Electric Vehicle Lithium-Ion Battery Life Cycle Management

Course No: M04-052
Credit: 4 PDH

Ahmad Hammouz, P.Eng., LEED AP

CED engineering.com
PDH FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.com

This course was adapted from the National Renewable Energy Laboratory, Publication No. NREL/TP-5700-84520, "Electric Vehicle Lithium-Ion Battery Life Cycle Management", which is in the public domain.

Executive Summary

There has been significant growth in annual sales of plug-in electric vehicles (EVs) in the last 12 years, from thousands annually to millions (Kane 2021). This has been driven largely due to EVs' attractive features of better driving performance, improved battery energy density, lower fuel cost, reduced environmental footprint, and, of course, incentives offered by governments around the world. Proposed bans on sales of light-duty gasoline and diesel vehicles by 2030–2035 are already in place in India, Ireland, the Netherlands, Denmark, Norway, and the United Kingdom. Many other countries and now some U.S. states have also set EV-only sales targets. In the United States, China, European Union (EU), United Kingdom, and Canada, EV sales jumped 41% to around 3 million vehicles in 2020, despite the sales of internal combustion engine vehicles dropping by 15% due to the COVID-19 pandemic. Global electric vehicle sales reached 10 percent of all new cars sold in 2022, an increase from 8.3 percent in 2021. (Klender 2023)

As the key component powering EVs, electric vehicle batteries (EVBs) are poised to play a major role in making transportation cleaner while addressing climate change and improving environmental quality (Muratori et al. 2021; Li et al. 2015). Lithium-ion batteries (LIBs) are currently the only choice for EVBs, a trend that is predicted to remain well into the future (Xu et al. 2020). Proper life cycle management (repair, reuse, recycle, and disposal) of LIBs must be a major consideration for their development and implementation (VTO 2021). Optimally managing EVBs during use and potential second life and ensuring responsible recycling at end of life are essential for supporting these goals while securing a sustainable supply of critical battery metals and minerals for EVBs and stationary storage systems well into the future.

The objective of this report is to inform all stakeholders in the life cycle management of EVBs of global initiatives, challenges, and opportunities for optimum EVB life cycle management and to encourage collaboration to support a sustainable EVB industry well into the future. This report is divided into two major sections: (1) technical aspects of recycling and reuse and (2) regulations, initiatives, and stakeholder perspectives. The first section presents a technical overview of the reuse and recycling technologies for electric vehicle (EV) batteries and the opportunities and challenges they face in creating a circular economy. We highlight the crucial role of lithium-ion batteries (LIBs) in transitioning to clean energy and examine the current methods for extracting critical battery minerals. We explore how battery design affects recycling and reuse and discuss innovative alternatives to conventional battery life cycle management that could enhance recycling and reuse efforts. The second section reviews global initiatives, including those in the U.S., aimed at promoting and regulating the responsible management of batteries throughout their life cycle. We examine the increasing number of initiatives and regulations designed to ensure a sustainable energy future and provide perspectives from various industry stakeholders. Additionally, we introduce new data management and other strategies that could simplify compliance and foster a circular economy for EV batteries.

Creating a circular economy to manage EVBs will help nations meet critical global greenhouse gas/carbon dioxide reduction targets and secure a long-term supply of battery minerals required to support this. We hope this report will stimulate broad discussion and action across industry sectors to ensure a sustainable new energy future, making a circular economy for EVBs a reality.

Table of Contents

List of Figures

List of Tables

1 Reuse, Recycle, and Reimage

In this first section, we explain why lithium-ion batteries (LIBs) are key to our transition to clean energy and describe the current technologies for recovering critical battery minerals. We explore how battery pack designs can hamper or support recycling and reuse efforts, and how some alternate approaches to traditional battery life cycle management can help increase recycling and reuse.

This section focuses on lithium-ion life cycle management, so we will not cover nickel metal hydride (NiMH) batteries that have successfully been used in hybrid electric vehicles in the last 20 years. Currently, more than 50% of new hybrid electric vehicles use LIBs. These battery sizes range from 0.6–1.4 kWh, whereas an electric vehicle (EV) LIB size ranges from 40–100 kWh. Therefore, with large EV market penetration, the amount of end-of-life LIB would be much larger than those of NiMH batteries. Currently, many of the collected NiMH batteries from various stakeholders (e.g., dealers, auto recyclers) have been refurbished and sold as aftermarket replacement for hybrid electric vehicle batteries (Best Hybrid Batteries 2022). Some NiMH modules are packaged into power systems to provide backup power (Hirai et al. 2000) for developing countries. When NiMH batteries no longer have energy or power, they can be recycled to recover nickel and other valuable metals (ERI 2022; Call2Recycle 2022).

1.1 Why Electric Vehicles?

There has been significant growth in annual sales of plug-in electric vehicles (PEVs) in the last 10 years—from thousands annually to millions (Dobson 2021). This has been driven largely by EVs' attractive features of better driving performance, improved battery energy density, lower cost, reduced environmental footprint, and, of course, incentives and deadlines imposed by governments around the world. Bans on sales of gasoline and diesel vehicles by 2030 are already on the books in India, Ireland, the Netherlands, Denmark, Norway, and the United Kingdom (What Car? 2021). Many other countries and now some U.S. states have also set targets for EV-only sales by 2035. In the United States, China, European Union (EU), United Kingdom, and Canada, EV sales jumped 41% to around 3 million vehicles in 2020, despite the sales of internal combustion engines dropping by 15% due to the COVID-19 pandemic (EV-Volumes 2021). By September 2021, PEVs accounted for 10% of the global passenger market for the first time (Kane 2021). First quarter 2021 global EV sales soared 140% to 1.1 million vehicles, and BloombergNEF (2019) forecasts that by 2030, annual sales of PEVs will reach more than 20 million globally. Figure 1 provides a forecast of future annual EV sales around the world. As can be seen, a significant amount of EVs is predicted to come to market, requiring a significant mass of materials for making batteries for these EVs.

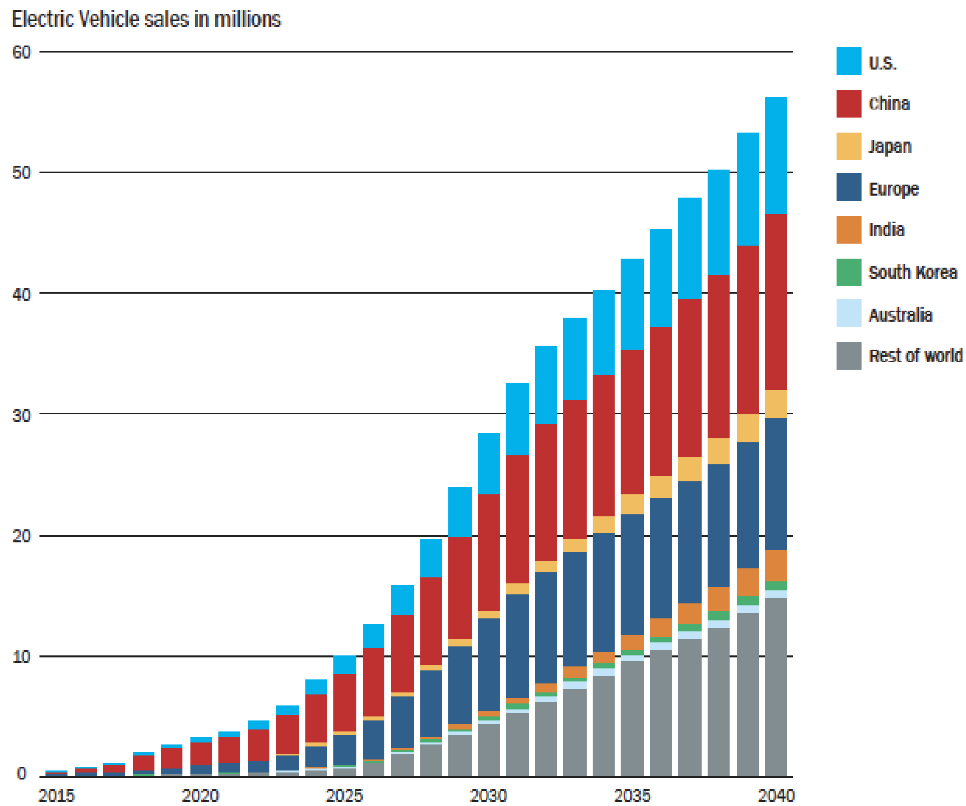

Figure 1. Annual sales of passenger EVs—past 5 years and future projections.

Source: VTO (2021)

1.1.1 Electric Vehicle Batteries

These projections translate to the need for a significant amount of batteries. LIB technology has become the energy storage of choice for PEVs because of its high performance and decreasing costs. Annual demand for LIBs is projected to exceed 2 TWh by 2030 (BloombergNEF 2019). In 2020, 400,000 tons of cathode materials were used in LIBs, a number that is projected to rise to about 1.2 million tons by 2030 (Zhou et al. 2021).

1.1.2 Current Lithium-Ion Battery Technologies and Materials

Currently, LIBs are the main choice for consumer electronics, electric-drive vehicles, and grid energy storage due to their high energy and power, longevity, modularity, and relatively low cost. In rechargeable LIBs, lithium ions move from the anode through an electrolyte to the cathode during discharge, and vice versa during charge.

Electric vehicle battery (EVB) technology is continuously improving, with aims to reduce cost, size, and weight; improve safety; extend driving range; enable faster charging; and much more. Unlike many other battery types (like lead acid), LIBs can be made from different chemistries for anodes, cathodes, and even the electrolyte. The current choices for cathodes are olivine (typically lithium iron phosphate), spinel (typically lithium manganese oxide), and transition metal oxides (cobalt oxide, nickel cobalt aluminum, and various formulations of nickel manganese cobalt) (Battery University 2021). Current anode choices include graphite, hard carbon, lithium titanate, and silicon-carbon composites, but graphite is the most used in commercial LIBs. Pairing these anodes and cathodes provides battery cells with different voltages, energy and power densities, cycle life, calendar life, cost, and safety thresholds. Currently, nickel cobalt aluminum and high-nickel nickel manganese cobalt cathodes matched with graphite are used in EVs because of their high specific energy, relatively long cycle and calendar life, and reasonable cost.

1.1.3 Key Lithium-Ion Battery Materials: Current and Future

Key materials used in current and advanced LIBs are lithium, cobalt, nickel, manganese, copper, aluminum, graphite, organic electrolyte, polyolefin, plastics, salts, and small amounts of other elements. Cell components also include copper and aluminum current collectors, polypropylene separators, carbonate electrolytes, $LiPF_6$ salts, and organic binders.

Access to cobalt could be challenging and lead to price spikes (Azevedo et al. 2018). There is enough lithium and nickel to supply millions of EVs, but production capacity is limited. Cobalt is the highest material supply risk for EVBs due to a variety of factors, including resource availability, mining practices, and environmental impact. There are concerted efforts to reduce or eliminate the amount of cobalt in EVBs (using high-nickel cathodes) while increasing specific energy (VTO 2018). With price increases, environmental mining issues, and limited reserves, cobalt can be a risky choice. Supply chain risk is a significant concern, particularly from geographic locations that have unsustainable environmental, political, and financial impacts.

To alleviate supply chain issues, options include (EERE 2019):

1. Replacing chemistries with low cobalt (less than 50 mg/Wh) or no cobalt and/or other earth-abundant materials.
2. Finding a secondary use for batteries.
3. Recycling LIBs at the end of life to recover materials to be reintroduced into future batteries.

1.1.4 EVB Recovery Technologies

Data in Figure 2 predict a dramatic increase in the United States in the number of end-of-life EVBs by 2030. These spent batteries will need to be reused in second-life applications or recycled for recovery of valuable materials. This graph excludes batteries from consumer electronics and power tools, and instead focuses on more demanding and higher-capacity automotive, stationary storage, uninterrupted power supply/backup, and marine applications.

In accordance with the U.S. Environmental Protection Agency's waste management hierarchy (U.S. Environmental Protection Agency 2022), the best approach to life cycle management is to eliminate the possibility of waste in the first place (reduce and reuse), followed by recycling to prevent waste and recover valuable materials, using the energy in waste to create power, and, as a last resort, disposal. For the purposes of this discussion, we will bypass repair and refurbishment, which enable EVBs to continue powering an automobile, and focus on second life and recycling.

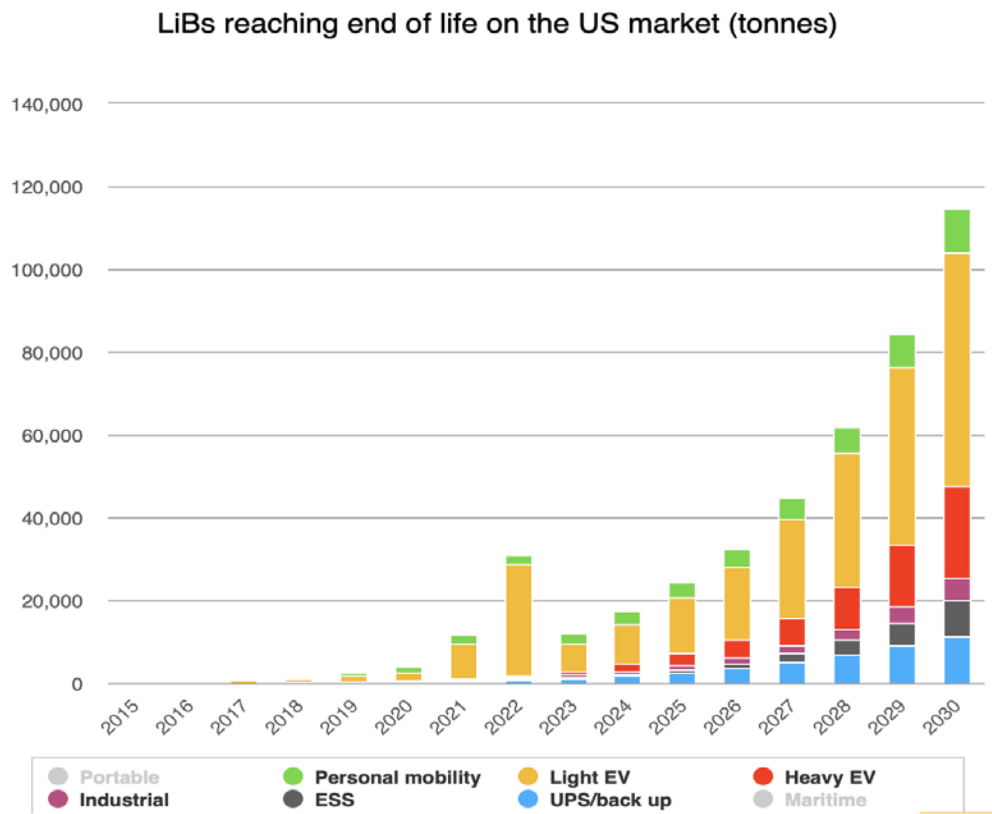

Figure 2. Projected available lithium-ion tonnage for reuse and recycling by application in the United States.

Courtesy of Hans Eric Melin of Circular Energy Storage

1.2 Second Life

Expected rapid uptake in EV sales demands requires advance planning for when batteries reach end of use in a car. Currently, EV manufacturers provide battery warranties for 8–10 years (Najman 2021), taking responsibility for any repairs or replacements. If the warranty is voided for any variety of reasons, or if it has reached its end of useful life for the EV or end of the vehicle life, these batteries could go through different paths of remanufacturing, refurbishing, swapping, and repurposing (second life) and eventually become available for recycling.

After the warranty period, the batteries usually last longer due to implementation of design margins by original equipment manufacturers (OEMs). Some experts believe EVBs can perform well for another 2–6 years beyond warranty, giving a battery life of 12–16 years in a vehicle (Melin 2021). This calendar life could be impacted by charging behavior (e.g., repeated fast charging or discharging degrades battery life) or environmental conditions, such as exposure to extreme heat or cold.

According to the United States Advanced Battery Consortium, a battery could lose 20% of its capacity and power by the end of a vehicle's life. Therefore, they recommend a 20% extra margin for the battery capacity and power at the beginning of life. In other words, a battery reaches its end of life when it has lost more than 20% of capacity or power (United States

Advanced Battery Consortium 2020). Considering individual driving habits and distances, batteries at much lower capacity can continue to perform well below this level. When EVBs are no longer suitable for powering a car, there is often enough remaining capacity to provide a stationary energy source for renewable energy storage for grid and/or home power backup (Neubauer, Wood, and Pesaran 2015).

1.2.1 Second-Life Battery Market

Second-life batteries are end-of-first-use EVBs that have use beyond that in a car (Motavalli 2022). The remaining capacity can be more than sufficient for most energy storage applications; the second-life battery can continue to work for another 10 years or more (Neubauer et al. 2015).

1.2.2 Value of Second-Life Batteries

Battery second life has been studied by several researchers (Neubauer et al. 2015; Martinez-Laserna et al. 2018; Hossain et al. 2019). The value of batteries for second life extends far beyond the cost savings of using existing batteries to make new ones. Besides value measured in dollars per kilowatt-hour, second-life battery valuation also presents the following opportunities:

- **Providing power to those without access.** Populations that live in areas with little or no energy infrastructure or dependable grid support (e.g., South Africa's rolling blackouts or Puerto Rico's unstable grid after Hurricane Maria) have energy requirements for basic human needs including heat, water, medical services, education, and much more. Second-life batteries can provide economical energy storage for renewable energy in these areas.
- **Supply chain challenges for new batteries.** Critical mineral reserves for key battery chemistries are either in short supply or concentrated in areas of the world where human rights and child labor violations at the mine (and in the supply chain) are rampant. Supply chains can also be disrupted (e.g., COVID-19), causing delays for weeks or months for new batteries to become available. In addition, mineral processing capacity for new batteries is currently not sufficient to meet the worldwide commitments and deadlines for transitioning to zero-emission vehicles (Ballinger et al. 2019).
- **Offsetting lithium-ion battery recycling costs.** Currently, LIBs with high cobalt or nickel contents have positive value (even accounting for cost of transportation) when recycled. However, LIBs such as lithium iron phosphate batteries that have low or no nickel or cobalt content in the cathodes are usually of negative value when recycled; that is, the cost of recycling exceeds the value of materials recovered, such as iron (Zhu and Chen 2020). On the other hand, batteries that are suitable for second life currently generate revenue and have a lower environmental footprint. For example, when mining truck battery packs powered by lithium iron phosphate can no longer be used to power the vehicle but have ample residual energy, they can become off-grid second-life renewable energy stationary storage systems. This can offset diesel generator fuel costs at the mine and resulting emissions.
- **Affordability.** One critique of second-life batteries is that with the price of new batteries continuing to decline, spending time and money on used batteries will no longer be practical. However, for lower-demand applications such as back up in rural areas where the use of new LIBs would not be feasible, the reduced cost of the batteries could open new doors. The National Renewable Energy Laboratory has developed a techno-

economic analysis tool that provides insight on the economic viability of second-life applications depending on various technical and economic factors (Neubauer et al. 2012).

- **Scalability of supply of second-life batteries.** Currently, many hybrids and EVBs are working well beyond the warranty period because they are not cycled as often as designed for. If this trend continues, a growing number of batteries will be suitable for second life. A larger, more stable supply can reduce production costs per kilowatt-hour.

1.2.3 Second-Life Battery Market Evolution and Challenges

The second-life battery industry has evolved from recovering 18650 cells from laptops and other consumer devices (1 kWh) to developing 10-kWh or larger energy storage systems. YouTube has many examples of these "Powerwall"-type (Tesla 2021) developments using off-the-shelf or self-developed battery management system software and hardware. Some are not ready for commercialization, while others have been "productized" to be used as residential solar energy storage systems. Most notably, and particularly for do-it-yourself and small producers, many are not being UL or CSA certified to ensure they have been independently tested to meet recognized standards for safety and performance. UL 1973 (energy storage), UL 1974 (second-life EV conversion to stationary energy storage), UL 9450 Energy Storage, and UL 9450a (fire prevention) protocols are very expensive and can be easily ignored by smaller producers (UL Solutions 2021). As such, some of these products are sold domestically to unaware consumers or shipped overseas to countries that may not require such fire and electrical safety standards. Such products could pose a serious fire risk if the engineering and lack of testing hide unrealized hardware or software faults. In addition, the opportunity for recycling these batteries may be small or nonexistent in many of these countries.

1.2.4 Second-Life "Big Lift"

These problems aside, the value that can be achieved from second life has ignited business interest from auto OEMs and entrepreneurs alike. OEMs with battery-as-a-service or battery leasing models can take advantage of owning the batteries at the end of first life by profiting from second life. This can also be onerous for the second-life developer since it requires several important steps. Second-life companies face a "big lift" in market identification; system design, building, testing, and UL/CSA certification; and marketing the new second-life battery system. These tasks also include:

1. Identifying customers that need a solution for which a second-life system may offer more value.
2. Finding markets, designing a solution, and providing customer service and support, which involves:
    A. Finding marketing, sales, and engineering talent.
    B. Sourcing enough of the same models and types of second-life batteries.
    C. Harmonizing the different power capacities of the modules so cell or module balancing is safe.
    D. Building or using a battery management system and hardware.
    E. UL or CSA certifying the batteries.

F. Selling and delivering long-term customer service support.

G. Combining and integrating different battery chemistries from different EVs.

H. There are a growing number of companies specializing in various parts of the second-life ecosystem (e.g., testing equipment, reverse logistics, repurposing). Partnering can reduce the "big lift" that would be required for an individual company to deliver full value to the customer.

1.3 End-of-Life Lithium-Ion Battery Recycling Technologies

The primary goal of LIB recycling is to recover critical minerals such as nickel, cobalt, and lithium from the cathode, along with other compounds such as high-grade graphite from the anode (Gaines 2018). EVBs are also composed of other potentially recyclable materials such as steel, aluminum, copper, and plastics, but for the purpose of this report we focus on critical battery minerals used in the cathode and anode. To recover these materials from LIBs, there are three major technologies currently in various stages of commercialization: pyrometallurgy, hydrometallurgy, and direct recycling (Harper et al. 2019). In addition to these methods, mechanical treatment (through disassembly, crushing, shredding, and separation) is a major element of any recycling technology. There are also new methods being developed, including the use of robotics for more efficient disassembly, ultrasound for improved metals separation, chemical removal of impurities from black mass, separation through electroplating or electrochemistry, and much more. We focus here on currently available recycling technologies, noting that direct recycling is not yet widely available (see Table 1 for a comparison).

1.3.1 Pyrometallurgy

Pyrometallurgy is the process of high-temperature thermal treatment of batteries in a furnace to extract metals and intermediate compounds that can be further processed to create battery-grade precursors (Assefi et al. 2020). The feedstock to a pyrometallurgy plant could be the whole battery or the black mass. The output could be metal alloys and other byproducts such as slag. These alloys are then further refined to make the input lithium-ion cathode battery chemicals. Pyrometallurgy is energy-intensive, and the plants require large capital investment.

As with any smelting process, impurities in the melted alloy in the furnace need to be removed. This is done by adding minerals that float to the top of the melted alloy. This layer is known as slag or dross. Unfortunately, the dross also captures the much lighter (in terms of density) lithium compounds. The dross is then poured off and separated from the target melted alloys. The net result is that the captured lithium is often lost in the slag heap unless recovered in an additional hydrometallurgical process. Slag can be added to concrete to make it stronger for commercial applications. Although it is technically possible to refine the dross further to recover the lithium compounds, it is not economically feasible to do so. Umicore, a major producer of cathode materials from ores and recycled batteries, has indicated that they can recover lithium in their new process that incorporates hydrometallurgy (Umicore 2022). Low-value sodium sulfate is a byproduct of hydrometallurgical processing.

1.3.2 Hydrometallurgy

Hydrometallurgical processing uses chemical treatment to extract the key compounds in the black mass, including the lithium compounds (Vieceli et al. 2021). The process uses leaching fluids such as inorganic acid, organic acid, alkali, or even bacteria solutions that dissolve metals in cathode to salts that can be used as precursors to make new cathodes. The process involves a series of chemical methods such as precipitation, solvent extraction, and electrolytic deposition to make desired compounds. This process has a much higher rate of metal compound recovery, including lithium compounds. Hydrometallurgical plants use much less energy than pyrometallurgy plants. In addition, the plant size can be much smaller than those required for pyrometallurgy, thus needing less capital investment and possibly less environmental permitting and permit acquisition delay. Hydrometallurgical processes are currently considered the most suitable method for recycling LIBs. Commercial plants already exist, and several startups are building plants in the United States and Canada based on the hydrometallurgical approach.

1.3.3 Direct Recycling

Direct recycling involves recovery of cathode while maintaining its molecular structure, rather than breaking it down into constituent metals for reprocessing into battery-grade cathode. Eliminating these steps makes the prospect of direct recycling most economically viable (Gaines et al. 2021).

In direct recycling, the black mass feedstock (from shredding and separation operations) needs to be further refined. Some impurities are taken out within the shredding process, such as binders and plastics within black mass. These are of no value, and shipping it only moves the waste further upstream and adds unnecessary shipping costs in terms of weight and volume within a truck or container. The direct recycling involves:

- Binder removal.
- Separation of cathode from anode and other components.
- Separation of different cathodes from each other to their original formula.
- Rejuvenation of the cathode by relithiation (the aged cathode may lose lithium).
- Removal of impurities.
- Upcycling to produce new cathode materials competitive with future cathodes.

For example, if an EVB pack was mostly made from nickel cobalt manganese oxide with equal stoichiometry (NMC111) cathode, direct recycling processes will result in the same formulation of NMC111 that needs to be relithiated, impurities removed and then upcycled to a future cathode such as with higher nickel and lower cobalt contents. Direct recycling is still in the R&D stage, but analyses have shown that it could be economically and environmentally superior to hydrometallurgy. Pilot plants need to demonstrate that the technology can be built economically at commercial scale. As previously indicated, LIBs are made of many chemistries with frequently updated reformulations and will continue to be in the future, so these chemical variations could present technical and economic challenges in direct recycling processes.

Table 1. Advantages and Disadvantages of Various LIB Recycling Technologies.

Sources: Gaines (2018); Harper et al. (2019); Assefi et al. (2020). Note: mechanical disassembly is part of the three technologies.

	Pyrometallurgy	Hydrometallurgy	Direct Recycling
Recycling type	Smelting	Chemical leaching	Physical/chemical
Temperature	High	Low	Low
Discharge/shredding requirements	Not much	Yes, needed	Yes, needed
Wastewater	Least	More	Some
Materials recovered	Co, Ni, Cu alloys; (Li + Al slag) or Li carbonate	Metals or salts, Li_2CO_3 or LiOH	Cathode, anode, electrolyte, metals
Sorting required?	No	Yes, less degree	Yes
Energy requirements	High	Medium	Low
Capital costs	High	Medium	Medium (not known yet)
Commercially deployed?	Yes (Europe and Asia)	Yes (United States, Europe, Asia)	No

1.4 EVB Recycling Challenges

1.4.1 Value or Cost?

Out of the five leading types of lithium-ion EVBs on the market (not including NiMH, which is mainly used in hybrid electric vehicles), only two are currently producing net revenue after logistics and recycling costs. Table 2 lists the five major cathode compound blends and indicates positive or negative value based upon most of today's recycling markets.

As battery recycling infrastructure increases globally and demand for EVB minerals continues to soar, it is expected that for most chemistries, the recovered mineral value will soon exceed logistics and processing costs, enabling recyclers to pay for used batteries. This positive value can have far-reaching implications on encouraging recycling and discouraging dangerous situations such as storage stockpiling.

Table 2. Recycling Value of Current Major Lithium-Ion Battery Chemistries.

Source: Harper et al. (2019)

	Possible Positive Value Pricing
Cathode Acronym	**Cathode Name and General Formulation**
LCO	Lithium cobalt oxide ($LiCO_2$ or LCO)
NMC ($N_xM_yC_z$)	Lithium nickel manganese cobalt oxide ($LiN_xMn_yCo_zO_2$)
NCA	Lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$)
	Negative Value Pricing
Acronym	**Name and General Formulation**
LFP (cathode)	Lithium iron phosphate ($LiFePO_4$)
LTO (anode)	Lithium titanate ($Li_4Ti_5O_{12}$)

1.4.2 Transportation Costs

About 50% or more of the cost of recycling any type of LIB is transportation (Dai et al. 2019), for a variety of reasons:

- Size and weight of EVBs
- EVBs can be bulky and difficult to pack in a way to take advantage of the truck's full capacity, increasing the cost per pound to ship
- Low volumes
- Higher transportation rates from less-than-truckload (LTL) shipments
- Special packing and handling requirements for damaged, defective, or recalled batteries.
    - U.S. Department of Transportation packaging regulations for damaged, defective, or recalled batteries increase the dimensional volume of each of these batteries in the truck, further reducing the number of batteries the truck can accommodate.
- Few available recycling facilities often means shipping batteries long distances for recycling

Since October 2019, shipping costs per pound have steadily increased, followed by a huge jump in 2021 because of the COVID-19 pandemic's impact on supply chains worldwide. Shortages of both professional truck drivers and intermodal containers, along with other disruptions, have put strains on transportation networks. As a result, battery recycling transportation costs have appreciably risen, squeezing potential net profit margins.

1.4.3 Battery Reverse Logistics: Meeting Regulatory Requirements

As required by domestic and international law, transportation of hazardous material ("hazmat") requires the shipper, transporter, and receiver to be trained and certified to legally offer, transport, and receive and sign the bill of lading (shipping document) when shipping EVBs and other LIBs.

e variable. To avoid multiple moves, it is beneficial to diagnose batteries in-field and ship them to the nearest qualified refurbisher, second-life developer, or processor, and if possible, ship in FTLs. Consolidating LTL shipments to a warehouse and then shipping them again to a processor adds unnecessary cost and carbon footprint. Using the same carrier, a "merge-in-transit" method can aggregate geographically dispersed LTL pickups destined to the same address and time them so they are consolidated by the carrier's nearest local terminal and delivered as a single LTL volume or FTL shipment. Merge-in-transit can work with FTL or containers destined and coordinated for rail or ocean shipping.

Federal regulations allow NiMH batteries (49 CFR 172.102; IMDG 117 & 963) and lithium (49CFR 173.185 (a)(b)(d)) batteries with solid outer containment walls to be hazmat shipped when securely strapped onto pallets. If, however, the outer shell of an LIB is not solid or is broken, a shipping container must be used. The watt-hour capacity and the state of health (i.e., whether damaged, defective, or recalled) will determine the type of hazmat packaging and shipping requirements. FTL transportation costs can vary from a few hundred dollars for one-time use in a non-UN-rated container (i.e., on a pallet) to thousands of dollars for UN-rated hazmat packaging materials required for shipping damaged, defective, or recalled LIBs. Reusing undamaged hazmat packaging multiple times provides valuable packaging savings, even when figuring in the cost of return transportation.

1.4.4 Reducing Transportation Costs and Impacts

Rail vs. Highway

Using rail for long-distance shipping can reduce costs. Although rail takes a bit longer for delivery, prices on similar transcontinental intermodal rail shipments in the United States in 2021 were around 30% less than truck costs. In an example of truck travel from Los Angeles, California, to Syracuse, New York, rail would prevent generation of about 4,410 pounds of greenhouse gas emissions compared to truck transit over the 2,768-mile trip, or 1.6 pounds of carbon dioxide per mile.

Hub and Spoke

The cathode material in EVBs that recyclers are primarily interested in is a component of the cells that make up the modules that account for most EVB pack volume. As such, disaggregating the battery "close to home" where markets for many non-cathode materials are plentiful and then only shipping the modules or cells for cathode recovery makes good economic sense.

One way the market is addressing this is the emergence and growth of primary recycling businesses that disassemble packs and ship materials downstream for final recovery. Depending on battery design, these businesses generally ship whole modules containing the cells or, if possible, remove and pack the cells for shipment to further processing.

In addition, some larger battery recycling companies have adopted "hub-and-spoke" models where initial processing facilities are strategically located to reduce transportation costs. These facilities sometimes involve shredding operations that grind and separate module and cell materials to produce "black mass," which contains the cathode materials. The cathode materials are then shipped to final cathode recovery operations where battery-grade minerals are produced.

1.5 State of EVB Design: Recycling Challenges & Opportunities

Considering we are still in the early stages of transition toward electrification, EV engineering has focused primarily on the best battery performance with the lowest cost. One cost-cutting measure is the use of non-serviceable components in an EVB pack, leading to costly disassembly at the end of first life. Increasingly, however, OEMs are designing EV packs with serviceability in mind. The same design provisions that facilitate serviceability are also favorable in reducing costs of reuse and recycling. Figure 3 provides an overview of battery disassembly challenges in vehicles.

1.5.1 Disassembly Constraints

The rapid uptake in EVs and impending regulations are likely to quickly implore EV engineers to take a broader view on design for circularity. The argument for serviceable/reusable EVBs also strengthens as cells become safer, cheaper, and more efficient. Automakers and suppliers are already using or developing ways to tackle these problems. One example is the use of serviceable adhesives and seals, which in some cases can also be reused. Exploring the cost associated with design and packaging decisions at every level will help accelerate this transition.

1.5.2 Thermal Materials

The safety and stability of battery cells depends on maintaining internal temperatures within specific limits. If the temperature exceeds the critical level on either end, thermal runaway can occur, destroying the battery or, even worse, starting a fire.

Thermal runaway is a chain reaction within a battery cell that can be very difficult to stop once it has started. It occurs when the temperature inside a battery reaches the point that causes a chemical reaction to occur inside the battery. This chemical reaction produces even more heat, which drives the temperature higher, causing further chemical reactions that create more heat. In thermal runaway, the battery cell temperature rises incredibly fast (milliseconds) and the energy stored in that battery is released very suddenly. This chain reaction creates extremely high temperatures (around 752°F, or 400°C). These temperatures can cause gassing of the battery and a fire that is so hot it can be nearly impossible to extinguish (Dragonfly Energy 2022).

Several factors can lead to thermal runaway, including internal defects that can cause shorts, external impacts or punctures, and even overcharging. Although batteries are designed to minimize these occurrences, there is still a heavy reliance on insulating materials to prevent thermal runaways (i.e., from overheating) and to help contain them if they do occur.

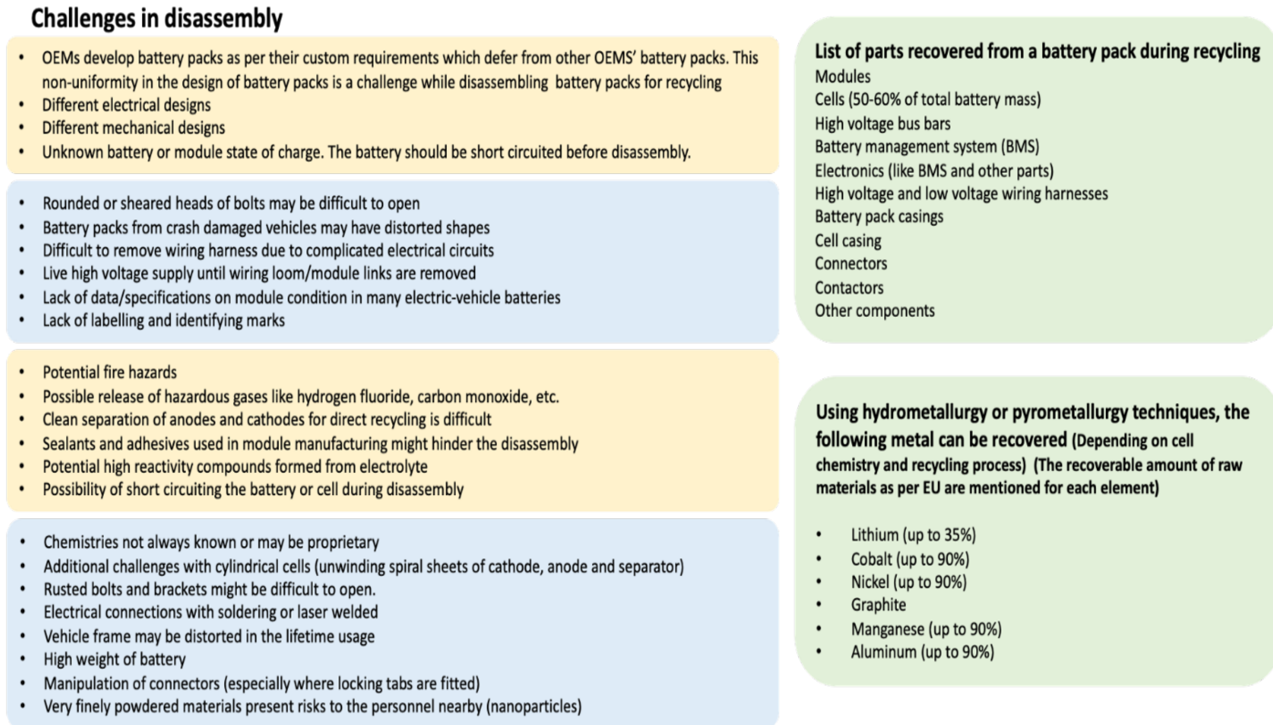

Figure 3. Battery disassembly challenges for recycling EVBs.

Image from Kapil Baidya, Tata Motors

During the engineering process, protecting high-voltage parts is paramount (e.g., cells separated into modules).

Until recently, cell manufacturers, pack integrators, and EV makers have focused on reducing battery cost, increasing energy, and extending battery life while meeting safety requirements. As such, design for recycling and secondary use has not been a top priority. Now that battery costs have decreased and performance has improved, there is more attention to recycling and reuse. This interest has been accelerated over the last year, particularly because of recent supply chain issues and government policies to produce batteries and battery materials domestically. With safety being the highest priority, moving from traditional thermal materials to more easily removable and recyclable alternatives could be a difficult transition. However, the rate of development and adoption of safer cell chemistries that are less prone to fires could help accelerate this transition. Regulations on minimum serviceability or reuse will also help prioritize this as one of the key attributes that engineers must consider.

Advanced simulation technologies also offer a cost-effective way for battery engineers to experiment with different materials and designs that can have a positive impact on recyclability.

Figure 4. Pack disassembly—thermoplastic materials challenges.

Photo from Kerry Manning, Experimental Vehicle Engineering

1.5.3 Plastics & Composites

Another battery recycling challenge involves plastics and composite materials. Polycarbonate blends are well suited for manufacturing modules, housing parts, cell holders, and crash absorbers for electric car batteries. They are lightweight yet robust and dimensionally stable and, depending on requirements, they also come equipped with flame retardants.

Although these thermoplastics can help reduce battery weight and provide some thermal protection, unless carefully selected, these materials are often difficult or not practical to recycle to original materials (see Figure 4). Again, simulation exercises can help accelerate the transition to more environmentally friendly materials (Moore 2019). Thermoplastics may present obstacles for pack repair and reuse of cells in secondary applications, as well as hinder the ability to recycle them back to the original formulation. Nevertheless, the lower density of these materials is expected to not affect the recycling and recovery of metals used in lithium-ion batteries, and actually be useful for separation from other components after mechanical shredding processes.

1.5.4 New Dismantling Solvents & Solutions

Of course, problems also drive innovation. One example is a bath chemistry that allows for passive, non-manual removal of battery cells from modules and packs that are glued together with adhesives. These innovative materials swell the engineered adhesives (urethanes, acrylics, silicone, and epoxies) until the internal stresses within the base polymer exceed its bonding force to the cell, causing adhesives, coatings, and tapes to de-bond from cell walls and cooling plates such that the cells can be recovered passively. The solid residual material can then be filtered and removed. The filtered recycling solution can be reused multiple times to continue recycling cells. Processes like these not only optimize disassembly, but also reduce hazardous waste disposal costs with circular processes.

The European Commission and legislative bodies across the globe are proposing and enacting legislation to promote the reuse and recycling of EVBs to protect the environment and ensure a long-term supply of battery minerals and materials (discussed in Section 2). Many of these regulations place responsibility for the cost of recycling on the vehicle manufacturers. To reduce these costs, electric vehicle OEMs will be working more closely with battery suppliers on designs that reduce disassembly and recycling costs and recover more material. The European Commission's proposed Batteries Regulation also includes requirements to declare levels of recycled content in batteries by 2025 and increase the levels required in 2030 and again in 2035. These types of incentives will reduce the cost of recycling while increasing material recovery levels.

1.6 Other Battery Life Cycle Management Models

1.6.1 Battery as a Service

"Battery as a service" is a business model where the consumer can purchase battery services from the vehicle OEM or battery asset company monthly rather than purchasing the battery with the car. An advantage of this business model is that by removing the cost of the battery from the total price of the electric vehicle, the upfront cost of the vehicle is reduced, which lowers the financial burden on the consumer and can generate more EV sales. This also frees the consumer from the fear of rapid battery depreciation. The OEM or battery asset company would take care of value management issues such as maintenance, salvage, and risk of obsolescence. By maintaining ownership, the electric vehicle OEM has both the opportunity to repurpose the batteries for second life and the assurance of responsible recycling, reducing risk. Currently, Renault and Nio are two of very few vehicle OEMs offering this option for certain models.

1.6.2 Battery Leasing

In an EVB leasing model, consumers would not have ownership of the battery, nor would they have to pay the purchase price upfront. They would have exclusive access to the battery for a certain period and would make a fixed monthly payment, while the car itself could be purchased or leased, reducing upfront purchase costs. This business model shifts part of the risk from consumers to the OEM and reduces uncertainties regarding the residual value of the car. The OEM will provide a replacement battery when required. As battery technology advances, customers will be able to replace an old battery with a newer and improved one. Under this business model, OEMs will have the opportunity to resell older batteries to the stationary storage market for secondary use. According to the McKinsey Institute, OEMs could add more than $1,000 in revenue per vehicle through a successful battery leasing program during an assumed lease term of 5 years.

One challenge posed by this model arises when a consumer decides to sell their used EV. Since they do not own the battery, they must settle the issue with the OEM. Because of this, some OEMs that used this model to reduce the purchase price of the car have ceased doing so. That, however, surfaced new problems for the OEM: Not retaining ownership of the battery hampers their ability to fully manage the rest of the battery's life, lessening second-life opportunities and the ability to validate end-of-battery-life recycling.

1.6.3 Environmental Handling Fee

This model puts the responsibility for recycling the battery on the user of the vehicle by charging them a fee at time of purchase (when the vehicle is new). The money paid for recycling is held by a third-party organization and used to pay for the battery's recycling when and where it comes out of the market. The model considers revenue earned from end-of-car-life batteries that are either resold into the second-life market or recycled to recover valuable metals. This model removes complexity for the OEM, while at same time increasing the price of the new vehicle at time of purchase (which may reduce market penetration).

1.6.4 Free-Market Model

In a free-market model, natural supply-and-demand economics guide the outcome, namely where batteries will be at end of life and who will ultimately pay for their recycling. This model will put a value on end-of-car-life batteries that can be refurbished or used for second life, while at same time devaluing an older car with batteries that will need to be replaced, requiring the new buyer to budget for a new battery. Companies that operate at the end of the value chain—notably auto recyclers—will be penalized in this model, as they will be holding old EVBs and facing recycling costs. This will reduce the value they can bid on a vehicle at auction, while also causing a safety issue with used EVBs stored in yards. This model has clear winners and non-winners.

1.6.5 Dual Model: Battery as a Service/Leasing & Environmental Handling Fee

A two-model approach will work based on a buy vs. service/lease decision to be made by the consumer. If the consumer opts for service or leasing when they acquire the vehicle (both options are equivalent for this example), the OEM assumes responsibility for paying for end-of-car-life management of the battery, and this cost is built into the service/leasing pricing. If the car buyer opts to purchase the vehicle (with cash or traditional financing/leasing), they will be charged an environmental handling fee that covers the cost of managing the battery at end of car life. This model puts the decision in the hands of the buyer without them feeling legislated by the government as the sole option.

1.7 Conclusions

EVs and the batteries that power them are key to electrification of transportation and reducing the impacts of climate change. Manufacturers and other stakeholders are aware of the supply chain challenges for battery minerals and the importance of innovating battery designs and recovery technologies that can ease and reduce the costs of recycling processes.

Time is of the essence, however, as regulators around the globe are proposing and implementing regulations that have far-reaching impacts on EV manufacturers. These are explored in Section 2. Engaging with stakeholders now and creating profitable circular economy solutions will help ease these impacts and possibly stave off some of the most difficult provisions being proposed.

2 Regulations, Initiatives, and Stakeholders' Perspectives

In this section, we identify some of the related global initiatives and regulations, including the proposed European Batteries Regulation, which will impact every stakeholder in the supply and value chains. Surveys of auto recyclers, battery recyclers, repurposers, and others reveal the need for critical battery data to reduce costs and improve safety. Information technologies such as blockchain hold great promise for sharing these data, and new technologies such as those capturing battery state of health (SOH) and state of charge (SOC) are improving the likelihood of extended battery use and tracking batteries for recycling. Proper engagement from stakeholders, policymakers, and regulators in life cycle management could also alleviate future lithium-ion battery materials supply chains for EVs.

2.1 Stakeholder Challenges and Opportunities

Figure 5 identifies the key stakeholders in the life cycle of EVBs from production through the warranty period and on to possible end-of-life reuse and recycling. Please note that the flow of EVBs during their life cycles is far from linear and that the image in Figure 5 is mostly intended to identify all the parties that may engage with handling of batteries, not necessarily in order.

The life cycle begins with the battery being deployed into a vehicle and moves on to the dealership, repairs, second life, and recycling.

As discussed in Section 1, recycling is often conducted in two phases, with a primary recycler removing modules, cells, or cathodes and then moving those materials to a secondary recycler, who employs either pyrometallurgical, hydrometallurgical, or perhaps direct recycling for cathode recovery. Although Figure 5 does not explicitly include logistics providers, they are key stakeholders and share similar challenges in ensuring that batteries have been properly identified and the state of health is known to ensure aspects such as packing and placarding follow transport regulations.

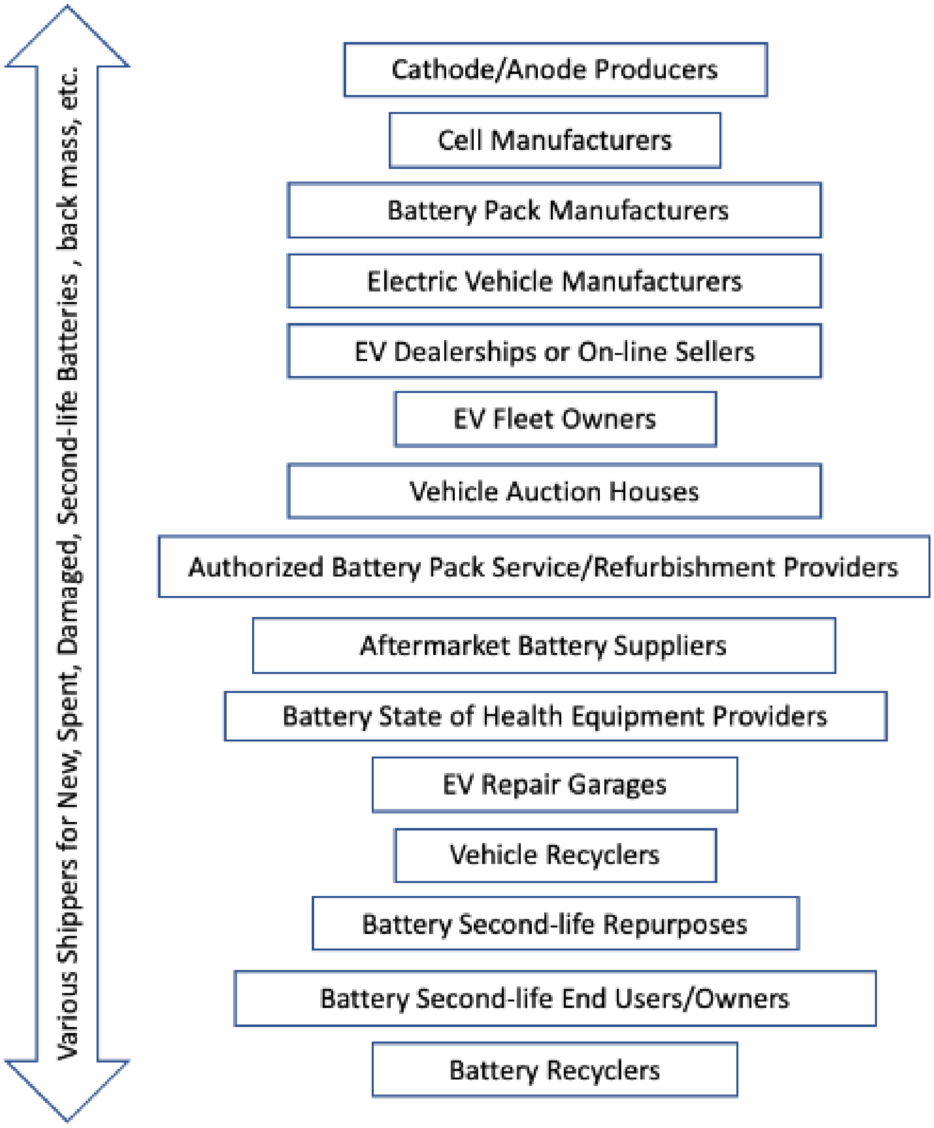

Figure 5. EVB industry stakeholders (not including regulatory agencies or interested associations).

This image depicts most of the stakeholders, but flow of batteries not always linear from one to another.

2.1.1 Life Cycle Stakeholders Survey Results

In March 2020, the Suppliers Partnership for the Environment's (SP's) Responsible Battery Working Group conducted a survey of its members to identify challenges and opportunities in EVB management.[1] SP is a forum for global automotive manufacturers and their tiered suppliers to work together toward a shared vision for an automotive industry with a positive environmental impact. The working group, consisting largely of representatives of automotive OEMs and EVB recyclers and repurposers, identified information and data points about EVBs that members indicated they would like to have access to. Table 3 identifies the results of those data points and information needed. Please note that there was a total of 20 survey responders, 5 of which were

[1] Provided by Kellen Mahoney, Suppliers Partnership for the Environment (https://www.supplierspartnership.org/).

vehicle OEMs. As such, the results do not represent the broad view of the entire industry. We recommend conducting a larger survey with participation from many stakeholders.

Table 3. Data Points Identified by SP Survey Respondents.

Data from Kellen Mahoney, Suppliers Partnership for the Environment, 2021.

- Identification of any OEM designated battery repurposers and/or recyclers
- Transportation requirements (regulatory, such as packing, permits, and placarding)
- Identification of parts to return to vehicle OEM or designated parties
- Key disassembly and safety instructions and tools required
- State of charge
- State of health
- New battery voltage
- Chemistry
- Manufacturing dates (pack, modules, cells)
- Battery configuration diagram
- Battery bill of materials
- Vehicle identification number (VIN) or other identifiers
- Weight and dimensions.

The Automotive Recyclers Association[2] and the Institute of Scrap Recycling Industries[3] were also engaged to learn what auto recyclers and other scrap processors encountering EVBs need to know about the batteries. All three organizations offered the list of data points in Table 4 from member surveys to learn what information was most critical to members, with some overlapping results.

[2] Data from Virginia Whelan, Automotive Recyclers Association (http://a-r-a.org).
[3] From David Wagger, Institute of Scrap Recycling Industries (https://www.isri.org/).

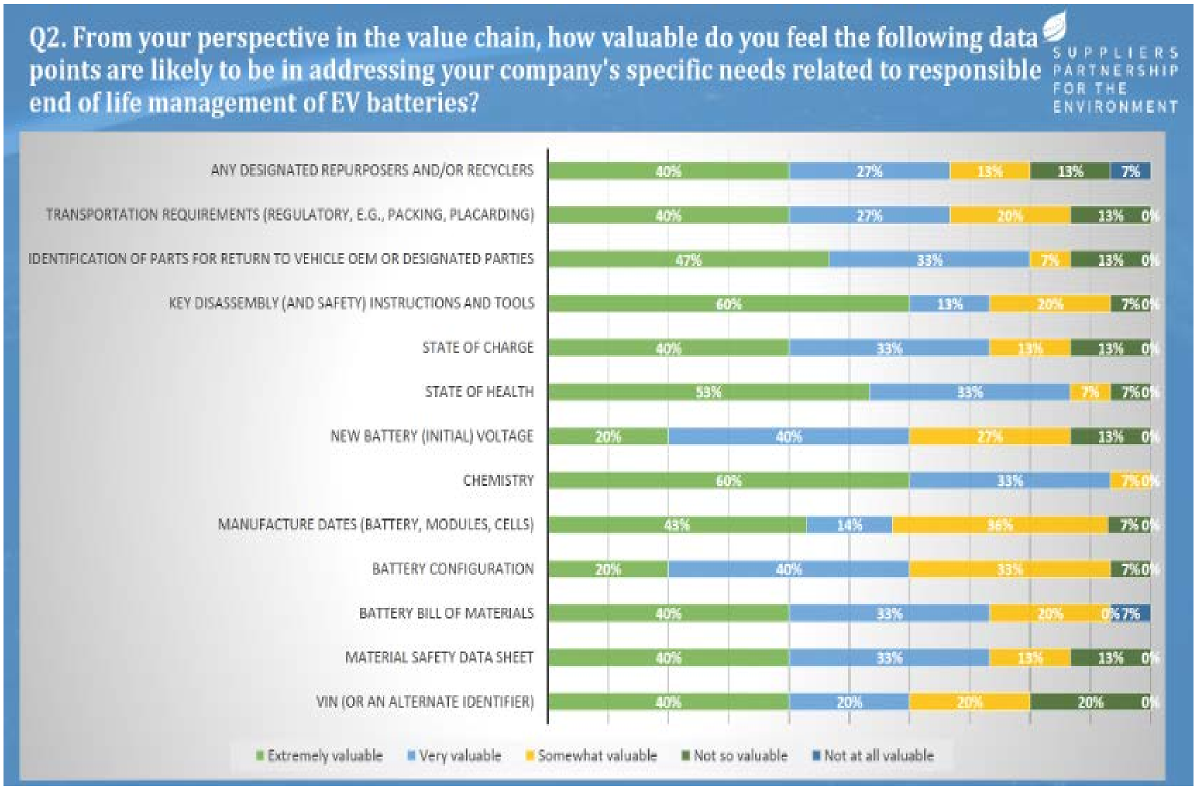

Figure 6. Key results of the survey by SP's Responsible Battery Working Group

The top data points identified by responders in the SP survey were:

1. Chemistry
2. Key disassembly and safety instructions and tools required
3. State of health.

In addition, the Automotive Recyclers Association asked its member an overarching question: Would having access to information about EV batteries such vehicle make and model, condition, history, state of charge, etc. prior to accepting or acquiring an EV be beneficial? Out of 30 responders, 83% said yes and only 17% said no.

The Institute of Scrap Recycling Industries also asked its auto recycler members what battery information would have the most value. Figure 6 shows the results, with the following in priority order:

1. Worker safety
2. Market information
3. Condition/state of charge/SOH.

Table 4. Sample Survey Results From Institute of Scrap Recycling Industries Members on the Value of Information About EVB Attributes With Respect to Handling

Value Level	Safe Handling/ Removal Info	Market Info	Condition/ State of Charge	Age	Vehicle Make/Model	Detailed Life Cycle History	Detailed Activity Records
None/little	0	5	11	26	47	47	58
Reasonable	16	26	32	32	16	32	21
Extremely high	84	68	58	42	37	21	21
Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**

A respondent to the Automotive Recyclers Association survey provided a particularly poignant comment in response to the following stimulus:

Share any experiences, good or bad, with EV batteries that might inform this effort: "Currently, other than reuse markets, the value (for recycling) of Li-ion batteries (EV or hybrid) is negative, and that is an expense that will not be accepted by the auto or scrap recycler. There should be an immediate dialogue with ALL stakeholders to find a reasonable solution to this looming problem—hopefully without burdensome governmental regulation/intervention—which will otherwise be the result."

To this end, this paper identifies options for implementation of EVB life cycle management and the perspectives of industry stakeholders who can provide leadership to carry out solutions they see as best for the industry today and well into the future.

A suite of new technologies has emerged and continues to develop that can help EVB ecosystem stakeholders access and share information for optimal battery management. These are identified and discussed later in this report.

2.2 Technologies To Provide EVB Data for Stakeholders

2.2.1 Barriers and Opportunities for Accessing Battery Data

Due to the complexities and risks around data, electric vehicle OEMs' positions on sharing battery data vary widely. Some battery management system (BMS) data are considered intellectual property and are thus proprietary. There are also concerns that certain data might compromise consumer privacy. Some might consider sharing certain data for a fee or as part of using of their battery pack in second-life applications. Some OEMs already participate in providing batteries and associated data to third-party integrators and installers. As the number of second-life batteries increases in coming years, and potential business case for second-life applications improves, other OEMs might consider engagement in second-life applications.

2.2.2 Accessing Battery SOH and SOC When the BMS Is Intact

A BMS is the information center of a battery. It controls and monitors the charge and discharge of rechargeable batteries in EVs, along with cellphones, laptops, and myriad consumer devices. The job of the BMS is to keep the battery safe and in good condition.

During its life in the car, the BMS communicates critical battery data to the onboard diagnostics system, which tracks and regulates the vehicle performance. With the proper tools, dealerships and independent auto service providers can access this information to provide warranty or repair services.

2.2.3 BMS Data via Telematics

Battery data (temperature, current, voltage, and state of charge as a function of time) can also be shared via telematics, which is essentially a tracking device installed in a vehicle that enables the transmission and storing of telemetry data, which can include location, speed, acceleration, braking information, and more. China's GB/T standard requires vehicle telematics systems to transmit battery data to a national cloud-based analytics system that publishes the output on a dashboard that is available in the public domain. This provides battery manufacturers with critical information for warranty claims and can also be valuable to other stakeholders who can enhance safety and efficiency in their processes by knowing chemistry, state of health, and other critical information about the battery. It should be noted that data can also be partitioned so that only certain data are accessible by certain permissioned parties.

2.2.4 Battery State of Health Capture Outside the Vehicle: Ultrasonic Testing

A challenge to the second-life lithium-ion market is grading cells or modules to clearly understand the SOH. This is required for two purposes:

1. Grouping batteries with a similar SOH in a string so that the batteries can charge and discharge at similar rates or profiles.
2. Knowing the remaining usable life of the battery to understand the commercial value and appropriate applications (such as reuse or recycling).

This type of evaluation (measuring voltage, current, and temperature) has typically been accomplished with traditional battery cyclers using a process known as coulomb counting, which essentially completes one to two complete charge/discharge cycles and measures the electrons in and electrons out to determine the usable capacity of the cell or module. This process is accurate but also very time-consuming and requires trained individuals using expensive lab-grade equipment. Recently, a rapid battery testing technology has been developed using ultrasonic techniques that can perform SOH evaluation with a similar result to lab-grade cycling equipment within a few seconds (TitanAES 2022; Liminal Insights 2022). The equipment can be used by nontechnical operators and dramatically reduces the cost of preparing batteries for second-life applications.

Ultrasonic testing equipment, after further validation and cost reduction, could solve a major challenge for second-life battery companies but may not be widely available to stakeholders such as garages and auto recyclers.

2.2.5 Identification of Second-Life SOH Capture Methods

The European Automobile Manufacturers' Association is asking the European Commission to consider certification of the state of post-first-life EVBs based upon standardized test methods to measure performance levels instead of relying on open access to BMS data to inform decisions about repair, reuse, and second life. However, standardizing SOH testing could impede innovation around new ways of producing and calculating SOH data. As such, the market may need more time to mature in this area.

2.3 Information Technologies Supporting Battery Data Sharing

2.3.1 IoT Enabling Batteries and Critical Parts for Track and Trace

To effectively manage an asset, product, or material from a circularity perspective, it is important to know its provenance—where the materials required to create it came from, who has it, its chemistry, and what condition it is in both from physical and performance SOH perspectives. This requires tracing battery materials back to the source, tracking batteries during their useful life, and sharing important data with all those involved. The current state of the art for accomplishing this is to first enable an asset for the "Internet of Things" (IoT) (i.e., connect the EVB and key components to the internet), or give it a "digital identity" enabling connection to a cloud-based information management system capable of reporting key measures against compliance to sustainability claims and performance.

If connectivity is not inherent to an object (e.g., mobile phones *are* inherently connected), a secure digital identifier and/or sensor can be incorporated into the object supporting automatic data capture and connectivity. There is a plethora of advanced automatic identification and data capture (AIDC) technologies that can be securely applied to or embedded within an object, enabling it to connect to the cloud through either passive means. These include a radio frequency identification (RFID) or ultrahigh frequency RFID (RAIN) tag using various standards (either battery-assisted or passive), or other common auto-ID solutions such as near-field communication (NFC) tags, beacon technology, or Bluetooth tags. (Some 12-V, 100-Ah consumer LIBs are Bluetooth enabled and have Android or iOS apps to interrogate the BMS.) The connectors may or may not have sensory capability and may be able to send or receive data from the device, such as sensor-captured temperature information or transaction data.

RFID or NFC technologies are well established, with associated governing standards for connectivity and deployed infrastructure supporting connectivity. RFID is already extensively used within the automotive industry from the deployment of low-frequency transponders used for automated key access or parts identification and management using RAIN RFID. The latter is also being used extensively in tire identification and management.

Unless such tags or sensors are connecting directly to the BMS or onboard vehicle management systems, they will need to have connectivity to the cloud. This is facilitated only when these tags are connected via their infrastructure component, such as an RFID reader, reading from a smartphone or tablet (in the case of NFC), or in a peer-to-peer manner with a similar NFC device, such as one smartphone presented to another and swapping credentials or payment or triggering connectivity.

Traditional and common automatic identification and data capture technologies such as barcodes, data matrix, or QR codes can be used to trigger cloud-connected sensors to operate. Some OEMs, particularly battery manufacturers, already include a battery ID relating to their own products or standards such as GS1 and Electronic Product Code Information Services (EPCIS) enabling open reading and adoption across the supply chain through common devices such as 2D barcode scanners or mobile phones/computers. However, these battery IDs are used by a specific company, and its collaborators and are not available universally to other entities.

The emergence of new IoT technologies can be incorporated into a product rather than attached to its surface. These include digital watermarks, passive and active (battery-powered) Bluetooth or beacon tags, and secure QR codes (displaying both open readable data and blinded encrypted data only accessible with a proprietary application and key management system).

Other sensor-capturing aspects such as temperature, location, humidity, orientation, pressure, and vibration connected to the cloud through conduits such as General Packet Radio Service, 4G/5G, RFID, low-power Bluetooth, or other beacon technology further support the connected world of objects and myriad value propositions that come with IoT connectivity.

2.3.2 Data Sharing Throughout Battery Life Cycles

IoT-enabling batteries and critical parts is one approach toward sharing battery information with actors throughout the life cycle who engage with the battery for the purposes of servicing, second life, and recycling. Several of the global initiatives and regulations outlined herein have identified blockchain as state of the art in supporting secure, immutable data sharing within permissioned ecosystems where those updating information about the battery are known and trusted sources and that the information they are uploading is valid.

Blockchain, as a platform to an IoT-connected supply chain, assists in connecting either all or permissioned stakeholders in the network. Blockchain enables independent and distributed data capture (Sedlmeir et al. 2020) supported by coded smart contract structures (Arora 2022) triggered by predetermined transactional events. Network participants operate in accordance with an agreed data governance policy.

It is important to distinguish enterprise blockchain solutions from those used in cryptocurrency. Cryptocurrencies, like Bitcoin, run on public blockchain platforms that are accessible to anyone with an internet connection. They also require massive computing power to perform complicated mathematical algorithms, also called "mining." Private blockchains, on the other hand, require a minuscule fraction of the energy required in cryptocurrency. For example, Hyperledger Fabric Raft, a type of blockchain framework supporting private solutions, uses 10 billion times less energy per transaction than Bitcoin (Hyperledger 2018).

In essence, IoT technologies are enabling chain of custody across an ecosystem, supporting greater trust and transparency, and, in some cases, enabling detection of tampering or flags to breaches in supply chain security.

2.3.3 Lithium-Ion Batteries and Advanced Information Technology: The Battery Passport

A good demonstration of how blockchain and IoT can work is with a high-risk/high-opportunity asset such as lithium-ion batteries. These batteries are not only dangerous to handle, but also have a supply chain at risk due to extensive reliance on small and artisanal mines that can involve child and conflict labor and severe environmental issues. Brand owners want to ensure a sustainable supply of critical metals and minerals (e.g., cobalt and lithium) by keeping track of batteries to ensure maximum recovery of resources for reuse in new batteries. The Global Battery Alliance has placed great focus on traceability and circular initiatives for this still-young economy, including life cycle greenhouse gas emissions calculations and offsets. The Global

Battery Alliance and other leading global battery organizations refer to technology-supported battery management as the Battery Passport (Global Battery Alliance 2022a).

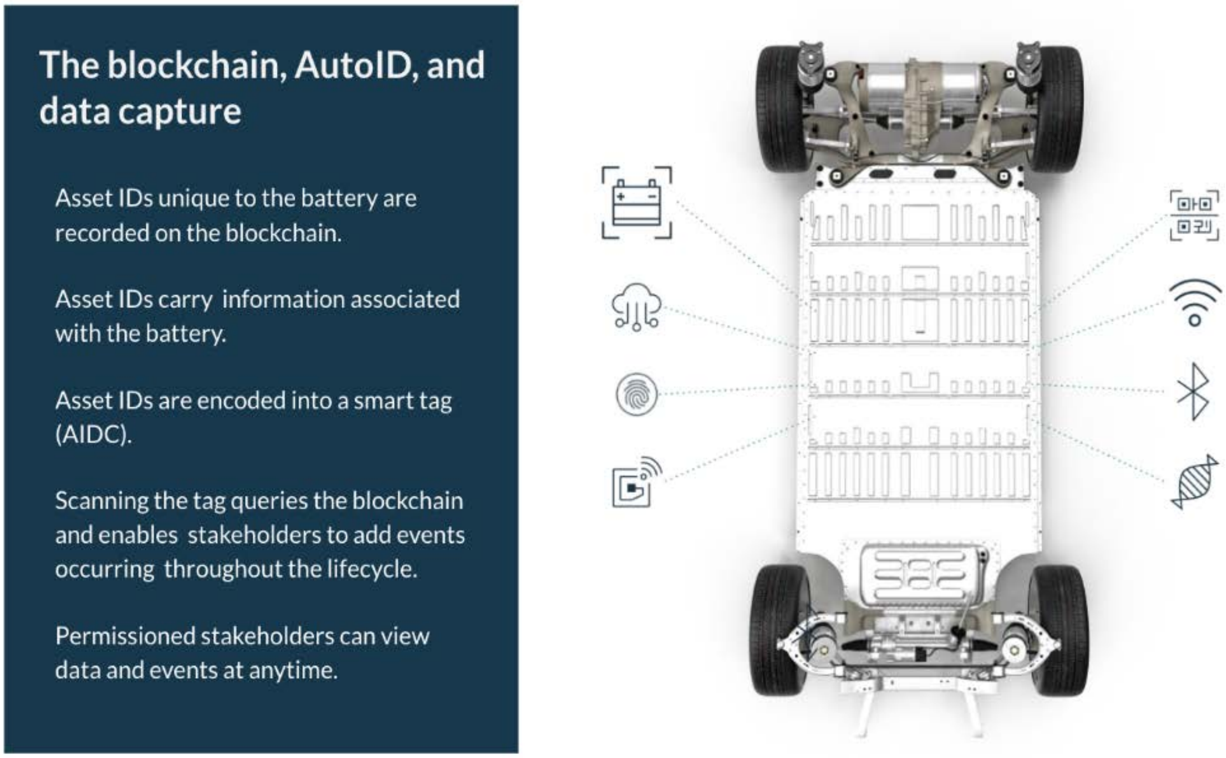

Figure 7. Blockchain, auto ID, and data capture.

Figure from Lauren Roman, Everledger (https://everledger.io/)

The Battery Passport supports transparency by allowing users to use, store, and search asset information on demand and make it available to other battery life cycle stakeholders. By making asset information easily accessible and verifiable, blockchain allows trust to take root and spread throughout industries. By creating a unique identity (i.e., digital twin) of an asset, users can trace its journey on a secure, unalterable, and private platform. Sustainability and compliance claims are supported with actual shared evidence of audits and certifications.

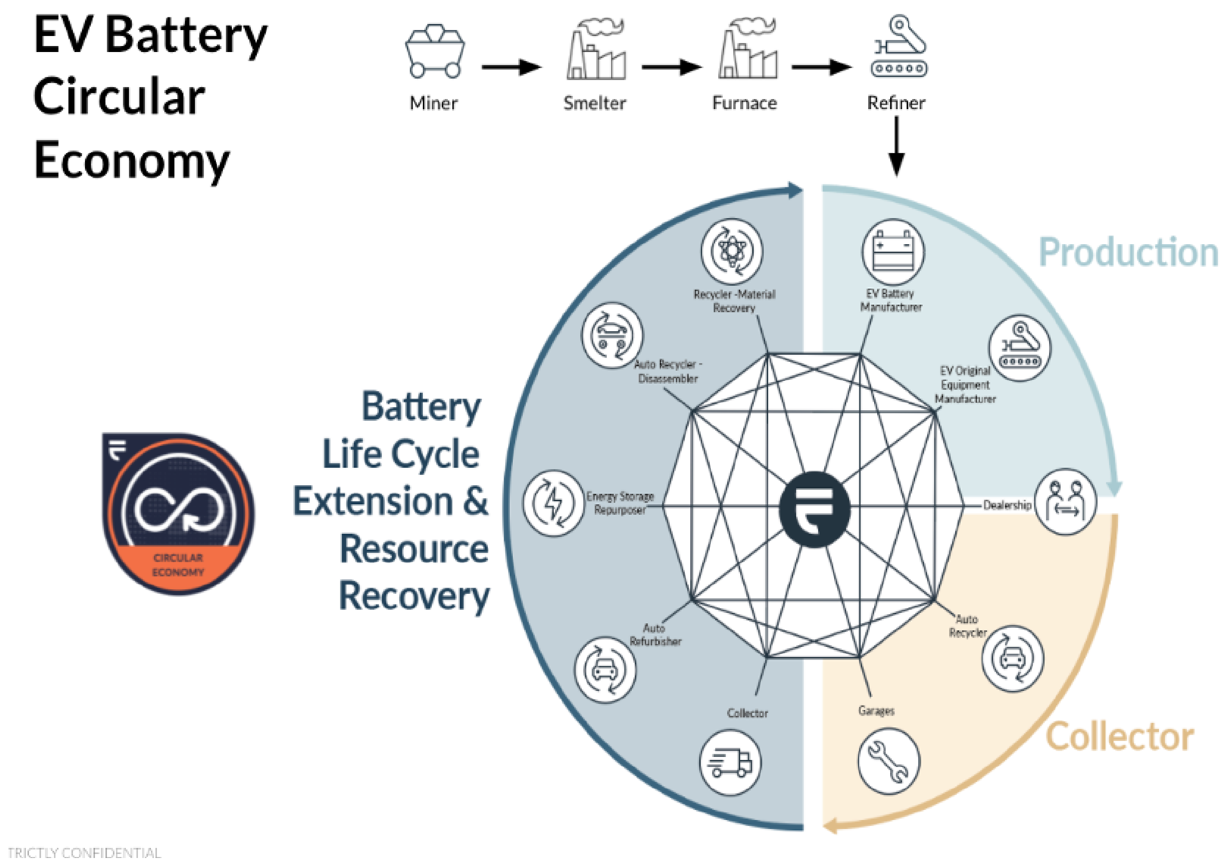

Figure 8. Data sharing on a blockchain platform.

Figure from Lauren Roman, Everledger (https://everledger.io/)

2.4 Global Initiatives and Regulations

The following are some of the global initiatives underway and regulations both in place and proposed that can impact EVB life cycle management. The selection is not comprehensive, and their inclusion is not an indication of any endorsement by the authors of this report.

2.4.1 Global Initiatives To Increase EV Adoption

A growing list of countries have committed to banning the sales of internal combustion engine vehicles and establishing official targets for electric car sales, signaling a need to move to zero-emission vehicles to meet climate and air quality goals. In the United States, California is requiring automakers with annual sales between 4,501 and 60,000 vehicles to produce electric cars equal to 8%–9% of their overall sales by 2025 (Alternative Fuels Data Center 2020). Additionally, legislation already passed in India, Ireland, the Netherlands, Denmark, Norway, and the United Kingdom will ban sales of gasoline and diesel vehicles by 2030 (Stafford 2019). The following subsections sample some of the initiatives taking place around the globe to accelerate EV adoption.

2.4.2 Chinese Initiatives

Over the past decade, the Chinese government has spent somewhere between $60 billion and $100 billion increasing the domestic market for lithium batteries, subsidizing the production of cheap (i.e., ~$4,500) EVs, and helping companies build out the lithium mining and refining infrastructure to support them (OneCharge 2022). As a result, China has come to dominate the lithium battery market from end to end. Although the Chinese government's investment and incentives have tapered off in the last couple years, Chinese companies have picked up their own investments, particularly in their domestic supply chain.

2.4.3 Global Battery Alliance

The Global Battery Alliance is a collaboration of organizations working to establish a sustainable battery value chain (Global Battery Alliance 2022b). They worked with industry stakeholders to develop the concept of the Battery Passport, which would provide for securely sharing information and data to identify, validate and track EVB responsible sourcing of minerals, battery life cycles, responsible recycling, and carbon dioxide footprint throughout. Their targeted impact programs include establishing rule books for responsible and sustainable battery minerals supply chains, a low-carbon economy program, and a circular economy for lithium-ion batteries.

2.4.4 EU Green Deal: Strategic Action Plan on Batteries

The goal of the Strategic Action Plan on Batteries is to make Europe a global leader in sustainable battery production and use in the context of the circular economy and to propose legislation to ensure a safe, circular, and sustainable battery value chain for all batteries. More than 120 industrial and innovation actors have participated in and collectively endorsed recommendations for the following priority actions (European Commission 2020b):

- Secure access to raw materials.
- Support European battery cell manufacturing at scale and a full competitive value chain in Europe.
- Strengthen industrial leadership through EU research and innovation.
- Develop and strengthen a highly skilled workforce in all parts of the battery value chain.
- Support the sustainability of the EU battery manufacturing industry with a low environmental footprint.
- Ensure consistency with the broader enabling and regulatory framework in support of batteries.

2.4.5 United States Government

Realizing the importance of the role of key battery materials and challenges with availability of resources in the United States, Executive Order 13817 identified the need for "developing critical minerals recycling and reprocessing technologies" as part of a broader strategy to "ensure secure and reliable supplies of critical minerals."

The U.S. Department of Energy led the U.S. government's effort in decreasing dependence on these materials by reducing the amount needed for battery production by recycling materials already in use. The department issued a "Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries" in June 2019 (EERE 2019). The major elements of this initiative include:

- Developing the next generation of cathodes for lithium-ion batteries with low or no cobalt.
- Establishing a lithium battery recycling R&D center focused on cost-effective recycling processes to recover lithium battery critical materials.
- Launching the Lithium-Ion Battery Recycling Prize to develop innovative solutions to enable safe and affordable collection, sorting, storage, and transport of spent lithium-ion batteries.

Since then, major accomplishments have been achieved under various funding commitments.

- $40 million funding to industry, universities, and national labs for developing low- or no-cobalt cathodes (U.S. Department of Energy 2018).
- $15-million/3-year funding for establishing the ReCell Recycling R&D center at Argonne National Laboratory with support from the National Renewable Energy Laboratory and Oak Ridge National Laboratory (U.S. Department of Energy 2022b).
- $5.5-million funding for the first Lithium-Ion Battery Recycling Prize series (U.S. Department of Energy 2022a).
- The Biden administration has paid significant attention to the lithium-ion supply chain and manufacturing, as these batteries are a significant component in EVs for decarbonization of transportation. This included Executive Order 14017, which resulted in a report calling for several initiatives to strengthen the U.S. supply chain and manufacturing with strategies identified in the National Blueprint for Lithium Batteries (VTO 2021) developed by the Federal Consortium on Advanced Batteries. One of its major recommendations is enabling U.S. end-of-life reuse and critical materials recycling at scale and a full competitive value chain in the United States. These initiatives became a reality in Bipartisan Infrastructure Law on November 5, 2021, providing significant funding for the demonstration of second life of EVBs in grid services, battery recycling and reuse R&D, and extending the Battery Recycling Prize competition series (U.S. Congress 2021). The evoking of the Defense Production Act (April 2022) has placed more focus on sourcing battery minerals and securing national U.S. battery energy supply chain development.
- On October 19. 2022, DOE announced (DOE October 2022) that $2.8B of Bipartisan Infrastructure Law funding going to 20 projects across 12 states for Battery Materials Processing and Battery Manufacturing Recycling developing
    - Battery-grade lithium, graphite, nickel, iron phosphate cathodes
    - Lithium electrolyte salt, separators, and PDVF binder
    - Battery grade silicon anodes, prelitigation, and lithium anode
    - Cathodes from minerals or recycled batteries
- On November 16, 2022, DOE announced (DOE November 2022) that nearly $74M of Bipartisan Infrastructure Law funding going to 10 projects to advance domestic battery recycling and reuse, strengthen nation's battery supply chain.

- The Clean Vehicle Credit was amended by the Inflation Reduction Act in August 2022 and now has new requirements for battery sourcing/assembly, which will take effect on January 1, 2023 (DOE Battery Policy and Incentive Search 2022). To be eligible for the credit, vehicles must meet certain criteria related to the extraction and mining of critical minerals, processing, recycling, and manufacturing of battery components. The Act removed the cap of 200,000 vehicles per automaker for EV tax credit. If a vehicle meets the new sourcing/assembly requirements, it may be eligible for a tax credit of $3,750 for critical minerals, $3,750 for battery components assembly, or a total of up to $7,500 for meeting both requirements. The new sourcing requirements for EVs intend to grow battery mineral and component supply chains within North America and amongst countries with which the United States has free trade agreements. The percentage of sourcing requirements increases each year until 2029. Further information could be found in IRA EV Tax Credits (Electrification Coalition August 2022)

2.4.6 US State Governments

On September 23, 2020, **California** Governor Gavin Newsom signed Executive Order N-79-20, setting the following zero-emission vehicle targets for California (Newsom 2020):

- 100% of in-state sales of new passenger cars and light-duty trucks will be zero-emission by 2035 (GO-Biz 2021).
- 100% zero-emission medium- and heavy-duty vehicles in the state by 2045, where feasible, and by 2035 for drayage trucks.
- 100% zero-emission off-road vehicles and equipment operations by 2035, where feasible.

In addition to these targets, California has intermediate goals including 5 million zero-emission vehicles on California roads by 2030 and 250,000 public and shared charging stations and 200 hydrogen fueling stations by 2025 (California Energy Commission 2022). Through the first quarter of 2021, over 860,000 zero-emission light-duty vehicles had been sold, with zero-emission vehicle sales representing over 9% market share in the first quarter of 2021.

After California announced its ban, **New Jersey** and **New York** followed closely with similar goals. On April 15th, 2021, the **Washington State** legislature passed "Clean Cars 2030", a bill setting a goal to require all light-duty vehicles of model year 2030 or later to be electric. This bill made Washington the first US state to pass a gas car ban legislatively (as opposed to executive order), and now has the earliest gas car ban in the US.

2.4.7 European Battery Alliance

The European Battery Alliance, a collaboration between the European Commission, EU countries, industry, and the scientific community, was launched in 2017 (European Commission 2022). Because batteries are a strategic part of Europe's clean and digital transition and a key enabling technology, they are essential to the automotive sector's competitiveness. This alliance aims to make Europe a global leader in sustainable battery production and use. The aim is to invest in production of lithium-ion materials, cells, and batteries in Europe. More than $3 billion was allocated in 2021.

2.5 Regulations

2.5.1 China Producer Responsibility

Under China's producer responsibility scheme, or GB/T standard (GB/T 3404-2017), electric vehicle OEMs are legally responsible for both battery recycling and assessment of second-life potential. Guidelines published by China's Ministry of Industry and Information Technology push OEMs to standardize batteries and design products that can be easily disassembled (Xu et al. 2017).

The GB/T standard was enacted on February 1, 2018. It defines coding structures and representations and what battery parts they apply to (i.e., pack, modules, cells). The regulation enables traceability for new and second-life batteries and specifies labeling requirements and the associated tracking system.

2.5.2 European Commission Proposed Batteries Regulation

EU legislation on waste batteries has been embodied in the 2006 Battery Directive, which intends to mitigate the negative impacts of batteries on the environment, minimize waste, increase collection, and ensure proper end-of-life management of batteries. The directive addressed this by defining measures to establish recycling and collection schemes and mandates that producers of batteries and products incorporating batteries are responsible for providing battery takeback programs and recycling arrangements (European Commission 2020a). The European Commission proposed a new Batteries Regulation (European Parliament 2022)—with annexes (European Commission 2020b)—on December 10, 2020. This regulation aims to ensure that batteries placed in the EU market are sustainable and safe throughout their entire life cycle. Figure 9 shows the EU's proposed regulation covering the battery and stakeholder through its entire life cycle.

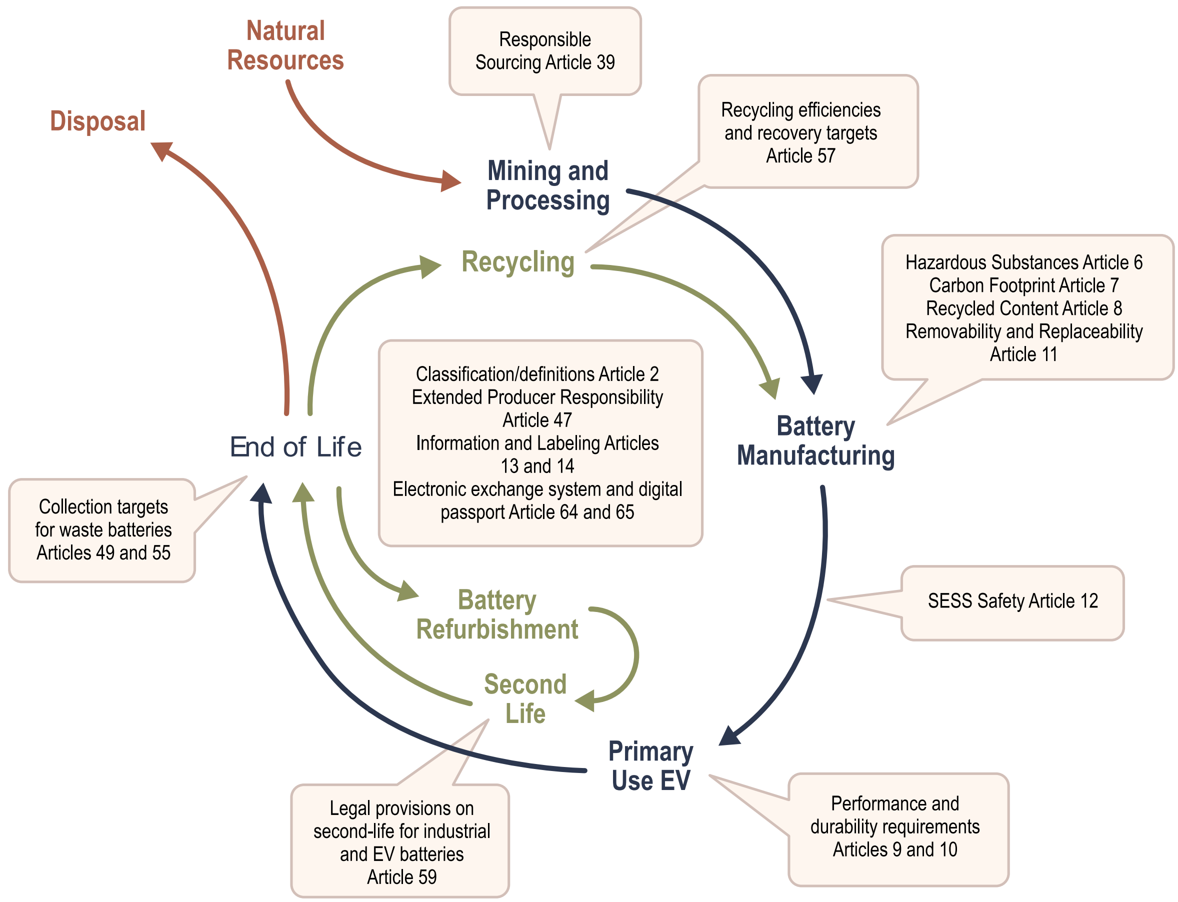

Figure 9. Proposed European Commission Batteries Regulation.

Source: Deurwaarder (2021)

An essential part of the Batteries Regulation is the battery passport, which will provide users/owners access to EVB information regarding key materials in the battery, tracing them back to their origin. Recycling will also be a key part. The European Commission is looking at introducing specific recovery rates for key materials used in batteries, such as lithium, cobalt, and nickel. An increase in the collection rate of used batteries is expected to lay the groundwork for mandatory levels of recycled content in new batteries as of 2030. The Batteries Regulation was scheduled to come into force in January 2022, but it is delayed as various stakeholder are debating various sections of it.

2.5.3 German Battery Act

The first act amending the Batteries Act was published on November 9, 2020 and entered into force on January 1, 2021. The German Battery Act stipulates that manufacturers of electric cars take batteries back from their vehicles at no charge or appoint a disposal partner (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection 2021). The legally required takeback of battery packs applies to cases when a drive battery must be replaced due to falling below its guaranteed minimum capacity. It also allows that those batteries do not have to be disposed of, but can instead be used in a second-life application for years to come. Additionally, it addresses the issue of what happens to the battery in the event of damage, such as in a vehicle accident, and who must dispose of the battery.

2.5.4 Japan's Law on Promotion of Effective Utilization of Resources, 2001

Under this Japanese law, lithium-ion batteries are considered specified resource-recycled products, and producers are required to promote self-collection and recycling (Sabin Center for Climate Change Law 2022). Additionally, battery manufacturers and manufacturers of products containing batteries, such as automotive OEMs, have a responsibility to disclose information annually regarding metrics for self-collection and recycling of waste sealed batteries that they conducted individually or collectively.

2.5.5 California Environmental Protection Agency

The Lithium-Ion Car Battery Recycling Advisory Group was created to advise the California Legislature on policies pertaining to the recovery and recycling of lithium-ion vehicle batteries sold with motor vehicles in the state, with the goal of ensuring that as close to 100% as possible of lithium-ion vehicle batteries in the state are reused or recycled at end of life in a safe and cost-effective manner. It is being led by the California Environmental Protection Agency, the Department of Toxic Substances Control, and the Department for Resources Recycling and Recovery. Additional members come from the environmental community; auto dismantlers; public and private representatives involved in the manufacturing, collection, processing, and recycling of EVBs; and other interested parties. The advisory group was formed in 2019 in response to Assembly Bill 2832. The final draft of the recommendations to the California Legislature was released on March 16, 2022 (California Environmental Protection Agency 2022). Two policy proposals that designate end-of-life management responsibility gained most of the support:

- Core exchange with a vehicle backstop.
- Producer takeback.

The core exchange and vehicle backstop policy define responsibility for out-of-warranty batteries and assigns responsibility for EVBs as follows (Kendall, Slattery, and Dunn 2022):

1. *EVs still in service:* The entity removing the battery is responsible for reuse, second life, or recycling, and a core exchange program shall be used to track and validate proper management. This is essentially a deposit program for certain automotive parts. The customer pays a deposit on a new part, and the deposit is then refunded when the part is returned.
2. *EVs at end of life acquired by an auto recycler or dismantler:* The auto dismantler or recycler is responsible for reusing, refurbishing, second life, or recycling end-of-life batteries.
3. *EVs at end of life and not acquired by an auto dismantler or recycler:* The vehicle manufacturer is responsible for ensuring the vehicle is properly dismantled and the battery is properly reused, refurbished, repurposed, or recycled.

Under the producer takeback proposal, the auto manufacturer is responsible for the management of batteries at end of their first life, including transportation and recycling costs and documenting proper disposition.

2.5.6 Massachusetts Right to Repair

On November 4, 2020, Massachusetts voters overwhelmingly approved a "Right to Repair" law by a margin of 75% to open car data to vehicle owners and garages (Techdirt 2020). The measure expands an earlier law to include telematics data that can assist owners and repair shops to access the vehicle's data to use for diagnostics and repair. The law affects model years beginning in 2022.

Right-to-repair bills are gaining traction across the United States and abroad. According to The Repair Association, 34 U.S. states are drafting or have implemented right-to-repair legislation. Most of these laws relate to "digital electronic products" rather than automobiles in particular, but they directly impact all new cars that now contain extensive electronic systems. The first test of these data sharing laws impacting EVBs is China's GB/T standard, as described in Section 2.5.1. The law requires telematics data to be transmitted to a cloud for public sharing. Beyond repair, sharing of these data can support safety, more economical battery second life, and much more.

2.6 Stakeholder Insights and Perspectives

2.6.1 Automotive Recyclers Association

Automotive recyclers play a valuable role in the efficient, environmentally friendly recycling of inoperable motor vehicles (Automotive Recyclers Association 2022). Automotive recycling preserves natural resources, reduces the demand for scarce landfill space, and plays an important role in reducing air and water pollution.

Automotive Recyclers Association members are keenly aware of the challenges that vehicle electrification can present and are already developing efficient means of EVB removal, reuse, and recycling. The focus is on determining how an automotive recycler can safely manage end-of-life EVBs without liability. The industry is keenly focused on addressing the costs of handling and recycling EVBs in a manner that best serves customers while preserving business revenue and protecting the environment.

2.6.2 Automotive Service Association

The mechanical and collision repair segments of the independent automotive service industry have been dealing with advancing vehicle technology since the beginning of the automotive manufacturing industry (Automotive Service Association 2022). Vehicle advancements in powertrains, electronics, safety, and materials have to this point been taken in stride and generally incorporated into the repair shop population seamlessly once the tools and training became available. The move toward vehicle electrification is no different, and another seamless adaptation to changing vehicle technology is anticipated given the tools, training, and service information availability as in years past.

The major concerns of automotive service providers center around several areas:

1. The **cost of training, tooling, and safety equipment** associated with EV service. We don't know yet what EVs will need in the way of regular maintenance, but it can be assumed things like tires, brakes, suspension components, and the need for collision repair will be similar. While it's clear that things like vehicle lifts will need to be able to

accommodate the access necessary for EVB replacement, the total cost for a repair shop to be properly equipped in tools, diagnostic equipment, safety equipment, training, and information for general EV service is unknown at this time.

2. Without knowing the specific **maintenance requirements** of future EVs, particularly if they are Level 5 autonomous vehicles, the economic impact of EVs that will likely require fewer repair parts in the shop is another unknown. Also unclear is how service requirements unique to EVs and autonomous vehicles will offset some of the parts revenue losses, such as periodic system inspections to ensure proper functioning in autonomous vehicles.
3. **Liability** is a major concern, particularly as it relates to battery recycling and disposal. The high-voltage systems typical of EVs pose dangers to technicians and first responders working on and around these vehicles. While proper training and safety equipment can mitigate some of these risks, a clear understanding of the liability exposure and established battery recycling infrastructure for shops working on these vehicles must be achieved.

2.6.3 Energy Storage Association

The Energy Storage Association (2022), now part of American Clean Power (2022), supports the energy storage industry and recommend policies for clean energy. While currently small in comparison to the flow of EVBs into reuse/recycle pathways, stationary battery energy storage systems (BESS) also reach the end of their useful life and face various disposition pathways. Large utility BESS facilities typically contain large numbers of standardized battery cells/modules, with clear documentation regarding their composition and well-established procedures for decommissioning. Firms that offer turnkey disposal services for large BESS upon decommissioning are emerging to ensure compliance with applicable rules and conformity to the BESS owners' environmental, social, and corporate governance commitments, and some OEMs for large BESS facilities agree to take responsibility for decommissioning.

Smaller, but still sizable commercial and industrial BESS facilities also are good candidates for disposition via emerging service providers. Homeowners who install small (typically single- or several-module systems) may not be as aware of disposal options. Nevertheless, removal by a licensed service provider compliant with utility disconnection rules should increasingly offer an opportunity for proper disposition.

2.6.4 EVB Recyclers

This section compiles input from EVB recyclers listed in the Acknowledgments.

Due to the myriad of differing lithium-ion cathode formulations and the inability to distinguish these formulations without chemical analysis, companies that manage battery end-of-life recycling operations for EVBs see a benefit of having these cathode formulations identified, in advance of the physical battery processing, to minimize the time and expense of chemical analysis. This is important when weighed against the expected growth in EV sales vis-à-vis batteries that will need to be recycled at the end of life in the future.

In addition to the cathode formulations, anode formulation identification would be helpful. Moreover, perhaps accompanying the tracking (in whichever form; somehow accompanying across an EVB's life), dismantling instructions would be helpful, at least to a module level. Some recyclers that have recently entered the market are moving toward minimal to no manual dismantling by using shredding operations. However, for safety across the supply chain and depending on where end-of-life packs are directed, accompanying dismantling instructions would be helpful.

2.6.5 Electric Vehicle OEMs

Electric vehicle OEMs have not had a unified perspective on the issue of battery reuse and recycling. Some OEMs want end-of-auto-life batteries used in applications that can provide economic, energy, or environmental benefits without creating liabilities. Among other benefits, this secondary use serves to delay or even possibly avoid the costs of recycling altogether. Although current recycling costs usually exceed recovery values, some anticipate that the fast-growing demand for critical battery minerals will soon make EVB recycling profitable. Thus, extending battery life now via other uses could result in avoiding the cost of recycling at end of battery life.

Whether a battery is reused or recycled, making some of the battery data available to stakeholders is key to improving safety and reducing costs by adding efficiencies. OEMs have differing views and concerns on sharing battery data. While some are actively exploring how certain battery data can be shared to improve efficiencies and reduce risks, others consider it proprietary.

It is anticipated that as the EV industry continues to quickly evolve, the OEM community will find more common ground in solving these and many other issues.

2.6.6 Zero Emission Transportation Association

The Zero Emission Transportation Association is an industry-backed coalition advocating for the full adoption of EVs in the United States by 2030, creating thousands of new jobs, enabling leadership of American manufacturing, dramatically improving public health, and significantly reducing carbon pollution (Zero Emission Transportation Association 2022).

To fully realize the economic benefits of the expanding EV and advanced battery market, however, the United States needs to implement policies to spur adoption, cultivate advanced battery processing, and grow the U.S. manufacturing base to ensure those jobs are created right here at home.

Luckily, the race for EV supply chain control isn't over. American innovators are developing sustainable critical mineral and advanced battery recycling systems that will minimize dependence on foreign-sourced materials, reduce vulnerability to supply chain disruptions, and mitigate negative environmental impacts. The U.S. government is doing its part, too, by implementing the battery manufacturing, second use, and recycling initiatives identified in the 2021 Bipartisan Infrastructure Law. This emerging domestic market could be accelerated by creating positive incentives to drive EV adoption, promote domestic manufacturing, and secure U.S. supply chains for decades to come.

2.7 Conclusions

Throughout history, humankind has created materials and products to improve lives. Most often, no thought was given to how creating and using those products might negatively impact vulnerable populations or the environment—especially in the long term—such as the adverse impact of plastic bottles in oceans. It is now abundantly clear that our take, make, and dispose habits have put the planet on a perilous trajectory. We also know that we have the tools to change those habits for good and to become responsible stewards of our planet.

EVs will play a key role in reducing carbon emissions and staving off continuously worsening effects of climate change. The prospects for a circular economy for EVBs are promising. EVB technology is already evolving to reduce the need for the riskiest battery minerals and to support more efficient repair and disassembly. Reuse and recovery technologies with smaller carbon footprints are also under development and will be deployed in increasing numbers, further reducing carbon emissions by shortening distances between facilities. Material identification and tracking technologies can help manufacturers ensure sustainable sourcing, account for greenhouse gas emissions in the supply and value chains, and help streamline potentially burdensome regulations. This report outlines the challenges for life cycle management of EBVs along with efforts and solutions underway to address them.

At no other time have we had the skills, tools, and resources to support circular economy systems like we have today. If there is any industry with the expertise and history of innovation to create a blueprint for sustainable products, it is the automotive industry. It is exciting, it is daunting, and it will require being bold.

Glossary

Term	Definition
black mass	A mixture of grounded constituents of a lithium-ion battery cell after shredding, sieving, and separation.
digital twin	In terms of electric vehicle batteries, a digital representation of the battery and components.
first life	Original equipment manufacturer battery, battery pack, or module deployed in its first use in a device, automotive, or stationary storage system (also "1st-life," "1st use," or "first use").
GS1	A neutral, not-for-profit, international organization developing and maintaining standards, including barcodes.
refurbish	To service a battery so it can continue its life in a vehicle.
repurpose	See "second life."
repurposer	A company that recovers used electric vehicle or stationary batteries or modules into new stationary storage systems, including integrating battery management system and power electronics and external communications.
second life	Use of an end-of-first-life electric vehicle battery or stationary storage battery for energy storage use in a different application.
smart contracts	Programs on a blockchain that run when predetermined conditions are met. They can automate execution of an agreement (or contract) so all participants can immediately see the result without any intermediary's involvement.

References

Alternative Fuels Data Center. 2020. "Zero Emission Vehicle (ZEV) Production Requirements." Accessed Nov. 16, 2020. https://afdc.energy.gov/laws/4249

American Clean Power. 2022. "The American Clean Power Association." Accessed Oct. 26, 2022. https://cleanpower.org/

Arora, Shivam. 2022. "What is a Smart Contract in Blockchain and How Does it Work?" *Simplilearn*, last updated July 5, 2022. https://www.simplilearn.com/tutorials/blockchain-tutorial/what-is-smart-contract

Assefi, M., S. Maroufi, Y. Yamauchi, and V. Sahajwalla. 2020. "Pyrometallurgical recycling of Li-ion, Ni–Cd and Ni–MH batteries: A minireview." *Current Opinion in Green and Sustainable Chemistry* 24: 26–31. https://doi.org/10.1016/j.cogsc.2020.01.005

Automotive Recyclers Association. 2022. "Automotive Recyclers Association." Accessed Oct. 26, 2022. http://www.chooserecycledparts.com/

Automotive Service Association. 2022. "Home – Automotive Service Association." Accessed Oct. 26, 2022. https://www.asashop.org/

Azevedo, Marcelo, Nicolò Campagnol, Toralf Hagenbruch, Ken Hoffman, Ajay Lala, and Oliver Ramsbottom. 2018. "Lithium and cobalt: A tale of two commodities." McKinsey & Company report, June 22, 2018. https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-and-cobalt-a-tale-of-two-commodities

Ballinger, Benjamin, Martin Stringer, Diego R. Schmeda-Lopez, Benjamin Kefford, Brett Parkinson, Chris Greig, and Simon Smart. 2019. "The vulnerability of electric vehicle deployment to critical mineral supply." *Applied Energy* 255. https://doi.org/10.1016/j.apenergy.2019.113844

Battery University. 2021. "BU-203: Types of Lithium-ion." Last updated Oct. 22, 2021. https://batteryuniversity.com/article/bu-205-types-of-lithium-ion

Best Hybrid Batteries. 2022. "Hybrid Battery Replacement and Repair." Accessed Feb. 12, 2022. https://www.besthybridbatteries.com/

BloombergNEF. 2019. *Electric Vehicle Outlook 2019*. London, U.K.: BloombergNEF. https://legacy-assets.eenews.net/open_files/assets/2019/05/15/document_ew_02.pdf

California Energy Commission. 2022. "Zero Emission Vehicle and Infrastructure Statistics." Accessed Oct. 27, 2022. https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics

California Environmental Protection Agency. 2022. *Lithium-ion Car Battery Recycling Advisory Group Final Report*. Sacramento, CA: California Environmental Protection Agency. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf

California Governor's Office of Business and Economic Development (GO-Biz). 2021. *California Zero-Emission Vehicle Market Development Strategy*. Sacramento, CA: GO-Biz. https://static.business.ca.gov/wp-content/uploads/2021/02/ZEV_Strategy_Feb2021.pdf

California State Legislature. 2018. "Recycling: lithium-ion vehicle batteries: advisory group." Assembly Bill No. 2832. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB2832

Call2Recycle. 2022. "Explore the Secret Life of Batteries." Accessed Feb. 13, 2022. https://www.call2recycle.org/explore-the-secret-life-of-batteries/

Dai, Qiang, Jeffrey Spangenberger, Shabbir Ahmed, Linda Gaines, Jarod C. Kelly, and Michael Wang. 2019. *EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model*. Lemont, IL: Argonne National Laboratory. ANL-19/16. https://publications.anl.gov/anlpubs/2019/07/153050.pdf

Deurwaarder, E. 2021. "European Commission proposal for an EU Regulation on batteries and waste batteries 'COM/2020/789.'" Presented at Navigating EVB Regulatory Compliance with the Battery Passport, Everledger, June 23, 2021. https://www.youtube.com/watch?app=desktop&v=lHc_kfZ4sFQ&ab_channel=Everledger

DOE, October 19,2022, "Biden-Harris Administration Awards $2.8 Billion to Supercharge U.S. Manufacturing of Batteries for Electric Vehicles and Electric Grid," accessed October 20,2022, https://www.energy.gov/articles/biden-harris-administration-awards-28-billion-supercharge-us-manufacturing-batteries

DOE, November 16, 2022, "Biden-Harris Administration Announces Nearly $74 Million To Advance Domestic Battery Recycling And Reuse, Strengthen Nation's Battery Supply Chain," accessed November 17, 2022 https://www.energy.gov/articles/biden-harris-administration-announces-nearly-74-million-advance-domestic-battery-recycling.

DOE Battery Policy and Incentive Search, 2022, "Battery Requirements for Electric Vehicle (EV) and Fuel Cell Electric Vehicle (FCEV) Tax Credit," Accessed September 1, 2022, https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=204

Dobson, Geoff. 2021. "Global EV sales back on track." *EVs & Beyond*, Aug. 19, 2021. https://evsandbeyond.co.nz/global-ev-sales-back-on-track/

Dragonfly Energy. 2021. "What Is Thermal Runaway In Batteries?" Accessed Oct. 26, 2022. https://dragonflyenergy.com/thermal-runaway/

Electrification Coalition, August 2022, "Fact Sheet IRA EV Tax Credits," Accessed November 12, 2022, https://electrificationcoalition.org/wp-content/uploads/2022/08/SAFE_1-sheet_Webinar.pdf

Energy Storage Association. 2022. "Energy Storage Association Homepage." Accessed Oct. 26, 2022. https://energystorage.org/

ERI. 2022. "How to Recycle NiMH Batteries." RecycleNation, Accessed Feb. 13, 2022. https://recyclenation.com/2015/06/how-to-recycle-nimh-batteries/

European Commission. 2020a. "Batteries and accumulators." Accessed Nov. 13, 2020. https://ec.europa.eu/environment/waste/batteries/

European Commission. 2020b. *Proposal for a Regulation of the European Parliament and of the Council Concerning Batteries and Waste Batteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No 2019/1020.*

European Commission. 2022. "European Battery Alliance." Accessed Oct. 26, 2022. https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-battery-alliance_en

European Parliament. 2022. "New EU regulatory framework for batteries: Setting sustainability requirements." Briefing, March 2022. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf

EV-Volumes. 2021. "EV-Volumes – The Electric Vehicle World Sales Database." Accessed Oct. 8, 2021. https://www.ev-volumes.com/

Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. 2021. "Batteries Act." Last updated Jan. 1, 2021. https://www.bmuv.de/en/law/batteries-act/

Gaines, Linda. 2018. "Lithium-ion battery recycling processes: Research towards a sustainable course." *Sustainable Materials and Technologies* 17. https://doi.org/10.1016/j.susmat.2018.e00068

Gaines, Linda, Qiang Dai, John T. Vaughey, and Samuel Gillard. 2021. "Direct Recycling R&D at the ReCell Center." *Recycling* 6 (2): 31. https://doi.org/10.3390/recycling6020031

Global Battery Alliance. 2021, accessed September 22, 2022 https://www.globalbattery.org/about/,

Global Battery Alliance. 2022a. "Battery Passport." Accessed Oct. 26, 2022. https://www.globalbattery.org/battery-passport/

Global Battery Alliance. 2022b. "Establishing a sustainable and responsible battery value chain." Accessed Oct. 26, 2022. https://www.globalbattery.org/

Harper, Gavin, Roberto Sommerville, Emma Kendrick, Laura Driscoll, Peter Slater, Rustam Stolkin, et al. 2019. "Recycling lithium-ion batteries from electric vehicles." *Nature* 575: 75–86. https://doi.org/10.1038/s41586-019-1682-5

Hirai, T., Y. Shikano, K. Asakura, M. Shimomura, H. Hasui, and I. Yamada. 2000. "Long-life nickel-metal hydride batteries as a backup power supply for optical fiber networks." *Twenty-Second International Telecommunications Energy Conference (INTELEC)*, Phoenix, AZ, 6 Aug. 2000. https://doi.org/10.1109/INTLEC.2000.884242

Hossain, E., D. Murtaugh, J. Mody, H. M. Resalat Faruque, S. H. Sunny, and N. Mohammad. 2019. "A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies." *IEEE Access* 7: 73215–73252. https://doi.org/10.1109/ACCESS.2019.2917859

Hyperledger. 2018. *Hyperledger Blockchain Performance Metrics*. V1.01. https://www.hyperledger.org/wp-content/uploads/2018/10/HL_Whitepaper_Metrics_PDF_V1.01.pdf

Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2022. *Lithium-ion Car Battery Recycling Advisory Group: Draft Report*. AB 2832 Advisory Group. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/03/AB-2832-Final-Draft-Policy-Recommendations-Lithium-ion-Car-Battery-Recycling-Advisory-Group-As-of-3-11-22.a.hp_.pdf

Klender, Joey. Global EV sales reach 10 percent of new cars sold in 2022, https://www.teslarati.com/electric-vehicle-sales-2022/ January16, 2023

Li, Canbing, Yijia Cao, Mi Zhang, Jianhui Wang, Jianguo Liu, Haiqing Shi, and Yinghui Geng. 2015. "Hidden Benefits of Electric Vehicles for Addressing Climate Change." *Scientific Reports* 5: 9213. https://doi.org/10.1038/srep09213

Liminal Insights. 2022. "Home." Accessed Oct. 26, 2022. https://www.liminalinsights.com/

Martinez-Laserna, E., I. Gandiaga, E. Sarasketa-Zabala, J. Badeda, D.-I. Stroe, M. Swierczynski, and A. Goikoetxea. 2018. "Battery second life: Hype, hope or reality? A critical review of the state of the art." *Renewable and Sustainable Energy Reviews* 93: 701–718. https://doi.org/10.1016/j.rser.2018.04.035

Melin, Hans Eric. 2021. "Circular Energy Storage." Presentation at the 2021 NAATBatt Annual Meeting.

Moore, Stephen. 2019. "Tailor-made plastics protect the heart of electric cars." *Plastics Today*, May 8, 2019. https://www.plasticstoday.com/automotive-and-mobility/tailor-made-plastics-protect-heart-electric-cars

Motavalli, Jim. 2022. "Predicting How Much Range EV Batteries Lose over Time." *Autoweek*, April 13, 2022. https://www.autoweek.com/news/a39713122/predicting-how-much-range-ev-batteries-lose-over-time/

Muratori, Matteo, Marcus Alexander, Doug Arent, Morgan Bazilian, Pierpaolo Cazzola, Ercan M. Dede, et al. 2021. "The rise of electric vehicles—2020 status and future expectations." *Progress in Energy* 3 (2): 022002. https://doi.org/10.1088/2516-1083/abe0ad

Najman, Liz. 2021. "How Long Do Tesla & EV Batteries Last?" *Recurrent*, July 8, 2021. https://www.recurrentauto.com/research/how-long-do-ev-batteries-last

Neubauer, Jeremy, Ahmad Pesaran, Brett Williams, Mike Ferry, and Jim Eyer. 2012. "A Techno-Economic Analysis of PEV Battery Second Use: Repurposed-Battery Selling Price and Commercial and Industrial End-User Value." Presented at the 2012 SAE World Congress and Exhibition, Detroit, MI, 24–26 April 2012. https://doi.org/10.4271/2012-01-0349

Neubauer, Jeremy, Ahmad Pesaran, Eric Wood, and Kandler Smith. 2015. "Second Use of PEV Batteries: A Massive Storage Resource for Revolutionizing the Grid." Presented at the Energy Storage Association Annual Conference & Expo, Dallas, TX, 27–29 May 2015. https://www.nrel.gov/docs/fy15osti/64149.pdf

Neubauer, Jeremy S., Eric Wood, and Ahmad Pesaran. 2015. "A Second Life for Electric Vehicle Batteries: Answering Questions on Battery Degradation and Value." *SAE International Journal of Materials and Manufacturing* 8 (2): 544–553. https://doi.org/10.4271/2015-01-1306

Newsom, Gavin. 2020. "Executive Order N-79-20, Zero-Emission by 2035." Sept. 23, 2020. https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf

OneCharge. 2022. "How China came to dominate the market for lithium batteries and why the U.S. cannot copy their model." Jan. 27, 2022. https://www.onecharge.biz/blog/how-china-came-to-dominate-the-market-for-lithium-batteries-and-why-the-u-s-cannot-copy-their-model/

Sabin Center for Climate Change Law. 2022. "Law for Promotion of Effective Utilization of Resources." Accessed Oct. 27, 2022. https://lpdd.org/resources/law-for-promotion-of-effective-utilization-of-resources/

Sedlmeir, Johannes, Hans Ulrich Buhl, Gilbert Fridgen, and Robert Keller. 2020. "The Energy Consumption of Blockchain Technology: Beyond Myth." *Business & Information Systems Engineering* 62: 599–608. https://doi.org/10.1007/s12599-020-00656-x

Stafford, Michael. 2019. "The Future of Electric Vehicles in Fleet." *Automotive Fleet*, Oct. 15, 2019. https://www.automotive-fleet.com/342585/the-future-of-electric-vehicles-in-fleet

Techdirt. 2020. "Massachusetts Voters Overwhelmingly Support Expanded 'Right To Repair' Law." *Above the Law*, Nov. 6, 2020. https://abovethelaw.com/2020/11/massachusetts-voters-overwhelmingly-support-expanded-right-to-repair-law/

Tesla. 2021. "Powerwall." Accessed Sept. 15, 2021. https://www.tesla.com/powerwall

TitanAES. 2022. "Ultrasound Battery Management." Accessed Oct. 26, 2022. https://www.titanaes.com/

UL Solutions. 2021. “Batteries and Energy Storage.” Accessed May 20, 2021. https://www.ul.com/industries/energy-and-utilities/batteries-and-energy-storage

Umicore. 2022. “Lithium.” Accessed Oct. 26, 2022. https://www.umicore.com/en/about/our-metals/lithium/

United States Advanced Battery Consortium. 2020. “Goals for Advanced High-Performance Batteries for Electric Vehicle (EV) Applications.” https://uscar.org/download/246/energy-storage-system-goals/12837/goals-for-advanced-high-performance-batteries-for-electric-vehicle-ev-applications.pdf

U.S. Congress. House. 2021. *Infrastructure Investment and Jobs Act*. HR 3684. 117th Cong. Introduced in House June 4, 2021. https://www.congress.gov/bill/117th-congress/house-bill/3684

U.S. Department of Energy. 2018. “Department of Energy Announces $80 Million Investment in Advanced Vehicle Technologies Research.” Sept. 5, 2018. https://www.energy.gov/articles/department-energy-announces-80-million-investment-advanced-vehicle-technologies-research

U.S. Department of Energy. 2022a. “American-Made Lithium-Ion Battery Recycling Prize.” Accessed Oct. 26, 2022. https://americanmadechallenges.org/challenges/batteryrecycling/index.html

U.S. Department of Energy. 2022b. “ReCell Center.” Accessed Oct. 26, 2022. https://recellcenter.org/

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE). 2019. “Vehicle Technologies Office’s Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries.” https://www.energy.gov/sites/prod/files/2019/07/f64/112306-battery-recycling-brochure-June-2019%202-web150.pdf

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office (VTO). 2021. “National Blueprint for Lithium Batteries.” June 7, 2021. https://www.energy.gov/eere/vehicles/articles/national-blueprint-lithium-batteries

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office (VTO). 2022. “Batteries.” Accessed Oct. 26, 2022. https://www.energy.gov/eere/vehicles/batteries

U.S. Environmental Protection Agency. 2022. “Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy.” Last updated July 5, 2022. https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy

Vieceli, N., R. Casasola, G. Lombardo, B. Ebin, and M. Petranikova. 2021. “Hydrometallurgical recycling of EV lithium-ion batteries: Effects of incineration on the leaching efficiency of metals using sulfuric acid.” *Waste Management* 125: 192–203. https://doi.org/10.1016/j.wasman.2021.02.039

What Car? 2021. “Government’s 2030 ban on the sale of new petrol and diesel cars under fire from MPs.” May 24, 2021. https://www.whatcar.com/news/governments-2030-ban-on-the-sale-of-new-petrol-and-diesel-cars-under-fire-from-mps/n23064

World Economic Forum. 2022. “The World Economic Forum.” Accessed Oct. 26, 2022. https://www.weforum.org/

Xu, Chengjian, Qiang Dai, Linda Gaines, Mingming Hu, Arnold Tukker, and Bernhard Steubing. 2020. “Future material demand for automotive lithium-based batteries.” *Communications Materials* 1: 99. https://doi.org/10.1038/s43246-020-00095-x

Xu, ChengJian, Wenxuan Zhang, Wenzhi He, Guangming Li, Juwen Huang, and Haochen Zhu. 2017. “Generation and management of waste electric vehicle batteries in China.” *Environmental Science and Pollution Research* 24: 20825–20830. https://doi.org/10.1007/s11356-017-9890-8

Zero Emission Transportation Association. 2022. “ZETA.” Accessed Oct. 26, 2022. https://www.zeta2030.org/

Zhou, Yan, David Gohlke, Luke Rush, Jarod Kelly, and Qiang Dai. 2021. *Lithium-Ion Battery Supply Chain for E-Drive Vehicles in the United States: 2010–2020*. Lemont, IL: Argonne National Laboratory. ANL/ESD-21/3. https://publications.anl.gov/anlpubs/2021/04/167369.pdf

Zhu, Lingyun, and Ming Chen. 2020. “Research on Spent $LiFePO_4$ Electric Vehicle Battery Disposal and Its Life Cycle Inventory Collection in China.” *International Journal of Environmental Research and Public Health* 17 (23): 8828. https://doi.org/10.3390/ijerph17238828