## **ACCUREC:** Comprehensive and sustainable battery recycling

Headquartered in Krefeld, Accurec operates recycling facilities in Krefeld and Mülheim in Germany. Accurec recycles 2.2 million kg/yr of NiCd batteries, 0.7 million kg/yr of NiMH batteries and 4.3 million kg/yr of lithium batteries. Accurec's EcoBatRec process was finalized in 2016 and is characterized by no HF emissions, low energy consumption and nearly 0% off-gas emissions. Phase 3 expansion of the recycling facility in Krefeld is planned to commence by the beginning of 2022.

## **REDUX:** Zero waste, closed-loop, Battery2Battery

Located in Offenbach, Germany, REDUX relies on its patented process to recycle lithium-ion batteries, achieving recycling efficiencies between 60-70%. Lithium-ion batteries are collected by REDUX and then discharged into the power grid to save energy and keep the recycling loop at its highest level. The batteries are dismantled where the casings, electronics and modules are separated into plastics, iron, copper and aluminium. Along with the parent company Saubermacher, REDUX is re-configuring the industrial lithium-ion batteries division, accepting the industrial batteries at the Bremerhaven location exclusively. With the help of the patented X-ray sorting process, REDUX is able to achieve up to 99% sorting accuracy.

## **DUESENFELD:** Ecofriendly recycling of lithium-ion batteries

Duesenfeld, a German-based company uses a combined method of mechanical, thermodynamic and hydrometallurgical processes to recover materials from batteries with minimum energy input. The process recycles graphite, electrolyte, lithium as well as the usual metals available within the battery. The Duesenfeld mechanical process has an efficiency of 72% extracting the electrolyte, copper, aluminium, black mass (graphite, cobalt, nickel, manganese, lithium). When the mechanical process is supplemented with a hydrometallurgical step to treat the black mass, the efficiency can reach up to 91% extracting $CoSO_4$, $NiSO_4$, $MnSO_4$, $Li_2CO_3$ and graphite unlike most industrial hydrometallurgical processes that only recover cobalt and nickel.

## **UMICORE:** First-of-its-kind technology to recover most of the lithium from LIBs

Umicore is a global materials technology and recycling group with headquarters in Brussels, Belgium. With 47 production sites, 15 R&D technical sites and over 10 thousand colleagues, Umicore has an annual capacity of 7000 tons of Li-ion batteries. The company follows a closed-loop business strategy where the metals are transformed into functional materials to be used later in new batteries. Umicore signed an agreement with Automotive Cells Company (ACC) on February 11, 2022, on battery recycling services for the ACC pilot plant in Nersac, France. Through improving the metallurgical process, the extraction efficiency of cobalt, nickel and copper can now reach 95% yield for a wide variety of battery chemistries.

## **VEOLIA/EDI:** Supporting the creation of the raw materials of tomorrow

With headquarters in Paris, France, Veolia focuses on designing and providing solutions for waste, water and energy management. Through their subsidiary Euro Dieuze Industrie, they are deploying solutions for the recycling of EV batteries, mainly through hydrometallurgical process, to recover key metals. Initially, the battery's voltage is reduced (for safety reasons) before deconstructing the battery components and cells. The grinding phase is then carried out followed by a cold hydrometallurgical process to treat the residue and extract the key recyclable metals. This occurs by mixing the metal bearing powder with reagents to separate the metal elements, which are then purified and concentrated. The recovered metals are reused in a variety of industrial sectors. In 2011, EDI and Renault set up a scientific and commercial partnership to carry out the processing and recovery of the used EV batteries. Veolia also signed a partnership with Belgian chemicals group Solvay in September 2020; the partnership will enable Veolia to go further in the value chain.

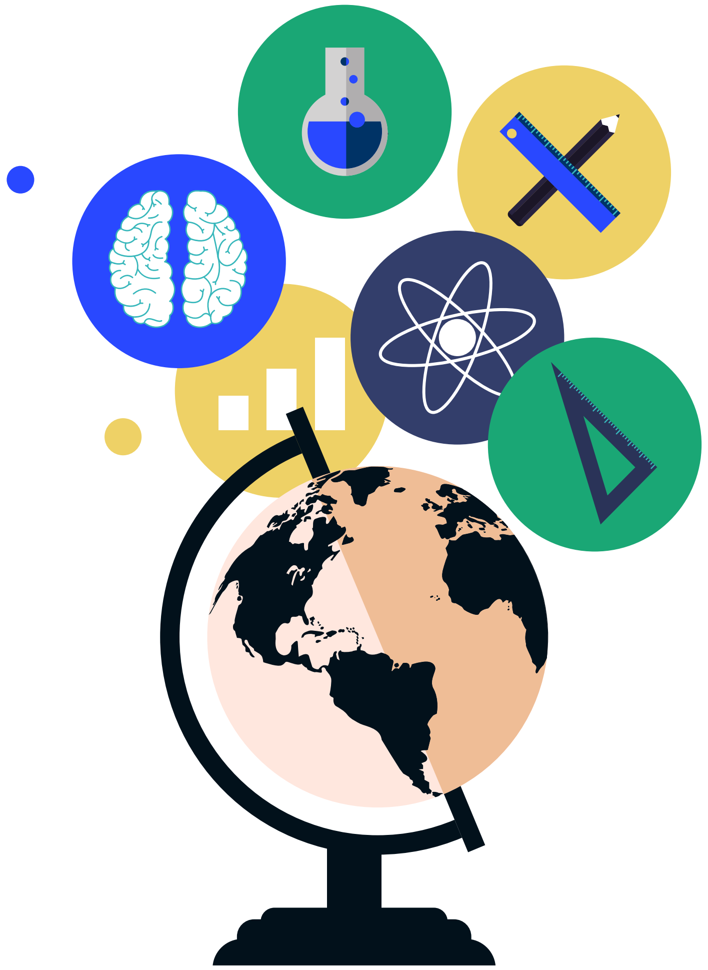
## **AKKUSER:** Safe and efficient battery recycling

AkkuSer has built a recycling plant in Nivala, Finland, to recycle hazardous batteries in an environment-friendly manner. The company receives all the spent portable batteries collected in Finland and sorts them before processing each battery type. The process of recycling over 50% of the battery materials uses 0% water, chemicals, or heating so it doesn't produce any related emissions. AkkuSer utilizes a Dry-Technology method starting with mechanical crushing and separation (magnetic /mechanical) followed by delivering the metal concentrates to metal refineries.

## **TES:** High recovery rate, closed-loop recycling

With 40+ locations worldwide, TES offers full sustainable technology lifecycle solutions. The technology offers 90% recovery rate and 99% purity for the extracted cobalt and lithium metals. TES technology can be divided into 2 main stages, the black mass process and the chemical refinement process. The first stage shreds, dismantles, and separates the feed batteries into Cu/Al product and black mass. The second stage leaches the black mass and passes it through several stages of reaction and filtration, obtaining graphite, cobalt hydroxide and lithium carbonate.

# Recent advances from academia



## The past 18 months have seen a surge in academic research focused on battery recycling

Presented here is a selection of a few promising advances.

### Ultrasonic delamination technique returns high purity materials for reuse in new battery manufacturing - *June, 2021*

As part of the Faraday Institution project's on the recycling of lithium-ion batteries (ReLiB), researchers at the University of Leicester and Birmingham are using ultrasonic waves to develop a new method to recycle EV batteries. By working on the disassembled components of the Li-ion batteries the researchers are able to recover around 80% of the original material in a purer state than recycling shredded material. The researchers devised a novel ultrasonic delamination technique that separates the active material from the supporting foil, leaving metals like aluminium or copper. The process is highly efficient in separating graphite and lithium nickel manganese cobalt oxides (NMC) and is 100 times quicker than the conventional recycling techniques. The process uses water or dilute acids as solvent, making it less expensive and greener. The technology has been tested on four different battery types and similar results were obtained.

### Ultrasound can enable faster, more sustainable battery recycling - *October, 2021*

Researchers at the KTH Royal Institute of Technology are working with ultrasound to extract valuable metals from EV batteries, specifically, NMC. In the conventional process, mechanical stirring is used along with harmful leaching agents such as sulfuric acid to extract the metals. Researchers found that by using ultrasonic baths with frequencies of 40 kHz, the waves create microbubbles that can generate local temperatures of nearly five thousand degrees along with highly reactive free radicals. The agitation helps in the mass transfer of metals wit out the need for any harsh chemicals. The process reduces the extraction time by 50% and achieves a 97% metal ion recovery on average.

### Researchers develop new metal-free, recyclable polypeptide battery that degrades on demand - *May, 2021*

A team of researchers at Texas A&M University are working on a new battery technology that is metal-free. The new technology relies on polypeptides which are protein components, making the batteries degradable, non-toxic and recyclable. In acidic conditions, the new batteries can be degraded into amino acids. The metal-free batteries would eliminate the need to mine precious metals such as cobalt, which is mined in dangerous working environments and in some cases using child labor. By using an all-polypeptide organic radical battery composed of redox amino acid macromolecules, the researchers believe significant progress can be made towards sustainability.

### Expanding on the potential of bioleaching as a sustainable method for recycling LIBs - *2021/2022*

Biological leaching (also called biomining) has been widely used in the mining industry but is now finding potential applications within the recycling of LIBs. A major challenge in recycling of LIBs is the selective separation of metals from battery leachates at a purity that allows for its reuse. The incorporation of biological methods may provide the answer, as bioprocessing occurs at relatively low temperatures (<37 °C) and does not involve the use of hazardous compounds. Faraday Institution researchers report employing two bacterial species to recover Mn, Co and Ni, from EV LIBs through the biosynthesis of metallic nanoparticles, while Li remains within the leachate. Researchers at Singapore's Nanyang Technological University report the development of a green closed-loop cathode regeneration technique from spent NMC-based LIBs through bioleaching. 85.5% of Ni, 91.8% of Mn, 90.4% of Co, and 89.9% of Li were leached out from NMC-based spent LIBs.

# Dominant LIB chemistries within the next decade

## EV battery manufacturer market overview

The EV battery market has experienced steady growth rates over the past few years. 30 gigawatt-hours of storage capacity were produced by EV-battery manufacturers worldwide in 2017, a 60% increase compared to 2016. Predictions indicate that by 2040 about 70% of all vehicles sold in Europe will be electric (passenger cars, vans, trucks and buses, reaching a total of 1,200 gigawatt-hours annually in the same year.

The market is mainly dominated by players from Japan, China and South Korea. Less than 3 percent of the global demand was supplied by players from outside these three countries in 2018. Some of the reasons for this are, for instance, in China, the infrastructure is better and getting the necessary permits to construct a factory is relatively easier than other locations such as in Europe.

Several cell chemistries are in the market under the Li-ion battery family for electric vehicles applications and are presented in Table 1.

### TABLE 1. VARIOUS LIB CHEMISTRIES FOR EV APPLICATIONS

| Cell Chemistry | Cathode / Anode | Capacity (Ah) | Gravimetric energy density (Wh/kg) | Volumetric energy density (Wh/L) | Range (km) |
|---|---|---|---|---|---|
| **LFP** | LFP / C | 20 | 131 | 247 | 130 |
| | LPF | - | 12 | 220 | 300 |
| **NCA** | NCA / C | 3.2 | 236 | 673 | 330-500 |
| | NCA / Si-C | 3.4 | 236 | 673 | 330-500 |
| | NCA / SiO-C | | | | |
| | NCA / Si-C | 4.75 | 260 | 683 | 350-500 |
| **NMC** | NMC / LTO | 20 | 89 | 200 | 130 |
| | NMC / C | 59 | 241 | 466 | 400 |
| **Blended Chemistries** | NMC-LMO / C (Samsung) | 63 | 172 | 312 | 140 |
| | LMO-NCA / C (AESC) | 40 | 167 | 375 | 172 |

In general, Li-ion batteries use a negative electrode principally from carbon or lithium titanate. Some novel materials are under development such as Li metal and Li (Si) alloys. The choice of materials is based on the desired performance properties such as: energy, power density, safety concerns, cost and lifespan. Table 2 summarizes the different cell chemistries available in the market.

| Positive electrode (cathode) | Chemistry | Advantages | Disadvantages | Applications |
|---|---|---|---|---|
| | **Lithium Iron Phosphate (LFP)** | · The phosphate provides higher tolerance to heat, limiting the break down of the material (the higher safety characteristic enables the manufacturing of larger cells leading to a higher cell-to-pack ratio)<br>· Wide temperature range (+60°C to – 30°C)<br>· Efficient power-to-weight ratios<br>· Low raw-material cost<br>· 20% less cost per kilowatt-hour compared to the NMC532 battery | · Higher self-discharge compared to other Li-ion batteries, causing balancing issues with aging<br>· Moisture content can limit the battery lifetime | Hybrid vehicles, EVs in China, electric buses, portable applications such as powertools, toys, etc. |
| | **Lithium Nickel Manganese Cobalt Oxide**<br>e.g: NMC111, NMC442, NMC622, NMC811, NMC532 | · NMC are characterized by high specific energy<br>· Excellent thermal characteristics<br>· NMC811 has the highest energy density compared to NMC532 and NMC622 | · Requires humidity control<br>Higher nickel content leads to more difficulty in manufacturing | The most successful Li-ion system used in many EV manufacturers including Nissan Leaf, Chevy Volt and the BMW i3 energy storage systems. |
| | **Lithium Nickel Cobalt Aluminium Oxide** | · Similar to the NMC batteries, the NCA offers high specific energy and specific power<br>· Characterized by long life span | · NCA batteries are not as safe as other batteries<br>· High manufacturing cost | Tesla uses NCA chemistry with lower cobalt content than the NMC811. The Tesla current battery contains less than 5% cobalt and will soon eliminate it totally |
| | **Lithium Titanate** | · Temp. range from -30 to 55 °C<br>· 98% recharge efficiency<br>· Life cycles between 3000-7000 cycles<br>· High safety and stability performance | · Low voltage (2.4V/cell)<br>· Relatively low energy density<br>· More difficult manufacturing processes | Advanced nano-technology applications |
| | **Lithium Manganese Oxide** | · Low internal cell resistance enables fast charging and high-current discharging<br>· Better thermal stability than lithium cobalt oxide batteries | · 33% lower capacity than lithium cobalt oxide battery and a lower life span | · EVs, Hybrid electric vehicles (HEV)<br>· used as a mixture alongside NMC to give NMC batteries better power characteristics |
| | **Lithium Cobalt Oxide** | · High energy density<br>· Long life cycle<br>· Ease of manufacturing | · Highly reactive<br>· Poor thermal stability (must be monitored during operation)<br>· Limited availability of cobalt making it more expensive | · Tesla original Roadster<br>· Smart Fortwo electric drive (ED)<br>· Cells, tablets, laptops, cameras, medical applications |
| | **Lithium Nickel Oxide** | · Lower cost of materials as it is Co free<br>· High capacity | · Formation of a self-passivation layer at the surfaces cause difficulties during usage<br>· Difficulty in synthesizing stoichiometric $LiNiO_2$ | - |

## CURRENTLY, CARBON-BASED ANODES ARE THE DOMINANT TYPE OF ANODES BEING USED

- **Carbon-based electrodes:** Natural and synthetic graphite are chosen due to its relatively high specific capacity of ~370 Ah/kg and high overall cell voltage and roundtrip energy efficiency. The carbon material is abundant, available at low cost and non-toxic.

  On the down side, the carbon reacts with atmospheric $O_2$ and can cause fire in the event of a thermal runaway.

  Silicon carbon anodes are currently being deployed in automotive lithium-ion batteries (Tesla Model S and Model 3). By introducing 6-10% Si to the synthetic graphite, the specific volume exceeds 550 mAh/g and an energy density of 300 Wh/kg. Predictions foresee that by 2030 Si content may reach 30% in automotive applications.

- **Lithium titanate electrode (LTO):** The electrode offers an extremely long operational lifetime, as it has no volume change during lithiation. The electrodes have a flat discharge and charge plateau, thus providing improved safety.

  Applications of titanate batteries include: certain Japanese versions of the Mitsubishi i-MiEV, Honda Fit EV, Tosa concept electric bus and mobile medical devices (owing to their high level of safety).



# State of the EV LIB market

According to PreScouter's State of the Electric Vehicle Lithium-Ion Battery Market 2019-2030, it is expected that the lithium-ion cells will continue to dominate the EV markets as the primary energy storage for the next decade. Specifically, LFP batteries are to be leading the market by 2030, growing from 10% of the market in 2015 to more than 30% in 2030.

Continuous research and development will increase the energy density of LFPs causing it to overtake the NMC batteries as cobalt prices rise. The toxic and hazardous nature of cobalt will cause a shift away from NMC batteries.

The LFP battery will remain popular in the Chinese EV market, retaining more than 20% of EV battery installations by 2025 and expected to have a market share of 60% between 2030-2050 if Tesla proceeds with equipping the Chinese version of Model 3 with LFP batteries. With the growing market share of LFP over NMC in the future, the Chinese market will become the center of the EV scene including stakeholder, R&D and manufacturing.

## APPLICATIONS FOR RECYCLED ANODE GRAPHITE:

Despite the long charging and discharging cycling, the graphite structure of the anode is not destroyed, making it possible to recycle the spent material. Some of the possible applications for the recycled anode graphite include:

- **Regenerated anode material:** According to several published research papers, the used anode material may be regenerated to be used again in batteries. The regeneration process removes acetylene black (AB), styrene butadiene rubber (SBR) and carboxymethylcellulose sodium (CMC) through heat treatment. The anode material is coated with pyrolytic carbon from phenolic resin. Technical indexes of regenerated anode are higher than that of the same type midrange graphite. Partial technical indexes are close to the unused graphite material, fully meeting the reuse criteria for Li-ion batteries. EcoGraf has achieved >99.95% purity carbon through their recycle program to recover graphite anode material to be able to reuse it in LIBs in EVs. The acid-treated graphite can be used directly in sodium ion batteries (SIB). Otherwise, structural reconstruction is necessary to be able to use the graphite as anode material in LIBs.

  On the industrial level, Nouveau Monde Graphite Inc. and Lithium Recycling formed a collaboration agreement to recover the recycled graphite for reuse as anode material in LIBs. The recycled carbon electrodes achieve a specific capacity of 162 mAh/g in sodium ion batteries and 320 mAh/g in potassium ion batteries.

- **Fe-N-doped Carbon ORR Catalyst:** The carbon material in general can be used as a carrier for catalysts due to their structural ductility, electrical conductivity and high alkali/acid resistance. Studies have shown that the spent graphite can be recycled through several stages starting with the crushing, milling and sieving of the spent graphite to remove any large impure particles. Nitrogen and iron-doped carbon composite can be obtained by uniformly mixing spent graphite $(FE2(SO_4)_3$ and polyaniline. The precursor is then pyrolyzed in nitrogen atmosphere and then employed as an optimized catalyst named C-PANI-FE.

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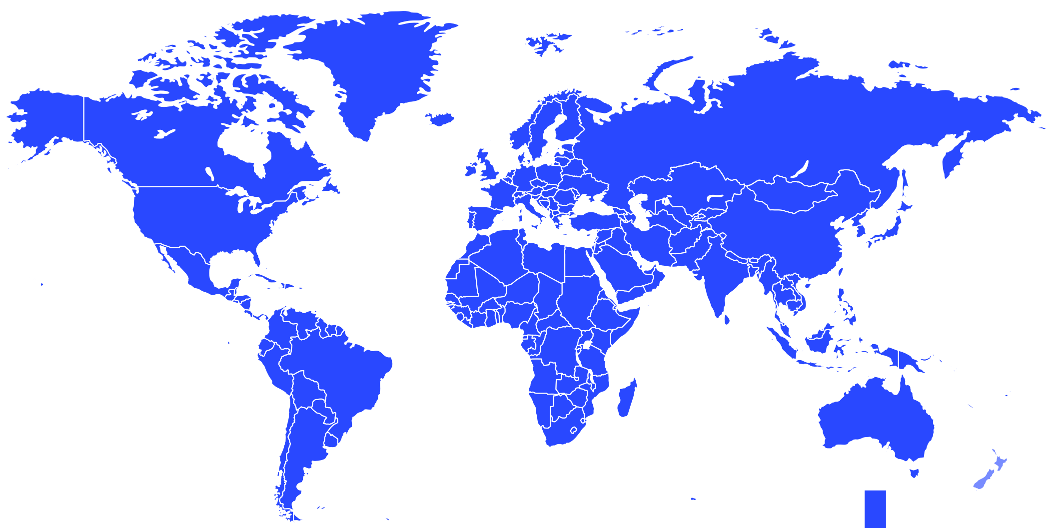

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