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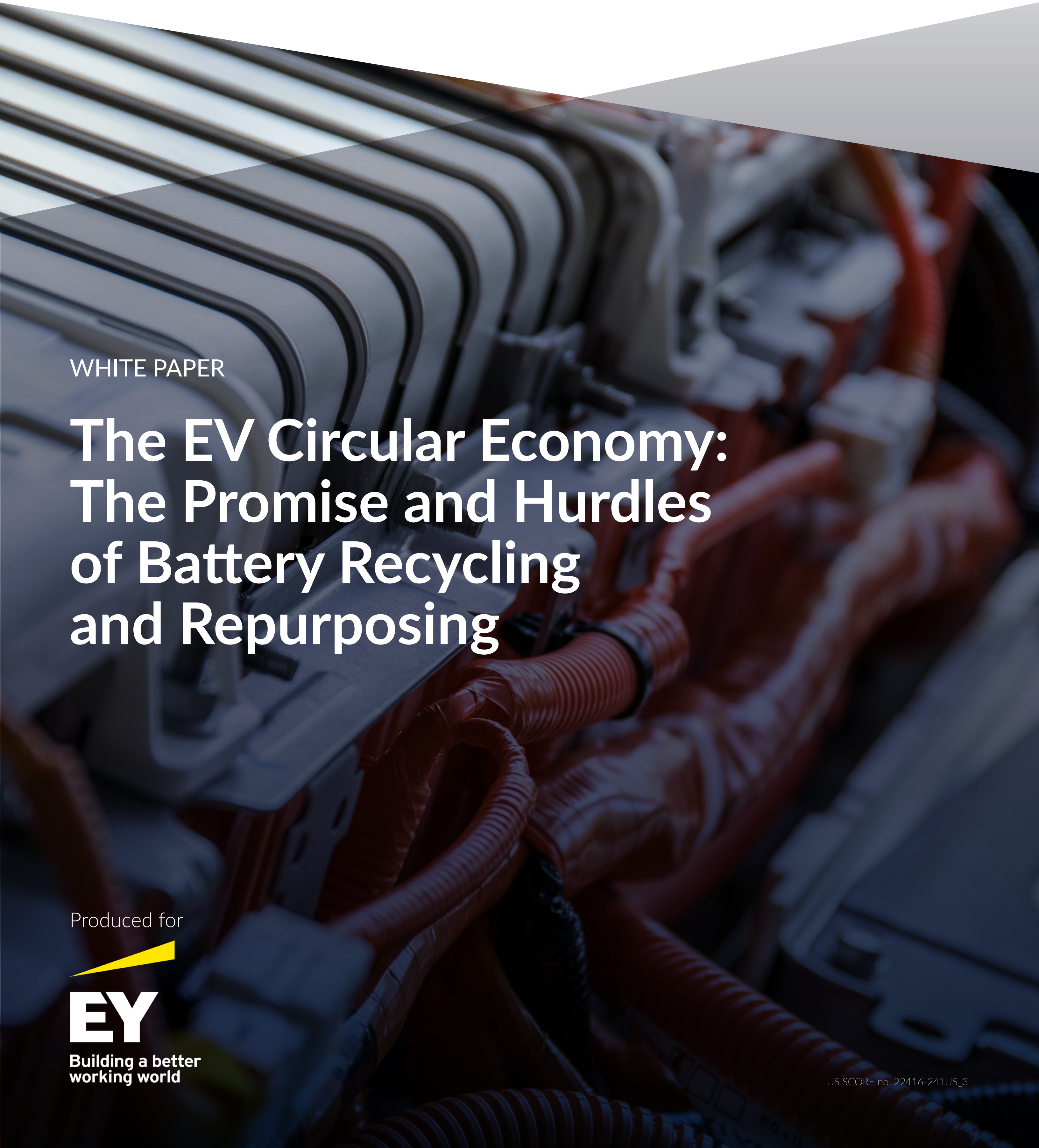

WHITE PAPER

The EV Circular Economy: The Promise and Hurdles of Battery Recycling and Repurposing

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Table of Contents

The Promise and Hurdles of Battery Recycling and Repurposing 3

Circularity in the Battery Lifecycle 4

Repurposing 5

Recycling 6

Business Case for Circularity 7

Secondary Materials Use Less Energy 8

Recyclables to the Rescue 9

Barriers to Circularity 9

Implementation Costs 11

Overcoming the Barriers 12

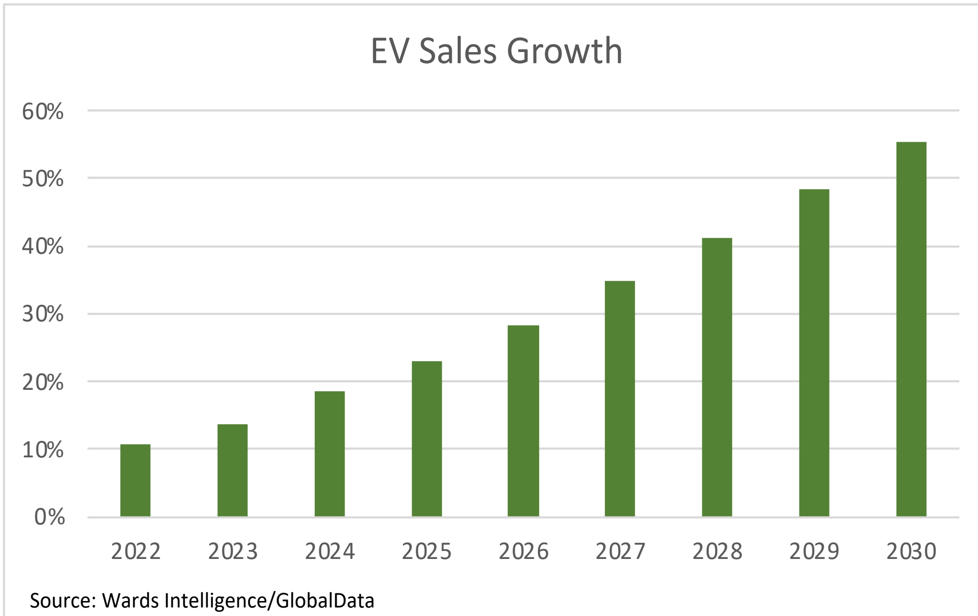
Outlook 13

The Promise and Hurdles of Battery Recycling and Repurposing

As the automotive industry evolves toward cleaner, zero-emission modes of transport, batteries and their minerals increasingly will be a determinant of that transition's success.

Despite news about a slowdown, sales of electric vehicles (including both full battery-electric vehicles and plug-in hybrid-electric vehicles) grew more than 50% in 2023 compared to the same period last year. By 2025, EVs will make up 23% of global auto sales, and, by 2030, their share will reach 55% of the global fleet — that equates to more than 36 million new EVs leaving showrooms annually by the end of the decade.

Figure 1: Global EV Sales Growth



Global growth of electric vehicle sales.

Parallel to the rise of EVs is the need for more advanced batteries and the critical materials needed to manufacture them, with the most common elements being lithium, nickel, cobalt, manganese, iron and graphite.

It's a common misconception that these minerals are rare. In fact, the United States Geological Survey ranks the "rarest" of these minerals, lithium, 33 out of 94 for its abundance on Earth. And the USGS projects global lithium stores at 98 million tons, with the US holding 12 million tons.

While they may not be rare, not every mineral source can be extracted profitably. Furthermore, any extraction comes at an environmental and, for materials such as cobalt, social cost. For example, lithium extraction from brines requires hundreds of thousands of gallons of water in some of the most arid areas on Earth. Graphite processing can pollute air and water resources. Estimates are that the battery accounts for up to 60% of the embedded greenhouse-gas emissions in EVs.

This means that the transition to zero emissions hinges on automakers' ability to produce EVs and their batteries in a sustainable, cost-effective and environmentally friendly way.

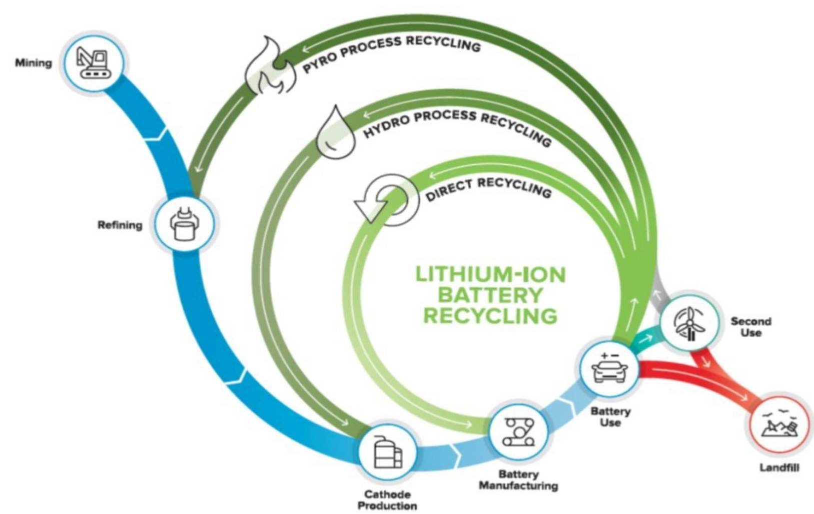
"How these batteries are designed and made will define their environmental impact for generations to come. Creating a circular economy for batteries is crucial to prevent one of the solutions to the current environmental crisis becoming the cause of another," concludes a MacArthur Foundation report.

Circularity in the Battery Lifecycle

An EV's battery pack will last between 10 and 20 years before its energy-storage capacity degrades below 80%. At that point, it is no longer suitable for autos and can go in one of three directions:

- It can be recycled. Here, the valuable metals, including cobalt, manganese, nickel and lithium, are recovered from the pack's cells. They are then sold for use in a future battery manufacturing process. (See Fig. 2).
- It can be repurposed for a second life. Here, the cells are resold for a new use without dismantling them, often in combination with a new management software and housing structure. This is most often associated with stationary storage, renewable energy and low-speed mobility applications.
- Or it gets discarded. When this happens, the battery enters a landfill or other disposal facility, and the metals and whatever remaining value they had is lost. Increasingly, regulations are mandating that lithium-ion (li-ion) batteries enter the circular economy rather than get discarded.

Figure 2: Battery Lifecycle



Recycling options bring material back into the production chain at different stages. Graphic courtesy of Argonne National Laboratory.

Within an EV's lifecycle, three recycling methods return materials to different areas along the value chain.

Circularity doesn't have to wait until the battery's end of life. There are other opportunities within the value chain to recover and reuse waste materials.

Battery manufacturers generate waste after the rolls of copper and aluminum foil on which the anode or cathode materials (respectively) are coated, then cut to fit specific battery formats (cylindrical, prismatic or pouch) and sizes (e.g., 2170 cylindrical vs. 4680 cylindrical).

This invariably leads to scrappage that, instead of being sent to a landfill, can be recovered and recycled using one of several methods:

- Pyrometallurgy is an energy-intensive technique that recovers only heavier metals like cobalt but requires less labor for battery disassembly.
- Hydrometallurgy preserves more of the critical metals than pyrometallurgy but requires more labor for battery disassembly and component sorting.
- Direct recycling is a relatively new, more energy-efficient and environmentally friendly approach that restores the cathode (the most expensive part of the battery) to its original state.
- Electro extraction is another new, energy-efficient process that uses a combination of electrochemistry, chemical precipitation and filtration to selectively recover metals.

Depending on which method is used, recyclers can return pre-consumer material to either the refiners, the electrode manufacturers or the battery makers.

Repurposing

Because li-ion cells still have 70%-80% of capacity remaining after they are no longer suitable for use in vehicles, businesses have developed around giving old packs a second life. A growing number of companies are engaged in the remanufacturing sector, including battery health companies, manufacturers and automakers. These companies analyze depleted li-ion and nickel-metal-hydride packs from EVs. Packs with sufficient remaining capacity can be remanufactured or refurbished for reuse in EVs, while packs deemed insufficient for reuse in automobiles can be repurposed for stationary storage or low-speed vehicle applications.

Repurposing packs for second-life applications that have a lower duty cycle is undertaken when packs don't have enough remaining capacity for use in EVs but do have enough for applications that don't require constant repeated charge and discharge cycles.

The most popular second-life application for remanufactured cells is in stationary storage systems, also known as energy-storage systems (ESS). These ESSs can be used as a backup power source for large buildings experiencing power outages or shifted to when utility rates are high. ESSs also are used by utilities to balance demand for grids and can store power for solar and wind – renewable but intermittent – energy generation. A variety of companies have undertaken demonstration projects for reusing automotive batteries in ESSs, including auto manufacturers, utility companies and recyclers.

Cells and modules that are no longer robust enough for their first life in EVs potentially also can be utilized in low-speed vehicles, such as e-mobility products for industrial applications or for commerce or pleasure and by municipalities. Reusing depleted cells from EV battery packs in forklifts; e-scooters, e-bikes and golf carts; and street sweepers and sanitation trucks appears to offer some promise. In 2019, Audi undertook a demonstration project by using spent e-tron and hybrid-vehicle cells in forklifts used at its Inglostadt, Germany, vehicle-assembly plant. Retailer Greentec Auto sells used modules from EVs to enthusiasts who use them for converting internal-combustion-engine vehicles, as well as for installation in bicycles, golf carts, ATVs and RVs and for solar-energy storage.

Recycling

The recovery of materials for the creation of new batteries is seen as crucial to supporting a circular economy for li-ions in North America and Europe and to limit reliance on Asia and Asia-based suppliers. Today, EY analysis says that only 5% of li-ions are recycled, with an estimated 11 million tons set to be discarded by 2030. With regulations requiring a minimum of 40% domestic materials content now in place in the US and European regulations prioritizing recycled content in the battery supply chain, it is likely that recycling rather than repurposing will be the more viable business sector for li-ions coming out of vehicles in North America and Europe.

Both legacy and startup companies are engaged in li-ion battery recycling in North America and Europe. However, the majority of the world's battery recyclers are in Asia, specifically China and South Korea, as they also are the top two lithium-ion-producing countries.

Li-Cycle can shred whole packs with its hydrometallurgical process.

While there is a keen public focus on the potential secondary life of EV batteries, until critical mass exists in the number of packs coming out of vehicles, recyclers will rely on cathode scrap from the cell-manufacturing process as a key feedstock. Several recyclers have inked deals with automakers and cell makers to collect this scrap material, notably Li-Cycle, which is working with the General Motors-LG Ultium Cells joint venture, and Redwood Materials, which has a relationship with Ford.

Estimates are that 10%-20% of battery-manufacturing capacity goes into creating cathodes that don't meet quality requirements and are scrapped at the factory. However, in the startup phase of production, its estimated scrap accounts for 50% of capacity. With the expectation that it will take years for individual gigafactories to reduce defect rates below 10%, cathode scrap containing valuable cobalt, nickel and lithium is seen as a more predictable feedstock for recyclers in the medium term than end-of-life automotive li-ions.

Another form of battery recycling and an example of circularity is the extraction of valuable battery materials from mining waste. The process is seen as a more efficient way of refining, compared with the labyrinthian traditional processes that also have a poor carbon footprint, given that materials mined in North America currently are refined in Asia, where most of the refining capacity exists.

Electrometallurgy is being promoted by startups such as Nth Cycle of the US, NEU Battery Materials of Singapore and Canada's Ronin8 as a means of locally and more sustainably refining scrap material, including mining tailings.

Nth Cycle claims that it can extract up to 30% of metals not captured in the original refining process. The company points to independent studies showing that its refining process – via its OYSTER (Optimized hydrolYsis System Targeting Element Recovery) electro-extraction technology, which uses filtration and electricity to remove valuable metals from mining tailings – produces 92% lower emissions than traditional refining techniques. Electrochemical recycling is also applicable for recycling EOL packs, as the black mass created when spent li-ions are shredded can be put through an electrochemical process. Nth Cycle says that Oyster has 44% lower emissions than "more modern critical minerals" recycling technologies.

Electrochemical recycling facilities typically have a smaller footprint (as small as 1,000-2,000 sq. ft. [93-186 sq. m]) vs. the tens of thousands of square feet of floor space needed for pyrometallurgical or hydrometallurgical recycling processes. They also require less initial investment than the others, which can cost hundreds of millions – even billions – of dollars to construct. Because of that, these facilities can be located closer to their source of supply, such as a mine, reducing or even eliminating the need for shipping. However, electrochemical plants may be unable to process as much tonnage per day as a larger pyrometallurgical or hydrometallurgical facility.

Business Case for Circularity

The COVID-19 pandemic exposed the fragility of the supply chain for North American and European automakers and Tier 1 suppliers, which led to idle assembly plants as shortages of critical parts and components from Asia persisted for months. In terms of li-ions, recovery of the critical materials from packs already in Europe and North America can be fed back into the creation of new batteries at gigafactories operating, or soon to be operational, in these regions, thus reducing reliance on the Asian supply chain that presently dominates the battery sector.

There is potential to achieve lower costs by utilizing recycled materials vs. mining new materials. Recycler Li-Cycle says that cobalt and nickel sulphate produced by its hubs will achieve price parity with mined cobalt and nickel. Competitor RecycLiCo notes that its high-purity recovered cathode materials, though potentially priced at a premium compared to mined materials, will be competitive because they eliminate the need for costly and time-consuming processing and refinement steps required by mined materials.

Driving the march to battery circularity more than ever before are regulations in both the US and European Union that eventually will restrict heavy use of Asia-sourced raw materials and components for batteries, as well as the growing opposition from environmental groups to proposed new North American and European mines.

Secondary Materials Use Less Energy

Mining and refining ores into usable materials requires a lot of energy. The Coalition for Minerals Efficiency reports that communition – the crushing and grinding of material, the most energy-intensive part of mining operations – is responsible for 3% of all global electricity consumption. To put that into perspective, the entire country of Japan consumes 3% of global electricity production.

And when it comes to mining battery metals, their energy consumption is no different.

Albemarle brine pools in Atacama desert, Chile.

Nickel comes from two different types of deposits: laterite – a widely available, yet lower-grade, material that utilizes open-pit mining and needs a series of energy-intensive leaching, solvent extractions and electrodeposition for processing – and sulfide deposits, which have a dwindling supply but are less costly and energy intensive to process.

According to a study by Singapore-based consultancy Engeco, sulfide deposits use just under 200 gigajoules of energy per ton of material extracted and processed, or a little over 55,000 kWh of energy for every ton of material.

However, as nickel demand grows, miners will increasingly have to look to the more energy-intensive laterite deposits to sate demand. On average, Engeco finds that extracting these deposits requires 244 GJ per metric ton of material; that's equivalent to almost 68,000 kWh for every ton of extraction and processing.

By contrast, lithium has a much smaller energy footprint compared to nickel. Data from the Engeco study shows that lithium mining, processing and refining use approximately 15 GJ/t lithium produced, or just over 4,100 kWh/t.

Mining also has the curious distinction of operating costs increasing the longer a material is mined. That's because the best ore grades are exploited first. These contain the highest concentration of the target mineral, resulting in lower costs and requiring less energy.

So, as particular ore bodies are depleted, mining operations are forced to chase lower and lower grades of ore. These are generally more difficult to extract and contain lower concentrations of the target mineral, resulting in higher costs and more energy consumption.

Recyclables to the Rescue

Recycling these metals requires much less energy. Conventional methods, such as mechanical separation and hydrometallurgy, can reduce energy consumption by more than 25%, according to Stanford University research. And some companies boast even better results. Redwood Materials says that its recycling process reduces energy consumption more than 88% for recycled scrap and over 77% for recycled batteries. Nth Cycle reports that its electro-extraction process consumes only 3-4 kWh per kg of input.

Barriers to Circularity

Several years ago, when the auto industry was first developing and releasing its latest generation of electrified vehicles, it was a very different outlook for the recycling industry.

EV demand forecasts were steep curves ever upward, with the larger battery carrying BEVs expected to dominate the growth (Figure 3). OEMs were investing billions of dollars to achieve their electrification goals with the promise of double-digit increases in annual BEV sales eyed by 2020. And, collectively, legacy OEM EV production targets were in the millions of units per year.

At the same time, commodity experts were predicting that battery metal shortages were just on the horizon. And the markets seemed to be reinforcing that view, as battery metals prices were rising steadily.

But the economics around recycling began to change after 2022, when the mining industry, responding to high prices and potential shortfalls, brought new supplies of battery metals online faster than anticipated. This was especially true for lithium, where mines in China's Xinjiang region were fast-tracked into production, and it also was true for cobalt and nickel.

Furthermore, the process of recycling EOL EV batteries is not a simple endeavor. As automakers develop and design packs for vehicular aerodynamics, weight and packaging attributes – not for recyclability – there is no standardized battery pack design spanning multiple OEMs; even within an automaker's lineup of EVs, pack design may differ. Cells in some li-ion packs are essentially glued in place, while some automakers use modular packs grouping cells into boxes. As a result, the dismantling process cannot be fully automated, and EOL batteries almost always require some manual disassembly.

However, there are exceptions that may make for a more promising future. Li-Cycle is one recycler that says it can shred whole packs. At its Gilbert, Arizona, and Tuscaloosa, Alaska, Spoke facilities, Li-Cycle processes full packs without manual disassembly or the need for discharging via its proprietary submerged shredding process that it says produces no wastewater.

The process of recycling EOL batteries also can be expensive due to costs associated with collection and transportation. At roughly 1,000 lbs. (454 kg), automotive battery packs are heavy. Additionally, they are classified as Class 9 hazardous waste under the U.S. Dept. of Transportation's Hazardous Materials Regulations (HMR: 49 C.F.R., Parts 171-180), meaning that precautions are required during transport. In Europe, li-ions are not classified as dangerous goods, but rather hazardous waste. However, they still require specialized transport. Global logistics firm Nefab says that li-ion shipping regulations differ based on the state of the battery, further complicating transport, with unique packaging required for prototype, waste, and damaged or defective li-ions.

European and US regulations require shipping li-ions in specialized containers, essentially fireproof boxes, to prevent thermal runaway (smoking, smoldering, fires) by damaged or short-circuiting li-ions. These aluminum-alloy containers cost a few hundred to a few thousand dollars – perhaps up to $10,000 for boxes to fit the largest automotive packs. Li-Cycle has cited collection and transportation costs for li-ion packs as high as $10/kg, far above the actual recycling costs of just $1-$3/kg.

Freezing batteries has been proposed as a solution to the high cost of li-ion pack shipping and transportation, both by University of Warwick researchers in the UK and startup Redivivus in the US. However, that requires that the pack temperature be kept consistently below freezing through the use of refrigerated trucks, which can cost roughly five times more than nonrefrigerated transport vehicles.

Implementation Costs

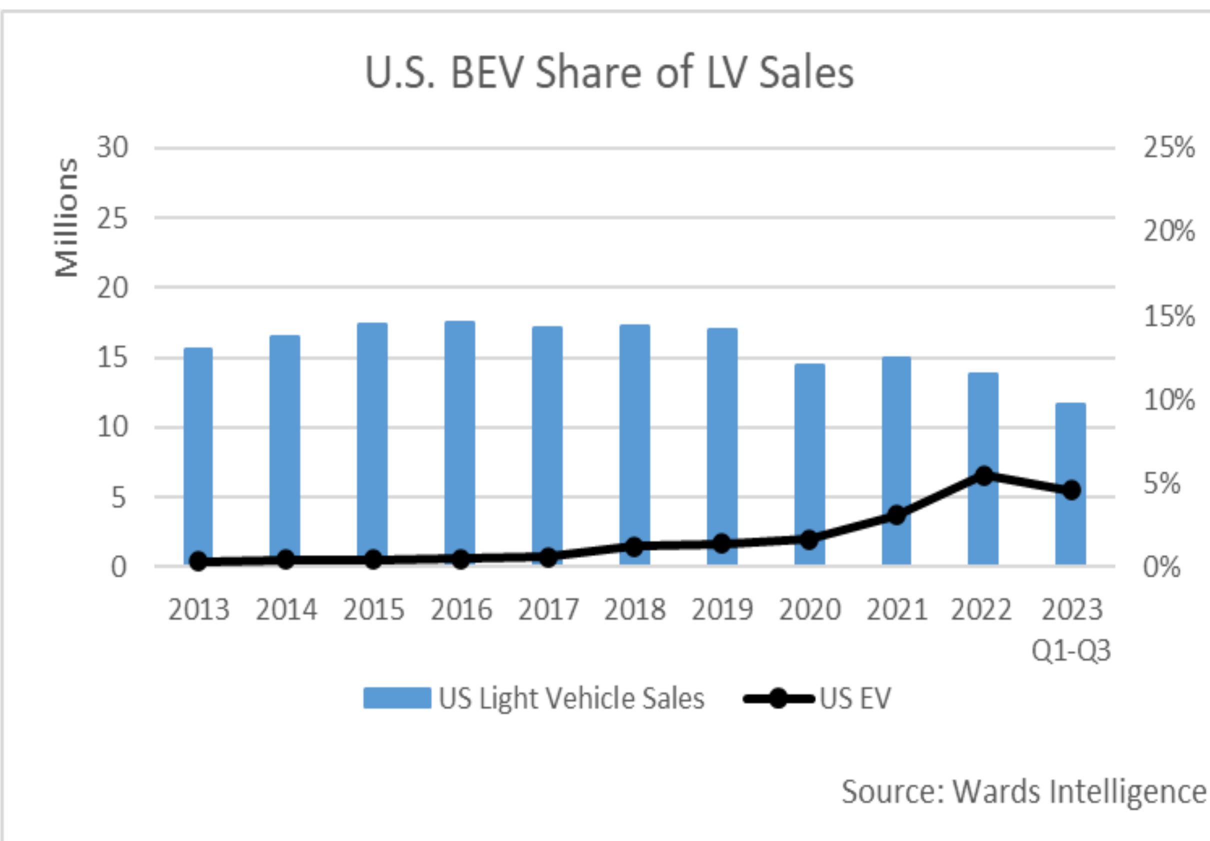
Establishing battery-recycling facilities usually requires heavy capital. Li-Cycle, for example, recently paused construction of its Hub facility near Rochester, New York, which was to use hydrometallurgical recycling to process black mass from its regional Spoke operations, due to construction costs ballooning to $1 billion, double what it previously intended to spend on the site; pyrometallurgical battery recycling sites similarly can cost that much.

Also at issue is the wider embrace of lithium-iron-phosphate batteries by automakers looking to grow the market for BEVs by making them more affordable. While LIP packs are less expensive than those using NMC or NCA cells, they lack the cobalt and nickel content prized by recyclers. The metals are the two most valuable cathode materials per London Metal Exchange prices. Therefore, there is much less interest in recycling LIPs, although some are pursuing the practice, including Singapore's NEU Battery Materials.

But perhaps the biggest issue impacting both scalability and circularity is the relative lack of cathode scrap and EOL batteries in North America and Europe.

There are about 40 operational gigafactories in those regions. That compares with Asia, where in China, alone, there are more than 200. Thanks to the rules on localizing battery materials and components to qualify EVs for the federal tax credit, more than a dozen are scheduled to come online in the US. However, more than half remain at least two to three years in the future.

Figure 3: BEV Share of Light Vehicles



An additional hurdle for recyclers may be the longevity of li-ion packs, extending further than originally anticipated. Seemingly, most packs placed in early-model BEVs have outlasted their decade-long warranties, and, as BEV volume was low until recently (as evidenced by Wards Intelligence US data above), it's projected that there won't be a sufficient supply of spent packs until the 2030s. This not only delays their arrival into the recycling stream, but also for use in ESS applications. There's also evidence that packs that could be recycled instead are being held onto to extract more value out of them. Spiers reportedly is warehousing batteries, at automakers' requests, for when their materials may be worth more in the future.

OEMs and battery makers further inadvertently upended recycling's business case when they altered battery chemistries to use 15% less cobalt, the most valuable of the metals. But 15% less cobalt means 33% less salvage value, according to a study from Boston Consulting Group. And by 2030, the low-cobalt formula NMC 811 will account for about 30% of the battery cathode market, according to a Wards Intelligence/GlobalData forecast.

Overcoming the Barriers

Electric vehicles are the future of transportation. But it is a monumental shift from how the world moves. Businesses are finding the transition costly and fraught with numerous and often complicated challenges – Not the least of which is keeping battery metals out of landfills and incinerators.

The International Energy Agency estimates that, by 2030, over 550,000 tons of battery materials will need recycling. And that number will more than quadruple to 450 GWh by 2040.

Despite the barriers to recycling EV batteries, the business case to do so, once at scale, is compelling.

The global EV battery recycling market is projected to grow over threefold from 2022 to hit $9.8 billion by 2028, according to a report by the market research firm IMARC Group. And by 2040, some analysts expect the global EV battery recycling market to reach $95 billion per year.

But before the EV battery recycling industry can capitalize on that growth and become a sustainable part of the EV battery lifecycle, stakeholders will need to incorporate four ideas into their business models:

- Strategic partnerships can mitigate uncertainties brought about by changes in the business environment and are vital for creating industry standards and improving economies of scale.
- Designing for recyclability will lower costs by streamlining pack components, standardizing pack design and optimizing the disassembly process for recycling.
- Incorporating a data-driven business model (DDBM) insulates the decision-making process from biased emotions. It can highlight problem areas, drive innovation and reduce costs.
- Technology and automation will lower costs, improve accuracy and safety, and contribute to the sustainable management of end-of-life batteries.

Outlook

The outlook for electric vehicle battery recycling and circularity is generally positive and is even required for the sustainable development of the electric vehicle industry. However, there are still two factors to consider before recycling and circularity can realize success.

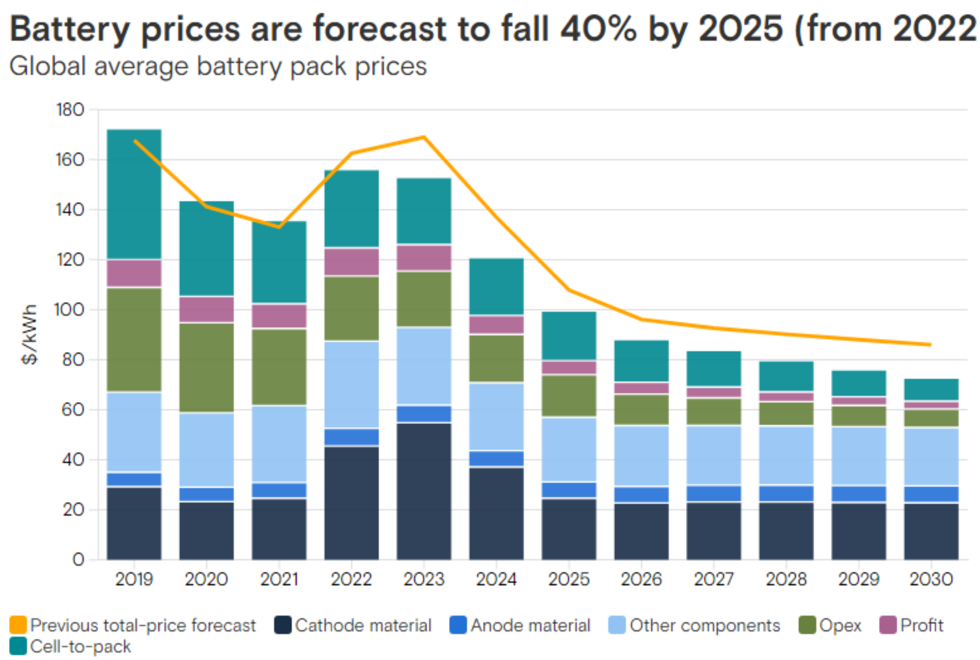
1. Batteries Still Evolving

By 2024, at least three Chinese EV makers will offer a sodium-based battery (sodium batteries do not use lithium, nickel, cobalt, manganese or graphite); by 2035, these could displace 7% of lithium demand.

2. Battery Prices Declining

Lithium, nickel and cobalt prices are down 80% (Li), 25% (Ni) and 60% (Co) from last year, and they could drop 40% (compared to 2022 prices) by 2025, according to research by the investment bank Goldman Sachs.

Figure 4: Battery Prices



Source: Goldman Sachs

Battery material prices are falling faster than previous predictions.]

This could put pressure on recyclers' margins as their revenue shrinks but fixed costs remain the same. Additionally, this may make the second-life pathway for batteries cost prohibitive compared to buying a new battery.

In the face of evolving chemistries and falling mineral prices, the success of circularity and EV battery recycling directly depends on the ability of stakeholders to work together to develop better designs and more efficient processes and lower overall operational costs.