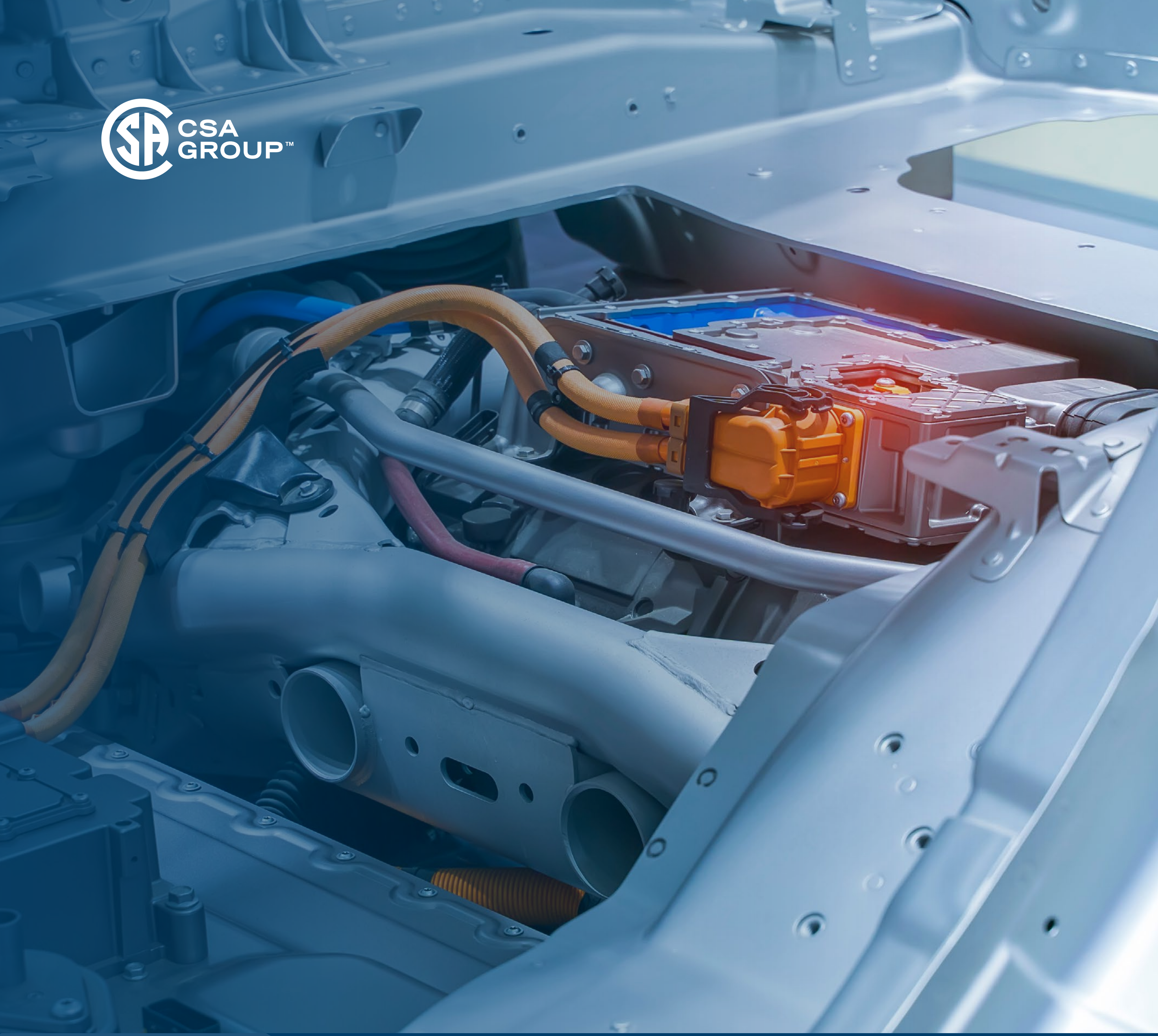


STANDARDS RESEARCH

Circularity and Recycling of Lithium-Ion Batteries for Electric Vehicles — Standardization and Safety Requirements

December 2022

Authors

Maria Kelleher, **M. Eng., P.Eng.,** Kelleher Environmental

Yemi Oyediran, **PhD., PEng.,** NOK Associates Limited

Andrew Pollock, **MBA,** Pollock Environmental

Project Advisory Panel

Liz Lappin, Common Good Mining

Alissa Kendall, University of California, Davis

Andrew McKinnon, Global Automakers of Canada

Steve Fletcher, Automotive Recyclers of Canada

Albert Lipson, Argonne National Laboratory

Dragica Jeremic Nikolic, CSA Group

Umer Khan, CSA Group

Disclaimer

This work has been produced by Kelleher Environmental and is owned by Canadian Standards Association. It is designed to provide general information in regards to the subject matter covered. The views expressed in this publication are those of the authors. Kelleher Environmental and Canadian Standards Association are not responsible for any loss or damage which might occur as a result of your reliance or use of the content in this publication

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ANSI	American National Standards Institute
BMS	Battery management system
BSI	British Standards Institution
CAM	Cathode active material
EOL	End of life
EPR	Extended producer responsibility
ESA	Energy Storage Association
EU	European Union
EV	Electric vehicle
IEA	International Energy Agency
IFC	International Fire Code
IP	Intellectual property
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
NCA	Nickel cobalt aluminum
NMC	Nickel manganese cobalt
NCMA	Nickel cobalt manganese aluminum
OEM	Original equipment manufacturer
SAE	Society of Automotive Engineers
SOH	State of health
TDGA	Transportation of Dangerous Goods Act
ZEV	Zero-emission vehicle

Executive Summary

The use of lithium-ion batteries (LIBs) has been growing exponentially due to the rapid development and deployment of electric vehicles (EVs).

In a circular economy, once a product can no longer be used for its intended purpose, it goes back into the supply chain instead of to a landfill. Circularity of EV LIBs refers to directing LIBs that are no longer suitable to power an EV (i.e., when they retain less than 80% of their charge) to a second life in energy storage or other applications before they are ultimately recycled to recover valuable materials (nickel, cobalt, lithium, graphite, and manganese) to make new LIBs.

By 2030, recycled materials recovered from end-of-life (EOL) EV LIBs are projected to meet 13% of the global battery demand for cobalt, 5% for nickel, and 9% for lithium. While recycling of LIBs will not solve the supply issue, it will help.

This research project assessed the potential role of standards and safety requirements in supporting the circularity (recycling and reuse/repurposing) of EV LIBs. Information was collected through a literature review, interviews with 30 representatives from the LIB supply chain, and a gap analysis.

Currently, there are only a few EV LIB circularity businesses in operation. Most are at the early stage of the business cycle, all are still developing and innovating, and new companies continue to enter the EOL EV LIB circularity business to meet the growing demand for recycling and reuse or repurposing services. This is a complex and evolving market with many variables to consider.

Most EV LIBs will not reach EOL for many years, so the supply of EOL LIBs to circularity businesses will be modest until then. Estimates of EV LIB lifespans vary from 12 to 15 years for their first life as an EV LIB, and another, assumed 5 to 10 years for their second life in energy storage or another application before they are sent for recycling.

This research identified several aspects of the EV LIB's second life where guidelines, codes of practice, and standards could contribute to the developing reuse, repurposing, and recycling business models, including: definitions to clarify ownership and liability when an EV LIB (or its cells or packs) enter a second life; state of health (SOH) information; traceability and the history of an EV LIB; and identification of EV LIB design and chemistry.

The key gaps identified by this research include:

- **Safe EV LIB handling knowledge gaps:** There is a need for a concierge service that curates all currently available safety information related to EV LIBs (particularly discharging EV LIBs and managing EV LIB fires) that is easily accessible to relevant stakeholders;
- **Second-life EV LIB gaps:** There is a need for transparency, traceability, and information about second-life LIB provenance, and a need for documents to educate financial and insurance companies about the second-life EV LIB business to facilitate investment;
- **EV LIB recycling-related gaps:** There is a need for labelling of EV LIB chemistry and design to facilitate recycling;
- **EOL EV LIB transportation and storage gaps:** There is a need for a simplified, harmonized set of transportation rules for EOL EV LIBs in North America; and
- **Data and information gaps:** There is a need for estimates for EOL EV LIBs entering the Canadian marketplace from now to 2050 that consider longer than initially estimated EV LIB lifespans and second-life uses.

The key recommendations emerging from this research include:

- Periodically revisiting the EOL EV LIB landscape because the market is evolving rapidly;
- Developing an EV LIB circularity standards roadmap;
- Researching a design for environment/design for recycling guideline for EV LIBs;
- Updating and developing specific second-life EV LIB documents;
- Creating a guideline to calculate the environmental footprint of EV LIB recycling and reuse/repurposing; and
- Developing publicly available EOL EV LIB projections to 2050 for Canada.

> “The Government of Canada’s 2030 Emissions Reduction Plan includes a zero-emission vehicles (ZEVs) sales mandate that sets the following targets: ZEVs account for at least 20% of new light-duty vehicle sales by 2026, at least 60% by 2030, and 100% by 2035”

1 Introduction

In 2019, there were approximately 23.5 million light-duty vehicles in Canada [1]. Every year, an estimated 1.6 to 1.8 million vehicles reach their end of life (EOL) and 1.86 million [2] new vehicles are sold. The Government of Canada’s 2030 Emissions Reduction Plan [3] includes a zero-emission vehicles (ZEVs) sales mandate that sets the following targets: ZEVs account for at least 20% of new light-duty vehicle sales by 2026, at least 60% by 2030, and 100% by 2035. These targets will translate to annual new ZEV sales of approximately [4]:

- 395,000 units in 2026, with about 1.4 million ZEVs on the road (about 5% of total light-duty vehicles);
- 1.2 million units in 2030, with about 4.6 million ZEVs on the road (about 16% of total light-duty vehicles); and
- 2.0 million units in 2035, with a projected 12.4 million ZEVs on the road (about 40% of total light-duty vehicles).

At this time, most ZEVs are electric vehicles (EVs), although hydrogen fuel cells may gain market share in the coming years, and all EVs contain a lithium-ion battery (LIB), which must be properly managed at EOL.

In 2021, approximately 6.75 million EVs were sold globally [5] and about 86,000 units of battery-electric and plug-in hybrids were sold in Canada [6]. The International Energy Agency (IEA) projects 300 million EV sales globally by 2050, representing 60% of all new vehicle sales [7]. EV sales projections are not currently publicly available for Canada.

Rapid growth in the demand for LIBs is anticipated due to the current and projected growth of EV sales. Furthermore, demand for LIBs for use in energy storage systems (ESS) is expected to account for between 5% [8] and 8% [9] of global demand by 2030.

Currently, all EV batteries are based on variations of lithium-ion chemistry. Although alternative chemistries and designs (sodium, zinc-air, lithium metal or silicon anodes, and solid-state batteries) are being explored, they are a few years away from full commercialization and adoption at scale.

Circularity of EV LIBs refers to directing LIBs that are no longer suitable to power an EV (i.e., when they retain less than 80% of their charge) to second-life applications, such as energy storage for small-scale renewable energy systems (wind and solar) and larger grid systems, and other uses (as batteries for wheelchairs, drones, RVs, uninterruptible power supply, etc.). When the second life of EV LIBs or their component cells or packs is complete, in a circular economy they are recycled to recover valuable materials (nickel, cobalt, lithium, graphite, and manganese), which are then used to manufacture new LIBs, making the EV LIB supply chain fully circular.

EV LIB circularity is increasingly important to both automotive original equipment manufacturers (OEMs) and battery makers. Recovery of metals and other materials from EOL EV LIBs can contribute to the circular economy commitments of various companies and to the mandates laid out in the European Union (EU) proposed Batteries Regulation (discussed in Section 4). Recycling LIBs reduces the carbon footprint of the new battery cells, which is a significant benefit for both automotive OEMs and battery makers, as mandatory carbon footprint reporting is required under the proposed EU Batteries Regulation.

Throughout this report, there are references to ESS containing LIBs. Due to recent reductions in the cost of LIBs, they are being increasingly installed in ESS connected to the electrical grid as well as to renewable solar and wind power systems. LIBs are considered a good choice for ESS where relatively short (1 to 4 hours) storage times are required.

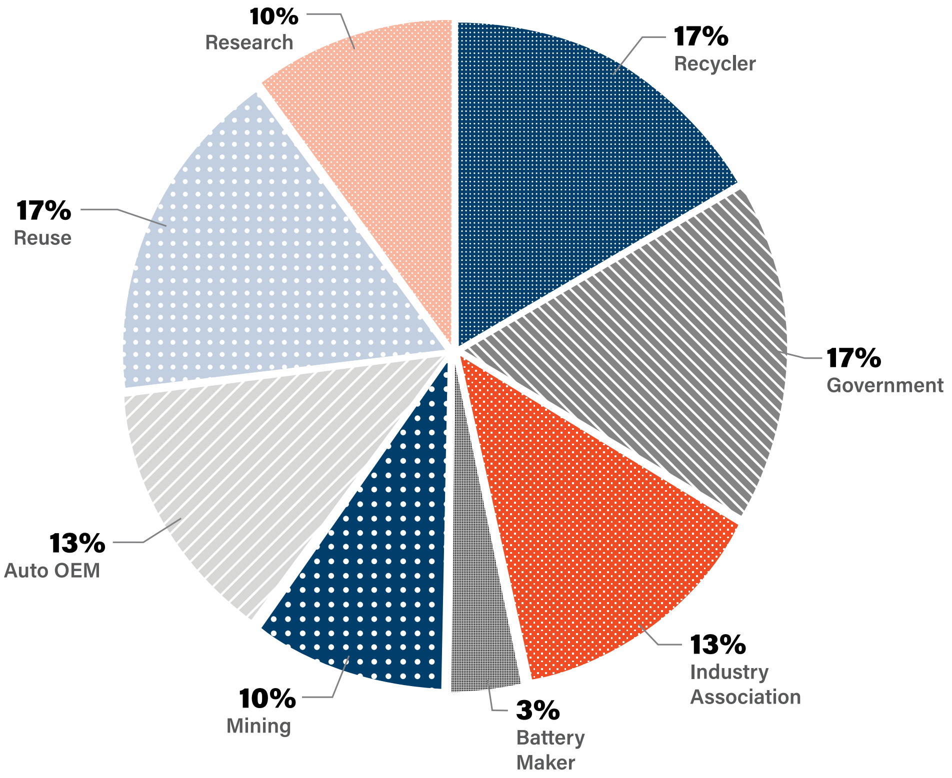
This report describes EV LIB circularity pathways and identifies existing policies, codes of practice, guidelines, and standards that promote EV LIB circularity. It also presents needs and gaps, which were identified through a comprehensive literature review, and through consultations with experts and key stakeholders, which were conducted through a series of 30 interviews.

2 Methodology

Information on EV LIB circularity pathways, existing policies, codes of practice, guidelines, and standards that promote EV LIB circularity was collected through an extensive literature search, including internet searches and review of trade publications, scientific journal articles, conference and webinar presentations, and other recent and current research sources.

Interviews with 30 stakeholders from the EV LIB circularity supply chain were also conducted to explore the following questions:

Figure 1: EV LIB circularity project interviewees by category.



- Explain your business and your specific role in the EV LIB supply chain.
- Do you believe there is circularity happening in the EV LIB supply chain at this time?
- What do you think would encourage more circularity in the EV LIB supply chain?
- What are the benefits and drawbacks of standards in general?
- Are you aware of existing standards related to EV LIB circularity?
- How would standards improve EV LIB circularity?
- How could standards/policies on EV LIB circularity impact your business segment of the EV LIB supply chain?
- Are you aware of gaps (regarding standards) in the EV LIB supply chain where there are no standards, or where standards are needed and should be developed?

The interviewees were also asked to identify other potential candidates for interviews. The breakdown of interviewees by their general industry category is presented in Figure 1.

The interviewees provided a broad range of opinions on whether EV LIB circularity was currently in place and what actions could be taken to increase circularity. The role of standards and policies in advancing EV LIB circularity was explored, along with standardization options for improvement of EV LIB circularity.

A virtual workshop was held with the CSA Electric Vehicle Advisory Group on May 18, 2022, wherein the research findings were presented and additional input was gathered through a question-and-answer period.

The information collected through the literature review and the interviews was used to characterize the current state of EV LIB circularity, which is described in Section 3, and to identify existing codes of practice, guidelines, and standards related to EV LIB circularity, which is described in Section 4.

The information collected through the interviews was also used as a foundation for the gap analysis and to identify actions and additional research on the development of standards, codes of practice, and guidelines to advance EV LIB circularity. The gap analysis and recommendations emerging from this research are presented in Section 5. Conclusions of the research are summarized in Section 6.

3 EV LIB Supply Chain and Circularity Pathways

3.1 EV LIB Supply Chain

The EV LIB supply chain presented in Figure 2 shows that when an EV LIB is no longer suitable to power an EV (generally after losing 15% to 20% of its initial capacity) [10], it reaches end of its first life and can be either sent to an auto recycler as an integral part of the EOL EV, or it can be returned to an auto dealer. Auto recyclers may send the EOL EV LIB directly to a reuse company or to a recycler. At an auto dealership, the LIB is removed from the EV and managed in compliance with automotive OEM requirements (i.e., it may go to a reuse pathway or directly to recycling). Both EV LIB reuse and recycling circularity pathways are described in Sections 3.4 and 3.5.

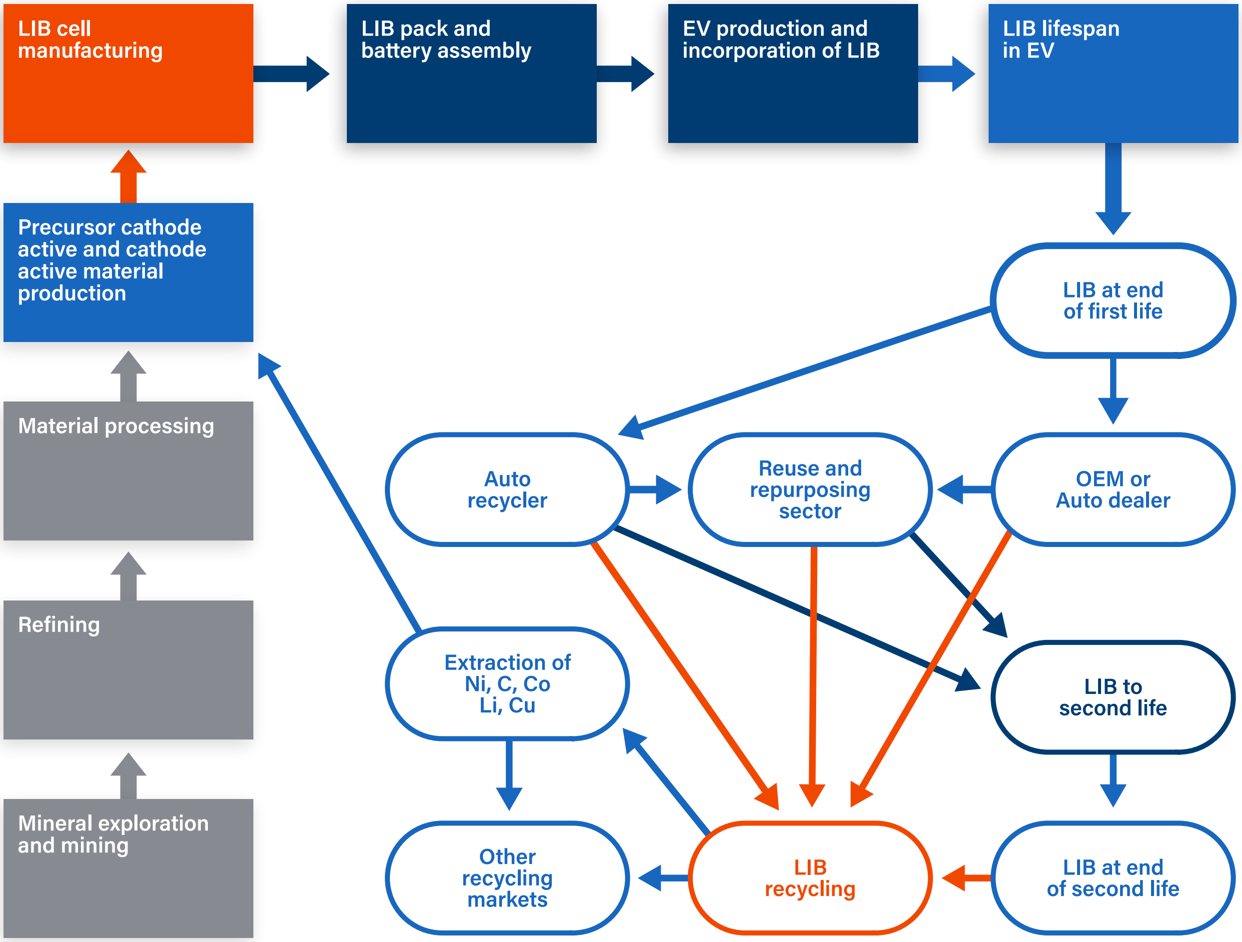
In Figure 2, the steps related to circularity (reuse/repurposing and recycling) are shown in circles, while other steps in the EV LIB supply chain (exploration, mining and processing raw materials into chemical salts, manufacturing of battery materials, battery assembly, EV production, etc.) are presented as rectangles and described in detail in Appendix A.

3.2 EV LIB Design and Construction

Figure 3 illustrates the construction of a LIB cell, which consists of:

- a graphite or graphite/silicon anode;
- a liquid lithium-ion electrolyte;
- a polyolefin separator; and
- a cathode that can be made from several different metal combinations (discussed in Section 3.3).

Figure 2: EV LIB supply chain with circularity pathways.



From the EV LIB circularity perspective, recyclers are particularly interested in recovering valuable metals such as nickel and cobalt from LIB cell cathodes. New and developing recycling technologies are also recovering lithium, as well as graphite from the anode.

Figure 4 illustrates how LIB cells are combined into LIB packs that power an EV. The cells can use a cylindrical, prismatic, or pouch design. The decision on which cell design to use varies by manufacturer.

All LIBs are managed by a battery management system (BMS), which consists of copper wiring and a series of circuit boards, as shown in two examples in Figure 5.

3.3 EV LIB Chemistries

EV LIBs chemistries refer to the different combinations of minerals and metals used in the battery cathode. For EV LIB circularity, these chemistries are of particular interest to recyclers, who want to recover the minerals and metals from LIBs at EOL. The value of the metals varies significantly, with cobalt and nickel being the most valuable, and therefore EV LIBs with high nickel and cobalt content hold the greatest value for recyclers.

Nickel manganese cobalt (NMC) and nickel cobalt aluminum (NCA) are the most common chemistries used in EV LIBs in North America. General Motors (GM) is using a new chemistry manufactured by LG Chem for their Ultium EV LIBs, called NCMA (nickel cobalt manganese aluminum) [11].

Figure 3: Structure of LIB cells.

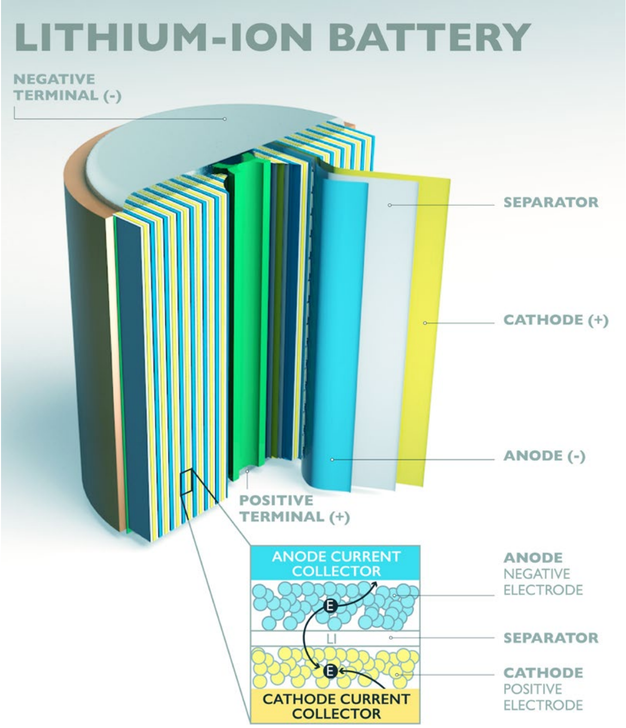
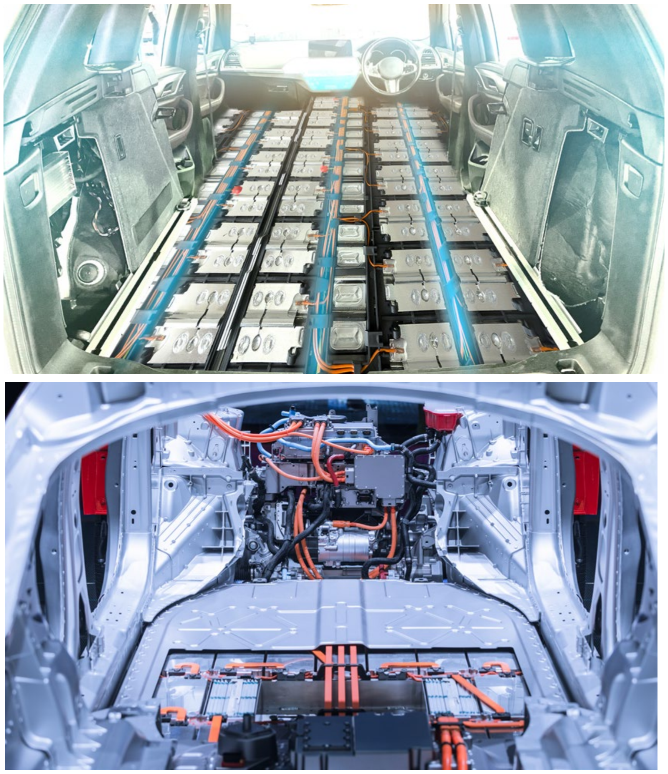


Figure 4: Exploded view of LIB packs from EV battery.

Note. Copper wiring shown in orange.

Figure 5: LIB packs with battery management system in EVs.



LIB chemistries vary in the amount of nickel and cobalt they contain, with nickel-rich chemistries containing on average 28 to 43 kg of nickel and 2 to 11 kg of cobalt for a 60 kWh LIB [12]. Lithium iron phosphate (LFP) LIBs are gaining popularity, particularly in China, because they contain readily available materials such as iron and phosphorous. In addition, LFP batteries contain neither nickel nor cobalt, and are therefore less expensive than other chemistries. A significant amount of graphite is also used for EV LIB anodes today, varying from 44 to 66 kg per anode for a 60 kWh LIB depending on the chemistry [12]. While this composition may change over time as more silicon or lithium-metal are used in LIB anodes, for the next few years anodes will predominantly consist of a mixture of synthetic and natural graphite (discussed in more detail in Appendix A).

In 2020, the average metal content of an EV LIB with 60 kWh capacity (excluding material in the electrolyte, binder, separator, and battery pack casing [12]) was 35 kg of aluminum, 29 kg of nickel, 20 kg of copper, 10 kg of manganese and 8 kg of cobalt [12]. Graphite is the material with the greatest weight, followed by aluminum, nickel, and copper—all valuable recyclable commodities that can be reintroduced to the LIB supply chain for a fully circular LIB economy.

In 2021, 54% of new EVs globally were powered by LIBs with “high nickel” cathode chemistries (referred to as NMC 6-, 7-, and 8-series, NCA, and NCMA), while 26% used LIBs with “low nickel” cathodes (NMC 5-series and lower) and 20% were powered by “no nickel” cathodes, primarily lithium iron phosphate (LFP) [13].

Currently, an estimated 28% of EV LIBs use NMC cathodes, with predictions that this will increase to 63% by 2027 [14]. With the high price of cobalt, and further increases possible, many believe that the use of NMC and NCA chemistries will grow.

Automotive OEMs and battery makers are continuously striving to improve EV battery design. Future trends anticipate numerous modifications to LIB designs, including the use of cobalt-free, high nickel content LIBs, potentially with silicon or lithium-metal anodes (replacing current graphite anodes). Other battery chemistry designs may increase in popularity, with solid-state designs receiving a lot of attention. Batteries with solid-state electrolytes are lighter, safer, and can provide much longer range than current LIBs, but are still 2 to 5 years away from commercialization.

The decision regarding which battery design (cylindrical, pouch, or prismatic) and which battery chemistry (LMO, NMC, NCA, LFP, or NCMA) to use in different EV LIBs involves several trade-offs, including battery weight, energy density, range, and cost. The typical advantages and drawbacks of the different EV LIB chemistries are presented in Table 1.

3.4 EV LIB Reuse and Repurposing Circularity Pathway

At the end of its first life, an EV LIB can be directed to reuse, repurposing, or to recycling. If an EV LIB is directed to reuse or repurposing, it should eventually be recycled (see Section 3.5) when it is no longer functional in its second life.

The following definitions of reuse and repurposing are used by the California Lithium-ion Car Battery Recycling Advisory Group to define EV battery pathways at end of first life [15]:

- **Reuse** refers to the second-life use of an EV LIB that is placed into another EV after refurbishment or reconditioning.
- **Repurposing** refers to the second-life use of an EV LIB in another application, such as an ESS or in a wheelchair or a drone.

Table 1: Comparison of EV Lithium-Ion Battery Cathode Chemistries

Battery Cathode Chemistry	Advantages	Drawbacks	Examples of EVs with Battery
Lithium manganese oxide (LMO)	▪ Higher cell voltage and temperature stability than cobalt-based chemistries. ▪ Charges quickly. ▪ Lower cost due to absence of cobalt.	Short lifespan. LMO batteries usually last 300–700 charge cycles, which is much lower than other LIB chemistries.	▪ Nissan Leaf (early models)
Lithium nickel manganese cobalt oxide (NMC)	▪ High energy density and long-life cycle. ▪ Cobalt content has been reduced gradually with each generation of NMC battery to reduce costs.	Slightly lower voltage than LIBs with higher cobalt content.	▪ Hyundai Kona and Ionic ▪ Ford Mustang Mach-E ▪ Nissan Leaf ▪ Chevrolet Volt ▪ BMW i3
Lithium nickel cobalt aluminum oxide (NCA)	▪ High energy density and long-life cycle.	More expensive production than other LIB types.	▪ Tesla 3
Lithium iron phosphate (LFP)	▪ Less expensive than NCA and NMC batteries due to absence of cobalt. ▪ Long cycle life, fast charging time, and a high level of safety.	Low energy density and reduced performance in cold temperatures.	▪ Tesla 3s made in China ▪ Many Chinese EVs
Lithium nickel cobalt manganese aluminum oxide (NCMA)	▪ Longer life cycle without a reduction in the driving range and faster charging capability compared to either NMC or NCA	None identified.	▪ GM HUMMER EV (Ultium battery)

Some reuse applications require breaking down the used EV LIB into its constituent parts (cells or battery packs) while others keep the unit intact, with low-performing cells being replaced with new or reconditioned cells.

Typically, the first step in reuse or repurposing of EV LIBs is a partial disassembly of the battery pack. Non-functional cells are replaced and the battery pack is reassembled, either in its original format or in a newer format suitable to the new application (e.g., energy storage, powering wheelchairs, or other lower-power requirement applications). This process involves diagnostic and screening tests to correctly identify the EV LIB chemistries and designs, and to determine the state of health (SOH) of each battery cell. For battery packs made up of several cells, each EV LIB cell usually needs to be evaluated individually because they are exposed to different charging and discharging conditions during their use in an EV.

SOH testing is carried out to determine the appropriate application of the used EV LIBs and cells. Using a BMS, SOH evaluates the current operating condition of a LIB compared to ideal operating conditions (i.e., when it was first introduced to the market at 100% capacity). Based on the SOH assessment, the remaining useful life of the LIB can be estimated, along with its suitability to a particular application. Metrics used to measure SOH by different battery companies include physical characteristics, such as age, temperature during its previous uses, and internal resistance; and electrical characteristics, such as impedance, conductance, capacity, and voltage self-discharge. In addition, the battery's ability to accept a charge, number of charge–discharge cycles, and total energy charged and discharged are often used to assess SOH [16], which is often reported as the percentage of the original charge capacity remaining (e.g., 60%).

Each reuse/repurposing company uses its own proprietary SOH testing equipment and protocols, and they guard their SOH intellectual property (IP) carefully. Following SOH assessment, EOL EV LIBs can be reused directly in EVs (as reconditioned batteries) or directed to alternative, lower-demand applications such as residential energy storage, grid-scale energy storage, EV-charging remote energy storage, backup power for campgrounds and cottages, or as battery cells in drones, wheelchairs, and other applications. For example, a Panasonic 18650 battery cell (used in Tesla vehicles) may have a capacity of 3,000 mAh (milliampere-hour) when new, but when degraded to a lower level, it still has appropriate uses, such as in wheelchair at 2,600 mAh, in a drone at 2,400 mAh, in a solar-powered video doorbell unit at 2,200 mAh, or in a strong LED flashlight at 1,500 mAh [17]. However, at 1,100 mAh, the remaining capacity is no longer powerful enough to be reused or repurposed and the battery should be sent for recycling.

Second-life EV LIBs have not been in use long enough to accurately measure their lifespans in different second-life uses. Estimates ranging from 5 to 10 years are typically used in the business, but those numbers are mostly theoretical.

In Canada, several companies have entered the EV LIB reuse and repurposing space on a small scale. For example, EOL EV LIBs are being used to provide energy storage pilot projects in Quadra Island and Seven Sisters Falls, British Columbia (BC), and in Westlock County, Alberta [18].

3.5 EV LIB Recycling Circularity Pathway

In its national blueprint for LIBs for 2021 to 2030, the US government emphasizes the recycling of EV LIBs, citing research that indicates using recycled materials from batteries can decrease costs by 40%, water use by 77%, and energy use by 82% [19].

As mentioned in Section 3.3, cobalt, nickel, and manganese are the major raw materials currently of most interest to EV LIB recyclers, although newer hydrometallurgical processes also recover lithium, with the potential to recover graphite in the future. Processing technologies used to treat EOL EV LIB materials are similar to the processes used for extracting key battery materials from primary ores.

The following processes are currently used to recycle small-scale, consumer-size (below 5 kg) non-EV LIBs, as well as larger EV LIBs, although more pre-processing is needed for larger EV LIBs.

Traditional LIB Recycling

Traditional LIB recycling involves some manual dismantling, hydrometallurgical production of black mass, and pyrometallurgy. Traditional pyrometallurgical LIB recycling focuses on recovering the cathode metals (particularly nickel and cobalt) in metal form [20]. Steel and other metals are sometimes recovered depending on market prices. For example, when steel prices are high, steel casings will be separated and sold to traditional recycling markets. Slags are used in road construction or sometimes disposed of in landfills. Plastics are generally not recycled and are disposed of in landfills or sometimes incinerated. Graphite is generally not recycled in traditional LIB recycling facilities with conventional recycling approaches. Metals are sent for pyrometallurgical (heat-based) processing in smelters, where the recovery rate is typically around 50%, but ranges from 40% to 80%.

Cirba Solutions (formerly Retriev Technologies) has been recycling LIBs for many years. LIBs are processed at their facility in Trail, BC, using a combination of hydrometallurgical separation techniques and manual dismantling. Technicians manually dismantle large format EV battery packs to the module and cell level. A full analysis is carried out on each LIB cell to determine its metal content.

Hydrometallurgical processing is performed to recover lithium, nickel, cobalt, and other materials from EOL LIBs, including graphite from anodes. It differs from traditional pyrometallurgical approaches in that lithium and graphite are also recovered. The recovered chemicals can be used to create cathode active material (CAM) such as lithium hydroxide, lithium carbonate, nickel hydroxide, nickel carbonate, cobalt hydroxide, and other materials in a format suitable for direct sale to battery makers. Every company in this space guards their processing IP, which has usually taken years of investment to develop. Pre-processing can include shredding in either wet or dry processes, one or two stages, with various leachate extraction techniques used to recover the LIB metals.

Direct or Cathode-to-Cathode Recycling

Direct or cathode-to-cathode recycling involves regeneration of degraded CAM by relithiation (i.e., reintroduction of lithium into spent CAM using mechanical, electrochemical, or cathode-healing methods) [21], [22]. Relithiation recovers CAM without decomposition into constituent chemicals or dissolution and precipitation of the whole material. This makes the recycling process more energy efficient than conventional hydrometallurgical methods. Several companies have developed cathode-to-cathode processes that are still at the pilot stage, with no full-scale operation currently in place. Some of the recycling technologies and processes currently in development aim to recover degraded CAM using non-destructive processes. The companies developing these new technologies are most interested in direct recycling or cathode-to-cathode recycling to recover chemicals and chemical powders suitable for direct sale to battery manufacturers rather than producing metal laden materials for smelting. Instead of breaking down cathode materials, they are trying to remove impurities from degraded CAM to effectively regenerate new CAM. Some of these companies only process battery cathodes, leaving the discharging and dismantling of the EV LIB to a separate company.

3.6 Projected EOL EV LIBs for Reuse, Recycling, and New LIB Production

The anticipated EV LIB lifespan is critical when planning for circularity because it impacts the timeline of the EOL EV LIB supply for reuse/repurposing and recycling businesses. Until recently, the lifespan of EV LIBs was assumed to be 8 to 10 years, but recent research by Circular Energy Storage suggests a much longer lifespan of 10 to 20 years [23]. This longer LIB lifespan means that, in some cases, the LIB may last longer than the EV, and the EV LIB will have a second life separate to the EV in which it was initially sold. For this reason, in the following text, EOL EV LIB refers to the battery itself, not the complete EV.

According to the IEA's Sustainable Development Scenario [24], the number of LIBs reaching the end of their first life is expected to surge after 2030, reaching 1.3 TWh (terawatt-hours) in 2040 (for both EV and ESS LIBs combined). More than 80% of the spent batteries in 2040 are expected to come from EVs, more than 10% from electric two- and three-wheelers, more than 5% from buses and trucks, and just over 1% or about 15 GWh (gigawatt-hours) from ESS [24]. These projections suggest that retired LIBs from energy storage facilities will make a small contribution to LIB recycling compared to EOL EVs.

Other estimates of future LIB recycling amounts are even higher. For example, the US Department of Energy's Vehicle Technologies Office reported that about 8 million tonnes of EOL EV LIBs could require proper EOL management by 2040 [25], while Circular Energy Storage predicted that in 2030, the total supply of LIBs available for reuse will be 145 GWh (or 799,000 tonnes), out of 170 GWh (or 820,000 tonnes) available for recycling. Only 16% of this total is projected to be available in Europe and only 10% in the US.

It has been estimated that over 900,000 EV LIB units (from hybrid EVs, plug-in hybrid EVs, and EVs) will reach EOL in the US by 2030, based on an assumed 8- to 10-year lifespan with a modest number of LIBs being directed to reuse [17]. Transport Canada has published projections of ZEV sales in Canada to meet the Government of Canada's mandatory ZEV sales targets [4] discussed in Section 1. Currently, most ZEVs are EVs, with the potential for sales of hydrogen-powered vehicles to increase over time. No projections of EOL EV LIBs (based on the sales projections) have been developed to date. For planning purposes, it is reasonable to expect that the EOL EV LIB number for Canada would be about 10% of the US value, based on the pro-rated populations of the two countries.

There are varying estimates on the extent to which recycling of EV LIBs can contribute to the demand for materials to make the increasingly large number of LIBs needed to electrify transportation. In all cases, the estimates are relatively low, indicating that recycling alone cannot meet the demand for new materials to make new EV LIBs. One estimate is that recycling of LIBs could supply approximately 12% of future demand for cobalt, 7% for nickel, and 5% for lithium [24], while another suggests that metal from recycling EOL EV LIBs and production scrap could account for 15% to 25% of LIB metal needs in 2030 [26]. Either way, while recycling will contribute a valuable material stream to the manufacturing of new LIBs, mining, processing, and refining of raw materials will still need to provide most of the supply.

4 Standards, Codes of Practice, Guidelines, Policies, and Legislation Related to EV LIB Circularity and Safety

4.1 Safety Guidelines, Codes of Practice, and Standards Related to EOL EV LIBs

In this research, interviewees identified safety of EV LIBs as their primary concern, which suggests that industry stakeholders may not be aware that a significant amount of information is already available on this topic. Table 2 provides a list of standards, codes of practice, and guidelines related to EV LIB circularity and safety that were included in the literature review. It should be noted that ESS-related standards deal with batteries that are in stationary locations and have greater storage capacity than EV LIBs. Nonetheless, the documents in Table 2 may provide valuable information for future use in an EV LIBs standardization process.

This research identified five key themes for current standardization efforts, which are discussed below in conjunction with the standards, codes, guidelines, and other documents that are most relevant to each.

1. Fire and Accident Risks

SAE J2990 [50] outlines recommendations for handling of EV LIB risks associated with the chemical, electrical, and thermal risks of high voltage systems to first and second responders to EV accidents. Recommended procedures are focused on emergency responders, tow truck operators, and storage, repair, and salvage personnel after an EV incident.

Although it does not specifically address EV LIBs, NFPA 855 [42] has requirements for the fire protection of ESS installations based on the technology, location, size, and separation of ESS installations, and the fire suppression and control systems in place, which might be considered in the development of similar practices for storage and recycling facilities for EV LIBs. Additional considerations addressed in NFPA 855 include ventilation, detection, signage, listings, and emergency operations responding to ESS emergencies [42].

ANSI/CAN/UL 9540 [28] ensures that electrical, electro-chemical, mechanical, and thermal ESS operate at an optimal level of safety, including ESS that contain LIBs.

Table 2: Standards, Codes of Practice, and Guidelines Related to EV LIB Circularity and Safety

Document	Title	Reference #
ANSI/CAN/UL 9540A (Standard)	Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Storage Systems	[27]
ANSI/CAN/UL 9540 (Standard)	Energy Storage Systems and Equipment	[28]
ANSI/CAN/UL/ULC 2580 (Standard)	Batteries for Use In Electric Vehicles	[29]
ANSI/CAN/UL 1974 (Standard)	Evaluation for Repurposing Batteries	[30]
BSI PAS 7060 (Publicly available specification)	Electric vehicles – Safe and environmentally-conscious design and use of batteries – Guide	[31]
BSI PAS 7061 (Publicly available specification)	Batteries for vehicle propulsion electrification. Safe and environmentally-conscious handling of battery packs and modules – Code of practice	[32]
BSI PAS 7062 (Publicly available specification)	Electric vehicle battery cells. Health and safety, environmental and quality management considerations in cell manufacturing and finished cell – Code of practice	[33]
BSI (Report)	Battery manufacturing and technology standards roadmap	[34]
International Code Council (ICC) IFC (Code)	International Fire Code (new LIB storage requirements were approved for incorporation into 2024 IFC)	[35]
Energy Storage Association (ESA) (Guideline)	Guidelines for end-of-life and recycling of lithium ion battery energy storage systems	[36]
IEC 62660 (Series of Standards)	Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing Part 2: Reliability and abuse testing Part 3: Safety requirements	[37], [38], [39]
ISO 6469-1 (Standard)	Electrically propelled road vehicles — Safety specifications — Part 1: Rechargeable energy storage system (RESS)	[40]
ISO 12405-4 (Standard)	Electrically propelled road vehicles —Test specification for lithium-ion traction battery packs and systems — Part 4: Performance testing	[41]
NFPA 855 (Standard)	Installation of stationary energy storage systems	[42]
SAE J1798 (Standard)	Recommended practice for performance rating of electric vehicle battery modules	[43]
SAE J2288 (Standard)	Life cycle testing of electric vehicle battery modules	[44]
SAE J2464 (Standard)	Electric and hybrid electric vehicle rechargeable energy storage system (RESS) safety and abuse testing	[45]
SAE J2936 (Standard)	Electrical energy storage device labeling recommended practice	[46]
SAE J2950 (Standard)	Recommended practices for shipping transport and handling of automotive-type battery system — lithium ion	[47]

Document	Title	Reference #
SAE J2974 (Standard)	Technical information report on automotive battery recycling	[48]
SAE J2984 (Standard)	Chemical identification of transportation batteries for recycling	[49]
SAE J2990 (Standard)	Hybrid and EV first and second responder recommended practice	[50]
SAE J3042 (Standard)	Measuring properties of Li-ion battery electrolyte	[51]
SAE J3071 (Standard)	Automotive battery recycling identification and cross contamination prevention	[52]
SAE J3108 (Standard)	xEV labels to assist first and second responders, and others	[53]

ANSI/CAN/UL 9540A [27] specifically addresses fire safety hazards at a battery ESS. The data obtained from the test methodology is used to identify the fire and explosion protection required in a battery ESS to prevent thermal runaway.

Finally, SAE J3108 [53] identifies clear and consistent labelling approaches for identifying high voltage locations on various types of EVs and communicating important high voltage information to first responders.

2. Battery Life Expectancy and Module Performance

Standardized testing of battery life expectancy and module performance mainly address EV LIBs and components before they reach the market; few currently address EV LIBs at EOL.

SAE J1798 [43] sets standards to determine EV battery module performance and identifies whether battery modules meet the specifications established by vehicle manufacturers or other purchasers. Battery longevity is tested through SAE J2288 [44], which defines a standardized method to determine the expected service life of EV battery modules in cycles. It uses several baseline assumptions regarding operating conditions to identify the expected decline in electrical performance based on the lifespan of the battery module. It also identifies potential failure mechanisms. EOL is established based on module capacity and power ratings, which allow battery manufacturers to identify the various trade-offs between power and energy in establishing ratings for a battery module.

ANSI/CAN/UL/ULC 2580 [29] evaluates the ability of an EV battery pack and individual modules to safely withstand simulated abuse conditions to prevent any human exposure to hazards as a result of the abuse. The evaluation is based on the manufacturer's specified charge and discharge parameters at specified temperatures. Abnormal operation testing is also considered in SAE J2464 [45] which describes a set of tests for "abuse testing" of EV or hybrid EV batteries to measure the response to conditions or events that are outside normal operating range. Abuse test procedures cover a wide range of vehicles and batteries, including individual cells (batteries or capacitors), modules, and packs.

Test procedures in ISO 6469-1[40] address mechanical, electrical, and functional safety tests, as well as simulated vehicle accident tests for EV RESS (i.e., LIB packs). ISO 6469-1 does not specifically address safety requirements for manufacturing, maintenance, and repair personnel or any issues related to circularity.

3. Labelling and Shipping

SAE J2936 [46] provides labelling guidelines for different components of LIB systems through their lifecycle, from manufacturing to EOL reuse and recycling.

SAE J2950[47] references existing international hazardous materials (dangerous goods) transportation regulations, and provides guidance on determining the transportability of a damaged or defective LIB.

> "First responders dealing with EV LIBs at accidents must be trained to handle the risks posed by EV LIB fires, which create significant health risks and harmful air emissions."

As noted earlier, SAE J3108 identifies clear and consistent approaches to labelling of high voltage locations on EV batteries [53], and SAE J2984 [49] provides a chemistry identification system to support recycling of rechargeable battery systems used in transportation applications.

4. Used Battery Handling, Transportation, Collection, and Storage

The New Zealand Battery Industry Group released guidelines that cover handling and transporting of used battery packs, modules, cells, and other elements; the collection process for large used batteries; features of storage facilities for large used batteries; preparation of batteries for storage; and managing safety-related battery failure events during the handling, collection, storage, and transportation of large used batteries [54].

SAE J2974 [48] provides consistent language to use when an EOL EV LIB is transported between a recycler, dismantler, or another third party for recycling. SAE J2974 also provides flow sheets and describes the recycling technologies available at the time it was written. SAE J3071 [52] provides information on sorting EOL batteries by chemistry.

Transportation, packaging, and storage provisions related to consolidating loads of EOL EV LIBs for transportation to repurposing/recycling facilities have also been documented by a variety of organizations, including Suppliers Partnership for the Environment [55], Call2Recycle [56], and NAATBatt [57]. Information is posted on their websites with links to relevant documents, such as laws, regulations, and transportation best practices.

5. Storage

According to the Portable Rechargeable Battery Association (PRBA), the 2024 revision of the IFC will include new lithium battery storage requirements [58]. The proposed new Section 321 in Chapter 3 of the IFC will include detailed safety requirements for almost all locations that collect and store LIBs, with five exceptions [35].

4.2 EV LIB Safety Training Programs

First responders dealing with EV LIBs at accidents must be trained to handle the risks posed by EV LIB fires, which create significant health risks and harmful air emissions.

To avoid electric shock or serious injury, first responders and others involved with EV LIBs must be trained in how to fully discharge an EV LIB before the EV is moved from the accident site. Emissions from EV LIB fires can create hydrogen fluoride gas, which is toxic to humans and must be avoided [59]. Water used to suppress EV LIB fires can create hydrofluoric acid, which causes environmental pollution that can damage water quality [60].

There are already many training programs on the safe dismantling and discharging of LIBs in EVs, as well as on fire management and safety. The National Fire Protection Association (NFPA) compiled all first responder manuals from automotive OEMs that address specific handling requirements for first responders dealing with fire in an EV, including EV accidents that pose a fire risk and protection of first responders from injury when a fire is already underway. The surrounding environment also needs to be protected from water and air damage related to managing the EV LIB fire [61].

Comprehensive safety resources and protocols for handling LIBs in EVs have been developed by the BC Auto Recycling Association in collaboration with the provincial government, automotive dealers, and a dedicated industry Technical Advisory Committee [62]. The BC training project goals were: (i) to increase occupational health and safety (OHS) awareness among employers, supervisors, and workers about the hazards associated with handling EV LIBs during transportation, dismantling, and storage; and (ii) to improve the understanding of workplace safety risks, effective control measures, OHS program elements, and compliance requirements.

EV training resources have also been created and curated by the Automotive Recyclers of Canada (ARC) [63] and the US-based Automotive Recyclers Association (ARA) [64]. In addition, the Automotive Aftermarket Retailers of Ontario recently launched an EV technician training program for managing LIBs from hybrids and full EVs [65].

4.3 Existing Circularity Standards, Guidelines, and Codes of Practice Related to EV LIBs

Because EVs have only been on the market for a short time, there is a limited number of published documents regarding the circularity of EV LIBs. In 2021, the US Department of Energy's Argonne National Laboratory signed a memorandum of understanding with the National Electrical Manufacturers Association to cooperate on developing recycling standards for LIBs [66] that manufacturers and recyclers can use to assess the amount of extractable and recyclable material in various battery systems. Similarly, in 2019, the British Standards Institution (BSI) established the Faraday Battery Challenge to explore existing standards, regulations, and key knowledge gaps related to production, use and recycling of batteries [67]. BSI proposed to address the most immediate challenges through three Publicly Available Specifications (PAS), which are fast-tracked standardization documents. PAS 7060 addresses vehicle design, battery integration, and battery use for EVs, hybrid EVs, and plug-in hybrid EVs [31]. PAS 7061 provides recommendations for safe and environmentally-conscious handling and management of packs and modules of batteries throughout the life cycle of the battery [32], and PAS 7062 specifies health and safety, fire and environmental performance, and quality management in the manufacture of battery cells [33]. As part of the Faraday Battery Challenge, BSI also published the "Battery Manufacturing and Technology Standards Roadmap" [34], which highlights key areas and themes to support the ongoing growth of EV batteries and provides recommendations for future standards development and supporting activities. While the roadmap focuses on battery manufacturing, it also addresses reuse and recycling of EOL EV LIBs. Key concerns identified in the roadmap consultation process included safety, particularly related to fires, and design for environment or design for recycling to ensure circularity. The roadmap stresses the importance of "the right standard at the right time" [34, pp. 24] in the business cycle.

ISO 12405-4 [41] provides test specifications for lithium-ion traction packs and systems. SAE J3042 [51] provides test methods for measuring the performance of LIB electrolytes. The IEC 62660 series provides testing approaches for lithium-ion cells, including performance testing (Part 1), reliability and abuse testing (Part 2), and safety requirements for lithium-ion cells in EV applications (Part 3) [37], [38], [39].

ANSI/CAN/UL 1974 [30] provides standards to evaluate batteries for repurposing and addresses sorting and grading process for battery packs, modules, and cells for reuse in ESS and other applications in cases where batteries were originally configured and used for other purposes. The standard does not cover remanufactured (i.e., refurbished or rebuilt) batteries. Stakeholders interviewed for this report noted that ANSI/CAN/UL 1974 should be updated to acknowledge new and innovative technologies used for SOH determination.

Although ESS LIBs are much bigger than EV LIBs, some existing ESS LIB documents may provide relevant information for the development of an EV LIB EOL standard, including the Energy Storage Association's (ESA) white paper on options for decommissioning, transportation, second-life, and recycling processes for EOL ESS [36]. Concurrently, the ESA released guidelines for EOL and recycling of LIB ESS to address growing EOL management challenges and to serve as a reference to inform product development, project planning, execution, and policy related to EOL LIB management [36]. The guidelines address LIB ESS decommissioning and recycling, existing facility EOL planning guidelines, EOL considerations for ESS under development, and industry actions to promote and improve recycling.

4.4 Policies and Regulations Related to EV LIB Circularity

A variety of governments around the world are in the process of researching, developing, or implementing policies and regulations pertaining to the circularity of EV LIBs. Generally, most are in the early stages of development because the EV industry is still relatively new and EV LIBs are not expected to reach EOL in large numbers for many years. Table 3 lists existing and proposed policies and regulations related to EV LIB circularity, most of which deal with responsibility for managing EOL EV LIBs. Notes address the status of these policies and regulations, many of which are in flux.

4.4.1 EU and California EV LIB Policies and Regulations

The EU Batteries Directive 2006/66/EC has governed the management of batteries in the EU since 2006 [65]. In December 2020, the European Commission adopted a proposal for new batteries and waste batteries legislation, the EU Batteries Regulation [77], which will repeal Directive 2006/66/EC and pave the way for sustainable batteries as part of a circular, climate-neutral economy, delivering on the Commission's strategic action plan on batteries. Key changes include the shift to a Europe-wide regulation and the adoption of new requirements for social responsibility and environmental sustainability. The key provisions in the proposed Batteries Regulation are described in Table 4. Many are relevant to the longer-term EV LIB circularity business in Canada and the rest of North America, as the provisions may be adopted by automotive OEMs and battery makers on a voluntary basis. The provision for material availability signals a potential supply issue for LIB materials by 2030.

The battery passport requirements will be a digital twin to the physical battery and will contain information on environmental, social, and governance performance, manufacturing history and provenance, as well as advancing battery life extension and enabling recycling. The QR code required in new EV LIBs manufactured from 2027 will facilitate traceability.

To comply with requirements of the new EU Batteries Regulation, the Global Battery Alliance, through its Battery Passport Action Partnership, is developing a method to track the provenance and lifecycle of EV LIBs. The battery passport is expected to launch with full functionality by end of 2022 [78].

Using a different process, the State of California introduced Assembly Bill No. 2832 (AB 2832) in 2018, which convened the Lithium-Ion Battery Recycling Advisory Group to review the 2006 Rechargeable Battery Recycling Act and advise the legislature on policies pertaining to the recovery and recycling of EV LIBs. The advisory group's mandate specified that their recommendations ensure "that as close to 100 percent as possible of lithium-ion batteries in the state are reused or recycled at end-of-life" [15, pp. 98]. Their March 2022 report includes recommendations that focus on the following two areas:

1. "Clearly defining responsibility for the coordination and payment of recycling in cases where the cost presents a burden for the owner of the vehicle and the LIB is unwanted, and
2. Mitigating barriers that may currently inhibit the reuse, repurposing, and recycling of EV LIBs" [15, pp. 9].

To this end, the advisory group identified two key policies for EV LIB EOL management: (i) core exchange with a vehicle backstop, and (ii) producer take-back.

A core exchange policy covers when an EV battery pack, module, or cell is replaced before the vehicle reaches EOL. A core exchange program would be established by the EV battery supplier, who would

Table 3: Existing or Proposed Policies and Regulations Related to EV LIB Circularity

Title (Jurisdiction)	Publication Date, Status, and Notes
Directive 2000/53/EC on end-of-life vehicles (ELV Directive) [63] (European Union)	Originally published in 2000. Reviewed in 2018. Updated Directive expected late 2022 [64].
Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and waste batteries and accumulators (Batteries Directive) [65] (European Union)	Originally published in 2006. Reviewed in 2020. Likely to be replaced by EU Batteries Regulation [66].
Proposed EU Batteries Regulation [67] (European Union)	Stringent recycled content requirements imposed on EOL EV LIBs with provisions for mandatory recycled content and carbon footprint reporting.
California Assembly Bill No. 2832, Recycling: lithium-ion vehicle batteries: advisory group (AB 2832) [68] (California)	Bill established the Lithium-Ion Car Battery Recycling Advisory Group, which prepared a report to the California Legislature recommending "core exchange and vehicle backstop" or producer take back policies for EV LIBs at EOL" [15]. Report was not discussed in 2022 legislative session; next opportunity is in 2023. No recommended approaches moved forward.
Proposed Extended Producer Responsibility (EPR) Regulation, Current status, challenges, and perspectives [69] (Quebec)	Proposal to amend the "Regulation respecting the recovery and reclamation of products by enterprises" under the Environment Quality Act to include EPR Regulation for EV LIBs was released for comment in October 2021. The industry objected to recovery rates and targets, which were based on 10-year LIB lifespan and provided disincentives to good LIB design [70]. A voluntary industry program is now being developed in the province[71] [72].
EPR Five-Year Action Plan [73] (British Columbia	Schedule under Recycling Regulation (B.C. Reg. 449/2004). BC announced an update to the EPR Action Plan in August 2022, confirming that the government intends to add EV batteries to the Recycling Regulation in 2023, with full plan implementation by 2026 [74].
Chinese Ministry of Industry regulations requiring EV manufacturers to set up recycling facilities for batteries (as referenced in [75]) (China)	Announced in 2019.
Proposed product stewardship regulations: Tyres and large batteries [76] (New Zealand)	Announced in 2021. Developing a producer responsibility program for large format batteries, including EV LIBs.

supply the replacement battery (or any module or cell than needs replacing). In these contexts, a "core charge" is typically applied (i.e., the EV owner pays a deposit when purchasing a new battery for the EV). The deposit is refunded when the battery is returned to the dealer or another supplier. A vehicle backstop policy covers situations where the EOL vehicle does not contain an OEM certified battery, or the EOL EV is not processed by a certified dismantler. Under the advisory group's proposal, the vehicle manufacturer would be responsible for ensuring that the EV is dismantled and that the EV LIB is reused, repurposed, or recycled.

A producer take-back policy is when the EV OEM is responsible for ensuring the reuse, repurposing, or recycling of its EV LIBs by a licensed facility. One element of the producer take-back policy is that the consumer does not incur any costs when they no longer want the EV or the EV LIB, and no other entity has taken possession of the EV battery.

These recommended policies are in addition to current warranty regulations and programs that require the vehicle manufacturer to reuse, repurpose, or recycle EOL EV LIBs that are still under warranty.

Table 4: Provisions in Proposed EU Batteries Regulation

Category in Proposed Batteries Regulation	Provisions of Proposed Batteries Regulation
Carbon Intensity	Each model of industrial and EV battery will have to declare its CO2 footprint (from 2024), declare its performance class (from 2026), and meet mandatory CO2 thresholds (from 2027). The method to calculate the CO_2 footprint will be adopted in 2023, the performance classes will be adopted in 2024, and the thresholds in 2026.
Recycled Content	Industrial, EV, and automotive batteries will have to meet the following minimum values of recycled content: cobalt: 12%, lead: 85%, lithium: 4%, and nickel: 4% (by 2030), and meet higher minimum values of recycled content: cobalt: 20%, lead: 85%, lithium: 10%, and nickel: 12% (by 2035). The method to calculate the recycled content will be adopted by December 31, 2025. The targets are subject to a legal review, based on availability of waste materials.
Eco-Design	**Performance & Durability:** From 2026, rechargeable industrial and EV batteries shall meet minimum electrochemical performance and durability parameters. **Removability & Replaceability:** Industrial and EV batteries shall include a battery management system (BMS) containing state of health (SOH) data and expected lifetime of the battery. Access to the BMS shall be provided to the owner of the battery or any third party evaluating the residual value and capability for further use or facilitating reuse/repurposing/remanufacturing **Repurposing & Remanufacturing:** Independent operators shall be given access to the BMS. Independent operators shall be given access to the information relevant for handling and testing.
Information Requirements	**Label:** From 2027, batteries must carry a label containing manufacturer's information, battery type and manufacturing information, place of manufacture information, and substances information (state of charge and critical raw materials). Portable and automotive batteries must contain performance information (capacity, duration). **QR Code:** From 2027, batteries must have a QR code providing label information as well as information on conformity assessment (2023), reuse/repurposing (2023), due diligence (2024), CO_2 emissions (2026), and recycled content (2027). **Battery Passport:** From 2026, each industrial and EV battery must carry an electronic battery passport.
Conformity	Before a battery is placed on the EU market, the manufacturer or its authorized representative (for manufactures established outside the EU) must perform a conformity assessment on their product in the language of the Member State they place a battery onto. Conformity with the following articles must be demonstrated: hazardous substances requirements for cadmium and mercury (and potentially new substances); BMS requirements; safety requirements; labelling/QR code and circular economy marking requirements; performance and durability criteria; carbon footprint; recycled content; and due diligence.

The advisory group also supported labeling and digital identifier requirements, as well as incentive packages, guaranteed permitting timelines for recycling facilities, and enforcement of laws targeting unlicensed dismantlers. Moreover, they supported the development of collection and sorting infrastructure at strategic locations to reduce transportation costs. Finally, the advisory group also recommended that safety and regulatory requirement training programs should be developed for people who handle EOL EVs. The report was not addressed during the 2022 legislative session and will be reconsidered during the 2023 session.

4.4.2 EPR Legislation in Canada, New Zealand, and China in 2022

While efforts have been made to consider EPR for EV LIBs, the issue is complicated by the fact that EV LIBs can have a long first life in the marketplace, followed by a second life when they are no longer useful for the EV.

In September 2021, the province of BC announced that EV batteries will become eligible for province-wide recycling under the Recycling Regulation's Extended Producer Responsibility Plans, which are part of a

> “While efforts have been made to consider EPR for EV LIBs, the issue is complicated by the fact that EV LIBs can have a long first life in the marketplace, followed by a second life when they are no longer useful for the EV.”

five-year plan to advance recycling in the province. This provides sufficient time to set up the necessary systems, although the government has committed to accelerating proposed timelines where possible [74]. Under this strategy, manufacturers, sellers or distributors, owners or licensees of a trademark, and importers are responsible for implementing, funding, and managing recycling programs for a variety of materials (tires, electronics, paint, etc.). EV LIBs are scheduled to be added to the Recycling Regulation in late 2023, and EPR programs are scheduled to be operational in 2026 [74]. It is expected that compliance with the Regulation will be met through a combination of reuse/repurposing and recycling. The BC government held webinars in September 2022 outlining compliance requirements and obligations.

In October 2021, the province of Quebec released a draft update to an existing producer responsibility regulation proposing an EPR system for EV LIBs, making Quebec the first jurisdiction in North America to do so [79]. Assuming a 10-year EV LIB lifespan, the draft legislation included minimum recovery and recycling rates for EOL EV LIBs, ultimately reaching a 90 percent recovery rate after 10 years. However, the proposed legislation did not account for LIB second-life reuse and repurposing in its lifespan calculations. As current research indicates that LIBs can last up to 15 years in an EV, there were concerns that the draft legislation would encourage manufacturers to install inferior LIBs with limited 10-year lifespans in new vehicles to meet the requirements [70]. This would reward manufacturers of shorter lifespan EV LIBs and penalize companies manufacturing long-life LIBs. Feedback obtained through the consultation process suggested that LIB producers should be responsible for the batteries they produce and should have to collect their LIBs at EOL upon request, which would encourage automotive OEMs to focus on battery longevity.

The updated regulation was enacted on June 1, 2022, but due to the number of comments received from stakeholders, EV LIBs were removed from the list of products covered by the update. Instead, the government and the EV industry are in discussions about establishing a voluntary recovery program starting in the spring of 2023 [71], [72].

The Chinese Ministry of Industry and Information Technology established high minimum recovery rates for materials recovered from EOL EV LIBs, which have been effective since January 1, 2021, and include 98% recovery rates for nickel, cobalt, and manganese; 85% for lithium; and 97% for rare earth elements. These recovery targets are exceptionally high compared to targets set in most recycling regulations and are challenging to reach with currently available recycling approaches. The regulations are expected to increase supplies of metals to be used predominantly in new EV batteries [80]. It is worth noting that China adopted EVs faster than other countries, and the first LIBs from EVs introduced to the Chinese market in 2008 are expected to reach their end of first life in 2022. It is estimated that 720,000 tonnes of EV LIBs will be available for recycling in China by 2025 [81].

New Zealand's Ministry for the Environment is currently developing a producer responsibility program for large format batteries, including EV LIBs [76]. In 2020, an estimated 1,000 EV LIBs reached EOL in New Zealand, and by 2030, that number could be as high as 84,000 EV LIBs reaching EOL annually [76]. The producer responsibility program, which will include second-life repurposers, will be run by a product stewardship organization that will oversee and administer the payment of incentives to recyclers.

4.5 Regulation of Handling, Storage, and Transportation of EOL EV LIBs in the US, Canada, and Internationally

One critical need for a circular EOL EV LIB system is to establish collection systems and storage facilities to consolidate LIBs so larger loads can be transported to central locations for recycling and reuse or repurposing.

Given the highly reactive nature of lithium, most international regulations classify LIB cells and systems as dangerous goods. Lithium cells and battery systems are classified under Class 9, Miscellaneous dangerous goods, and numbered UN 3480 (Lithium-ion batteries) or UN 3090 (Lithium-metal batteries) [82]. UN 3536 is assigned to lithium batteries installed in cargo transport units [83].

In the US, the Hazardous Materials Regulations, contained within Title 49 of the Code of Federal Regulations, govern handling, transportation, and packaging of dangerous goods, including LIB systems and cells [84].

In Canada, handling of LIBs is subject to the Transportation of Dangerous Goods Act, 1992 (TDGA) and its regulations [85], and Transport Canada has published a document offering specific guidance on the transport of batteries [86]. Operators and recyclers indicated that transportation regulations in Canada are cumbersome and simplification is needed to move LIBs more efficiently with lower costs. Transport Canada is working with various stakeholders to address this issue.

Participants interviewed for this report specified that current transportation regulations for EV LIBs crossing the border between Canada and the United States are a barrier to EV LIB recycling because they are subject to both the TDGA and to Environment and Climate Change Canada regulations. For shipments of EOL EV LIBs crossing from one province or territory to another, ECCC regulations apply as well as the provincial or territorial hazardous waste regulations that apply may contain slightly different rules. These regulatory differences confuse recyclers and disincentivize their efforts to ship EOL EV LIBs for recycling in a different province. In some cases, interviewees reported that it is easier to ship EOL EV LIBs from Eastern Canada through the US to BC, rather than across Canada, to avoid a burdensome regulatory system.

In 2022, Suppliers Partnership for the Environment, in collaboration with Call2Recycle, published a guidance document on regulations governing transportation, packaging, and storage of EOL EV LIBs in the US [87].

5 Gap Analysis and Recommendations

Circularity of EV LIBs refers to keeping LIBs in service as long as possible through second-life applications and subsequent recycling to recover and, ideally, to reintroduce the valuable materials that they contain back into the supply chain to make new LIBs. In the past, second-life applications were not well developed and it is still a growing field with many small start-ups.

Until recently, recycling of LIBs (mostly consumer-sized LIBs from mobile phones and laptops, and some primary LIBs from military and other specialized applications) involved pre-processing to separate steel casings and other components, and creation of black mass, which was sent to smelters to recover nickel and cobalt. These recycling approaches recover lithium for a variety of applications and do not recover graphite. Graphite and sometimes lithium are lost or incinerated in the recycling process.

A range of new recycling technologies that use sophisticated hydrometallurgical approaches have been developed and will make the LIB supply chain and reverse supply chain highly circular in the long-term. Some of these technologies produce lithium, cobalt, and nickel sulfates, while others involve direct recycling or cathode-to-cathode recycling. All promise material recoveries of 90% or more compared to current recovery rates of 50% to 60%.

Because second-life applications and more sophisticated recycling technologies and approaches for EV LIBs are still new, many of the companies involved are currently in the commercialization stages and have yet to operate at a large scale. These companies need time to mature before standards can realistically be developed.

The supply of EV LIBs reaching the end of their first life is currently small and not expected to see a significant increase for many years. Recent research indicates that the lifespan of new EV LIBs may be 15 years or more, with additional second-life duration of 5 to 10 years. This means that EV LIBs introduced into the market today may not be available for recycling for 15 to 25 years. LIB recyclers need a greater supply of materials to operate at scale. While production scrap can provide some of the required supply, EOL EV LIBs are necessary for the operation of many planned recycling facilities.

Through the interviews with stakeholders from the EV LIB circularity supply chain, this research identified gaps where standards, guidelines, or codes of practice could be useful but are not currently available because the reuse and recycling of EV LIBs is a young business. These gaps are discussed in more detail in Sections 5.1 through 5.5, followed by recommendations emerging from this research.

5.1 Safe EV LIB Handling Knowledge Gaps

There are two critical safety issues regarding management of EOL EV LIBs:

1. Discharging an EV LIB safely, and
2. Managing an EV LIB fire.

The electrical charge of EV LIBs must be drawn before they can be moved from either a fire or an accident location. If the LIB is not fully discharged before relocation or removal, there is a risk of electric shock or serious injury to tow truck drivers or other workers (e.g., auto recyclers) handling removal of the EV or LIB and to first responders arriving at the scene of an accident or fire. It is essential that anyone dealing with an EV LIB understands how to safely discharge a LIB. Section 4 describes several resources on this topic that are available through different organizations, but there appears to be a coordination gap, which has resulted in unpublicized resources among various stakeholders involved in the need to discharge EV LIBs.

EV LIB fires can occur at a facility (warehouse, recycling facility, storage location) or at a vehicle collision involving an EV. There was a general concern expressed by nearly all of the 30 stakeholders interviewed for this report that the health and safety of many workers involved in managing EV LIBs is not sufficiently addressed through awareness or education programs.

First responders need to learn how to manage an EV LIB fire, and must understand the health and safety risks involved (explosions, high temperatures, and toxic gases). Municipal and environmental agency officials must fully understand the environmental impacts of managing EV LIB fires (e.g., production of hydrogen fluoride gas, and acid formation when water is poured on the fire).

Many organizations already provide training and manuals (discussed in Section 4) covering these health and safety topics, but this research suggests there is a lack of awareness across the EV LIB supply chain that these resources exist, which has contributed to the knowledge gap in this area.

One way to address this gap is through a concierge service, which could establish a repository for all existing public documents on safety related to EV LIBs, particularly for first responders, as well as for tow truck operators and auto recyclers.

5.2 Second-Life EV LIB Gaps

Because the second-life EV LIB business is in the early stages of development, the business models are not yet clear and there are many variations in business practices and approaches. SOH testing allows the functionality of the LIB components to be measured so the LIB can be directed to its highest and best use, consistent with circularity principles.

Interviewees identified the following gaps related to optimizing the second life of EV LIBs:

- Second-life companies and recyclers identified transparent labelling and traceability of information on the history of the EV LIB pack and cells as a critical need. They recommended a system to track duty cycles, such as information on whether the battery cells have been abused through poor cycle management, or whether the pack has been in an accident. Many approaches could potentially be used to address this, including standardized SOH testing to measure the parameters of interest or, when fully developed, the Global Battery Alliance's battery passport could address this need through open-source sharing of data. A QR code similar to that required by the EU Batteries Regulation could also be used to meet this need over time, but it would likely only be applicable to new LIBs and therefore would not be present in EOL EV LIBs for several years.

- Users of ANSI/CAN/UL 1974 (particularly small companies) suggested that the standard be updated to acknowledge new technologies used for SOH determination in EV LIB evaluation. In particular, a standard that addresses the needs of very small (under five people) operations may be required.
- Some new members of the second-life EV LIB business reported difficulty obtaining municipal building permits, financing, loans, and business insurance (general commercial) because the business risk is not well understood by bankers, insurance agents, municipal planning staff, and so on. They identified the need for a document to provide clarity on liability and risk concerns.
- Second-life battery companies noted that customers purchasing second-life EV LIBs, particularly electrical utilities, are asking for standards that specify the performance requirements and other characteristics of second-life EV LIBs. This is particularly a concern and need for second-life LIBs that are being used for grid-scale ESS.
- Interviewees identified liability and responsibility for EV LIBs through the supply chain as a concern for second-life applications, particularly in situations where there is a risk of fire, and it is challenging to identify the party responsible to pay for damages. There is no clear definition of who owns the second-life EV LIB or the cells or packs taken from an EV LIB and repurposed. Moreover, there is no clear definition of who is liable and responsible when a fire or other incident occurs with a second-life EV LIB cell, pack, or assembly. This gap could impede circularity due to risk aversion.

5.3 EV LIB Recycling-Related Gaps

Standards and regulations for EV LIBs are being developed in the EU and China with very high recycling/recovery rates for LIB materials, as well as mandatory recycled content for new LIBs, which can only be achieved by recycling EOL LIBs. The literature review and stakeholder interviews conducted for this report identified a few EV LIB recycling-related standards for North America, and it is likely that more will be developed as the supply of EOL EV LIBs increases.

Recyclers recommended the development of standards for design for recycling/design for environment for EV LIBs being manufactured today. Design for reuse and recycling needs to be addressed by OEMs at the front end of the EV and LIB manufacturing processes in order to overcome the gap in design for EOL. These standards would facilitate easier-to-dismantle LIB designs. In the UK, BSI PAS 7060 addresses design for recycling and reuse within a broader environmental context. North American guidelines addressing specific design for reuse and recycling issues would likely be well received.

Another gap noted by recyclers is the need for specific labelling by chemistry as well as cell design (pouch, cylindrical, prismatic) to assist in the efficient reuse and recycling of EV LIBs. While labelling standards such as SAE J2984 exist, it would appear that they are not currently widely applied.

5.4 EOL EV LIB Transportation and Storage Gaps

Current regulations for transportation and storage of EOL EV LIBs are complex and a burden on recyclers in particular, and in some cases, they impede optimal circularity of EV LIBs.

The lack of simple, harmonized transportation and storage regulations among North American countries to facilitate EOL EV LIB circularity was also noted as a gap. While the three countries function as an integrated auto and recycling market, they have different rules and regulations covering the recycling of EV LIBs.

5.5 Data and Information Gaps

Transport Canada has developed projections of ZEV sales based on current Government of Canada sales targets [4]. Estimates of EV LIBs reaching EOL are not publicly available for Canada at this time. This information would be useful for planning purposes for reuse and recycling companies supporting EV LIB circularity. Projections should be developed, assumptions clearly documented, and results should be shared publicly.

5.6 Recommendations

The literature review and interviews conducted for this report informed six key recommendations to support the circularity and recycling of EV LIBs in Canada.

Recommendation 1: Revisit EV LIB Landscape Periodically

Given the rapid pace at which the EV LIB reuse and recycling business is developing, along with provincial and federal government considerations for legislation targeting EV LIBs, the EV LIB landscape should be revisited periodically over the next 3 to 5 years to evaluate the need for additional standards to promote circularity. The need for specific standards will become clearer when the EV LIB circularity industry reaches a sufficient level of maturity where the presence of standards would be useful.

Recommendation 2: Develop EV LIB Circularity Standards Roadmap

An EV LIB circularity standards roadmap that provides a timeline for when specific EOL EV LIB circularity-related standards could be developed should be created. Because technologies are evolving rapidly, the development of a recycling standard for EOL EV LIBs is currently considered to be premature. However, it is anticipated that the circularity landscape and the need for particular standards will become more clear by 2024.

Recommendation 3: Research Design for Environment/Design for Recycling Guideline for EV LIBs

Current EV LIB designs (e.g., the use of glue to assemble the LIB) make it challenging to dismantle LIBs. Application of design for environment or design for recycling guideline or standard would facilitate EV LIB circularity.

Recommendation 4: Update and Develop Specific Second-Life EV LIB Documents

While ANSI/CAN/UL 1974 addresses sorting, grading, and evaluation for reuse or repurposing of batteries, it focuses on EV LIBs in ESS and other second-life applications. Stakeholders report that new SOH testing methodologies have been developed since ANSI/CAN/UL 1974 was released, so an updated standard, potentially one that addresses the needs of very small companies, is recommended. In addition, a summary document that includes specific EV LIB circularity needs as well as a description of second-life businesses is recommended to help inform those who issue municipal building permits or provide financing and insurance to second-life battery businesses.

Recommendation 5: Create Guideline for Calculating Environmental Footprint of EV LIB Recycling and Reuse/Repurposing

A guideline providing a calculation methodology and documentation of the carbon footprint and other environmental benefits of recycling EV LIBs as well as for reused and repurposed EV LIBs (compared to new LIBs) should be developed.

Recommendation 6: Develop Publicly Available EOL EV LIB Projections to 2050 for Canada

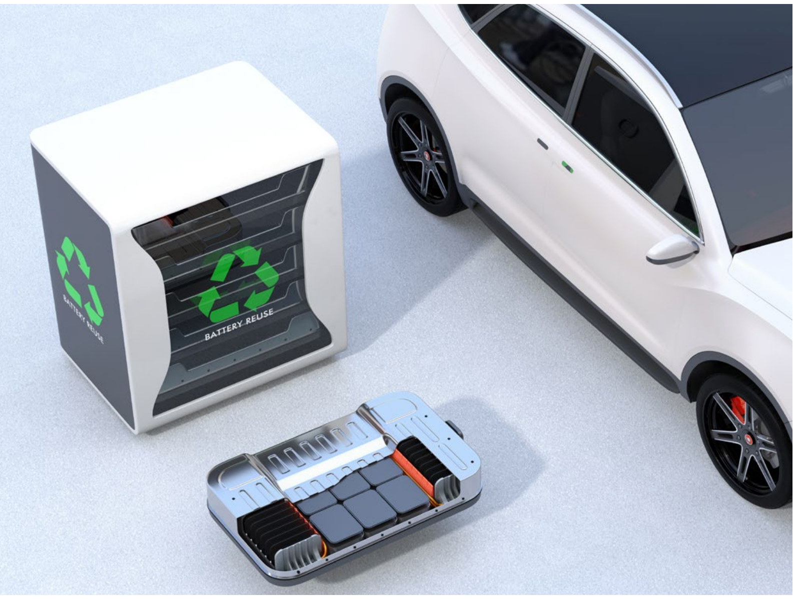
Estimates of EOL EV LIBs entering the Canadian marketplace from now to 2050 should be developed, as they would be useful to EV LIB circularity companies and would provide legitimate third-party estimates on which to base business planning.

6 Conclusions

EV LIB circularity refers to extending the life of a LIB after its first use in an EV through reuse/repurposing in a second-life application before it is ultimately recycled to recover valuable materials (lithium, cobalt, nickel, graphite, copper, manganese, and aluminum), which are then reintroduced into the supply chain to make new EV LIBs. Auto recyclers across Canada have reported seeing an increased number of LIBs at their facilities in EOL EVs, some through vehicle accidents and some through the vehicle EOL cycle. Although EV LIBs are not accumulating at auto recycler facilities in significant numbers yet, some facilities have indicated that they do not know what to do with the EV LIBs at this time.

Through a literature review, gap analysis, and interviews with 30 representatives from the EV LIB supply chain, this report assessed the potential role of standards and safety requirements in supporting the circularity of EV LIBs. Conclusions from this research are summarized below:

- LIBs are lasting longer than originally anticipated in their first life in an EV (between 12–15 years, according to current research). This has many implications for EV LIB circularity in terms of the



> “Auto recyclers across Canada have reported seeing an increased number of LIBs at their facilities in EOL EVs, some through vehicle accidents and some through the vehicle EOL cycle.”

supply that is available to reuse and recycling companies, and the rate at which the supply will become available. Accurate projections of the available supply must be developed to support planning for EV LIB circularity.

- Because most EV LIBs will not reach end of their first life for many years, and many may be directed to a second life of another 5 to 10 years, supplies of EOL EV LIBs will be modest for many years.
- Battery chemistries are changing, and longer lasting batteries are being developed, which will further delay the supply of EOL EV LIBs in the marketplace.
- EV LIB businesses (both reuse and recycling) are currently developing and innovating, and the industry is expected to move at a rapid rate in the coming years. The market structure and business model for EV LIB reuse/repurposing and recycling businesses is still evolving, which means there are many variables and significant complexity in this market at this time, which is expected to continue over the next few years.
- Standards have many benefits, including creating a level playing field among industry participants, giving credibility and structure to a business, driving transparency and confidence, as well as being popular with customers. However, the timing of when standards are developed is an important consideration.
- Guidelines, codes of practice, standards, and regulations could all help reduce liability ambiguities among different players in the EOL EV LIB circularity supply chain, and could provide clarity regarding the legal ownership of an EV LIB, particularly when it enters a second life.
- Access to the history of an EV LIB would help in assessing second-life options and ensure that the LIB or its components are directed to their highest and best use at the end of its first life. While some of this information can be found through SOH testing and the EV LIB BMS, this research found that traceability systems after an EV LIB’s first life would be helpful but do not currently exist.
- Identifying the specific EV LIB chemistry through labelling would be a valuable aid to increase LIB circularity through reuse and recycling. While SAE J2984 sets out labelling standards, they appear not to have been widely adopted by battery makers and auto companies to date. A process to encourage broad adoption of the labelling standard should be considered.
- Currently, estimates of EV LIBs reaching EOL are not publicly available for Canada, a gap that needs to be addressed in order to support circularity of LIBs over the long-term.

References

[1] Statistics Canada, "Table 23-10-0067-01, Vehicle registrations by type of vehicles," Statistics Canada, Ottawa, Canada, 2020. [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310006701

[2] Statistics Canada, "Table 20-10-0001-01, New motor vehicle sales," Statistics Canada, Ottawa, Canada, 2022. [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2010000101

[3] Environment and Climate Change Canada, "2030 emissions reduction plan: Canada's next steps for clean air and a strong economy," Environment and Climate Change Canada, 2022. Accessed: Sep. 27, 2022. [Online]. Available: https://publications.gc.ca/collections/collection_2022/eccc/En4-460-2022-eng.pdf

[4] Transport Canada, "Projected Annual Zero-Emission Vehicle Sales and Stock," Transport Canada, 2022. Accessed: Sep. 27, 2022. [Online]. Available: https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/projected-annual-zero-emission-vehicle-sales-stock

[5] R. Irle. "Global EV sales for 2021." EV-volumes.com. https://www.ev-volumes.com/ (accessed Jul. 2022).

[6] M. Rabson. "Canada EV sales grew in 2021 but are not on track for federal targets." CanadaAutonews.com. https://canada.autonews.com/electric-vehicles/canadian-ev-sales-grew-2021-are-not-track-federal-targets (accessed Jul. 2022).

[7] L. Paoli, "Electric vehicles," International Energy Agency, Paris, France, 2022. Accessed: Jul. 2022. [Online]. Available: https://www.iea.org/reports/electric-vehicles

[8] R. Berger. "Global demand for lithium-ion batteries to quadruple by 2030." Consultancy.uk. https://www.consultancy.uk/news/31072/global-demand-for-lithium-ion-batteries-to-quadruple-by-2030 (accessed Jun. 2022).

[9] M. Placek. "Projected global battery demand from 2020 to 2030, by application." Statista.com. https://www.statista.com/statistics/1103218/global-battery-demand-forecast/ (accessed Mar. 2022).

[10] M. Pagliaro and F. Meneguzzo, "Lithium battery reusing and recycling: A circular economy insight," *Heliyon,* vol. 5, no. 6, e01866, Jun. 2019, doi: 10.1016/j.heliyon.2019.e01866.

[11] K. Rudisuela. "Battle of the batteries – cost versus performance." Nickel Institute.org. https://nickelinstitute.org/en/blog/2020/june/battle-of-the-batteries-cost-versus-performance/ (accessed Mar. 2022).

[12] G. Bhutada. "The key minerals in an EV battery." VisualCapitalist.com. https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/ (accessed Jul. 2022).

[13] Adamas Intelligence. "High nickel battery chemistries led the pack in 2021." AdamasIntel.com. https://www.adamasintel.com/nickeliferous-battery-chemistries-led-the-pack-in-2021/ (accessed Apr. 2022).

[14] Mining.com. "NMC batteries dominating EV – sales to reach 63% of global market." Mining.com. https://www.mining.com/nmc-batteries-dominating-ev-sales-reach-63-global-market/ (accessed Mar. 2022).

[15] A. Kendall, M. Slaterry, and J. Dunn, "Lithium-ion car battery recycling advisory group final report," California Environmental Protection Agency, Sacramento, CA, US, Mar. 16, 2022. Accessed: Mar. 2022. [Online]. Available: https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf

[16] S. M. Rezvanizaniani, Z. Liu, Y. Chen, and J. Lee, “Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility,” *Journal of Power Sources,* vol. 256, pp. 110–124, Jun. 2014, doi: 10.1016/j.jpowsour.2014.01.085.

[17] Kelleher Environmental, “Research study on reuse and recycling of batteries employed in electric vehicles,” American Petroleum Insitute, Washington, DC, US, Sep. 2019. Accessed: Mar. 2022. [Online]. Available: https://www.api.org/~/media/Files/Oil-and-Natural-Gas/Fuels/Kelleher%20Final%20EV%20Battery%20Reuse%20and%20Recycling%20Report%20to%20API%2018Sept2019%20edits%2018Dec2019.pdf

[18] Moment Energy. “We can help you make a sustainable impact in your community.” MomentEnergy.com. https://www.momentenergy.com/our-projects (accessed Apr. 2022).

[19] Federal Consortium for Advanced Batteries, “Executive summary: National blueprint for lithium batteries, 2021–2030,” US Department of Energy, Washington, DC, US, Jun. 2021. Accessed: Feb. 2022. [Online]. Available: https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf

[20] O. Velázquez-Martínez, J. Valio, A. Santasalo-Aarnio, M. Reuter, and R. Serna-Guerrero, “A critical review of lithium-ion battery recycling processes from a circular economy perspective,” *Batteries,* vol. 5, no. 4, p. 68, Nov. 2019, doi: 10.3390/batteries5040068.

[21] ReCell Advance Battery Recycling, “Direct cathode recycling,” ReCellCenter.org. https://recellcenter.org/research/direct-cathode-recycling/ (accessed Mar. 2022).

[22] S. Sloop et al., “A direct recycling case study from a lithium-ion battery recall,” *Sustainable Materials and Technologies,* vol. 25, e00152, Sep. 2020, doi: 10.1016/j.susmat.2020.e00152.

[23] H. E. Melin. (2022). A second life for EV batteries [Online]. Available: https://www.slideshare.net/emmaline742/a-second-life-for-ev-batteries-by-hans-eric-melin

[24] International Energy Agency, “The role of critical minerals in clean energy transitions,” International Energy Agency, Paris, France, 2021. Accessed: Mar. 2022. [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[25] S. Gillard, L. Gaines, and J. Spangenberger. (2019). Lithium-ion recycling centre overview [Online]. Available: https://www.energy.gov/sites/default/files/2019/06/f64/bat377_spangenberger_2019_o_5.14_2.58pm_jl_chg6.4ls.pdf

[26] C. Pillot. (2019). The rechargeable battery market and main trends 2018–2030 [Online]. Available: https://rechargebatteries.org/wp-content/uploads/2019/02/Keynote_2_AVICENNE_Christophe-Pillot.pdf

[27] *Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems,* ANSI/CAN/UL 9540A, UL, Nov. 12, 2019. [Online]. Available: https://www.shopulstandards.com/ProductDetail.aspx?UniqueKey=36503

[28] *Energy Storage Systems and Equipment,* ANSI/CAN/UL 9540, UL, Feb. 27, 2020. [Online]. Available: https://www.shopulstandards.com/ProductDetail.aspx?productId=UL9540_2_S_20200227

[29] *Batteries for Use in Electric Vehicles,* ANSI/CAN/UL/ULC 2580,” UL Canada, Mar. 11, 2020. [Online]. Available: https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL2580

[30] *Evaluation for Repurposing Batteries,* ANSI/CAN/UL 1974, UL, Oct. 25, 2018. [Online]. Available: https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL1974_1_S_20181025

[31] *Electric vehicles. Safe and environmentally-conscious design and use of batteries. Guide*, BSI PAS 7060, British Standards Institution, London, UK, Jan. 31, 2021. [Online]. Available: https://knowledge.bsigroup.com/products/electric-vehicles-safe-and-environmentally-conscious-design-and-use-of-batteries-guide/standard

[32] *Batteries for vehicle propulsion electrification. Safe and environmentally-conscious handling of battery packs and modules. Code of practice,* BSI PAS 7061, British Standards Institution, London, UK, Jan. 31, 2021. [Online]. Available: https://knowledge.bsigroup.com/products/batteries-for-vehicle-propulsion-electrification-safe-and-environmentally-conscious-handling-of-battery-packs-and-modules-code-of-practice/standard

[33] *Electric vehicle battery cells. Health and safety, environmental and quality management considerations in cell manufacturing and finished cell. Code of practice,* BSI PAS 7062, British Standards Institution, London, UK, Jan. 31, 2021. [Online]. Available: https://knowledge.bsigroup.com/products/electric-vehicle-battery-cells-health-and-safety-environmental-and-quality-management-considerations-in-cell-manufacturing-and-finished-cell-code-of-practice/standard

[34] British Standards Institution, “Battery manufacturing and technology standards roadmap: Enhancing the UK’s battery manufacturing capabilities and enabling battery technology innovation,” British Standard Institution, London, UK, Jul. 2021. Accessed: Feb. 2022. [Online]. Available: https://www.bsigroup.com/globalassets/localfiles/en-th/industries-and-sectors/energy-and-utilities/fbc-battery-manufacturing-and-technology-roadmap-th.pdf

[35] G. A. Kerchner. (2021). New storage requirements for lithium batteries in International Fire Code [PowerPoint slides]. Available: https://www.prba.org/wp-content/uploads/2021/11/Update-on-Fire-Codes-and-Lithium-Batteries-for-EPA-Lithium-ion-Battery-Workshop-October-2021-4853-2255-9743-v.3.pptx

[36] Energy Storage Association, “ESA corporate responsibility initiative: Guidelines for end-of-life and recycling of lithium ion battery energy storage systems,” Energy Storage Association, Washington, DC, US, Aug. 2020. Accessed: Feb. 2022. [Online]. Available: https://energystorage.org/wp/wp-content/uploads/2020/08/ESA-Corporate-Responsibility-Initiative-Guidelines-for-End-of-Life-and-Recycling-of-Lithium-Ion-Battery-Energy-Storage-Systems.pdf

[37] *Secondary Lithium-Ion Cells for the Propulsion of Electric Road Vehicles – Part 1: Performance Testing,* IEC 62660-1:2018, International Electrotechnical Commission, Geneva, Switzerland, Dec. 12, 2018. [Online]. Available: https://webstore.iec.ch/publication/28965

[38] *Secondary Lithium-ion Cells for the Propulsion of Electric Road Vehicles – Part 2: Reliability and Abuse Testing,* IEC 62660-2:2018, International Electrotechnical Commission, Geneva, Switzerland, Dec. 12, 2018. [Online]. Available: https://webstore.iec.ch/publication/27387

[39] *Secondary Lithium-ion Cells for the Propulsion of Electric Road Vehicles – Part 3: Safety Requirements,* IEC 62660-3:2022, International Electrotechnical Commission, Geneva, Switzerland, 1 March 2022. [Online]. Available: https://webstore.iec.ch/publication/65084

[40] *Electrically Propelled Road Vehicles — Safety Specifications — Part 1: Rechargeable Energy Storage System (RESS)*, ISO 6469-1:2019, International Organization for Standardization, Geneva, Switzerland, Apr. 2019. [Online]. Available: https://www.iso.org/standard/68665.html

[41] *Electrically Propelled Road Vehicles — Test Specification for Lithium-Ion Traction Battery Pack and Systems — Part 4: Performance Testing,* ISO 12405-4:2018, International Organization for Standardization, Geneva, Switzerland, Jul. 2018. [Online]. Available: https://www.iso.org/standard/71407.html

[42] *Installation of Stationary Energy Storage Systems,* NFPA 855, National Fire Protection Agency, Quincy, MA, US, Apr. 1, 2020. [Online]. Available: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=855&year=2020

[43] *Recommended Practice for Performance Rating of Electric Vehicle Battery Modules (STABILIZED Nov 2019),* SAE J1798_201911, SAE International, Warrendale, PA, US, Nov. 13, 2019. [Online]. Available: https://www.sae.org/standards/content/j1798_201911/

[44] *Life Cycle Testing of Electric Vehicle Battery Modules (STABILIZED Nov 2020),* SAE J2288_202011, SAE International, Warrendale, PA, US, Nov. 30, 2020. [Online]. Available: https://www.sae.org/standards/content/j2288_202011/

[45] *Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing,* SAE J2464_202108, SAE International, Warrendale, PA, US, Aug. 23, 2021. [Online]. Available: https://www.sae.org/standards/content/j2464_202108/

[46] *Electrical Energy Storage Device Labeling Recommended Practice,* SAE J2936_201212, SAE International, Warrendale, PA, US, Dec. 7, 2012. [Online]. Available: https://www.sae.org/standards/content/j2936_201212/

[47] *Recommended Practices for Shipping Transport and Handling of Automotive-Type Battery System – Lithium Ion,* SAE J2950_202006," SAE International, Warrendale, PA, US, Jun. 9, 2020. [Online]. Available: https://www.sae.org/standards/content/j2950_202006

[48] *Technical Information Report on Automotive Battery Recycling,* SAE J2974_201902, SAE International, Warrendale, PA, US, Feb. 11,2019. [Online]. Available: https://www.sae.org/standards/content/j2974_201902/ /

[49] *Chemical Identification of Transportation Batteries for Recycling,* SAE J2984_202109, SAE International, Warrendale, PA, US, Sep. 10, 2021. [Online]. Available: https://www.sae.org/standards/content/j2984_202109/

[50] *Hybrid and EV First and Second Responder Recommended Practice,* SAE J2990_201907, SAE International, Warrendale, PA, US, Jul. 29, 2019. [Online]. Available: https://www.sae.org/standards/content/j2990_201907/

[51] *Measuring Properties of Li-Battery Electrolyte,* SAE J3042_202101, SAE International, Warrendale, PA, US, Jan. 27, 2021. [Online]. Available: https://www.sae.org/standards/content/j3042_202101/).

[52] *Automotive Battery Recycling Identification and Cross Contamination Prevention,* SAE J3071_201604," SAE International, Warrendale, PA, US, Apr. 5, 2016. [Online]. Available: https://www.sae.org/standards/content/j3071_201604/

[53] *xEV Labels to Assist First and Second Responders, and Others,* SAE J3108_201703," SAE International, Warrendale, PA, US, Mar. 2, 2017. [Online]. Available: https://www.sae.org/standards/content/j3108_201703/

[54] The Battery Industry Group. "The B.I.G. large battery scheme." BIG.org.nz. https://big.org.nz/ (accessed Feb. 2022).

[55] Suppliers Partnership for the Environment. "EV battery recycling resources for recyclers/dismantlers." SuppliersPartnership.org. https://www.supplierspartnership.org/evb-recycling/ (accessed Jul. 2022).

[56] Call2Recycle. “Charge up safety: Safely making a positive impact.” Call2Recycle.ca. https://www.call2recycle.ca/safety/ (accessed Feb. 2022).

[57] NAATBatt International. “Laws, regulations and best practices for lithium battery packaging, transport and recycling in the United States and Canada.” NAATBatt.org. https://naatbatt.org/lithium-recycling-laws/ (accessed Feb. 2022).

[58] Portable Rechargeable Battery Association. “Lithium batteries and fire codes.” PRBA.org. https://www.prba.org/areas-of-focus/fire-codes/ (accessed Apr. 2022).

[59] F. Larsson, P. Anderson, P. Blomqvist, and B-E. Mellander, “Toxic fluoride gas emissions from lithium-ion battery fires,” *Scientifc Reports,* vol. 7, Aug. 2017, Art. no. 10018, doi: 10.1038/s41598-017-09784-z.

[60] W. Mrozik, M. A. Rajaeifar, O. Heidrich, and P. Christensen, “Environmental impacts, pollution sources and pathways of spent lithium-ion batteries,” *Energy & Environmental Science*, no. 12, Oct. 2021, doi: 10.1039/D1EE00691F.

[61] National Fire Protection Association. “Training and certification: Emergency response guides.” NFPA.org. https://www.nfpa.org/Training-and-Events/By-topic/Alternative-Fuel-Vehicle-Safety-Training/Emergency-Response-Guides (accessed Feb. 2022).

[62] Evfriendly. “How to become an EV-friendly certified automotive recycling facility.” EVfriendly.ca. https://www.evfriendly.ca/how-to-become-an-evfriendly-certified-automotive-recycling-facility/ (accessed Jun. 2022).

[63] Ontario Automotive Recyclers Association. “EV/hybrid vehicle dismantling resources.” OARA.com. https://oara.com/resources/ev-hybrid-vehicle-dismantling-resources/ (accessed Mar. 2022).

[64] ARA University. “Electric and hybrid vehicle technology guide.” ARAUniversity.org. https://arauniversity.org/electric-hybrid-vehicle-technology-guide/ (accessed Feb. 2022).

[65] A. Ross. “Automotive Aftermarket Retailers of Ontario wins provincial funding for EV tech training.” JobberNation.ca. https://www.jobbernation.ca/automotive-aftermarket-retailers-of-ontario-wins-provincial-funding-for-ev-tech-training/ (accessed May 2022).

[66] Argonne National Laboratory. “Argonne and the National Electrical Manufacturers Association cooperate to develop battery recycling standards.” ANL.gov. https://www.anl.gov/article/argonne-and-the-national-electrical-manufacturers-association-cooperate-to-develop-battery-recycling (accessed Feb. 2022).

[67] British Standards Institution. “Faraday battery challenge.” BSIgroup.com. https://www.bsigroup.com/en-GB/industries-and-sectors/energy-and-utilities/faraday-battery-challenge/.

[68] European Union. (2000, Sep. 18). *Directive 2000/53/EC of the European Parliament and of the Council on end-of life vehicles.* [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611&from=HU

[69] Smart Waste Interreg Europe. “Upcoming new EU legislation on end-of-life vehicles.” Projects2014–2020. InterregEurope.eu. Available: https://projects2014-2020.interregeurope.eu/smartwaste/news/news-article/13239/upcoming-new-eu-legislation-on-end-of-life-vehicles/ (accessed Jun. 2022).

[70] European Union. (2006, Sep. 6). *Directive 2006/66/EC of the European Parliament and of the Council on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC.* [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32006L0066

[71] European Parliament. "A new EU regulatory framework for batteries." Europarl.Europa.eu. https://www.europarl.europa.eu/RegData/etudes/ATAG/2022/729285/EPRS_ATA(2022)729285_EN.pdf (accessed Jun. 2022).

[72] European Commission. "Green Deal: Sustainable batteries for a circular and climate neutral economy." EC.Europa.eu. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2312 (accessed Feb. 2022).

[73] California Legistlature. (2018, Sep. 27). *Assembly Bill No. 2832, Recycling: lithium-ion vehicle batteries: advisory group.* [Online]. Available: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180AB2832

[74] Propulsion Québec, "Study of extended prodcuer responsibility for electric vehicle lithium-ion batteries in Quebec," Propulsion Québec, Montreal, QC, Canada, Mar. 2020. Accessed: Feb. 2022. [Online]. Available: https://propulsionquebec.com/wp-content/uploads/2020/11/ETUDE-REP-EN-FINAL-WEB.pdf?download=1

[75] J. Dahn. "Quebec risks a critical circular economy misstep with proposed EV battery recycling plan." ElectricAutonomy.ca. https://electricautonomy.ca/2021/10/29/jeff-dahn-quebec-ev-battery-recycling/ (accessed Mar. 2022).

[76] M. Youden, E. Hobbs, and L. Mar. "Canadian product stewardship and EPR: 2022 summer update." GowlingWLG.com. Available: https://gowlingwlg.com/en/insights-resources/articles/2022/canadian-product-stewardship-epr-2022/ (accessed Oct. 11, 2022).

[77] Collision Repair Magazine. "Regional news Quebec: Battery bosses." CollisionRepairmag.com. https://www.collisionrepairmag.com/regional-news-quebec-crm-21-5/ (accessed Sep. 22, 2022).

[78] British Columbia Ministry of Environment and Climate Change Strategy, "Advancing recycling in B.C.: Extended producer responsibility five-year action plan, 2021–2026," Government of British Columbia, Canada, Sep. 2021. Accessed: Sep. 2022. [Online]. Available: https://www2.gov.bc.ca/assets/gov/environment/waste-management/recycling/recycle/extended_producer_five_year_action_plan.pdf

[79] C. Kim, N. Skuce, and K. Tam Wu, "Closing the loop: B.C.'s role in recycling battery metals and minerals to power the electric vehicle revolution," The Pembina Institute, Calgary, AB, Canada, Dec. 2021. Accessed: Feb. 2022. [Online]. Available: https://www.pembina.org/reports/closing-the-loop-battery-recycling.pdf

[80] C. Randall. "China releases battery recycling regulations." electrive.com. https://www.electrive.com/2019/11/11/china-releases-battery-recycling-regulations/ (accessed Feb. 2022).

[81] Ministry for the Environment, "Proposed product stewardship regulations: Tyres and large batteries," New Zealand Government, Wellington, New Zealand, 2021. Accessed: Feb. 2022. [Online]. Available: https://environment.govt.nz/assets/publications/RPS-tyres-large-batteries-consultation-document-final.pdf

[82] European Union, "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," Dec. 2020. Accessed: Mar. 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798

[83] Global Battery Alliance. "Action partnerships: Battery Passport." GlobalBattery.org. https://www.globalbattery.org/battery-passport/ (accessed Feb. 2022).

[84] L. Roy, "Quebec to impose new recycling measures on electric vehicle batteries, pharmaceuticals." CTVNews.ca. https://montreal.ctvnews.ca/quebec-to-impose-new-recycling-measures-on-electric-vehicle-batteries-pharmaceuticals-1.5623600 (accessed Feb. 2022).

[85] M. Sanders. (2021). Battery recycling: How are business models developing? [Online]. Available: https://www.forgenano.com/wp-content/uploads/2021/05/Avicenne-Energy-LIB-Recycling-MPSC-May-2021.pdf

[86] Bloomberg News. "China's next EV advantage is a mountain of retired batteries." Bloomberg.com. https://www.bloomberg.com/news/newsletters/2021-10-25/china-ev-battery-life-cycle-is-coming-full-circle-with-recycling (accessed Apr. 2022).

[87] Transport Canada, "Transportation of dangerous goods bulletin: Transporting batteries," Transport Canada, Ottawa, ON, Canada, Jan. 2018. Accessed: Feb. 2022. [Online]. Available: https://tc.canada.ca/sites/default/files/migrated/bulletin_transporting_batteries.pdf

[88] United Nations. Fifty-fifth session, Item 4(f) of the provisional agenda. (2019, July 1–5). *UN 3536, Lithium batteries installed in cargo transport unit lithium ion batteries or lithium metal batteries.* [Online]. Available: https://unece.org/DAM/trans/doc/2019/dgac10c3/ST-SG-AC.10-C.3-2019-8e.pdf

[89] National Archives and Records Administration. "Codes of Federal Regulations: Title 49, Chapter 1. eCFR.gov. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I (accessed Oct. 10, 2022).

[90] Government of Canada. *Transportation of Dangerous Goods Act 1992, S.C. 1992, c. 34*. [Online]. Available: https://lois-laws.justice.gc.ca/eng/acts/T-19.01/

[91] Transport Canada. "Transporting batteries." tc.canada.ca. https://tc.canada.ca/en/dangerous-goods/transporting-batteries (accessed Feb. 2022).

[92] Suppliers Partnership for the Environment. "Regulations governing shipment of electric vehicle (EV) batteries in the U.S." SuppliersPartnership.org. https://www.supplierspartnership.org/EVBtransportation/ (accessed Feb. 2022).

[93] International Energy Agency, "Global EV outlook 2022: Securing supplies for an electric future," International Energy Agency, Paris, France, 2022. Accessed: Jun. 2022. [Online]. Available: https://iea.blob.core.windows.net/assets/e0d2081d-487d-4818-8c59-69b638969f9e/GlobalElectricVehicleOutlook2022.pdf

[94] U.S. Geological Survey, "Mineral commodity summaries 2022," U.S. Geological Survey, Reston, VA, US, Jan. 31, 2022. Accessed: Mar. 2022. [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf

[95] Nickel Institute. "About nickel." NickelInstitute.org. https://nickelinstitute.org/about-nickel-and-its-applications/#03-nickel-mining-production (accessed Feb. 2022).

[96] BASF. "BASF's battery materials plants in Europe advance as planned." BASF.com. https://www.basf.com/global/en/media/news-releases/2020/06/p-20-214.html (accessed Feb. 2022).

[97] BASF. "BASF acquires site for North American battery materials and recycling expansion in Canada." BASF.com. https://www.basf.com/ca/en/media/News-Releases/2022/basf-acquires-site-for-north-american-battery-materials-and-recy.html (accessed Mar. 2022).

[98] D. Hull and D. Stringer. "Tesla dodges nickel crisis with secret deal to get supplies." Bloomberg.com. https://www.bloomberg.com/news/articles/2022-03-30/tesla-dodges-nickel-crisis-with-secret-deal-locking-in-supplies (accessed Apr. 2022).

[99] Northern Graphite Corporation. “Northern Graphite to acquire two graphite mines from Imerys Group.” NorthernGraphite.com. https://www.northerngraphite.com/media/news-releases/display/northern-graphite-to-acquire-two-graphite-mines-from-imerys-group (accessed Mar. 2022).

[100] M. Kane. “SVOLT's cobalt-free NMx cell are now available for order.” InsideEVs.com. Available: https://insideevs.com/news/483181/svoltcobalt-free-nmx-cell-available-order (accessed Feb. 2022).

[101] C. Nunez. “Researchers eye manganese as key to safer, cheaper lithium-ion batteries.” ANL.gov. https://www.anl.gov/article/researchers-eye-manganese-as-key-to-safer-cheaper-lithiumion-batteries (accessed Feb. 2022).

[102] Copper Development Association Inc. “How copper drives electric vehicles.” Copper.org. https://www.copper.org/publications/pub_list/pdf/A6192_ElectricVehicles-Infographic.pdf (accessed Mar. 2022).

[103] C. Jamasmie. “EV sector will need 250% more copper by 2030 just for charging stations.” Mining.com. https://www.mining.com/ev-sector-will-need-250-more-copper-by-2030-just-for-charging-stations/ (accessed Feb. 2022).

[104] “Global and China lithium-ion battery anode material industry report, 2021–2026,” Report Linker Market Report, Nov. 2021. Accessed: Feb. 2022. [Online]. Available: https://www.reportlinker.com/p04784303/Global-and-China-Lithium-ion-Battery-Anode-Material-Industry-Report.html?utm_source=GNW

[105] Battery University. “BU-306: What is the function of the separator?” BatteryUniversity.com. https://batteryuniversity.com/article/bu-306-what-is-the-function-of-the-separator (accessed Mar. 2022).

[106] S. Doose, J. K. Mayer, P. Michalowski, and A. Kwade, “Challenges in ecofriendly battery recycling and closed material cycles: A perspective on future lithium battery generations,” *Metals,* vol. 11, no. 2, p. 291, Feb. 2021, doi: 10.3390/met11020291.

[107] B. Venditti. “Ranked: Top 10 EV battery manufacturers.” VisualCapitalist.com. https://elements.visualcapitalist.com/ranked-top-10-ev-battery-makers/ (accessed Feb. 2022).

[108] Reuters. “GM to build new US$400-million battery plant in Quebec.” driving.ca. https://driving.ca/auto-news/local-content/gm-to-build-new-us400-million-battery-plant-in-quebec (accessed Mar. 2022).

[109] K. Fraser. “$4.9B electric vehicle battery plant announced for Winsor, Ont.” CBC.ca. https://www.cbc.ca/news/canada/windsor/automotive-announcement-windsor-1.6393463 (accessed Mar. 2022).

[110] J. Motavalli. “Automakers gearing up on North American battery production.” Autoweek.com https://www.autoweek.com/news/a38064546/automakers-north-american-battery-production/ (accessed Mar. 2022).

[111] Bloomberg. “CATL explores North America sites for US$5-billion EV battery plant, report says.” CanadaAutonews.com. https://canada.autonews.com/electric-vehicles/catl-explores-north-america-sites-us5-billion-ev-battery-plant-report-says (accessed Mar. 2022).

[112] Umicore. “Umicore prepares to construct first-of-its-kind battery materials production plant in Canada.” Umicore.com. https://www.umicore.com/en/newsroom/news/umicore-prepares-to-construct-battery-materials-production-plant-in-canada/ (accessed Jul. 2022).

[113] Reuters. “Umicore plans $1.2 billion battery materials plant in Ontario.” Mining.com. https://www.mining.com/web/umicore-plans-c1-5bn-battery-materials-plant-in-ontario/ (accessed Jul. 2022).

[114] A. Ohnsman. "Tesla's long-time partner Panasonic building $4 billion EV battery plant in Kansas." Forbes.com. https://www.forbes.com/sites/alanohnsman/2022/07/13/teslas-long-time-partner-panasonic-building-4-billion-ev-battery-plant-in-kansas/?sh=4be57fbc6c51 (accessed Jul. 2022).

[115] K. Field. "Everything you need to know about Tesla's new 4680 battery cell." CleanTechnica.com. https://cleantechnica.com/2020/09/22/everything-you-need-to-know-about-teslas-new-4680-battery-cell/ (accessed Feb. 2022).

[116] F. Lambert. "Panasonic announces start of Tesla 4680 battery cell production by March 2024." Electrek.co. https://electrek.co/2022/02/28/panasonic-start-tesla-4680-battery-cell-production-by-march-2024/ (accessed Mar. 2022).

[117] I-G. Kim. "Race to produce high-nickel batteries accelerates." KEDglobal.com. https://www.kedglobal.com/ev-batteries/newsView/ked202110170001 (accessed Mar. 2022).

[118] M. Wayland. "Ford and SK Innovation to spend $11 billion, create 11,000 jobs on new U.S. EV and battery plants." CNBC.com. https://www.cnbc.com/2021/09/27/ford-battery-supplier-to-spend-11point4-billion-to-build-new-us-plants.html (accessed Mar. 2022).

[119] U-H. Kim, L-Y. Kuo, P. Kaghazchi, C. S. Yoon, and Y-K. Sun, "Quaternary layered Ni-rich NCMA cathode for lithium-ion batteries," *ACS Energy Letters,* vol. 4, no. 2, pp. 576–582, Jan. 2019, doi: 10.1021/acsenergylett.8b02499.

[120] J-W. Kim. "LG Energy Solution begins mass production of NCMA batteries for GM electric trucks." ETnews.com. https://english.etnews.com/20211001200001 (accessed Feb. 2022).

[121] D. Vandewerp. "How GM's Ultium battery will help it commit to an electric future." CarandDriver.com. https://www.caranddriver.com/features/a36877532/general-motors-ev-ultium-battery-electric-future/ (accessed Feb. 2022).

[122] G. Venugopal. "Battery chemistries driving the electric vehicles and the evolution of battery materials." EVreporter.com. https://evreporter.com/evolution-of-the-battery-materials/ (accessed Mar. 2022).

[123] R. Bollini. "BYD blade battery – What makes it ultra-safe and comparison with ternary batteries." EVreporter.com. https://evreporter.com/byd-blade-battery-what-makes-it-ultra-safe/ (accessed Mar. 2022).

[124] BYD. "BYD announces all its pure EVs will now come with Blade Batteries." BYD.com. https://en.byd.com/news/byd-announces-all-its-pure-evs-will-now-come-with-blade-batteries/ (accessed May 2022).

[125] R. Tonapi. "BYD's HAN EV flagship model debuts in Brazil." Shifting-gears.com. https://shifting-gears.com/byds-han-ev-flagship-model-debuts-in-brazil/ (accessed Jun. 2022).

[126] M. Vousden. "How far away are mass-market solid-state EV batteries?" Just-Auto.com. https://www.just-auto.com/analysis/how-far-away-are-mass-market-solid-state-ev-batteries/ (accessed Mar. 2022).

[127] M. Hutchins. "New method to produce silicon anodes for lithium-ion batteries." pv-magazine.com. https://www.pv-magazine.com/2021/02/18/new-method-to-produce-silicon-anodes-for-lithium-ion-batteries/ (accessed Feb. 2022).

[128] D. Ellenby. "Silicon anode structure generates new potential for lithium-ion batteries." OIST.jp. https://www.oist.jp/news-center/press-releases/silicon-anode-structure-generates-new-potential-lithium-ion-batteries (accessed Feb. 2022).

[129] Group14 Technologies. “An elemental approach to better battery materials.” Group14.technology. https://group14.technology/en/ (accessed Mar. 2022).

[130] Argonne National Laboratory. “Silicon Consortium Project: Working to make silicon-based anodes for lithium-ion batteries a reality.” ANL.gov. https://www.anl.gov/access/research/projects/silicon-consortium-project (accessed Mar. 2022).

[131] M. Lewis. “This breakthrough may revolutionize lithium-sulfur batteries.” elecktrek.co. https://electrek.co/2021/02/24/breakthrough-lithium-sulfur-batteries/. (accessed Feb. 2022).

[132] D. J. Cross. “Lithium-sulfur battery breakthrough could quintuple electric vehicle range.” AZoCleantech.com. https://www.azocleantech.com/news.aspx?newsID=30965 (accessed Feb. 2022).

[133] R. Verger. “Why Dyson is going all-in on solid-state batteries.” PopSci.com. https://www.popsci.com/technology/james-dyson-solid-state-batteries/ (accessed Feb. 2022).

[134] Factorial Energy. “Factorial Energy emerges from stealth mode, unveiling groundbreaking 40 Amp-hour solid-state battery cell for EVs.” PRNewswire.com. https://www.prnewswire.com/news-releases/factorial-energy-emerges-from-stealth-mode-unveiling-groundbreaking-40-amp-hour-solid-state-battery-cell-for-evs-301272661.html (accessed Mar. 2022).

[135] QuantumScape. “Delivering on the promise of solid-state technology.” QuantumScape.com. https://www.quantumscape.com/technology/ (accessed Mar. 2022).

[136] D. Nichols. “Solid power’s solid-state batteries.” GreenCars.com. https://www.greencars.com/post/solid-powers-solid-state-batteries (accessed Mar. 2022).

[137] N. Winton. “Solid-state batteries promise electric car popularity boost, but technical mountains await.” Forbes.com. https://www.forbes.com/sites/neilwinton/2021/11/28/solid-state-batteries-promise-electric-car-popularity-boost-but-technical-mountains-await/?sh=1e82e65e632f (accessed Mar. 2022).

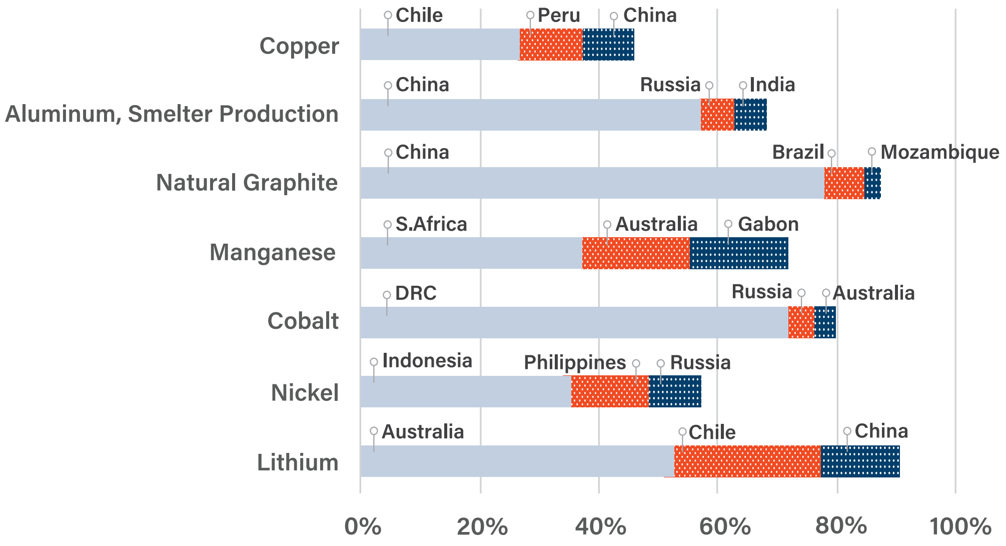
[138] B. Matich. “Saturday read: Promising alternatives to lithium-ion.” pv-magazine.com. https://www.pv-magazine-australia.com/2021/11/06/saturday-read-promising-alternatives-to-lithium-ion/ (accessed Feb. 2022).

Appendix A – EV LIB Manufacturing

Raw Materials for LIB Production

The key raw materials used in LIB manufacturing are lithium, nickel, cobalt, manganese, and graphite. Lithium, cobalt, nickel, and manganese play a significant role in battery performance, high energy density, and long service life. Current production of key LIB minerals and their known reserves are found in a small number of countries, particularly for lithium, cobalt, and natural graphite, with the top three producing countries controlling more than 75% of the global output. In some cases, one country is responsible for more than 50% of global production. For example, the Democratic Republic of Congo (DRC) produces 70% of cobalt, and China is responsible for more than 75% of mined natural graphite. Canada produces small quantities of most LIB raw materials, but exports most of these to China and other countries for processing. The processing and refining capacity for key LIB minerals is also highly localized. At this time, China dominates the processing and refining segment of the LIB supply chain, although other countries are rapidly developing capacity. China's share of global processing and refining for cobalt, nickel, and graphite is over 50% [88]. The share of the top three mining countries of key LIB minerals and aluminum smelting for 2021 is presented in Figure 6, and is based on US Geological Survey data [89].

Figure 6: Share of top 3 countries in global production of key LIB minerals in 2021.



Note. DRC = Democratic Republic of Congo.

Lithium: An estimated 74% of the global production of lithium is used in manufacturing LIBs [89]. Consumption for rechargeable batteries has increased substantially in recent years due to their use in portable electronic devices, hand-held electric tools, EVs, and grid power storage facilities. The world's largest lithium and lithium chemical producers are Jiangxi Ganfeng Lithium, Albemarle, Tianqi Lithium, Sociedad Quimica y Minera, and Livent Lithium Corp.

Lithium is produced mainly from brine operations in the salars (underground salt basins) of the Atacama desert in South America (Chile, Argentina, and Bolivia) and hard rock mining of spodumene in Australia. The majority of global lithium production comes from four mineral operations in Australia, four brine operations in Argentina and Chile (two in each country), and two brine operations and one mineral operation in China. Brazil, China, Portugal, the US, and Zimbabwe also contribute to world lithium production through smaller lithium operations [89]. Lithium is sold to the LIB market in two forms: lithium carbonate containing 19% lithium (mainly produced from brine), and lithium hydroxide containing 29% lithium (mainly processed from hard rock).

Nickel: Nickel is a key component of EV LIBs because it helps deliver higher energy density and storage capacity. Increased nickel content in battery chemistries has allowed battery manufacturers to reduce the use of cobalt, which is more expensive. Primary nickel is produced in metallic form, as ferronickel, nickel oxide, and other nickel chemicals, including battery-grade nickel sulphate. Nickel-bearing ores are currently mined in over 25 countries worldwide [90], with Indonesia, the Philippines, and Russia responsible for about 57% of the global output. Stainless and alloy steel, and nickel alloys account for about 85% of global consumption, with battery applications representing only 7% of the global demand for nickel. However, nickel consumption for battery manufacturing is expected to increase significantly in decades to come as the growth of EV adoption accelerates and more batteries develop toward nickel-rich cathode chemistries.

Nickel sulphate used in EV LIBs is currently manufactured by dissolving class 1 nickel metal (99.8% purity) in sulphuric acid. Nickel sulphate can also be produced from several intermediate products, such as nickel matte, nickel oxide concentrate (from nickel sulphide roasting), nickel sulphide, nickel hydroxide, and mixed nickel and cobalt hydroxide or mixed sulphide precipitates (from bioleaching or high-pressure leaching of ore).

LIB cathode material producers are moving away from using class 1 nickel by using purified nickel sulphate in leach solution, which is generated during the nickel refining process. Cathode material producers are now setting up in close proximity to nickel refineries to source nickel sulphate. For example, BASF's battery materials operation in Europe is located close to a Norilsk Nickel refinery in Harjavalta, Finland [91]. In March 2022, BASF announced an agreement to secure land for its future cathode active materials (CAM) and recycling site in Bécancour, Quebec [92]. Many hydrometallurgical plants for the processing of saprolite ore to intermediate nickel products are currently at the design stage in Indonesia, and the first high-pressure leach plant began operating in May 2021 on Obi island. The intermediate nickel products will be used as feed materials for the production of battery-grade nickel sulphate.

The largest producers of nickel in the world are Norilsk Nickel, Vale, Glencore, and BHP Group. Glencore, Sherritt International, and Vale are the three major companies with nickel/cobalt mining or refining operations in Canada. Sherritt International produces refined cobalt and nickel products from combined nickel and cobalt mixed intermediate products from its Moa, Cuba operations. Glencore produces nickel/cobalt matte from its Raglan mine in Quebec and its Sudbury Integrated Nickel Operations in Ontario. The nickel/cobalt matte is sent to its Norway Nikkelverk refinery for refining into high-grade metal products and powder. Vale's nickel/cobalt mines and processing operations in Canada are located in Sudbury, Ontario; Thompson, Manitoba; Port Colborne, Ontario; and Voisey's Bay and Long Harbour in Newfoundland and Labrador.

At the time of writing this report, none of the Canadian nickel/cobalt producers are significant players in the battery-grade nickel and cobalt sulphate market as they traditionally sell metals and powder products to the alloys market, to be used in particular in the aerospace industry and in stainless steel manufacturing. Their metal powder products are used for metal plating as well as for the manufacturing of chemicals, including battery-grade nickel and cobalt sulphate salts. However, this may change because Tesla recently signed a multi-year nickel supply agreement with Vale, which includes nickel from Vale's Canadian operations [93].

Cobalt: The majority of global cobalt resources are found with copper deposits or nickel mineralization. Most cobalt is produced from copper deposits in the DRC and Zambia and nickel-bearing laterite deposits in Australia, Madagascar, and Cuba. Nickel-copper sulphide deposits in mafic and ultramafic rocks in Australia, Canada, Russia, and the US are also sources of cobalt. DRC has the majority of cobalt reserves and produces about 72% of global production. In 2021, Canada produced 4,300 tonnes of cobalt, which represents about 3% of global output. Canadian cobalt production is primarily a by-product of nickel and copper mining. There are only two mines in the world where cobalt is the main product: Mukondo in the DRC and Bou Azzer in Morocco, which is owned by Managem Group with whom BMW signed a 5-year, €100 million cobalt supply agreement in July 2020. China is the world's leading producer of refined cobalt, most of which is produced from cobalt intermediate products imported from the DRC. China is also the world's leading consumer of cobalt, with more than 80% of its consumption being used by the LIB industry [89]. About 90% of cobalt is produced as a by-product from copper (55%) and nickel mining operations (35%). Global leaders in cobalt production are Glencore, China Molybdenum, Vale, Huayou Cobalt, and Nornickel.

Graphite: There are two forms of graphite: natural graphite from mine production and synthetic graphite, which is manufactured from petroleum coke. Both are used for manufacturing LIB anode active material (spherical graphite), with about 55% made from synthetic graphite and the balance made from natural graphite. Synthetic graphite is used particularly in EV applications because of its higher purity and quality, which also makes it more expensive than natural graphite. Natural graphite is mostly used in the consumer LIB electronics market, which does not require very long service life. China accounts for more than 75% of the world's natural graphite output, of which about 24% is amorphous (microcrystalline) graphite and 76% is flakes [89]. Canada has natural graphite mines in development, including Nouveau Monde Graphite, which is developing the Matawinie graphite mine and an advanced anode material plant in Quebec. Nouveau Monde is expected to be in operation by 2025. In December 2021, Northern Graphite announced an agreement to acquire 100% ownership of Lac des Iles graphite mine in Quebec and the Okanjande graphite deposit and Okorusu processing plant in Namibia from Imerys Group. Lac des Iles mine is the only significant graphite producing mine in North America [94].

Manganese: Manganese is used in oxide form for the manufacturing of cathode materials in zinc-carbon and alkaline batteries. Manganese usage in LIB manufacturing is on the rise, as it is used in various cathode chemistries in combination with lithium, nickel, cobalt, aluminum, and iron. The demand for high-purity manganese metal and high-purity manganese sulphate is expected to increase significantly in the future, driven largely by increased LIB demand. Manganese is an integral component of various LIB chemistries, including some of the high-performance NMC batteries used in EVs. There are ongoing efforts by battery manufacturers to completely replace cobalt with nickel and manganese in LIB CAM. For example, SVOLT Technology introduced high manganese, low nickel, and no cobalt battery cells in 2021 [95]. A manganese-rich cathode costs less and is safer than nickel-rich chemistries, but high manganese content decreases the cathode's stability, which can have negative impacts on performance over the longer term [96]. South Africa accounts for about 37% of global manganese production, with Gabon and Australia accounting for about 18% and 17%, respectively. There are no manganese mining operations in Canada or the US. However, Canada has a few manganese projects in development at the exploration stage, including the Woodstock Project (Canadian Manganese) and the Battery Hill Project (Manganese X Energy Corp.).

Copper: Copper is a major component in EV electric motors, inverters, wiring, batteries, and charging stations. The LIB cathode current collectors are made of aluminum foil, while copper foil serves as the anode current collector. The average copper content of EVs is about 83 kg, including wiring and other components in addition to the LIB [97]. The short-term demand for copper is expected to come from the growth of LIB charging stations [98]. The US Geological Survey reports that Chile (27%), Peru (10.5%), and China (8.6%) account for over 45% of global copper [89]. In 2021, Canada produced 590,000 t of copper, or 2.8% of global production, primarily from the Sudbury basin. Codelco, BHP, Freeport-McMoRan, Glencore, and Southern Copper Corporation are the major global producers of refined copper.

Components of a LIB Cell

CAM, anode active material, electrolyte, separator, and current collector foils are the main components required to make a LIB cell. The transformation of lithium, nickel, cobalt, and manganese into LIB chemical precursors and CAM involves many processing steps. First, the raw minerals or mineral concentrates are processed into their various metal salts using hydrometallurgical and pyrometallurgical extraction methods. Next, the metal salts are further refined to chemical precursors, which are tertiary hydroxides of nickel manganese cobalt or nickel cobalt aluminum. The chemical precursors are then transformed into CAM by combining them with lithium. Chemical precursors and CAM are manufactured by chemical companies from battery-grade chemicals that are sulphate, phosphate, or chloride salts of nickel, cobalt, manganese, iron, and lithium carbonate or hydroxide.

All LIB CAMs contain lithium and, depending on the cathode chemistry, the lithium oxide is combined with oxides of nickel, cobalt, manganese, and aluminum in various proportions. The quality specifications for CAM are sometimes battery chemistry specific and are not typically shared by manufacturers as they are considered trade secrets. Some of the largest global CAM producers are Hunan Shanshan Advanced Material, XTC New Energy Materials, GEM, BASF, Umicore, LG Chem, Samsung SDI, and Sumitomo.

LIB Anodes: LIB anode materials are mostly made of graphite in combination with silicon. Asian companies dominate the global production of LIB chemicals and active materials. Major manufacturers of anode active material include Hitachi Chemical, Mitsubishi Chemical, and Nippon Carbon. Hitachi Chemical primarily produces synthetic graphite, while Mitsubishi Chemical and Nippon Carbon supply natural graphite. Leading Chinese anode materials suppliers include Shenzhen Beterui New Materials Group (BTR), Ningbo Shanshan, Jiangxi Zichen, and Guangdong Kaijin, of which Shenzhen BTR produces both natural and synthetic graphite, while Jiangxi Zichen, Guangdong Kaijin, and Ningbo Shanshan all manufacture synthetic graphite [99].

Electrolytes: LIBs use liquid or gel electrolyte, which is usually a material with high ionic conductivity that allows lithium-ions to move back and forth between the cathode and the anode. The liquid electrolyte is composed of lithium salts dissolved in organic solvents and performance-enhancing additives. Organic solvents such as ethylene carbonate and diethyl carbonate are commonly used. Additive substances in LIBs are proprietary to the battery manufacturers and their chemical composition and the amount added are usually kept as trade secrets. Vinylene carbonate is one additive known to improve the cycle life of LIBs. Some of the major global electrolyte producers include Morita Chemical Industries, Mitsubishi Chemical Holdings, Guotai Huarong (GTHR) New Chemical Materials, Enchem, and Shenzhen Capchem Technology.

Separators: The anode and cathode are physically isolated from one another by a separator to avoid short circuiting. The separator should have excellent mechanical properties and good chemical stability. It needs to be an insulator and must be permeable with minimal electrolyte resistance to allow the exchange of lithium-ions from one electrode to the other. Currently, polyolefin separators with pore size in the range of 30 to 100 nm, and 16 to 25 μm thickness are used in commercial LIBs [100]. Separators also act as a safety valve to prevent thermal runaway (fire) at elevated temperatures by melting and closing their pores, thus preventing the flow of ions. Separators are either synthesized as sheets and assembled with the electrodes or deposited on the surface of one of the electrodes (the deposition method has proven to be more cost efficient). Chemical companies such as Asahi Kasei, Toray Industries, Sumitomo Chemical, and SK Innovation are the world's leading suppliers of lithium battery separators.

Electrodes: Electrodes comprise a metallic foil collector (usually copper for the anode and aluminum for the cathode), an active material (e.g., lithium iron phosphate [LFP] for cathodes, graphite for anodes), and a binder. During the manufacturing process, the slurries of active materials for the anode and cathode are coated onto a specific foil material and a binder is applied to bind the system together. Polyvinylidene fluoride is currently used as a standard binder on the cathode side, while a mixture of carboxymethyl cellulose and styrene butadiene rubber is usually used as a binder in the anodes [101]. Once the active materials are coated on to the foils, the foils are then stacked one on top of the other in layers, with a separator between an anode and a cathode to form a cell. Once individual cells are produced, they are usually assembled in modules, which are then packed and electronically connected for vehicle installation.

Other LIB Components: In addition to the electrodes and the separator, the LIB cell includes tabs, caps, insulators, and the casing.

LIB Manufacturers and Suppliers to Auto OEMs

The LIB is currently the highest cost part of an EV, ranging from 30% to 60% of total production cost, depending on the type of vehicle, energy density, and cathode chemistry, among other factors. Significant research and development efforts have been dedicated toward reducing the cost of LIBs in order to make EVs competitive with internal combustion engine vehicles and increase their market share.

Cell packing and battery assembly are two stages in the battery making and installation process that are increasingly being controlled and undertaken by automotive OEMs, as part of production cost reductions.

LIBs are produced by companies like Panasonic, LG Chem, Samsung SDI, Contemporary Amperex Technology (CATL), and SK Innovation among others. Combined, the top three battery makers, CATL, LG, and Panasonic, account for nearly 70% of the EV LIB manufacturing market. Automotive OEMs typically form partnerships with LIB suppliers to use specific LIB designs and chemistries in particular EVs.

Many of the key players for critical parts of the LIB supply chain are located in China, Japan, and South Korea. Through various strategies, the EU, US, and Canada are investing significantly in developing shorter, more local supply chains for critical materials needed to produce LIBs. Recent announcements of plans to locate facilities in North America include:

- In March 2022, GM and South Korean advanced materials company POSCO Chemical announced plans to build a US$400 million CAM plant in Bécancour, QC by 2024. The CAM will be used to make Ultium batteries, which will power an array of GM's EVs [102].

- In March 2022, Stellantis and LG Energy Solution also announced an agreement to build a CAD$4.9 billion EV battery plant in Windsor, ON, which is expected to produce 45 GWh of EV batteries annually and be operational by 2024 [103].
- In October 2021, Toyota announced plans to invest US$3.4 billion in US battery production by building a US plant that will start production in 2025, with investment continuing through to 2031 [104].
- In March 2022, China's CATL, the world's biggest maker of EV batteries, announced that it is considering sites across North America for a $US5 billion EV battery manufacturing plant to supply its customers, which include Tesla. The plant is expected to have the capacity to produce up to 80 GWh of EV batteries annually [105].
- In July 2022, Umicore, a Belgium-based global materials technology and recycling group, announced plans to build a CAD$1.5 billion LIB CAM and precursor materials manufacturing plant in eastern Ontario, with construction starting in 2023. The plant will supply battery material to power 1 million EVs by 2030. The Canadian government and Umicore have signed a memorandum of understanding and are negotiating a formal agreement that includes government support for the project [106], [107].
- In July 2022, Panasonic announced plans to build a US$4 billion EV LIB manufacturing plant in De Soto, Kansas. Panasonic, which is a key LIB supplier to Tesla and Toyota, did not specify which automakers it will supply from the new Kansas plant [108].

Appendix B – Future EV LIB Designs

A global race is underway to develop a new generation of batteries that are less expensive, can store more energy, and can charge faster. Several new battery chemistries with significantly enhanced performance have already entered the marketplace and several are scheduled to enter it soon. The most promising developments are highlighted below.

Tesla 4680 Battery [109]: Tesla started production of its cobalt-free cylindrical 4680 battery cell at the company's pilot factory in Freemont, California in January 2022. The 4680 batteries will be used to power Tesla's new Model Y sedan. The battery has several design enhancements that set it apart from other LIBs currently on the market:

- The large cylindrical cells (46 mm diameter x 80 mm high) reduce the number of cells in a battery pack.
- The cathode is a cobalt-free, nickel manganese structure, which increases the EV's range by 16% and has a lower cost due to the lack of cobalt.
- The tab-less design reduces the internal resistance within the cell, which allows the larger diameter cells to achieve thermal characteristics similar to those of a smaller cell.
- The 4680 contains more power in the same physical volume.

Tesla is expected to produce the 4680 battery for about 30,000 Model Y vehicles in 2022, and an estimated 484,000 vehicles in 2024. To meet the expected future demand, Tesla will expand production at its California factory and deploying large-scale production at other factories, including Gigafactory Texas and Gigafactory Berlin. In addition, Tesla will partner with other LIB producers. In February 2022, Panasonic (who previously produced NCA 2170 cells for Tesla at Gigafactory Nevada) announced plans to establish a new production facility, which will be operational by March 2024, at its Wakayama Factory in Japan to build Tesla 4680 batteries [110].

High Nickel Content Batteries [111]: LG Energy Solution, SK Innovation, and Samsung SDI are South Korea's largest EV battery makers and they are planning for full-scale production of high nickel (more than 80% cathode) content batteries, which provide longer mileage per charge, shorter charging times, and lower costs compared to other batteries.

- Samsung's SDI Gen 5 NCA battery cell, which has 88% nickel content, began being installed in BMW's SUV iX model (produced in South Korea) in December 2021.
- SK Innovation's next-generation NCM9 battery cell, which has 90% nickel content, will be installed in Ford's F-150 Lightning Truck, which launched in the spring of 2022. Ford and SK Innovation have formed a joint venture called BlueOval SK, which is building two NCM9 battery plants in central Kentucky that are scheduled to be completed in 2025, and a third plant to be located in west Tennessee [112].
- LG Energy Solution's NCMA battery cell, which has 85% nickel content, is being used in GM's new Ultium battery. The Ultium is being installed in GM's HUMMER EV Pickups and SUVs, which began limited production in December 2021. Tesla will also be installing NCMA batteries in its Model Y sedans being sold in China.

Analysis of the three high nickel content batteries over six performance parameters concluded that the NCMA battery cell had a longer cycle life without deterioration in range on a single charge and had faster charge capability compared to NMC and NCA high nickel battery cells [113].

GM's Ultium NCMA Battery: As mentioned, GM's Ultium LIB is made with LG Energy Solution's new NCMA flat pouch-style cells. Each cell measures 58.4 cm in length, 10 cm in width, and 1 cm in height, and contains 85% nickel, 5% cobalt, 5% manganese, and 5% aluminum. It is the largest pouch-style cell made to date, and it is the first time NCMA cathode material has been applied to a pouch [114]. One NCMA cell contains 20-times more energy than the small cylindrical NCA 2170 cell currently used in Tesla batteries [115]. In addition to its HUMMER Pickups and SUVs, GM plans to launch 30 new EV models globally by 2025, all powered by Ultium batteries. The cells will be produced in a joint venture with LG Chem (LG Energy Solution's parent company) at two new facilities in Ohio and Tennessee. When both plants are in production by the end of 2023, they will be able to produce an estimated 190 million cells per year, which will provide enough batteries for approximately 750,000 vehicles [115].

BYD Blade LFP Battery: CATL and BYD, among other Chinese battery makers, are installing LFP batteries in several EV models sold in China. Tesla Model 3s sold in China are also reported to contain LFP batteries, which have lower energy density, but are lower cost as they do not contain cobalt. LFP batteries have better thermal stability and therefore better safety characteristics compared to NMC materials. Simpler pack design is also possible with the higher thermal stability of LFP batteries [116]. The prismatic LFP cells in the new BYD Blade battery can be directly integrated into battery packs, bypassing module-level packaging, which facilitates greater packaging efficiency and results in improved energy densities and driving range compared to conventional LFP packs. It also results in lower costs. Furthermore, Blade LFP LIBs appear to be less susceptible to fire [117]. In April 2021, BYD announced that all of its EVs will now contain Blade batteries [118]. The first shipment of BYD's HAN EV sedans launched in Brazil in May 2022 [119].

Longer Term Trends

Based on current and planned investment in LIB production, LIBs will likely be the dominant EV battery for the next 5 to 10 years. However, researchers continue to explore enhancements to existing LIBs and alternative battery chemistries that could be less expensive to build, reduce demand for critical metals, offer faster charging times, and provide extended range compared to current leading-edge LIBs. Some of the leading alternative chemistries and designs for EV batteries are described below.

Silicon Anodes: Graphite or a mixture of graphite and silicon is currently used in the anodes of LIBs. Although graphite is a stable material, it has a comparatively low theoretical capacity, which it tends to lose at high current densities. Silicon is a preferred material for anodes because it has about ten times the theoretical capacity of graphite. However, silicon tends to expand and fall apart during battery cycling, resulting in rapid performance loss, which limits the amount of silicon that can be used in an anode [120]. The anode in Tesla's new 4680 LIB cell uses raw metallurgical silicon, which allows a higher percentage of silicon to be used. Researchers are continuing to work on developing an anode made of 100% silicon. For example, scientists at Mid Sweden University have developed a new aerogel process to manufacture silicon anodes for LIBs by growing nanometer-sized particles of silicon on graphite. While there are still challenges with stability and capacity retention, the approach could eventually result in low-cost, large-scale production [121]. Moreover, researchers at the Okinawa Institute of Science and Technology Graduate University have identified a silicon nanostructure that improves the anode in LIBs. The team deposited silicon atoms on metallic nanoparticles to form an arched nanostructure, which increased the strength and structural integrity of the anode. Electrochemical tests showed the test batteries had a higher charge capacity and longer lifespan than other LIBs [122].

Group14 Technologies has developed SCC55™, a stable silicon-carbon composite anode with five times the capacity and up to 50% more energy density than conventional graphite anodes. According to the company, the product's "unique hard carbon-based scaffolding keeps silicon in the most ideal form—amorphous, nano-sized, and carbon-encased" [123]. In January 2022, the company announced that it was starting to ship tons of SCC55™ to major OEMs and had begun planning for two additional battery active material factories (one in South Korea and one in Washington state), which will produce 12,000 tons or more of SCC55™ annually [123].

The US Department of Energy's Argonne National Laboratory has partnered with major national laboratories, including Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories, to develop an advanced anode based on silicon-carbon electrodes. This multi-laboratory program is comparing various silicon materials tested in full cells with commercial cathodes. Argonne Laboratory's Cell Analysis, Modeling, and Prototyping (CAMP) Facility is leading the cell-testing and evaluation team, who fabricate and test prototype electrodes, identify limitations in state-of-the-art cells, and create testing protocols. Argonne's Post-Test Facility evaluates the electrodes and cells from the CAMP Facility in order to identify and correct failure mechanisms, particularly those related to surface degradation [124].

Lithium-Metal Anodes: Lithium-metal anodes use a liquid-based electrolyte (unique to companies like Sion Power and SES). When at full scale, batteries with lithium-metal anodes will have significantly higher energy density compared to those with graphite anodes. They will also be much safer and less susceptible to fire.

Lithium-Sulphur Batteries: Given their light weight and theoretical high capacities, lithium-sulfur (Li-S) batteries are a promising alternative to conventional LIBs for large-scale ESS and electric vehicles, but they currently have poor longevity. However, scientists from the Gwangju Institute of Science and Technology in South Korea have discovered a new catalyst material that may significantly improve Li-S battery life [125], and University of Michigan researchers have created a new Li-S battery using a membrane made from recycled Kevlar that allows the batteries to be repeatedly charged for commercial use [126]. If these scientific breakthroughs can be commercialized, Li-S EV batteries may be able to compete with existing LIBs in the future.

Solid-State Batteries [94]: Solid-state LIB technology has attracted considerable interest and investment from OEMs across the globe. Current LIB cells use a liquid-based electrolyte, whereas solid-state cells typically use a wafer-thin solid electrolyte that is usually made with ceramic, polymer, or glass. Both types of cells generally use the same lithium-ion-based chemical reaction to store and discharge energy. Because solid-state cells are lighter and more compact than liquid-based cells, it allows battery pack weight to be reduced without compromising range, or energy capacity can be increased for the same weight, allowing for longer range.

Solid-state cells are expected to be more resistant to lithium dendrite formation, which will improve power discharge performance, raise potential charging speeds, and extend the service life of the battery pack. Production is also expected to be more efficient due to the removal of solvents and the reduced number of production steps compared to liquid-based LIB cells.

Another potential benefit of solid-state cells is increased battery safety. Fires can occur in current LIBs when external damage exposes the volatile liquid lithium electrolyte to the outside air, causing it to ignite. This can set off a chain reaction that can destroy the whole battery pack. Solid electrolytes are highly resistant to fire and explosion, even when they are punctured or damaged.

Companies developing solid-state cells for light vehicles are still at the bench-scale test stage. Several issues still have to be solved, including designing the solid electrolyte and electrodes so they interface evenly across their entire surface (even slight warping can create gaps that limit cell efficiency), and improving material stability because the rigidity of the solid electrolyte can lead to microscopic fractures that limit cell performance. Dyson invested significantly in developing a new EV, but eventually exited the market. However, Dyson continues to research a solid-state battery for many consumer applications, particularly vacuum cleaners and power tools [127]. Notwithstanding these technical hurdles, Toyota, working with its battery supplier Panasonic, has targeted 2025 for limited production of a solid-state battery. Stellantis and Mercedes-Benz are planning a limited deployment of solid-state cells in 2026, with both companies investing in US solid-state start-up Factorial Energy. Volkswagen, which has invested in solid-state start-up QuantumScape, is targeting 2024 for limited deployment. BMW and Ford are investing in another solid-state LIB developer, Solid Power. These three start-up solid-state battery technologies are described briefly below:

- **Factorial Energy** [128]: The Factorial Electrolyte System Technology™ (FEST™) is a proprietary solid electrolyte material that is safer than conventional LIB technology because it replaces the flammable liquid electrolyte with a more stable solid-state electrolyte that also suppresses lithium dendrite formation on lithium-metal anodes, thereby extending the life of the battery. According to Factorial, FEST increases driving range by 20% to 50% compared to traditional LIBs with liquid electrolyte.
- **QuantumScape** [129]: QuantumScape's solid-state lithium-metal battery replaces the polymer separator used in conventional LIBs with a solid-state ceramic separator coupled with an organic gel electrolyte. This means the carbon or silicon anode can be replaced with a lithium-metal anode, which has more energy density than traditional LIB anodes, thereby allowing the EV battery to store more energy in the same volume.
- **Solid Power** [130]: Solid Power is developing a solid-state battery that uses sulfides to create solid electrolytes. They have removed the flammable liquid electrolyte and replaced it with a solid ion-conducting sulfide electrolyte. According to Solid Power, their batteries have density that is at least 50% greater than conventional EV LIBs, and they can recover 90% of a charge in only 10 minutes. Solid Power hopes to have its battery packs in EVs by 2026.

Despite these advancements, wide-scale deployment of solid-state batteries is not expected until at least 2030 due to the technical challenges associated with scaling to mass production [131].

Other Battery Chemistries: Research continues into other battery chemistries that could displace LIBs in EVs. However, several of the alternative batteries currently in development are likely to complement current EV LIBs, rather than supersede them, by being used in ESS. Examples of these alternative battery chemistries include sodium-ion, nickel hydride, iron-air, hydrogen, nickel-hydrogen, and vanadium redox flow batteries [132].

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

CSA GROUP™