

BETTER BATTERY RECYCLING

Opportunities along
the lithium-ion battery
lifecycle value chain



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EXECUTIVE SUMMARY

From smartphones and laptops to emerging technologies such as electric vehicles, what the next wave of transformative technologies all have in common is that they are all powered by the same underlying source: the ubiquitous lithium-ion battery (LIB).

But popularity brings its own set of problems. The soaring demand for LIBs drives up the cost of raw materials like cobalt, which saw a 300 percent price increase between 2016 and 2018. And once those batteries reach the end of their usable lives, municipalities are faced with millions of tonnes of hazardous waste that cannot simply be disposed of in landfills and incinerators.

Recycling addresses both these issues, processing the spent batteries and generating new raw materials in the process. The generation of battery-grade materials effectively closes the loop, making LIBs and all the processes they enable more sustainable. It is little surprise then that China, the largest producer of LIBs in the world, is at the forefront of developing innovative ways of recycling LIBs.

This white paper provides an overview of the LIB recycling market and takes a deep dive into the latest developments in LIB recycling technology. Our in-depth analysis of the patent landscape reveals the pain points of the current LIB recycling industry and conversely, the opportunities where technology can make the biggest impact.

Key highlights

01

China leads the global LIB recycling movement

The high number of electric vehicles and regulatory restrictions on battery waste have spurred Chinese companies and research institutions to focus heavily on LIB recycling. Our analysis of patent filing activities related to LIB recycling revealed that China holds the largest number of patents, followed by Japan, South Korea and the United States.

02

Recycling matters to all players in the LIB value chain

LIB recycling is important not only for battery recycling companies but all players along the entire value chain. Automotive original equipment manufacturers and mining companies hold many of the key LIB recycling patents, underscoring the importance of recycling technology to both the demand and supply side.

03

Pre-processing will be a priority

The majority of the patents in the LIB recycling space focus on pre-treatment and physical disassembly, as these steps are common to different recycling methods. One possible way to facilitate greater recycling would be for the industry to develop a set of standards so that diverse types of batteries can be dismantled and pre-processed more easily.

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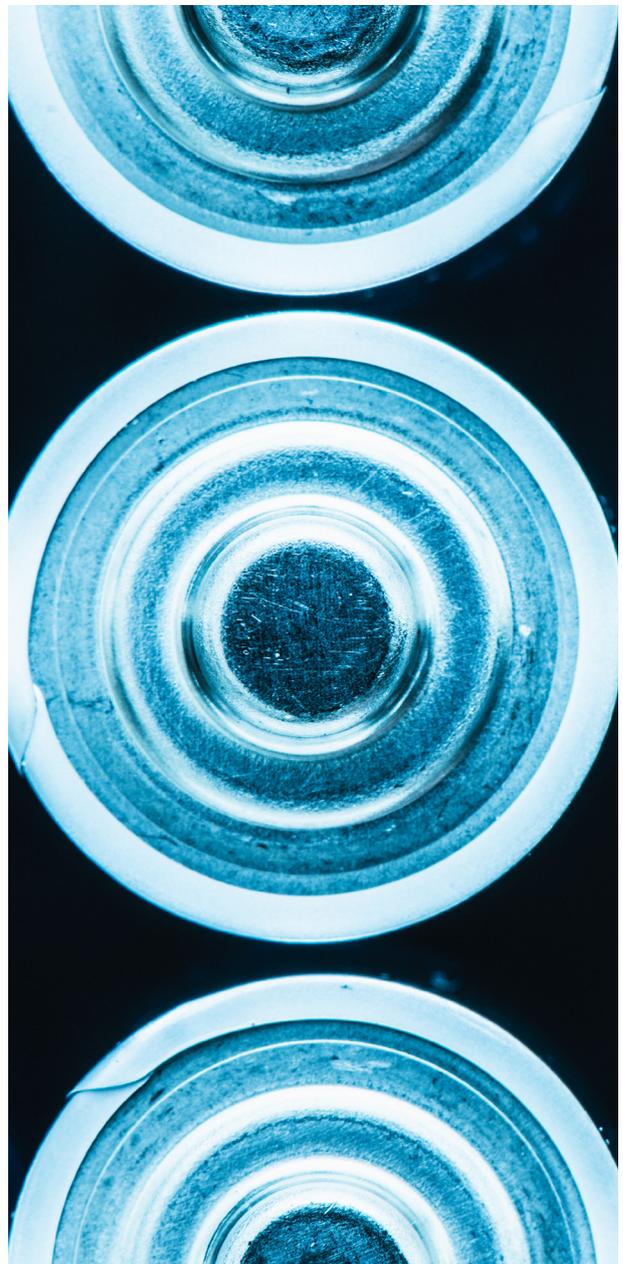
It's all about the metal

Following pre-processing, metal recovery processes are the next largest target of LIB recycling patents. In particular, the high metal recovery and lower operating temperatures of hydrometallurgy make it the preferred method, although other techniques that can be adapted to various battery chemistries are also popular.

05

Hybrid approaches

Increasingly, more recyclers are adopting a combination of both pyrometallurgy and hydrometallurgy, rather than single processes on their own. Emerging methods such as bioleaching and electrolysis, while currently expensive and largely experimental, are also being investigated.





THE PROBLEM: WHAT TO DO WITH SPENT LITHIUM-ION BATTERIES?

Our lives have been transformed through various technologies, particularly consumer electronics such as smartphones, which have placed instant communication and access to an unprecedented volume of information at our fingertips. Electric vehicles, hailed as a more intelligent, cleaner and greener alternative to conventional cars using fossil fuels, are also expected to revolutionise the way we view transportation.

Lithium-ion batteries (LIBs) have been indispensable to the development and implementation of these

technologies in our lives. While consumer electronics have been the major source of LIB demand for the past decade, worldwide demand for e-buses, bikes, scooters and cars have steadily grown since 2015 (Figure 1). In fact, global LIB sales catering to electric modes of transportation, as well as energy storage, are projected to eclipse that of consumer electronics after 2020.

The sheer volume of spent LIBs accumulated from these demands have begun to cause significant concern worldwide, with statistics predicting almost five million tonnes¹ of spent LIBs from sales in 2025 alone. Simply consigning this waste to landfills will constitute a considerable environmental and social burden, but advances in battery recycling and refurbishment technology mean that current and future waves of spent LIBs could be tackled in more meaningful ways that reduce environmental damage and provide alternative sources of revenue in the battery manufacturing industry.

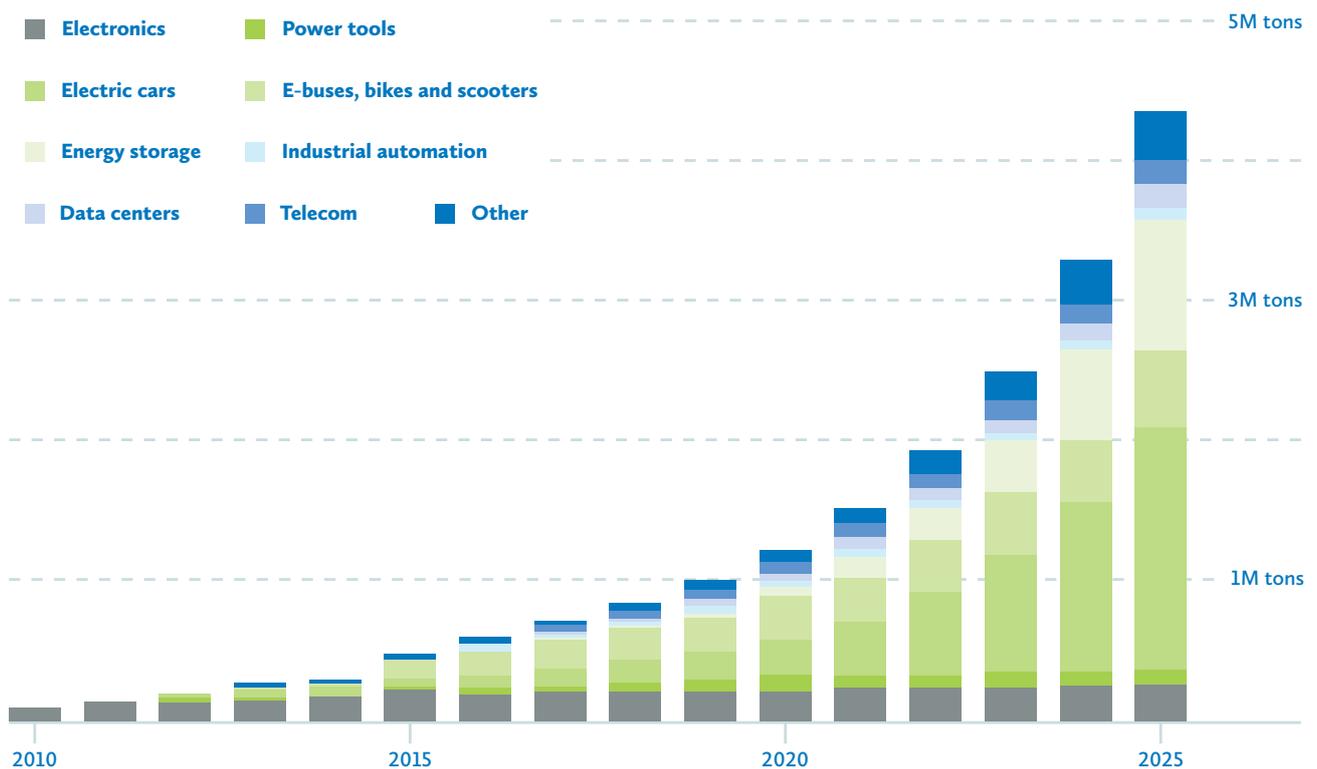
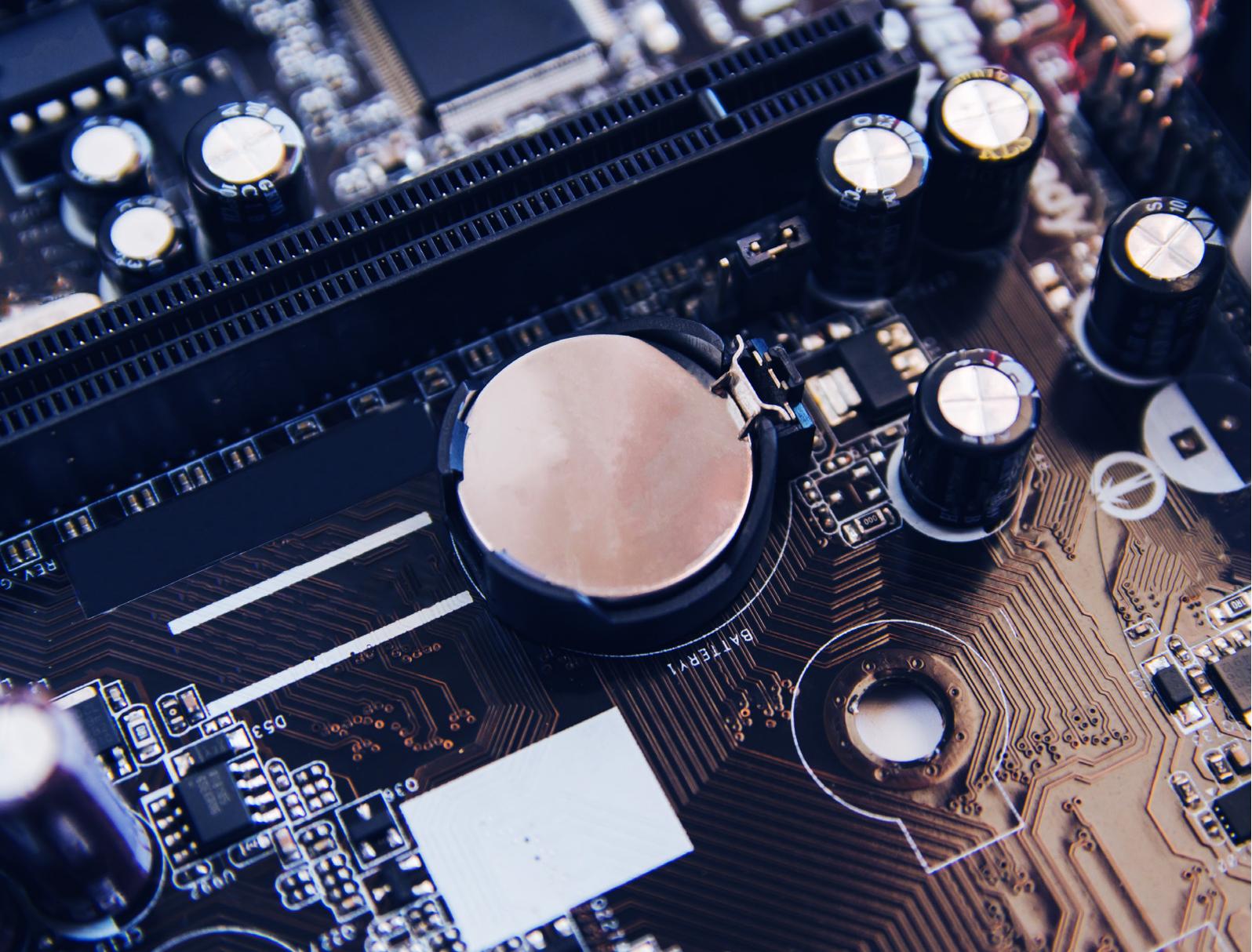


Figure 1

Global lithium-ion battery cell sales. Although currently only a relatively small segment of the market, electric vehicles are expected to become the main driver for LIB demand as soon as 2021. Source: Circular Energy Storage Research and Consulting.

¹ Circular Energy Storage Research and Consulting (2018). The lithium-ion battery end-of-life market 2018–2025.



Reuse: Giving LIBs a second life

The term ‘spent LIBs’ may give the impression that these batteries are no longer functional. In fact, spent LIBs from electric vehicles actually retain more than half their initial energy storage capacity along with a lifespan of at least seven years, properties which make them ideal candidates for battery refurbishment and reuse. For example, China Tower, the largest operator of telecommunication towers in the world, ceased purchasing lead-acid batteries in 2018, replacing them at 98 percent of their two million telecom tower base stations with refurbished LIBs instead².

Giving these batteries a second life before they are sent for metal recycling not only reduces their environmental impact over their prolonged lifecycle but also has an economic benefit: second life batteries can command US\$60 – 300 per kWh¹.

However, one of the main challenges is transportation, which could contribute up to half the total cost of refurbishment³. Current technology enabling battery collectors to assess a battery’s health at the point of collection remains highly limited, and many collected batteries may no longer be in a reusable condition.

The ability to sort and screen for battery health quickly and accurately at the point of collection is therefore a critical component to cost-effective and efficient battery refurbishment. Evaluating battery cells using electrochemical and physical tests, as well as monitoring their capacity and internal resistance to ensure safety during their second lives are technological needs to be addressed in this industry.

² Mario Pagliaro and Francesco Meneguzzo (2019). Lithium battery reusing and recycling: A circular economy insight. *Heliyon*. <https://doi.org/10.1016/j.heliyon.2019.e01866>

³ Sarah King, Naomi J. Boxall and Anand I. Bhatt (2018). Lithium battery recycling in Australia: Current status and opportunities for developing a new industry.

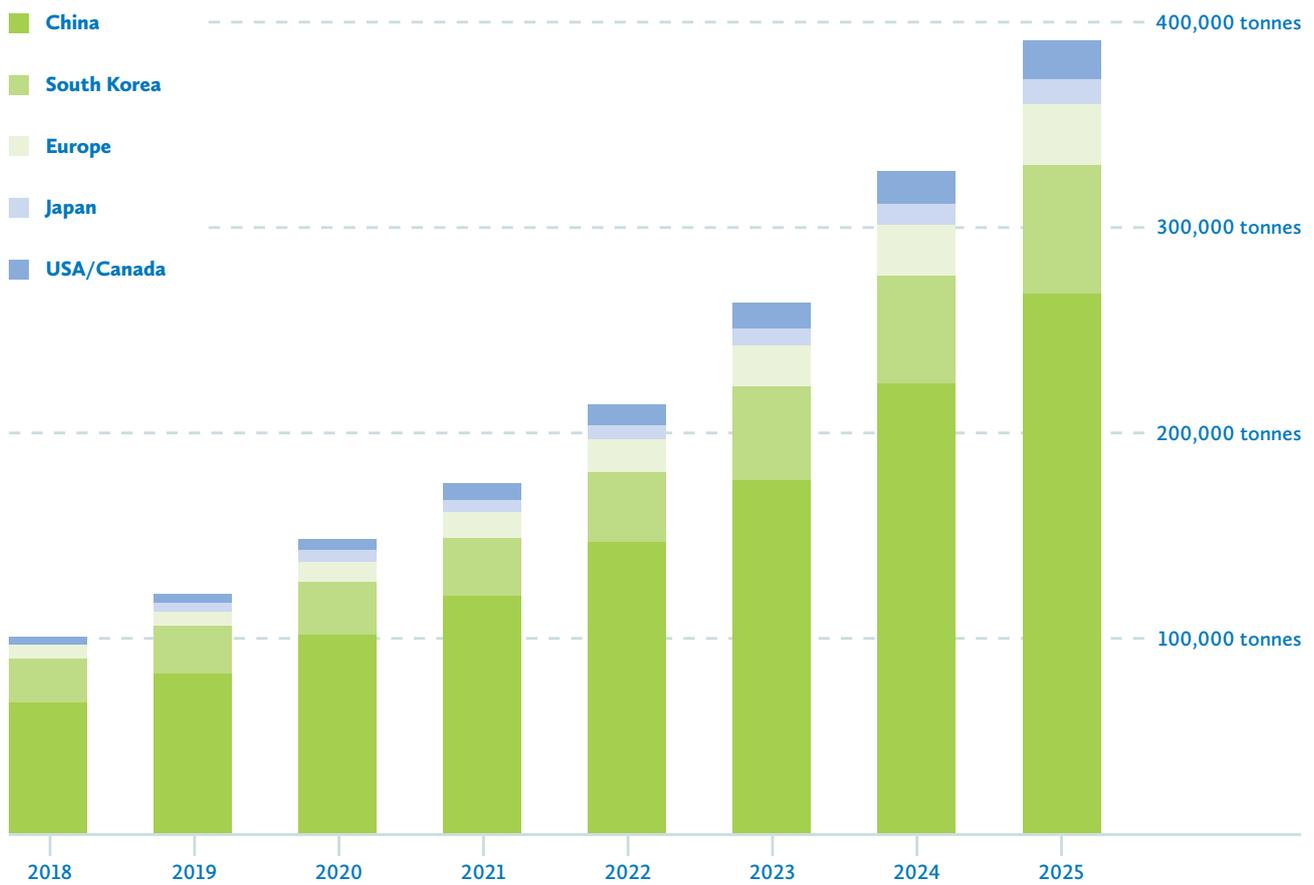


Figure 2

Recycling of lithium-ion batteries (LIBs) by geography. Of the 97,000 tonnes of spent LIBs reaching recyclers in 2018, 69 percent was handled by China, 19 percent by South Korea and the remaining 12 percent by other countries in Europe, Japan and North America. Source: The lithium-ion battery end-of-life market – A baseline study. Circular Energy Storage Research and Consulting.

Recycle: Waste not, want not

But what happens to spent batteries that fail the diagnostic tests? These batteries will ultimately have to be recycled, both to extract valuable metals and prevent toxic components from harming the environment. Worldwide, only half of all lithium-ion batteries derived from consumer electronics are recycled¹, with China holding the lion's share of the recycling market, receiving 69 percent of all spent lithium-ion batteries collected, while South Korea trails at a distant second with 19 percent (Figure 2). Both countries' significant market shares are underpinned by their strong demand for raw material in terms of battery manufacturing and cell production.

One of the key challenges for LIB recycling is the fact that batteries come in a wide variety of chemistries and designs, making it difficult to dismantle and process the different types of batteries within a single facility. At the moment, the main metal recovery method in use by recycling companies is pyrometallurgy, which is an energy intensive process that recovers low amounts of valuable raw material for battery manufacturing.

LIB recycling companies are all looking for ways to make battery sorting more efficient and develop flexible processes that can be adapted to various battery chemistries for higher recovery of valuable metals at a lower cost.

UNDERSTANDING THE LIB RECYCLING MARKET

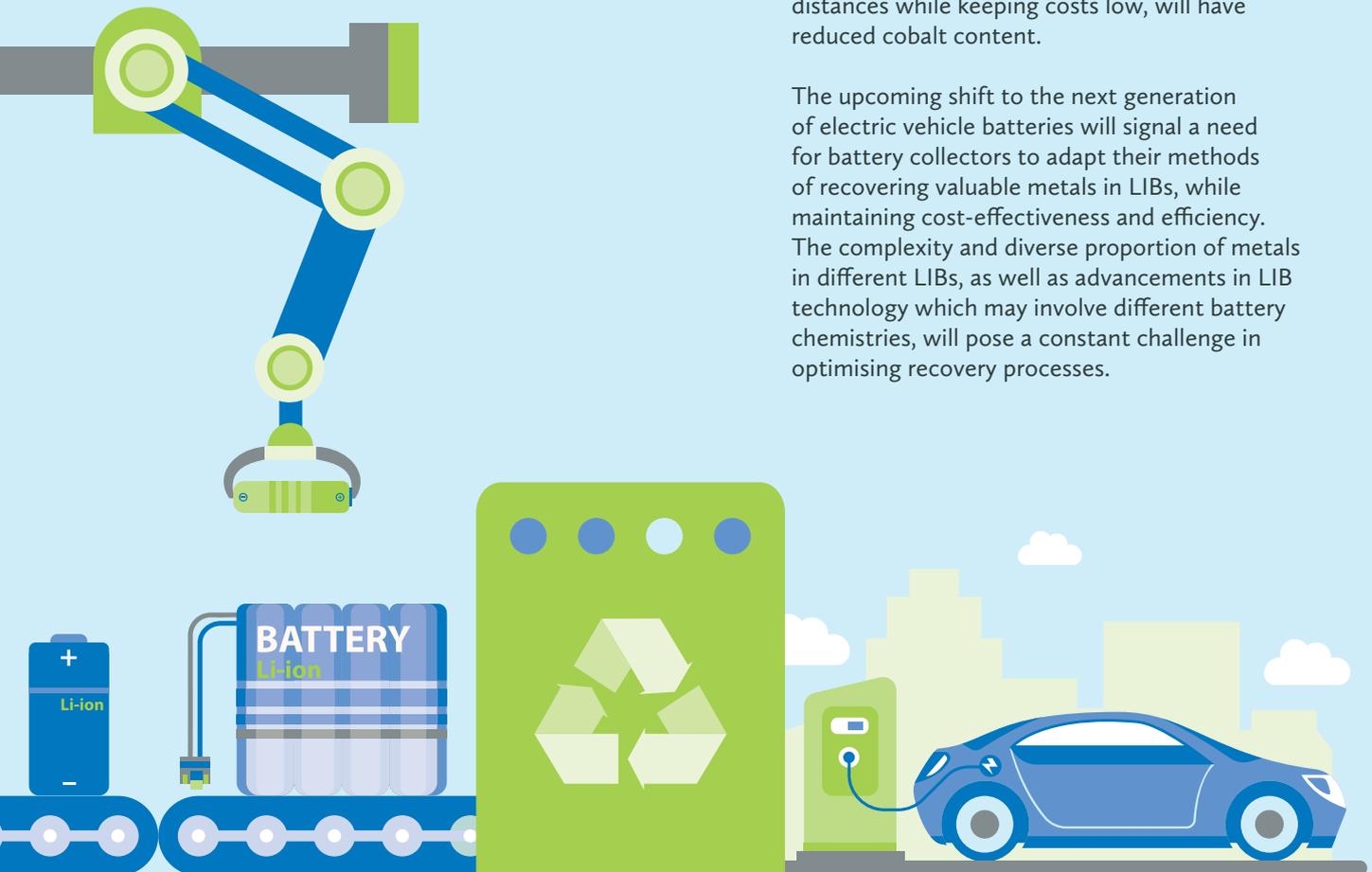
One of the biggest drivers in the battery recycling market is the revenue to be gained from metal recovery, the products of which are diverted towards meeting battery manufacturers' demands. Another driver is the increased regulatory pressure for stakeholders in the LIB value chain, such as battery and electric vehicle manufacturers, to manage the e-waste from their products responsibly.

Recovering valuable metals

Due to significant differences in metal valuation, the metal composition of an LIB is the single most important determinant of how the battery or its components will be repurposed. At its peak in 2018, cobalt commanded up to US\$100,000 per metric tonne; in contrast, nickel and lithium carbonate barely scratched \$20,000 per metric tonne⁴. Consequently, LIBs with high cobalt content are favoured by recyclers, while lithium iron phosphate batteries, which are the preferred choice for second-life applications, are prioritised for reuse instead of recycling.

The metal composition of LIBs will also be in flux depending on adaptations to emerging technologies. One example can be seen with electric vehicles, which have generally been powered by LIBs of high cobalt content such as lithium nickel manganese cobalt (NMC) batteries. However, the next generation of electric vehicle batteries, which have been designed to store greater energy over longer distances while keeping costs low, will have reduced cobalt content.

The upcoming shift to the next generation of electric vehicle batteries will signal a need for battery collectors to adapt their methods of recovering valuable metals in LIBs, while maintaining cost-effectiveness and efficiency. The complexity and diverse proportion of metals in different LIBs, as well as advancements in LIB technology which may involve different battery chemistries, will pose a constant challenge in optimising recovery processes.



⁴ S&P Global Platts. Insight: Lithium-ion batteries enter the fast lane. Accessed on 23 Oct 2019. <https://blogs.platts.com/2018/11/29/lithium-ion-batteries-enter-fast-lane/>

Responsibly managing waste

The rapid surge in e-waste volume, which includes spent LIBs and their sources, has led to increasing governmental concern over the potential worsening of pollution and shrinking of landfills. As toxic heavy metals used in batteries such as nickel and manganese can affect the respiratory tract and contaminate groundwater, nations are seeking to preempt the health, environmental and social impact from e-waste pollution by setting clear regulations for e-waste collection, disposal and treatment.

In 2018, electric vehicle makers in China were required to establish LIB collection and recycling facilities, in addition to a joint traceability system with battery makers to identify owners of discarded LIBs⁵. The European Union Battery Directive⁶ stipulates that producers of batteries or producers of products incorporating LIBs must bear the costs of collecting, treating and recycling these LIBs. In Canada, similar regulations apply as companies involved in the sale or import of LIBs or products with LIBs are legally obliged to appropriately manage end-of-life for these materials⁷.

Closer to home, the Extended Producer Responsibility law will come into effect in Singapore in 2021. This piece of legislature governing e-waste collection aims to increase the country's recycling rate, where only 0.15 percent of the 60,000 tonnes of e-waste collected annually are recycled⁸. In all these regulations, we can see a clear emphasis for battery manufacturers, importers and any other parties involved in battery production and sales to take responsibility for the e-waste they generate, instead of passing the buck to consumers or national agencies.

Key market players

With the rising global demand for battery metals that can be channeled towards LIB manufacturing and the regulatory pressure from authorities to manage e-waste, meeting the varied industry needs of the LIB recycling market will require input from stakeholders from all segments of the LIB value chain.

Besides battery recycling and collection companies such as Jiangxi Green Eco Manufacturing Resource (GEM) and Hunan Brunp Recycling, players along the entire battery manufacturing value chain have a keen interest in recycling. This spans upstream players like

raw mineral miners and battery material suppliers all the way to battery manufacturers and electric vehicle producers. In particular, companies like Glencore and Tianqi Lithium are market movers as the leading miners of cobalt and lithium respectively. Further downstream, end users in the automotive industry, like Chery Automobile and battery storage companies such as LG Chem, play an important role in driving the demand for LIBs.

The never-ending pursuit of new and improved methods for LIB reuse and recycling has also drawn the interest of public institutions worldwide which conduct research in second life applications for LIBs. Among such institutions are the Argonne National Laboratories and the Massachusetts Institute of Technology in the United States, while closer to home the National University of Singapore and Nanyang Technological University are key participants.



⁵ Reuters. China puts responsibility for battery recycling on makers of electric vehicles. Accessed on 22 Oct 2019.

<https://www.reuters.com/article/us-china-batteries-recycling/china-puts-responsibility-for-battery-recycling-on-makers-of-electric-vehicles-idUSKCN1GAoMG>

⁶ Recycling and Reuse: Batteries and Accumulators: European Union Directive. Accessed on 22 Oct 2019.

https://archive.epa.gov/oswer/international/web/html/200806_tl-eu-directive-batteries-accumulators.html

⁷ Call2Recycle. Stewards. Accessed on 23 Oct 2019. <https://www.call2recycle.ca/stewards-overview/>

⁸ The Straits Times. Singapore's mountain of e-waste. Accessed on 23 Oct 2019. <https://www.straitstimes.com/singapore/environment/singapores-mountain-of-e-waste>

STATE OF THE ART & EMERGING TECHNOLOGIES

The lightest of all the metals and yet capable of operating at a high voltage, lithium is the preferred choice for making rechargeable batteries. In all types of LIBs, lithium ions flow from the negative electrode (anode) to the positive electrode (cathode) during use, and from the cathode to the anode during charging. Cathodes are seldom made purely of lithium, but are instead combined with different elements, each with its own power and performance tradeoffs (see pullout box below).

The LIB recycling process

The differences in the electrical characteristics of LIBs on the market underpin the variety of applications in which LIBs can be employed. The diversity of their electrical properties, as discussed previously, is marked by the complex metal composition of different LIBs. Furthermore, with the variety of storage compartments in which LIBs are housed, one can expect that every end-of-life process will be unique to each LIB.

The need to address the compositional complexity of LIBs has led to an equally complex recycling process (Figure 3). Processes for both LIB recycling and reuse share the same initial stages, i.e. collecting and sorting LIBs based on their metal composition, followed by screening tests to evaluate their state-of-charge and state-of-health, which will determine whether the batteries retain sufficient function for second life use. LIBs which pass these tests are permitted to be refurbished for second life applications.

Types of LIBs in the market⁹

	LCO - Lithium Cobalt Oxide	LFP - Lithium Iron Phosphate	LMO - Lithium Manganese Oxide	NCA - Lithium Nickel Cobalt Aluminium Oxide	NMC - Lithium Nickel Manganese Cobalt Oxide	LTO - Lithium Titanate
	LiCoO ₂	LiFePO ₄	LiMn ₂ O ₄	LiNiCoAlO ₂	LiNiMnCoO ₂	Li ₂ TiO ₃
Specific Energy, Wh/kg	150-200	90-120	100-150	200-260	150-220	50-80
Cycle Life	500-1,000	>2,000	300-700	500	1,000-2,000	3,000-7,000
Applications	Mobile phones, tablets, laptops, cameras	High load currents and endurance, E-buses, e.g. BYD	Power tools, medical devices, electric powertrains	Medical devices, industrial, electric powertrain, e.g. Tesla EV, Panasonic	E-bikes, medical devices, EV, e.g. Nissan LEAF, iMiEV, Volt	Uninterrupted power supply, electric powertrain
Advantages	High specific energy	Thermal stability, long cycle life	High power but less capacity, safer than LCO	High specific energy, cost (US\$350/kWh)	High specific energy	Long life, fast charge
Disadvantages	Cobalt is expensive (~60% Co content)	High cost (US\$580/kWh)	Short lifetime, low energy density	Low thermal runaway temperature	High cost (US\$420/kWh), high nickel content	High cost (US\$1,005/kWh) - low market share

⁹ Modified from Types of lithium-ion. Accessed on 22 Oct 2019. https://batteryuniversity.com/learn/article/types_of_lithium_ion

Batteries that do not pass these screening tests for battery health are instead directed for recycling, which may involve pre-treatment for removing residual battery charge to mitigate risks of explosion, dismantling plastic cases that house LIBs, as well as electrolyte extraction using thermal treatment or acetonitrile. Following these steps, the individual components are crushed and

mechanically separated using magnets or sieves before the cathode materials are sent for further processing.

The two main methods of metal recovery are hydrometallurgy, which hinges on in-solution chemistry for isolating metals, and pyrometallurgy, which relies on extreme heat at 600 to 900 °C for smelting.

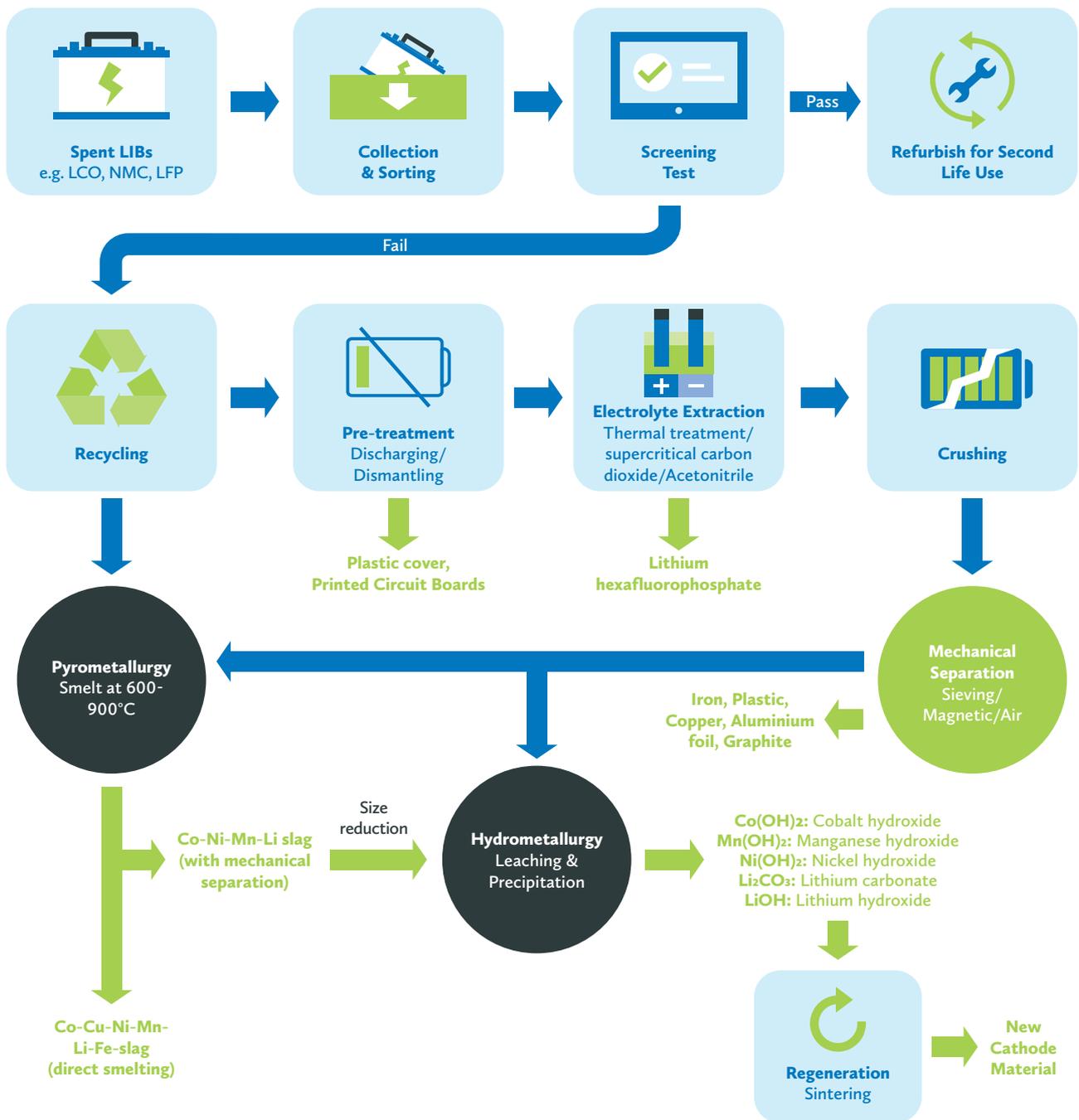
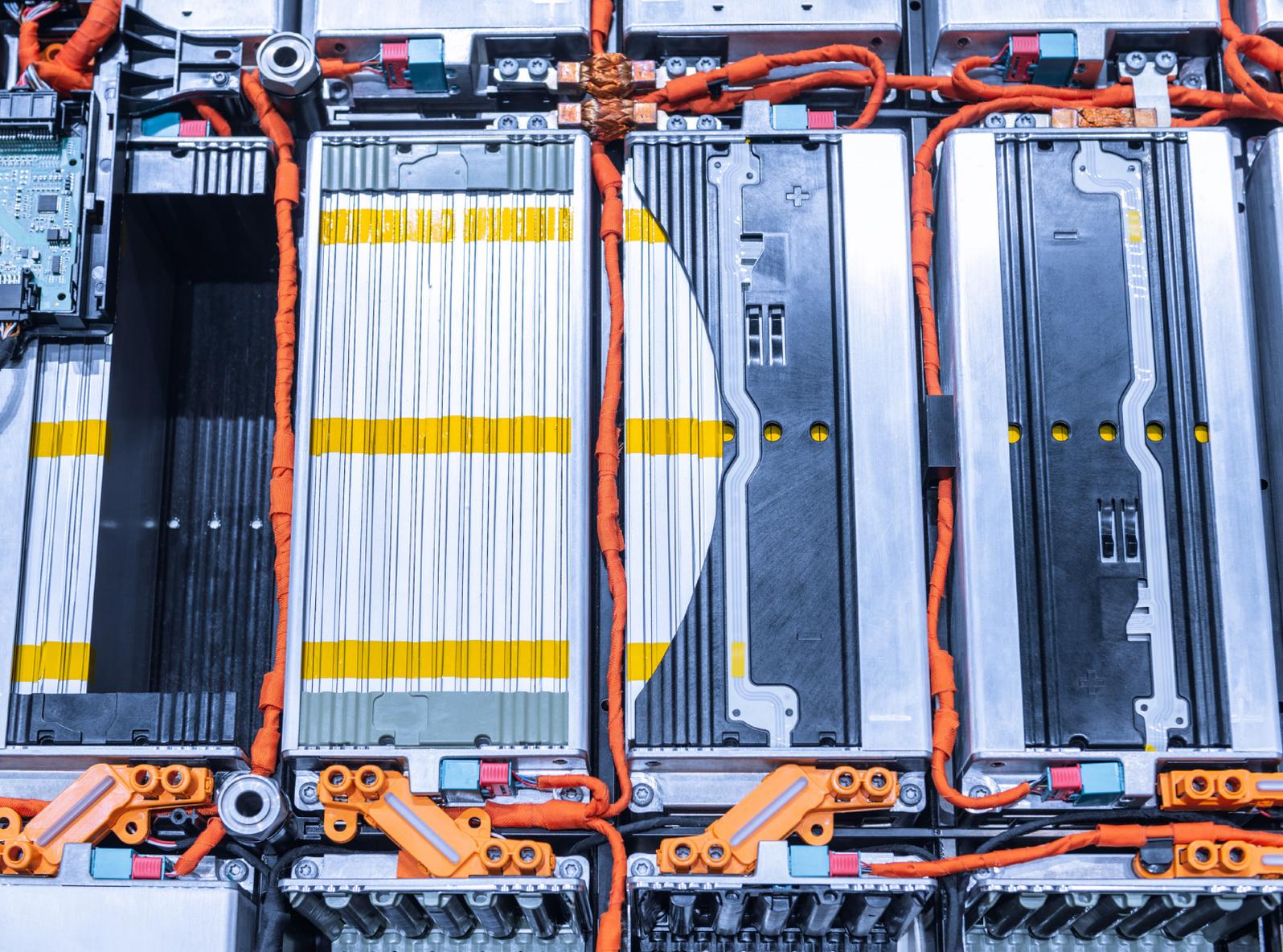


Figure 3 Generic process for end-of-life LIB reuse or recycling.



Hydrometallurgy produces the best metal recovery rates, with at least 80 percent recovery rates for all battery metals of interest and 95 percent recovery rates for lithium, nickel and cobalt. It is also a low energy method that can be conducted at 60 to 80 °C and generates fewer emissions. For this process to be effective, however, intensive LIB sorting and separation beforehand is a prerequisite. Furthermore, leaching reagents such as hydrochloric acid necessitate expensive liquid effluent treatment, and different battery chemistries require different types of leaching agents.

Pyrometallurgy, on the other hand, is a proven technology that has been scaled-up for industrial purposes and can be applied to a mixture of LIB types. For these reasons, it is viewed as a more reliable and convenient option by recyclers. However, its reliance on extreme heat makes it an energy-intensive—and potentially costly—process. It is also hampered by inefficient lithium recovery from slag, and thus will need to be complemented with hydrometallurgy if lithium is a priority for recyclers.

Apart from combining hydrometallurgy and pyrometallurgy, research efforts have focused on developing environmentally benign leaching processes, such as those using weak acids or acids derived from natural organic sources. Emerging alternatives such as electrochemical and bioleaching methods promise to recover metals at battery-grade purity levels while reducing acid consumption. However, both methods require sophisticated equipment and complex procedures. Bioleaching technology, in particular, is still nascent, with most patents in this area filed by research institutes rather than private companies.

Given the potential benefits and disadvantages unique to each method, it is likely that recyclers will find optimal results through a combination of methods suited to the types of LIBs they collect and the metals preferred for recovery, rather than only a single recovery method. Recyclers must consider which types of LIBs to focus their efforts on. Additional considerations for the implementation of metal recovery methods are the scalability of the methods and how well-understood the methods are, which translates to its reliability.

Technologies on the horizon

• NTU Singapore CEA Alliance for Research in Circular Economy (SCARCE) Lab

- ▣ Hydrometallurgy method
- ▣ Use of weak acid such as methanesulfonic acid to recover up to 75% of Li, Co, Ni, Mn

• NUS-Temasek Polytechnic

- ▣ Hydrometallurgy and electrochemical method
- ▣ Use of ferricyanide-based leaching solution to recover FePO_4 and LiOH (99.9% purity) from spent LFP battery

• Rice University

- ▣ Hydrometallurgy method
- ▣ Use of deep eutectic solvents (DES), a mixture of choline chloride and ethylene glycol for metal extraction from spent LCO battery

• OnTo Technology, LLC

- ▣ Mechanical treatment and hydrometallurgy method
- ▣ Developed cathode recovery and regeneration process to produce recycled cathode material for NMC batteries

• Li-Cycle

- ▣ Mechanical treatment and hydrometallurgy method
- ▣ Developed an automated dismantling and shredding of mixed LIBs and able to achieve more than 80% recovery of Co, Li, Ni, Cu, graphite

• Relectrify

- ▣ Second life battery management system
- ▣ Invented electronics and algorithm for cell-level condition monitoring that maximises lifetime of battery pack for energy storage applications



THE LIB RECYCLING PATENT LANDSCAPE

As the culmination of research and development efforts, patents can reveal an industry's greatest needs and the patent landscape provides insights into the innovation activities surrounding a particular technology. Surveying the worldwide patent database between 2008 and 2019, we identified a total of 982 patent families relevant to LIB recycling.

Where: China dominates the field

Our analysis revealed that China is the leading LIB recycling patent holder, with almost 74 percent of the LIB recycling patents worldwide, commensurate with its market dominance in battery recycling. Japan comes in at a distant second place with 12 percent, ahead of South Korea's 3.4 percent, despite holding a smaller market share.

China is expected to remain in the lead for LIB-related patent filing, due to regulations mandating that battery and electric vehicle manufacturers must be responsible for battery recycling networks and facilities to deal with spent LIBs. In 2018, 267 out of 300 patent applications (89 percent) were from applicants based in China, including Hefei Guoxuan High Tech Power Energy (38 patents), Central South University (25 patents) and the Institute of Process Engineering at the Chinese Academy of Sciences (24 patents).



Who: All across the battery value chain

Patent holders are predominantly battery manufacturers, recyclers, research institutions and even battery material miners. While it is easy to see how LIB-related patents are associated with the first three contributors, the link to battery material miners might seem less clear.

However, considering that battery material mining is key to providing raw material for battery-making, and that battery recycling recovers battery metals to be used as raw material for new batteries, the strong interest shown by battery material miners in battery recycling is clear. Furthermore, existing technology employed by battery material miners, particularly mechanical separation using gravity or froth flotation, are cost-effective and adaptable for LIB recycling. While an unexpected player, battery material miners could thus contribute its technological expertise to the battery recycling market.

What: Recovery a top concern

While patent filing activity is an indication of the level of interest in a subdomain, patent citations, which measure how many times a given patent is referenced by other patent applications, is a proxy for how impactful an invention is. In line with the economic value of the metals used in LIBs, the top three patent citations are all regarding the recovery of metals during the recycling process.

The top publication, a patent by Chery Automobile covering the use of acids and bases to extract metals from NMC batteries, was cited 39 times. The second and third most cited patents were from Jiangxi Green Eco Manufacturing Resource (GEM) and Umicore, covering pre-treatment and subsequent hydrometallurgy for LCO and LFP batteries respectively.

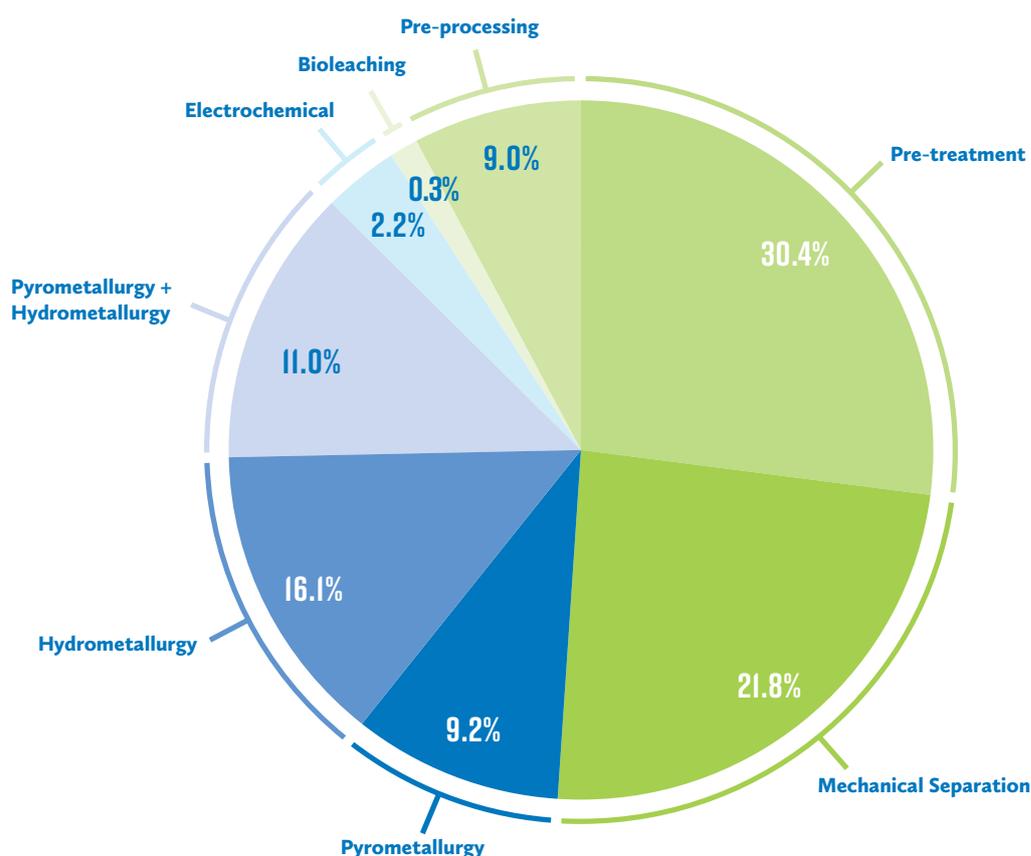


Figure 4

Lithium-ion battery recycling patents by family. Pre-processing covers battery sorting and battery health diagnostics, while pre-treatment steps include battery discharging, dismantling and crushing. Source: IPI.

Trends in LIB recycling R&D

The patterns seen in the most highly-cited publications are also repeated throughout the general patent landscape. Of all the patent families analysed, about 40 percent were for pre-processing and pre-treatment steps, such as battery discharge and dismantling (Figure 4). Another 22 percent were related to mechanical separation for the recovery of battery metals.

These findings suggest that these are areas requiring more study or speak to their relative importance in the recycling process, as both pre-treatment and mechanical separation are crucial to high-efficiency metal recovery. Pre-treatment in particular is necessary to mitigate the risk of fire or explosion, thus also playing a critical role in safety.

A clear trend favouring hydrometallurgy over pyrometallurgy as a means of metal recovery can

also be observed from their respective number of patents. This is expected since hydrometallurgy generally produces higher metal recovery rates without requiring the same amount of energy input. About 11 percent of patents explore a combinatorial approach using both hydrometallurgy and pyrometallurgy, which complements the strengths of both methods while buffering each other's weaknesses, providing a more comprehensive range of metals for recovery than can be achieved by using a single method.

The smallest shares in the LIB recycling patent landscape belong to the electrochemical methods and bioleaching techniques. Both of these technologies are still in their infancy—most patents are held by research institutions and their adoption by the recycling industry still awaits the completion of preliminary research and pilot testing.



OUR INSIGHTS

Global patterns in patent filing activities related to LIB recycling reveal who the major players are and the future directions of the market. This information is crucial for participants in the LIB recycling market to know what the most pressing industry needs are likely to be in the near future, as well as identifying potential gaps in addressing these needs.

01 China leads the global LIB recycling movement

With more electric vehicles on its roads than the rest of the world combined, dealing with spent LIBs is a particularly pressing issue for China. This urgency is reflected in our analysis of patent filing activities related to LIB recycling, which show that China holds the largest number of patents, followed by Japan, South Korea and the United States. China's current dominance in the LIB recycling market will be further entrenched by regulatory pressure for companies to implement appropriate battery waste management systems.

02 Recycling matters to all players in the LIB value chain

While battery recycling companies are understandably invested in LIB recycling research, battery manufacturers, automotive original equipment manufacturers (OEMs) and even battery metal mining companies are also seeking a share of the recycling market, as their position within the top tier of LIB recycling patent assignees shows. We have found that automotive OEMs, in particular, are responding to regulatory requirements by joining forces with recyclers to close the battery waste loop, suggesting that new entrants should consider partnerships with existing recyclers to meet the demand for technologies such as state of charge diagnostics. Further upstream, battery material miners are actively filing recycling related patents. This shows that waste batteries are an important source of raw materials for battery manufacturers, who are potential buyers of recycled battery-grade materials.

03

Pre-processing will be a priority

LIB-related patents show a strong emphasis on the study of pre-treatment and physical disassembly of batteries, essential for both safety and purity of cathode materials derived from the recycling process. Those who possess technological expertise in pre-processing can expect to attract strong support from relevant industry players. In particular, technology owners with expertise in battery sorting, battery health diagnostics, dismantling and refurbishment for second life reuse or recycling will be highly sought after. To streamline the recycling process and increase recycling rates, we foresee that the industry may come together to develop a set of standards on battery design so that they can be dismantled and pre-processed more easily.

04

It's all about the metal

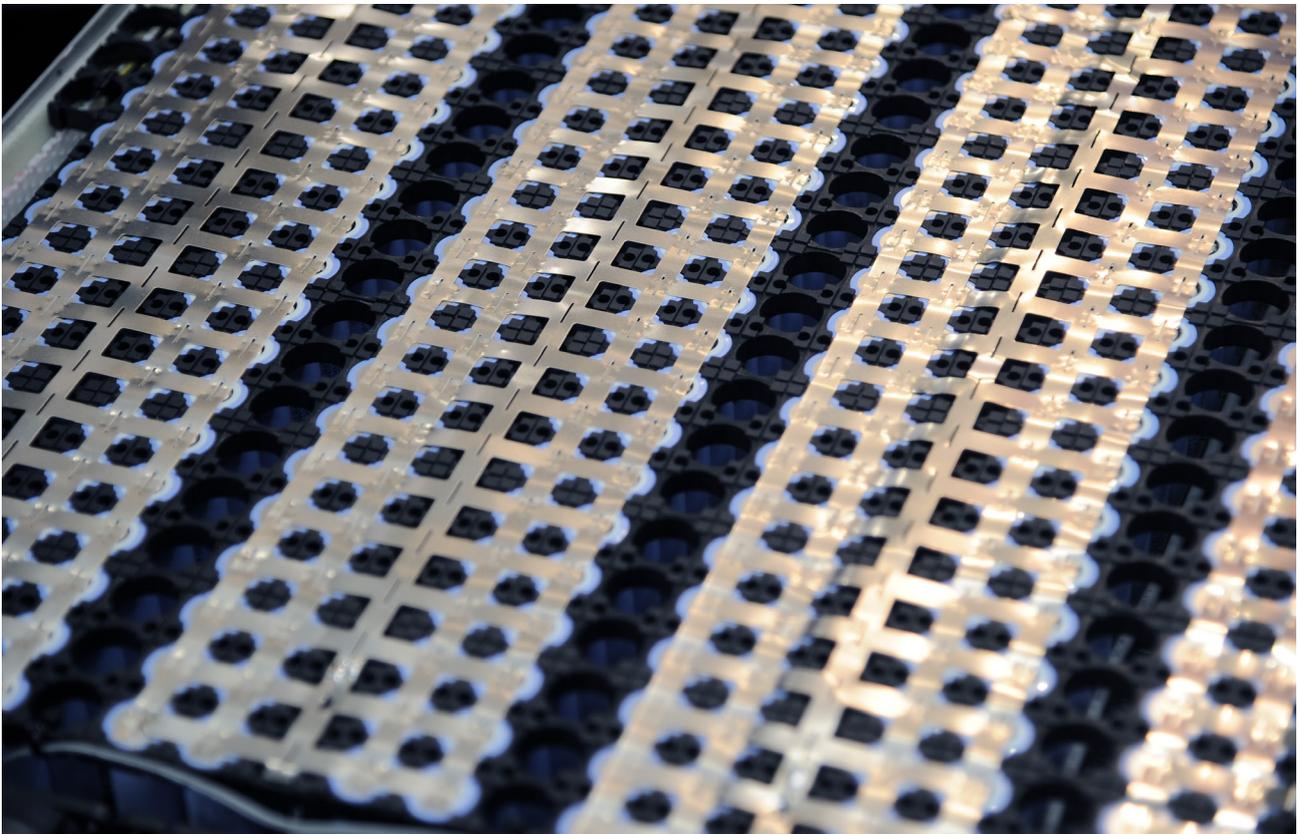
Battery metal recovery processes are also a major target in patents related to LIB recycling, with hydrometallurgy being the main process of interest. From this observation, we may conclude that

hydrometallurgy is the preferred method for metal recovery, due to its proven ability to achieve high metal recovery at relatively lower temperatures. That said, there will be strong demand for technologies that can achieve a high metal recovery rate and can be adapted to the various battery chemistries in use.

05

Hybrid approaches

Furthermore, both private companies and public research institutions are forging new paths ahead in battery recycling, particularly for the recovery of a wider range of valuable metals such as cobalt, nickel, lithium and manganese. A combination of pyrometallurgy and hydrometallurgy can be used for such purposes, although novel methods such as bioleaching of metals with the help of microorganisms and electrolysis will add to the repertoire of means by which recyclers can enhance metal recovery rates in future. However, these emerging techniques are likely to require expensive equipment and knowledge of microbial culture and process control to achieve good metal recovery rates.





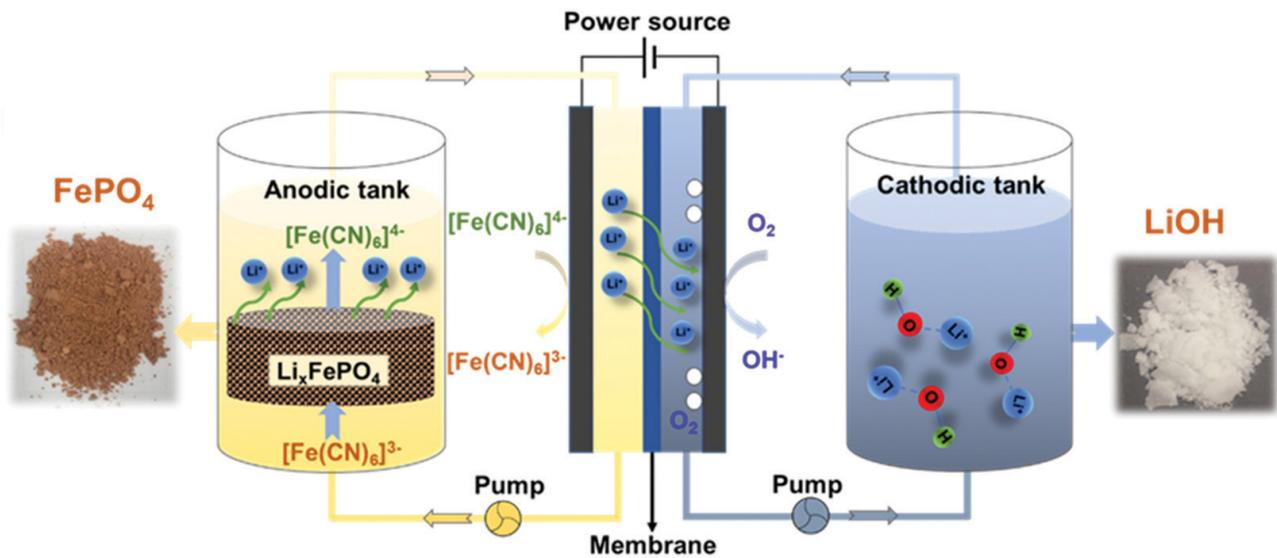
TECHOFFERS: BE A PART OF THE LIB RECYCLING REVOLUTION

Now that you've seen the opportunities LIB recycling technology can provide, are you thinking of ways to break into the industry? Look no further than these TechOffers, which offer a diverse range of technologies to suit the needs of different commercial partners.

Recycling lithium-ion battery cathodes using deep eutectic solvents

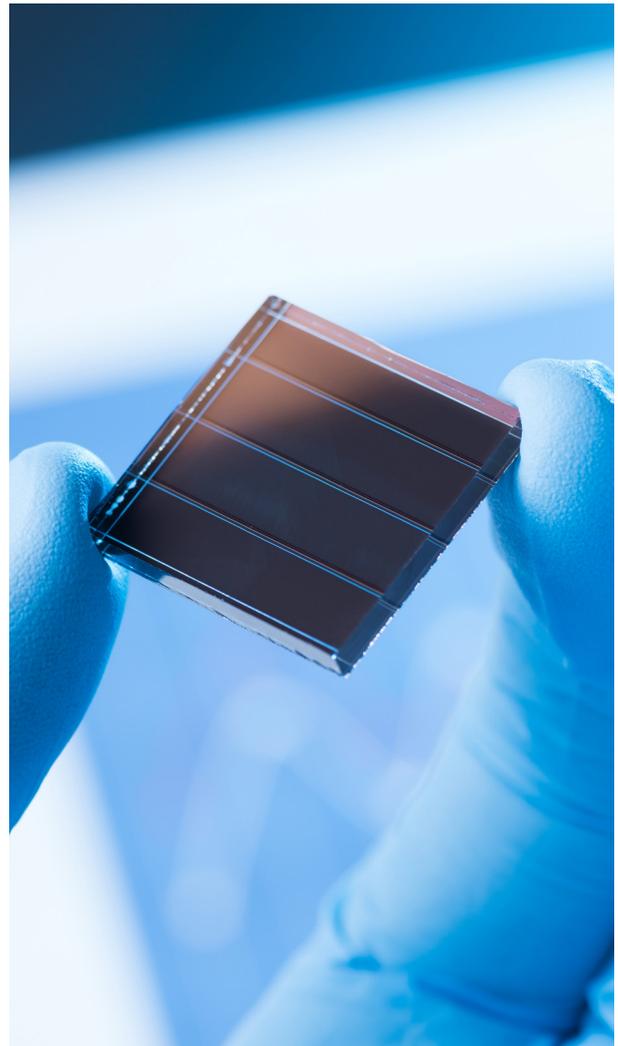
- Common metal recovery methods involve the use of highly corrosive acids in hydrometallurgy or extreme heat in pyrometallurgy, conditions which require expertise and strict safety requirements.
- This method uses a deep eutectic solvent (DES), which is environmentally-friendly, biodegradable and non-toxic to humans. DES can be produced using commercially available ingredients such as choline chloride and ethylene glycol, making this method suitable for industrial-scale applications.

- DES is an effective leaching and reducing agent on its own, therefore this method is simple and does not require extensive lists of supporting chemicals and processes for metal extraction
- Disassembled LIB cathode material is placed into the DES, which is then heated and stirred. Cobalt and lithium ions are extracted through dissolution and then precipitation or electrodeposition. Leaching efficiency of cobalt and lithium from LCO batteries exceeds 90 percent.
- Materials which do not dissolve in the solvent, such as aluminium foil and conductive carbon, can be recovered by filtering the leachate.
- Suitable for cobalt-rich LIBs, such as LCO and NMC batteries.
- The technology provider, which is currently scaling up their experiments and conducting further research and development, is seeking both technology licensing and co-development opportunities.



Redox targeting method for recycling of spent lithium-ion battery material

- ▣ Chemical leaching methods require tedious steps and large amounts of chemicals, which can lead to secondary pollution.
- ▣ This method hinges on a redox targeting-based process for recycling spent lithium iron phosphate batteries.
- ▣ The proprietary leaching solution is synthesized from Prussian blue and lithium hydroxide. Equipment required for this method can be self-built: an electrolyser, a tank, Nafion 117 ion-exchange membrane, pumps and tubes.
- ▣ Spent batteries are loaded in an anodic tank, while the leaching solution is pumped through the anodic tank and electrolyser. Pure water and air function as the cathode.
- ▣ Lithium hydroxide will be collected in the cathodic tank while iron phosphate is collected in the anodic tank. A very high purity of both lithium hydroxide and iron phosphate (above 99 percent) can be obtained within 50 minutes using this method.
- ▣ Suitable for use in the LIB recycling and manufacturing industries. The technology provider is currently seeking an industry partner to scale-up and commercialise the technology.



CONCLUSION

The global demand for LIBs is here to stay. Therefore, the accumulation of spent LIBs must be dealt with systematically and responsibly owing to the significant environmental concerns arising from limited landfill space and pollution. These concerns have led to increased regulatory pressure for battery makers and makers of products using LIBs to manage LIBs at their end-of-life.

With these challenges come opportunities, as this study shows, offering an overview on the trends, market opportunities, key players and the LIB recycling innovation landscape, as well as technologies which can be adopted for LIB recycling.

If you would like to find out more about the opportunities in this space, please contact: techscout@ipi-singapore.org

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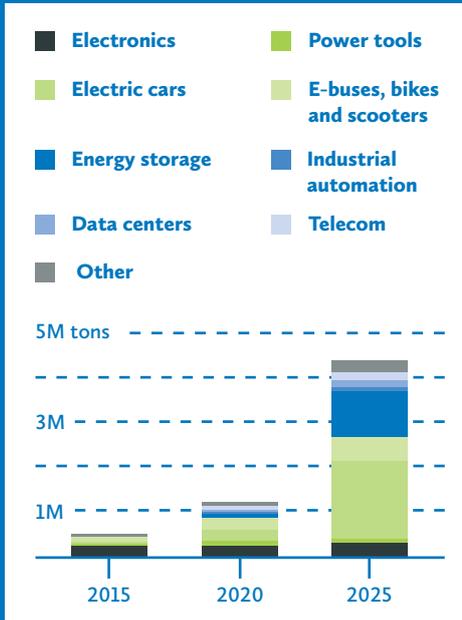


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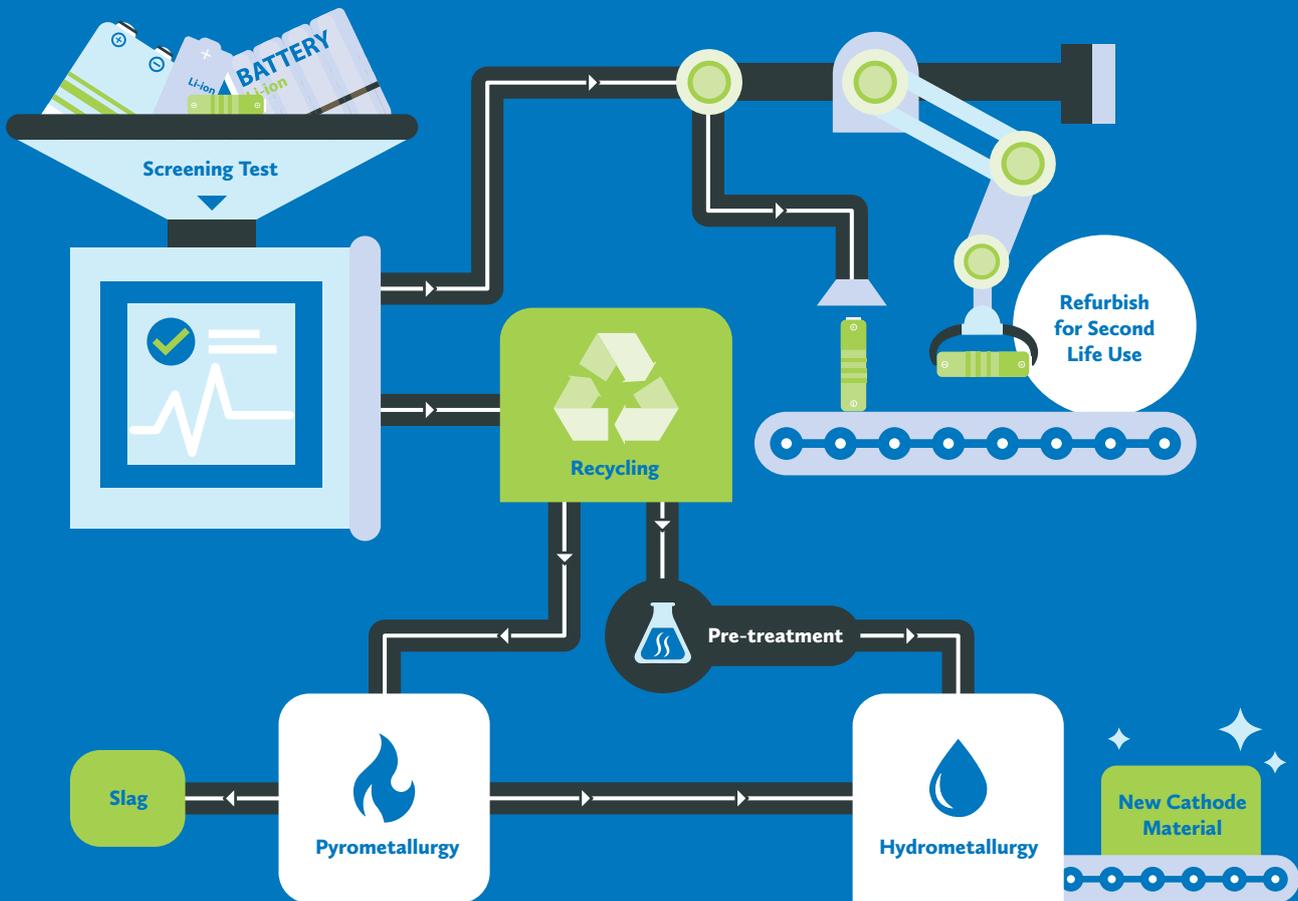
Demand for LIB growing



Two main forces driving LIB recycling: metal prices and regulation

Market Drivers	Industry Needs
<p>Surging volume of spent LIBs and sources:</p> <ul style="list-style-type: none"> consumer electronics (immediate term: LCO) EV and energy storage (long term: NMC & LFP) 	<ul style="list-style-type: none"> Battery sorting and extraction Rapid screening of spent battery health Safe storage and logistic
<p>Increased pressure from new regulations</p>	<p>Traceability system to improve collection and recycling rate</p>
<p>Valuable metals recovery - cobalt, lithium, nickel and manganese</p>	<ul style="list-style-type: none"> Low cost, high metal recovery yield process Adaptable for future battery chemistries

LIB recycling process





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