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End-of-Life Management of Lithium-Ion Batteries

Project Officer

Endalkachew Sahle-Demessie

U.S. EPA/Center for Environmental Solution and Emergency
Response/Land Remediation and Technology Division, Cincinnati, OH

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NOTICE/DISCLAIMER

Foreword

The U.S. Environmental Protection Agency (U.S. EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, U.S. EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The Center for Environmental Solutions and Emergency Response (CESER) within the Office of Research and Development (ORD) conducts applied, stakeholder-driven research and provides responsive technical support to help solve the Nation's environmental challenges. The Center's research focuses on innovative approaches to address environmental challenges associated with the built environment. We develop technologies and decision-support tools to help safeguard public water systems and groundwater, guide sustainable materials management, remediate sites from traditional contamination sources and emerging environmental stressors, and address potential threats from terrorism and natural disasters. CESER collaborates with both public and private sector partners to foster technologies that improve the effectiveness and reduce the cost of compliance, while anticipating emerging problems. We provide technical support to U.S. EPA regions and programs, states, tribal nations, and federal partners, and serve as the interagency liaison for EPA in homeland security research and technology. The Center is a leader in providing scientific solutions to protect human health and the environment.

Gregory Sayles, Director

Center for Environmental Solutions and Emergency Response

Abstract

Rechargeable lithium-ion batteries (Li-ion batteries) have been in nearly every portable electronic device manufactured in the past 20 years, from laptops to smartphones to electric cars. The use of Li-ion batteries will grow further with the expected technological innovation and decreasing costs. This remarkable utilization of a rather new electronic storage technology has encountered several obstacles. There is a growing interest in the environmental impacts associated with Li-ion batteries. The relative fragility of the batteries in some applications has become, at some stage of use, sources of flame and ignition, leading to extensive destruction of containers and recycling facilities, challenging the end-of-life management approaches. The poorly recognized failure modes of Li-ion batteries are now targets for developing an understanding of the necessary handling of in-use batteries to detect conditions leading to fires or explosive destruction. There is the possibility that emissions of volatile organic compounds, particulate matter and irritant gas such as $HF(PF_6)$, HF, or SO_2(FSI-) from a degrading battery could identify problematic batteries before they become critical and explosive.

Similar to most consumer products, the life cycle of Li-ion batteries is based on a linear model with little consideration of end-of-life management strategies. Li-ion batteries contain valuable metals, critical minerals, and other materials that can be recovered, processed, and reused to help support a circular economy.

The U.S. EPA established the Universal Waste program under the Resource Conservation and Recovery Act (RCRA) hazardous waste regulations to reduce toxic chemicals in the environment and encourage safe recycling and recovery of beneficial materials. The US EPA is also collaborating with other agencies and state regulators to promote the secure handling of Li-ion batteries and encourage sustainable stewardship. This document is intended to summarize the challenges of Li-ion batteries in terms of the recycling process, safety, current practices and policies for sustainable management, and achieving a circular economy.

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1 Introduction

Rechargeable lithium (Li)-ion batteries are in nearly every electronic manufactured in the past decade, from laptops to smart phones to electric vehicles (EVs). The North American Li-ion battery market value is estimated at $11.2 billion as of 2020 and is expected to grow at a compound annual growth rate of approximately 10 percent between 2021 to 2026 (Imarc, 2021). Globally, the Li-ion battery market is expected to grow from $40.5 billion in 2020 to $91.9 billion in 2026 (Research and Markets, 2021). Of the 180,000 metric tons of Li-ion batteries available for recycling worldwide in 2022, less than half were recycled (CAS Insights Report, 2022; Seltzer, 2022; Lewis, 2021). By 2030, researchers estimate there may be approximately 80,000 metric tons of Li-ion batteries available for recycling in the United States alone (Jacoby, 2021; Kelly, et al. 2019).

Li-ion batteries contain valuable metals (lithium, cobalt, nickel, and copper) and other materials that can be recovered and reused. Yet very little recycling occurs due to technical constraints, economic factors, and logistical issues. Product design (dimensions, size variability) and the ability to cost-effectively transport the batteries and recover the valuable materials across the range of battery chemistries are the main barriers. Additionally, informed and safe handling is required due to the tendency for battery fires, increasing the burden on end-of-life (EoL) management facilities to properly collect, store, and handle these materials. Moving from a linear to a circular economy through increased battery recycling can improve the environmental footprint and social impacts of battery manufacturing (including the mining of virgin minerals in developing countries) and create economic benefits in the U.S.

The objectives of this report are to provide an overview of rechargeable Li-ion batteries and their environmental and health hazards when improperly managed; EoL management options with a focus on recycling; and an assessment of the Li-ion battery infrastructure in the U.S.

The scope of this report includes consumer products powered by small- to medium-sized Li-ion batteries. Larger electric vehicle (EV) batteries and energy storage systems are briefly mentioned, but not included in the scope.

This report is organized as follows:

- Section 2 – Li-Ion Battery Basics
- Section 3 – EoL Management
- Section 4 – Policy Landscape for EoL Management
- Section 5 – Assessment of the Li-Ion Battery Recycling Network.

2 Li-Ion Battery Basics

A Li-ion battery is a rechargeable battery that generates direct current (DC) power through chemical reactions. Non-rechargeable, single use lithium batteries are referred to as lithium metal batteries. In a Li-ion battery, lithium ions move from a negative electrode (the anode) through an electrolyte to the positive electrode (cathode) when generating power, and in the reverse when recharging. The lithium ions are small enough to pass through a micro-permeable separator between the anode and cathode.

Li-ion batteries are used in a wide variety of products, including but not limited to the following applications:

- Portable electronic devices
- Personal computers
- Cellular phones, smart phones
- Tablets
- Camcorders
- Cordless tools, power tools
- Digital cameras
- Cordless phones
- Personal hygiene products (e.g., toothbrushes, shavers)
- Vaping devicestools
- E-bikes, e-scooters
- Security lighting
- Electric vehicles (HEV, P-HEV, EV)
- Medical devices
- Energy storage

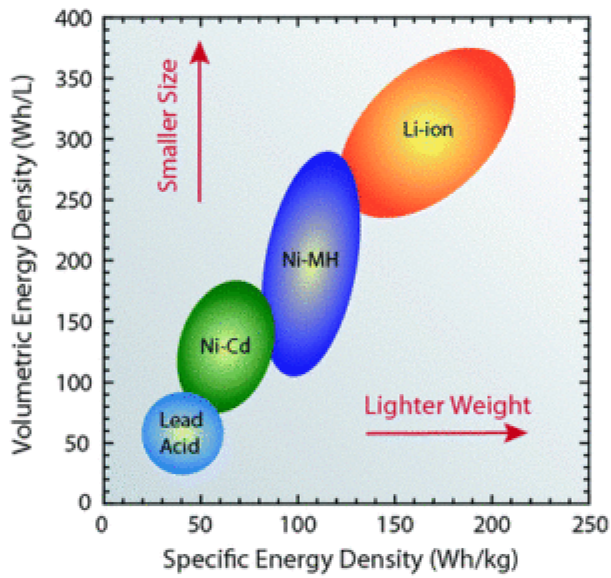

Figure 1. Energy Density and Volumetric Energy Density of Various Battery Types.

Source: CEI, 2020

The North American Li-ion battery market value is estimated at $11.2 billion as of 2020 and is expected to grow at a compound annual growth rate of approximately 10 percent between 2021 to 2026 (Imarc, 2021). Globally, the Li-ion battery market is expected to grow from $40.5 billion in 2020 to $91.9 billion in 2026 (Research and Markets, 2021). They are widely used due to their high volumetric energy density, smaller size, and lighter weight compared to other battery types (e.g., lead acid, nickel-cadmium [Ni-Cd]) as shown in **Figure 1**, the increasing importance of climate-forward policies, and consumer demand. Demand is being driven by the growth in personal electronic devices (e.g., smart phones, tablets, laptops), electric vehicles, increase in renewable energy generation and the need for electricity storage of excess power.

2.1 Battery Components

The main components of an Li-ion battery include the Li-ions, electrode material, separator, and the electrolyte (see **Figure 2**). The electrodes (the cathode and anode) in an Li-ion battery may be comprised of different materials as listed in **Table 1**. Cathodes in personal electronic devices typically consist of an electrochemically active powder such as lithium cobalt oxide (LCO) mixed with carbon black and glued to an aluminum foil current collector with a polymeric compound such as polyvinylidene fluoride (PVDF). Anodes typically consist of graphite, PVDF, and copper foil. The most common electrode combination is LCO as the cathode and graphite as the anode. Recent additions to the market replace the graphite with hard carbon or silicon. The separator is a thin, permeable plastic film such as polyethylene or polypropylene that insulates the electrodes to prevent short circuiting. The electrolyte is usually a solution of $LiPF_6$ dissolved in a mixture of ethylene carbonate and dimethyl carbonate.

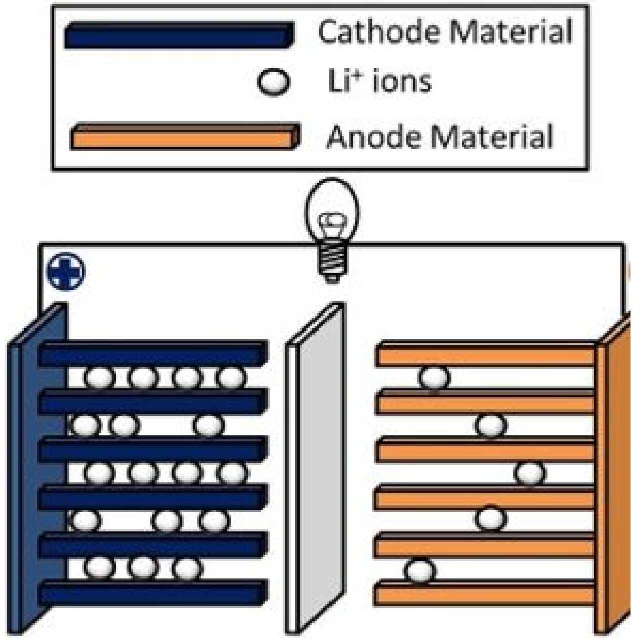

Figure 2. Generic Schematic of a Cathode and Anode in a Li-ion Battery

Source: CEI, 2021

Table 1. Commonly Used Li-ion Battery Electrode Technologies and Target Applications

Positive Electrode (Cathode) Technology

Material	Major Target Applications	Advantages	Disadvantages
LCO Lithium cobalt oxide ($LiCoO_2$)	Personal electronics, broad use due to high performance	Performance	Cost and resource limitations of Co, low capacity
NCA Lithium nickel cobalt aluminum oxides ($LiNiCoAlO_2$)	EVs	High capacity and voltage, excellent rate performance	Safety, cost and resource limitations of Ni and Co
NMC or NCM Lithium nickel manganese cobalt oxide variants ($LiNi_xMn_yCo_zO_2$)	EVs, power tools, grid energy storage	High voltage, moderate safety	Cost and resource limitations of Ni and Co

	Major Target Applications	Advantages	Disadvantages
LMO Lithium manganese oxide ($LiMn_2O_4$)	HEVs, cell phones, laptops, tablets	Low cost and abundance of Mn, high voltage, moderate safety, excellent rate performance	Limited cycle flow, low capacity
LFP Lithium iron phosphate ($LiFePO_4$)	Power tools, aviation products, Segways, automotive hybrid systems, PHEV conversions	Excellent safety, cycling, and rate capability; low cost and abundance of Fe; low toxicity	Low voltage and capacity, low energy density

Negative Electrode (Anode) Technology

Material	Major Target Applications	Advantages	Disadvantages
Graphite	Personal electronics, broad use	Long cycle life, abundant	Relatively low energy density, inefficiencies due to Solid Electrolyte Interface formation
LTO Lithium titanate (Li4Ti5O12)	Automotive, electrical grid	"Zero strain" material, good cycling, and efficiencies	High voltage, low capacity (low energy density)
Hard carbon	Home appliances and electronics	Less susceptible to disruption; suitable for pairing with LMO cathodes compared to graphite	Electrochemical properties vary considerably
Silicon	Smart phones	Added in small amounts to boost capacity; replacement for graphite; relatively new on the market	Increases in specific energy are contingent on higher capacity cathode material

Source: Kam and Doeff, 2017

The cathode and anode materials are mixed with a binder, conductive carbon and solve to create a paste, which is painted onto the current collector (e.g., graphite anode is painted onto the Cu foil; cathode is painted onto Al foil). The cathode and anode are then tightly wound into a spiral or cylindrical cell or cut and arranged into a stack (Wang et al., 2019). Battery packs come in a variety of shapes and sizes to form module that consists of multiple cells connected in series and/or parallel, encased in a mechanical structure. The cells are typically divided into four groups:

- Small cylindrical
- Large cylindrical
- Flat or pouch, and
- Prismatic (e.g., electric vehicle [EV] battery packs).

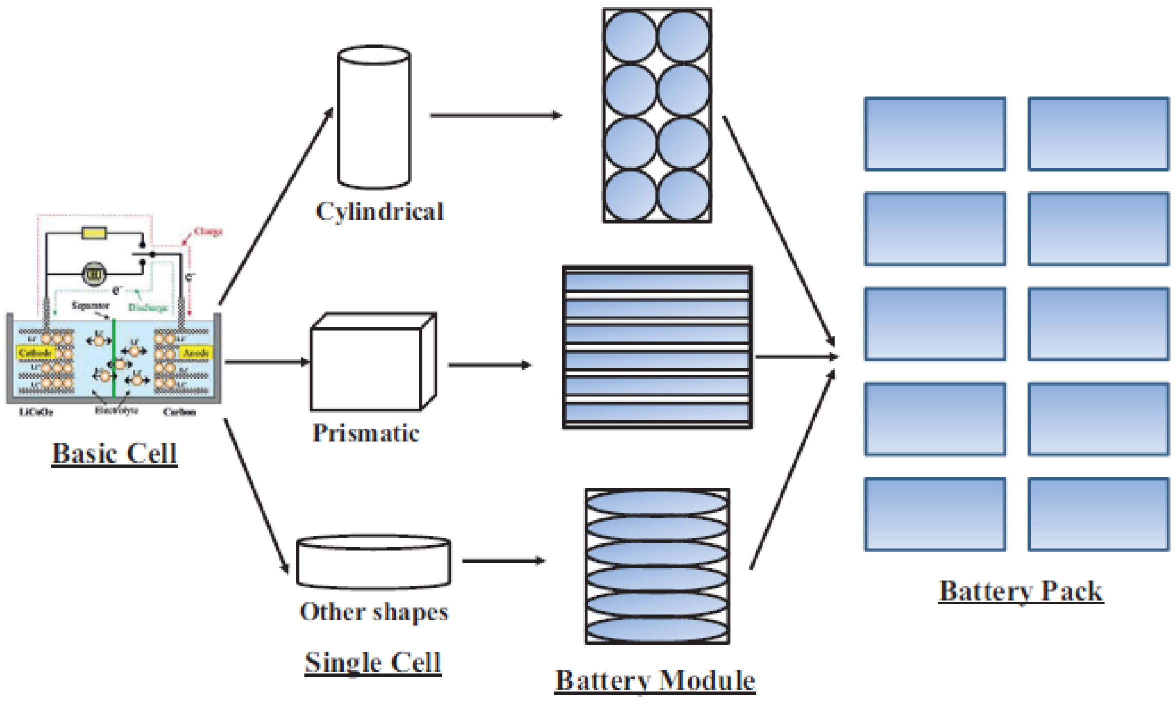

Figure 3 Schematics of battery pack design with different cell configurations referred to as a cell, module, or pack. Source: Al-Hallaj et al., 2002; Wang et al., 2019

2.2 Emerging Alternatives to Li-ion Batteries

Li-ion raw materials are not produced in sufficient quantities to meet the imminent demand from both of those markets and market research predicts the supply of lithium will be constrained in the near term. This shortage will become even more severe as governments around the world pass legislation adopting EVs and renewable energy. Emerging alternatives to Li-ion batteries are in various stages of research and development, as summarized in **Table 2**.

Table 2. Emerging Alternatives to Li-Ion Batteries

Battery Type	Description
Sodium-ion	Use abundant, cheap, and benign materials. There is over one-thousand times more sodium than lithium in the Earth's crust and it costs less to extract and purify. The cathodes can be made from plentiful materials such as iron and manganese, and the anodes are carbon, like Li-ion batteries. They are also more stable and safer due to low risk of fire. Sodium-ion batteries could give Li-ion batteries a run for their money in stationary applications where cost is more important than size and energy density. Based on currently available information, sodium-ion batteries may be approximately 10–20 percent less in cost than a Li-ion battery. Sodium-ion batteries are too inefficient for is in electric vehicles. Sources: Abraham, 2020; Patel, 2021
Zinc-ion	To date, zinc-ion batteries are the only non-lithium technology that can adopt Li-ion's manufacturing process. Zinc-ion batteries use the same principles as Li-ion batteries described by the manufacturer Salient Energy. Zinc ions react at both electrodes and travel between them through a water-based electrolyte. During discharge, zinc metal at the anode is dissolved into the electrolyte as zinc ions. At the same time, zinc ions are absorbed into the cathode from the electrolyte. This process is reversed during charge. Scientists have developed a proof-of-concept, rechargeable zinc-ion battery that forgoes the standard zinc anode, giving it a relatively high energy density (Nano Lett. 2021, DOI: 10.1021/acs.nanolett.0c04519). Zinc-ion's key differentiators from Li-ion are safety and supply chain security. Zinc-ion's intrinsic safety, due to its use of water as the electrolyte, means it will be able to gain traction in markets where Li-ion adoption has been limited due to safety concerns. Before Zn-ion batteries are used widely the challenges of them short circuiting should be resolved. Source: Wilke, 2021
Lithium-sulfur	These batteries could be on the market in a few years. Sony is one of several institutions working on this technology and claims the new lithium-sulfur batteries will have 40percent higher energy density and lower production costs than today's Li-ion batteries. The drawbacks of Li-S technologies are corrosion and shorter use life, although there are efforts to curb them. Source: Petrovan, 2021
Aluminum-graphite	Stanford University created an aluminum battery that could slash charging times. With some aluminum negatively charged cathode and a graphite anode, it is safe and lightweight and can potentially improve energy density. The output of 1.5v is unsuitable for powering a smartphone or more or less anything else, but researchers are working on it . Source: Petrovan, 2021

Battery Type	Description
Bioelectro-chemical	This technology uses anaerobic bacteria to process acetate with a reduction/oxidation method that releases electrons. Researchers in the Netherlands have gotten a prototype through 15 recharging cycles. The bioelectrochemical battery is intended for solar panels, as the researchers are tuning the battery to store energy for 16 hours and then release it over the following eight. Technically the bacteria could reproduce, and the battery could have a near-infinite lifespan, but there are a lot of hurdles to overcome. Source: Petrovan, 2021

Sources: Abraham, 2020; Patel, 2021; Petrovan, 2021; Wilke, 2021

2.3 Li-Ion Battery Failure and Associated Hazards

Lithium batteries are generally safe and unlikely to fail when properly handled throughout their life cycle; however, lithium batteries can, and do, fail and pose both a chemical and electrical hazard. A February 2018 report by the U.S. Consumer Product Safety Commission (U.S. CPSC, 2018) identified more than 25,000 overheating or fire incidents involving more than 400 types of lithium battery powered consumer products over a five-year period. This section focuses on Li-ion battery failure, how it happens, how to detect it, and how to prevent hazards associated with failure. The environmental and health hazards from improper storage, handling, and disposal are mentioned here and specifically discussed in **Section 3, EoL Management**.

Li-Ion Battery Failure Mechanisms

Lithium metal has unique properties as an ideal anode material due to the highest specific capacity (> 3860 Mah/g) and the lowest potential (-30.04 V). Li-ion batteries contain heavy metals and components with potentially negative human health and environmental hazards. The mechanism of failures are physical, chemical and mechanical in nature. The common physics of failure is the results of either tearing, piercing or collapsing of the anode-cathode separator, resulting internal short circuit. Short circuiting generates heat at a rate several times higher than the rates at which heat dissipates from the cell. Damage to lithium batteries can occur immediately or over time from physical impact, exposure to certain temperatures, and/or improper charging. Li-ion battery failures are categorized by the Fire Protection Research Foundation (2011):

- **Thermal abuse** results from extreme temperatures, both high and low. The optimum operating temperature ranges from 20 ºC to 40 ºC. Damage to all types of lithium batteries can occur when temperatures are too high (e.g., above 55 °C). External heat sources (e.g., open flames, heaters, etc.) can also accelerate failure in cells with defects or damage from other causes. Damage may also occur when the batteries themselves or the environment around the batteries is below freezing (O °C) during charging. Charging in temperatures below freezing can lead to permanent metallic lithium buildup (i.e., plating) on the anode, increasing the risk for failure. It is therefore important to design effective thermal management system to control both the maximum temperature and_temperature distribution in the battery pack withing the safe range.

- **Mechanical abuse** can result in physical impacts and load from the casing that can damage lithium batteries include dropping, crushing, and puncturing, which damage the battery casing and increases exposure to external elements. The damage leads to failure of the internal components such as separators and contact is attained between separator and cathode
- **Electrical abuse** stems from charging a device or battery without following the manufacturer's instructions. For example, some manufacturer-authorized chargers will cycle the power to the battery on and off before it is fully charged to avoid overcharging. Some ultra-fast chargers may not cycle power and should not be used unless the manufacturer's instructions include ultra-fast chargers as an option.
- **Poor cell electrochemical design** refers to the unexpected degradation of a cell component (electrodes, the separator, or the electrolyte) during usage. Faulty designs may cause poor venting, and failed battery wraps result in unexpected failures and heat propagation. In this instance, the battery may not operate according to the manufacturer's specifications.
- **Design and manufacturing flaw: Internal cell fault related to manufacturing defects** may also occur during usage despite manufacturer testing and certification. For example, there may be manufacturing-induced cell contamination, electrode damage (e.g., scratches, punctures, tears, active material displacement), burrs on electrode tabs, weld spatter from cell tab attachment points, wrinkles or kinks in windings or tabs, and electrode misalignment. These manufacturing defects may result in internal short circuiting early in the life of the battery.

What is Thermal Runaway?

Thermal runaway is a sequence of processes involving exothermic reactions and gas generation, which build up pressure in the cell. This may result from thermal failure, mechanical failure, short circuiting, and electrochemical abuse (e.g., overcharging).

When temperatures become elevated, decomposition of the cell material begins, eventually rising to the point of instability when all remaining thermal and electrochemical energy is released to the surroundings. Fires, explosions, and the release of toxic gases can occur.

A problem with one battery can cause a chain reaction in neighboring batteries.

The severity of a Li-ion cell failure is strongly affected by the total energy stored in the cell (FPRF, 2011). Heat released during failure can damage the cell and nearby batteries, potentially creating a chain reaction known as thermal runaway (defined in text box at left). In a Li-ion battery, thermal runaway occurs when heat generated by exothermic reactions is not offset by the heat loss to the environment, resulting in increasing temperature through an exponential increase in reaction rates (Wang et al., 2019) as illustrated in **Figure 4**. oxygen. The high energy density in lithium batteries makes them more susceptible to chemical and/or combustion reactions, as generally defined below.

- In chemical reactions, by-products from the electrolyte solution and electrodes can increase pressure in the cell, causing by-products to leak from the cell walls. Chemical by-products usually include carbon monoxide, carbon dioxide, hydrogen, and hydrocarbons. In many cases, the by-products are also combustible and could spontaneously ignite. (OSHA, 2019)

- In combustion reactions, a thermal runaway releases byproducts that may ignite to cause smoke, heat, fire, and/or explosion. The by-products from a lithium battery combustion reaction are usually carbon dioxide and water vapor. In some lithium batteries, combustion can separate fluorine from lithium salts in the battery. If mixed with water vapors, fluorine may produce hydrofluoric acid, which is particularly hazardous because workers may not feel its effects until hours after skin exposure. (OSHA, 2019)

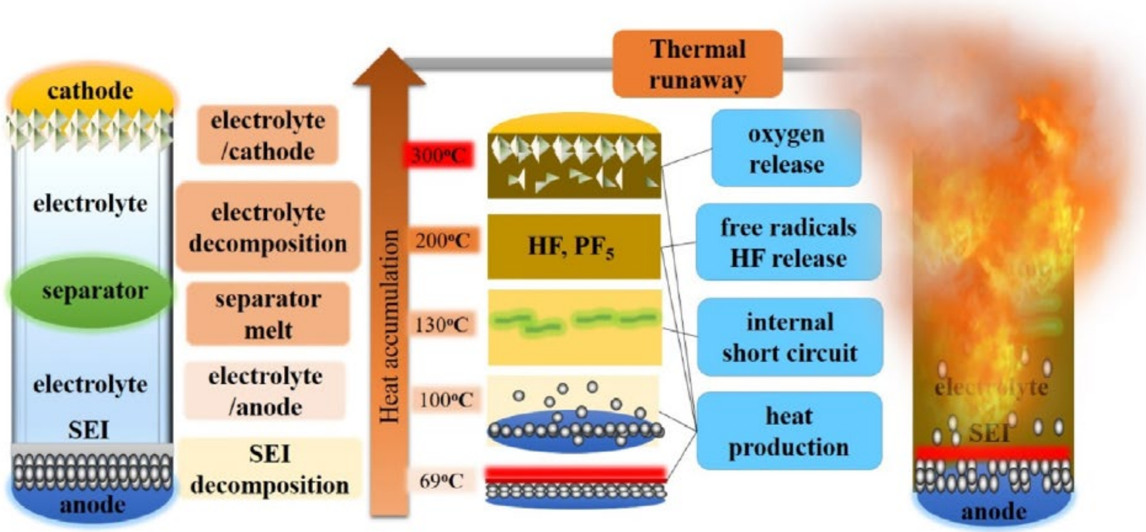

Figure 4. Overview of the Thermal Runaway Process of an LCO cell

Source: Wang et al., 2019; SEI = solid electrolyte interphase layer.

When the critical temperature of a battery is reached, the battery cell starts to break down, internal short-circuiting occurs, the separator melts and collapses, the solid electrolyte interphase (SEI) layer on the anode breaks down, reactions between the anode and electrolyte occur, and reactions between the cathode and electrolyte occur (Wang et al., 2019). These reactions release hazardous by-products such as hydrogen fluoride (HF) gas (Wang et al., 2019), particulate matter, elemental carbon, and volatile organic compounds (Premnath et al., 2022). Hydrogen fluoride, HF, and other generated gases can accumulate, react with water vapor, and eventually result in thermal runaway and explosion of the cell.

In addition to the type and extent of thermal, mechanical, and electrical abuse, the battery chemistry, and the state of charge (SOC) also factor into the potential for thermal runaway (FPRF, 2011). The onset temperatures for the various stages shown in Figure 4 range depending on the battery chemistry as presented in **Table 3**. Research suggests that LFP batteries are safer than LMO and LCO batteries in terms of fire risk (as summarized in Wang et al., 2019). However, when they catch fire LEP emit more gases than LMO and LCO batteries. LCO batteries, used in most consumer electronics, is more likely to combust vigorously because LCO releases a larger amount of oxygen at high temperature compared to LFP.

Table 3. Temperature Ranges of Decomposition for Various Li-Ion Cathode Types

Cathode Type	Temperature Range of Decomposition
LCO	220-500°C (428-932°F)
NCA	160-220°C (320-428°F)
LMO	89-400°C (192.2-752°F)
LFP	180-285°C (356-545°F)

Source: Summarized literature in Wang et al., 2019.

Thermal runaway is unlikely to occur in a cell at low SOC. SOC is the battery charge or discharge rate provided in percents where 0 percent is empty, and 100 percent is fully charged. Over-discharging of Li-ion batteries can cause temperatures to rise due to an over-lithiated cathode and over-lithiated anode, resulting in inside reactions from the abrupt changes of temperature and impedance and structural changes of both electrodes (Chao et al., 2017). Over-charging and over-discharging will shorten the service life of batteries. Overcharging or high SOC storage causes the release of gases from graphite exfoliation due to induced crack of solid Electrolyte Interphase (SEI) and loss of active area (Abe et al. 2004). Over-discharge hardly causes thermal runaway. However, over-discharged cells experience an irreversible capacity loss that affects the thermal stability and battery's tolerance to abuse. Batteries could suffer an extreme over-discharge below 0 V, leading to electrochemically driven solid-state amorphization (Meleki and Howard, 2006). Over-discharging Li-ion cells repeatedly will result in accelerated capacity degradation, whose level depends on the depth of discharge. For all Li-ion battery types, the total internal heat generation and the average rate of its production increased with increasing stored electrical energy; however, the rates of these increases became smaller as the battery SOC approached 100 percent (Wang et al., 2019).

Over-discharging has resulted in redox reaction of Cu at a potential of 3 V, resulting in Cu2+ precipitation and corroding the anode (Lai et al, 2018). Battery cathode chemistry, the state of charge, and aging have been shown to be closely related to common causes of battery fires. The state of charge is one of the dominant factors affecting Li-ion battery chemistry, which also affects the ignition of cells (Lui et al., 2021). Based on Sermenov's theory, the charged Li-ion battery materials are reactive substances with high activity that will undergo a thermal runaway process at temperatures above 75 ºC, based on battery chemistry (Wang et al., 2005). Sermenov's theory applies to analyzing the self-heating ignition of single cells. According to the Frank-Kamenetskii theory, the critical ignition temperature is a function of the characteristic length of the Li-ion battery ensemble. The temperatures and heat transfer affect the ignition of these additional materials during storage conditions and transport. Testing has indicated that severe crushing of cells below approximately 50 percent SOC will not lead to a severe reaction (FPRF, 2011). Many studies have shown that thermal runaway occurs for 30 percent to 100 percent state of charge cells, while even at 0 percent state-of-charge, there was a temperature increase due to self-heating (He et al, 2021). In general, reducing the SOC significantly reduces the maximum temperature achieved at the point of shorting (Wang et al., 2019).

Fire Behavior

The heat transfer environment of a cell undergoing thermal runaway can play a large role in the severity of the reaction. High ambient temperatures or adiabatic insulation will increase the likelihood that an internal fault can drive a cell to thermal runaway and increase the energy available to heat the cell. FRPF (2011) also notes that many manufacturers limit cell dimensions to ensure that an external short circuit will not cause sufficient internal heating to drive a cell into thermal runaway. Conversely, if a cell is surrounded by thermally conducting media (e.g., densely packed cells or coolant), heat loss may prevent or mitigate a thermal runaway reaction (FRPF, 2011). Additionally, thermal runaway in one cell can quickly propagate to nearby cells (Wang et al., 2019, OSHA, 2017; FPRF, 2011). Once thermal runaway begins, a fire is anecdotally quick to start and may begin within a few seconds to minutes.

Most fire behavior studies are done at a small-scale in laboratory-controlled environments. Large-scale testing for fire and fire suppression techniques have not been done (Wang et al., 2019; FRPF, 2011). Small-scale testing has been used to develop models to better understand and predict fire behavior. Multiple models of Li-ion battery thermal runaway to analyze combustion chemistry in various scenarios are available in the literature, but Wang et al. (2019) note that comprehensive modeling has not been conducted on the flames produced from materials ejected from Li-ion batteries during thermal runaway.

Emissions and Releases from Battery Fires

The solvents used in Li-ion batteries, such as ethylene carbonate, diethyl or dimethyl carbonate, start to break down in the presence of electrolytes such as Li-hexafluorophosphate (Larson, 2017). Battery failures could be triggered by normal aging during use, over-heating, over-charging or mechanical abuse (Lamb et al. 2015). As battery mechanical structure designs and thermal management have improved impacts of heat and mechanical abuse have declined.

Emitted gases include carbon dioxide, CO_2, carbon monoxide CO, and volatile organic compounds such as alkanes, benzene, toluene, styrene, biphenyl. Fluorinated VOCs in the emission may contain fluorine compounds such as lithium fluoride (LiF), hydrogen fluoride (HF), phosphoryl fluoride (POF3) and phosphorus pentafluoride (PF5), among others (Golubkov et al., 2014). These releases are dependent on battery chemistry. The study by Sturk et al., 2019 has shown that manganese Oxide (NMC/LMO) cells resulted in CO2 emissions rate two orders of magnitude higher than Lithium Iron Phosphate (LFP) cells. However, HF emissions were higher for LFP cells compared to NMC/LMO cells. Permnath et al., 2021, also showed significant particulate matter emissions from over-charging of LFP modules resulting from nail penetration tests.

Incidents of large-scale fires at used battery warehouses, recycling facilities, and energy storage systems have brought attention to public safety around the fire and environmental impact issues. Some of the significant battery-related fires include the 2021 fires at Morris, IL that involved more than 200,000 batteries, the 2018 five-alarm fire in Jamaica, NY, the Vistra Energy facility fire in Moss Landing, CA, and the 2019 incident in Arizona, when a two-megawatt Li-ion battery storage facility caught fire and exploded.

Failure Detection and Prevention

Failure detection for the purposes of this report is to be interpreted as battery fire detection resulting from thermal runaway. Fire detection is best achieved through a smoke detector compared to a heat detector. Wang et al., 2019, found that a smoke detector was able to detect the ignition of a lithium battery faster than the heat detector. Both the smoke and heat detector were useful in fire detection, and it may be best to use the two in combination. Limited studies were identified that specifically investigated Li-ion battery failure detection. Other failure detection measures include facility personnel seeing and smelling the fire.

A simplified risk assessment of fire hazards and potential mitigation and protection strategies is summarized in **Table 4**; note that there is a general lack of data to assess the probability and severity of each hazard considering the variety of battery types and sizes (Wang et al., 2019; Larksson and Mellander, 2017; FRPF, 2011). The sources for hazards 1 to 7 include any of the following: external heating, external fire, mechanical deformations, external short circuit, internal short circuit, overcharge, and over discharge. The source of hazard 8 is a faulty Battery Management System (BMS) and/or mechanical deformations. A BMS is incorporated into a battery module or single cell and monitors the state of the battery and/or its environment.

For batteries that are not device-embedded, fire prevention can largely be achieved through personnel training and proper handling when managing small Li-ion batteries. Fire development is dominated by packaging materials and airflow that affects heat release. For large batteries and battery packs, manufacturer design can incorporate safety features such as battery venting and battery management systems (BMS). Manufacturer design modifications, such as using different materials to coat cathodes and anodes, and different electrolyte additives (Wang et al., 2019) are also undergoing R&D.

After a fire has started, basic fire suppression techniques include isolation, smothering, cooling, and chemical suppression. The ideal fire suppressant will stay suspended and prevent re-ignition of a combustible mixture from hot cell surfaces (FRPF, 2011). Effective fire suppressants include:

- Inert gas / smothering of flames through firefighting foams and powders (will not cool the flames to prevent thermal runaway propagation to neighboring cells though);
- Carbon dioxide fire extinguishers (will not cool the flames to prevent thermal runaway propagation to neighboring cells though);

- Water (will cool the flames and is appropriate for EoL Li-ion batteries that are not being used in an operating system. Because water is conductive, if applied to an operating system, it may create external short circuits and promote thermal runaway.); and
- Halon (the least toxic is Halon 1301 and has superior fire extinguishing characteristics).

(Wang et al., 2019; FRPF, 2011).

Table 4. Simplified Risk Assessment of Li-ion Batteries for all Battery Sizes and Applications: Hazards, Consequences, and Potential Mitigation and Protection Strategies

Hazards[1]	Consequence	Potential Mitigation and Protection Strategy
1. Swelling (but no gas release)	Balloon of flammable gases; increases fire risk	▪ If minor, cooling via thermal management system ▪ Detection and removal or replacement of cell
2. Gas release / venting (toxic gas, corrosive acid / gas, accumulated gas ignition)	Acute toxicity	▪ Early detection and warning; personnel evacuation ▪ Propagation mitigation (limit the problem size/severity) ▪ Battery placing in separate Li-ion dry, cool place ▪ Ensure electrical equipment and chargers are fit-for-purpose ▪ Ventilation ▪ Detox gas filters
3. Electrolyte leakage	Increased risk of fire from flammable vapors and toxicity from decomposing products	▪ Ventilation ▪ No heat or ignition sources ▪ Cool and dry environment
4. High cell pressure (cell case rupture and explosion)	Spreading out of combustible material Increased fire risk Ballistic projectile hazards for persons, vehicles, etc.	▪ Cell designed with vents to release gas before extreme internal pressure is reached (pressure vents) ▪ Device design with circuit breaker ▪ Ballistic projectile protection
5. High temperatures	Burn hazards for persons Fire ignition source	▪ Cooling by thermal management system (if still operational)
6. Accumulated gas ignition	Damage to building and persons	▪ Pressure release in battery pack ▪ Propagation mitigation (lower amount of gas) ▪ Ventilation (dilution of gas) ▪ Pilot flame/controlled ignition

Hazards[1]	Consequence	Potential Mitigation and Protection Strategy
7. Fire in battery cell or pack	Heat release Damage to building and persons Fire source to spread to adjacent structures	▪ Fire barriers and storing in separate structures ▪ Fire fighting ▪ Smoke detectors placed in building
8. Electrical voltage hazards	Small burns to lethal injuries to persons	▪ Electrical insulation ▪ Floating ground ▪ Personnel training on electrical hazards and equipment ▪ Correct personnel handling technique and equipment ▪ Avoid overcharging

Source: Adapted from Larksson and Mellander, 2017
[1] The sources for hazards 1 to 7 include any of the following: external heating, external fire, mechanical deformations, external short circuit, internal short circuit, overcharge, and overdischarge. The source of hazard 8 is a faulty BMS, and/or mechanical deformations.

3 End-of-life Management

Available EoL battery management options include the following, which are described in this section:

1. **Collection** – Bulk collection of spent batteries, potentially still in consumer products, at a centralized location and usually intended for transport to a separate processing facility.
2. **Sorting and Disassembly** – Batteries are sorted according to size, shape, and/or battery chemistry to facilitate recycling, disposal, or reuse. Disassembly refers to removing the battery components from the outer packaging and separating the battery components and is only required for certain batteries (e.g., EVs) when recycling is the EoL management pathway.
3. **Storage** – Spent batteries may be stored until a shipment reaches a cost-effective size for transport to the processing facility. Used batteries may also be stored until assessment for reuse applications. The storage and holding time at a site-specific basis could be specified by the appropriate EPA Regional office or authorized State regulatory agency (EPA, May, 2023)
4. **Transport** – Spent batteries are transported by road, rail, water, or air to a processing facility. This report focuses on road transport only because that is the main method used in the U.S.
5. **Reuse** – Used batteries may undergo an assessment for reuse or recycling. Several diagnostics are performed to determine if a battery has reuse potential.
6. **Recycling** – The main Li-ion battery recycling processes include pyrometallurgy, hydrometallurgy, and direct recycling. Battery-grade materials, including lithium, cobalt,

nickel, aluminum, copper, and graphite are sold to manufacturers for use as inputs into new materials.

7. **Direct Disposal** – Although generally not allowed or recommended, users do dispose of Li-ion batteries and products containing these batteries directly into the municipal solid waste (MSW) stream for eventual disposal into a MSW landfill or incinerator.

3.1 Collection and Handling

Lithium batteries have the potential to leak, spill, or break during normal conditions of use and can expose employees to chemicals which can pose health and/or physical hazards. OSHA provides guidance on safe handling and storage in the Safety and Health Information Bulletin: Preventing Fire and/or Explosion Injury from Small and Wearable Lithium Battery Powered Devices. Employees who handle and store lithium batteries must be aware of the Hazard Communication Standards (29 CFR 1900.1200). Collection and handling are described in this section as precursors to battery recycling, assessment for battery reuse, and landfill disposal.

Collection & Handling

Battery handling occurs along many points during EoL management. For the purposes of this report, handling is intended to begin at the point of collection for EoL management and includes battery receipt at a collection point, battery sorting, storage, and any other activity where a spent or used battery is not being used in a consumer product or is on its way to its final disposition.

Spent batteries may be collected at a centralized drop-off location at a centralized location (such as those operated by Call2Recycle or an e-waste collection drive), a collection point within a business or retail store, household hazardous waste collection or through a manufacturer take-back program. For example, Call2Recycle offers more than 16,000 drop-off collection sites in the U.S. that accept:

- Dry-cell rechargeable batteries: small, sealed lead acid batteries (SSLA/Pb), Li-Ion batteries, nickel metal hydride (Ni-MH) batteries, nickel zinc (Ni-Zn), and nickel cadmium (Ni-Cd);
- Single-use batteries: alkaline, lithium primary; and
- Cellphones: all sizes, makes and models.

Figure 5. The Call2Recycle Collection Kit Box Source: Call2Recycle, n.d.

Call2Recycle also offers a Collection Kit and bulk shipping option for collected materials. The Collection Kit (see **Figure 5**) is a consumer-friendly display box that can be used for both collection and shipment of batteries and cellphones for recycling purposes. The box is patented and includes special U.S. DOT shipping permits for up to 66 pounds (lbs) of material and a pre-addressed shipping label. The Collection Kit is geared towards retail stores, businesses, government offices, and warehouses. Call2Recycle also coordinates bulk shipping for organizations that collect high volumes of batteries of 500 lbs or more per shipment.

Alternatively, sites can use their own large containers such as drums or receive Call2Recycle boxes flat on a pallet to ship the collected materials back.

Identification and Sorting

More than a decade ago, the Fire Protection Research Foundation (FPRF) has developed a comprehensive review of battery technology, failure modes and events, usage, codes and standards, and a hazard assessment during the life cycle of storage and distribution (Mikolajczak et al., 2012). There is potential for mechanical damage due to poor handling, such as boxes or pallets being dropped or damaged by shipping companies and forklift accidents, which may damage the batteries. Improper handling can lead to release of electrolyte, short circuiting, and possibly cell thermal runaway.

Why Should Batteries be Separated from Each Other?

When battery terminals contact each other, the risk for short circuiting and fire increases.

Handlers should cover battery terminals with a covering such as tape during storage, and place batteries in separate bags/containers until and during transport.

Batteries are usually identified by type, shape, and size and then sorted when planning to transport, recycle, or dispose of them. Identification and sorting may require product disassembly to remove the battery and may also require battery dismantling down to its modules (e.g., in the case of EV batteries).

General guidance for reduced-commodity testing and large-scale fire sprinkler testing and handling during the identification and sorting process is provided below (NAHMMA-2020)

Employees involved in handling EoL Li-ion batteries should wear protective equipment, including eye protection.

- Batteries may need to be removed from products or disassembled. Battery disassembly is not a simple process and there are numerous associated hazards. High voltage training and insulated tools are required to prevent electric shocks to personnel or short circuits during disassembly.
- To avoid damaging the equipment or battery, handlers should not use excessive force when removing batteries from consumer products. After removal, the battery should be placed in a metal or other container away from combustibles.
- The battery terminals should always be covered and separate from other batteries and battery terminals to prevent electrical shorts.

The steps for proper identification and sorting of Li-ion batteries are summarized below:

- Identify the type. Is the battery a lithium ion or lithium metal battery? Always isolate different battery types.
- If the battery is installed in a piece of equipment, determine if it needs to be removed or will stay with the equipment. Batteries can be shipped either way and the appropriate UN code will be assigned during labelling.

- Determine and sort by size, which is classified using the DOT thresholds.
- Sort the batteries by size (Wh rating). Battery size of Li-ion batteries is measured in Watt-hours (Wh), where the Wh rating is usually found on the battery case.
    - If the Wh rating is not shown on the case, it can be calculated using the following formula: Wh = Ampere-hours (Ah) x Volts (V).
    - Li-ion batteries are sorted by ≤100 Wh and ≤300 Wh (ground only)
    - Small batteries are those rated at ≤ 20 Wh per cell or ≤ 100 Wh per battery (for lithium-ion batteries), and those containing ≤ 1 g lithium per cell or ≤ 2 g lithium per battery (for lithium metal batteries).
- Sort the batteries by shape: cylindrical or rectangular.

Damaged, Defective, and Recalled Batteries

Look for damaged, potentially damaged, defective, or recalled batteries when sorting. Gaseous emissions from failing batteries make hissing and popping noise, release unusual odor and generate smoke. U.S. Department of Transport, Pipeline and Hazardous Materials Safety Administration (USDOT, PHMSA, June 2023) guidelines for shipper must follow to ship packages of lithium cells and batteries in various configurations. These batteries must be isolated because they cause a greater risk of causing heat, fire, and short circuiting. Individuals sorting the batteries should always be on the lookout for batteries that are defective, leaking or vented, obvious physical or mechanical damage; damage to safety features, components, or short circuit protection for batteries in equipment; and batteries where it is unclear if they are damaged.

- USDOT requires damaged, defective, or recalled batteries must be individually packaged for transport as follows:
    - Non-metallic inner packaging that completely encloses the battery.
    - Inner packaging surrounded by non-combustible, non-conductive, and absorbent cushioning material.
    - Single inner packaging must be placed in performance-oriented packaging at the Packing Group I performance level.
- Household-generated damaged, defective, or recalled batteries can be stored in a safe location until a proper disposal option such as a household hazardous waste center is located. A safe location may include a bucket filled with a fire suppressant such as cat litter, or sand, and away from flammable materials.

Storage

Batteries should be stored in a well-ventilated, dry area between 40 to 80°F, and away from direct sunlight, heat sources, and water (including high humidity).

- Do not stack batteries; this increase the chance they may be knocked over and damaged.
- Do not stack heavy objects on top of batteries.
- Isolate Li-ion batteries from other types of batteries.
- Keep all batteries isolated from flammable or explosive materials.
- Store battery types separately from each other.
- Store batteries at room temperature; temperature extremes (high and low) should be avoided.
- Store batteries at reduced SOC is possible to reduce the potential for thermal runaway.

Grid-level energy storage systems are used to store excess electrical energy during peak power generation periods and provide the vacant power during peak load.

3.2 Transport

If batteries are collected in bulk and sorted at a centralized location, they will likely need to be transported to an appropriate processing facility. This section primarily applies to businesses versus household consumers.

The Department of Transportation (DOT) classifies lithium batteries as a Class 9 hazardous material and regulates their transportation, including packaging and labeling, under the Hazardous Materials Regulations (40 CFR § 173.185). Regulatory requirements vary by mode (air, road, rail, water). The information contained herein focuses on transport of lithium batteries by motor vehicle for disposal or recycling. Always refer to the appropriate regulations for complete requirements.

Packaging requirements differ by battery size, with more stringent requirements for larger batteries. Packaging must meet specific requirements, but the DOT does not mandate exactly which packaging needs to be used. The DOT's Check the Box public awareness campaign seeks to increase awareness around everyday items that are considered hazardous materials in transport.

There are two major exemptions for Li-ion batteries:

- Batteries transported to a permitted storage, recycling, or disposal facility by motor vehicle are exempt from the testing and record keeping requirements of 49 CFR § 173.185(a) and the UN performance packaging requirements in (b)(3)(ii), (b)(3)(iii) and (b)(6) of section 173.185 when the batteries are packed in a strong outer packaging.

- A lithium cell or battery that meets the size, packaging, and hazard communication conditions in 49 CFR § 173.185 (c)(1)-(3) is exempted from the labeling and other requirements in subparts C to H of 49 CFR part 172[1]. This applies to Li-ion batteries with a Wh rating less than 20 Wh for a Li-ion cell or 100 Wh for a Li-ion battery with a lithium content that does not exceed 1 g for a lithium metal cell or 2 g for a lithium metal battery. Other stipulations apply for labeling and packaging.

Packaging Requirements for Small Batteries

In general, most Li-ion batteries in consumer products meet the definition of a small battery. Below are the general packaging requirements when transporting small lithium batteries from 49 CFR § 173.185:

- Small batteries are those rated at ≤ 20 Wh per cell or ≤ 100 Wh per battery (for lithium-ion batteries), and those containing ≤ 1 g lithium per cell or ≤ 2 g lithium per battery (for lithium metal batteries).

Figure 6. Example of Proper Packaging for Lithium Batteries During Transport.

Source: IATA, 2020

- Packaging requirements include: inner packaging, cushioning material (e.g., bubble wrap, styrofoam peanuts), rigid outer packaging (49 CFR § 173.185(b)(1)–(3)(c)).
- Inner packaging must: be non-metallic, completely enclose the battery and terminals, keep batteries separate from any contact with any conductive material.
- Good inner packaging examples: plastic bags, tape enclosures around the bag (e.g. ravioli taping); tape around any exposed circuits.
- Flexible materials (e.g. padded envelopes) are not considered acceptable packaging for shipping small batteries because they do not sufficiently protect the batteries from punctures or other direct blows.

[1] 49 CFR § 172 Subpart C is Shipping Papers; Subpart D is Marking; Subpart E is Labeling; Subpart F is Placarding; Subpart G is Emergency Response Information; Subpart H is Training.

Packaging Requirements for Large Batteries

Large batteries are those with a 300 Wh or higher rating (for Li-ion batteries) or 25 g or larger for lithium metal batteries, and/or packages greater than 66 lbs gross weight. Large batteries must be packaged in strong, impact-resistant outer casing and must be packed in strong outer packaging, in protective enclosures (e.g. crates), on pallets (49 CFR § 173.185(b)(5)).

Figure 7. Example of Proper Labeling for a Lithium Battery Shipment

Labeling Requirements

The DOT regulates labeling of lithium batteries for shipment. Battery packages being shipped by ground must be marked and labeled the same way as they are for shipment by air.

- The DOT requires the use of a label with one of six shipping names and identification number, in alignment with the United Nations Committee of Experts on the Transport of Dangerous Goods as shown in **Table 5**.
- The label must also contain the telephone number of a responsible person who can provide details about the shipment (49 CFR § 173.185(c)(3)). An example is shown in **Figure 7**.

Table 5. UN Shipping Categories for Lithium Batteries

Shipping Category	UN Number
Lithium-ion batteries	UN3480
Lithium-ion batteries contained in equipment	UN3481
Lithium-ion batteries packed with equipment	UN3481
Lithium metal batteries	UN3090
Lithium metal batteries contained in equipment	UN3091
Lithium metal batteries packed with equipment	UN3091

- Batteries between 100 Wh and 300 Wh require additional package markings, such as LITHIUM BATTERIES—FORBIDDEN FOR TRANSPORT ABOARD AIRCRAFT AND VESSEL or labeled with a cargo aircraft only label (see **Figure 8**).
- Damaged, defective, and recalled batteries require the same hazard communication as larger, fully-regulated lithium battery and a "Damaged/defective lithium ion battery" and/or "Damaged/defective lithium metal battery" markings on the outer package as appropriate.

Figure 8. Additional Package Marking for Large Lithium Batteries

International Shipping

There may be additional regulations for international shipping by other governing bodies. International shipment of Li-ion batteries managed as universal waste must also comply with RCRA requirements for export and import of universal waste. Although, the U.S. EPA's universal waste regulations do not mandate use of a uniform hazardous waste manifest, Department of Transportation regulations for Li-ion shipment do apply. Transport Canada, for example, regulates the importing of lithium batteries by specifying classification, documentation, labelling, packaging, and training requirements. Requirements vary by mode of transport, but generally align with the U.S. DOT, which relies on requirements developed by various organizations including the Internation Association of Civil Aviation Organization (IACO), International Air Transport Association (IATA), UNECE, 2022)

3.3 Reuse

Reuse mostly applies to EV batteries and large consumer electronics, which may be reused for stationary energy storage or another application (Pagliaro and Meneguzzo, 2019). Direct reuse of spent consumer Li-ion batteries does not appear to be common, because of their low performance after their regular lifetime (Gaines, 2011). Small-size Li-ion batteries are typically sold with or in a product versus by themselves. An indication of the prevalence of Li-ion battery reuse in the U.S. was not identified in the literature reviewed for this report. Flat packed and pouch batteries are custom designed, difficult and laborious to safely disassemble. Thus, flat packs are many time ground which results in complicated chemical separation process.

Before a battery is determined suitable for reuse, an appropriate vendor will conduct various diagnostic tests. The diagnostics include State of Health (SOH), State of Charge (SOC), and electrochemical impedance spectroscopy (EIS) (Osmanbasic, 2020).

- SOH is a measurement of the general condition of the battery compared to a new battery. It provides information about the battery's long-term capacity and how much of a battery's lifetime energy throughput remains. In other words, SOH estimates how many operating hours are left in the battery, which informs reuse applications. Charging performance, battery internal resistance, terminal voltage, and self-discharge are all considered.

- SOC is the rate of battery charge or discharge provided in percent where 0 percent is empty, and 100 percent is fully charged.
- EIS provides information about battery health and indications of aging mechanisms from lithium coating. EIS data identifies whether the battery could be reused or should be recycled. If the battery can be reused, EIS data also identify potential hazards from reuse.

3.4 End-of-life handling: Recycling

The rate of collection and recycling, and the profitability of the process and environmental impact depends on the battery technology. Battery recycling operations require the sorting of batteries according to their chemistry, where Ni-Cd, Ni-metal hydride, and Li-ion batteries are placed in designed collection boxes. The collection rate of batteries is low, and the technologies of recycling are challenging and costly. In the US, hazardous waste Li-ion batteries subject to the Resource Conservation and Recovery Act are frequently managed under the streamlined management standards of the universal waste program until they arrive at a recycler but can also be recycled under the solid waste recycling exclusion at 40 CFR 261.4(a)(24) if they meet the conditions.

All components of a Li-ion battery have value and can be recovered. However, recycling is generally suited toward recovering nickel, cobalt, and copper. The schematic in **Figure 9** shows typical percentages of the components inside of a lithium nickel cobalt aluminum oxide (NCA) battery. The active cathode material breakdown (i.e., the pie chart in **Figure 9**) will vary for other Li-ion battery types such as LCO and LFP.

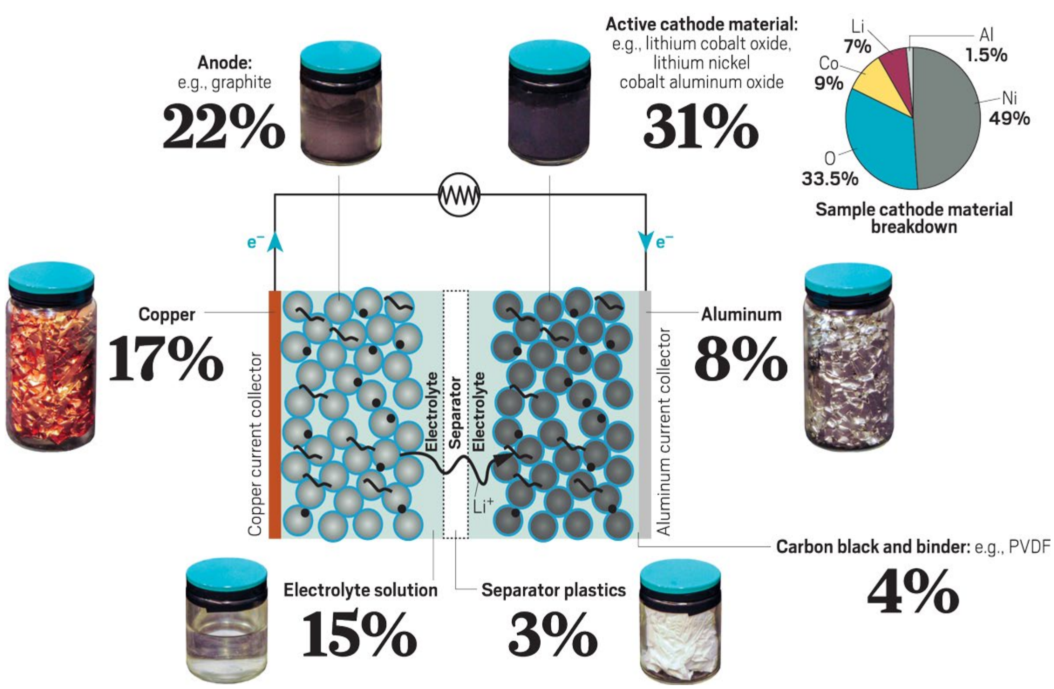

Figure 9. Inside a Li-Ion Battery (with a NCA cathode) (Source: Jacoby, 2021)

3.5 3.5 Recycling Processes

There are currently three major lithium-ion battery recycling – pyrometallurgy (pyro process), hydrometallurgy (hydro process), and direct recycling – as represented by the green loops in **Figure 10**. An emerging process, bioleaching, is also briefly summarized because it is a promising, emerging technology. Each process is described below, followed by a visual representation of the processes (**Figure 11**), and the main advantages and disadvantages of each (**Table 6**).

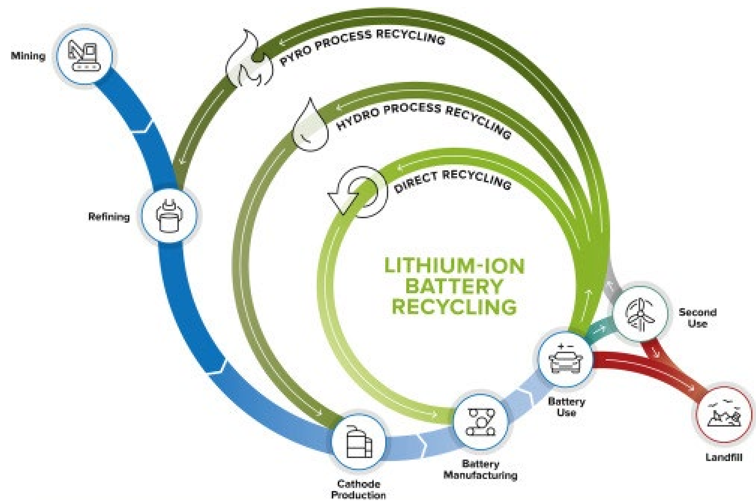

Figure 10. Closed Loop Life-cycle of a Lithium-ion Battery from Cradle to Grave (Source: Gaines, 2019)

Before any thermal, mechanical, or chemical treatment, the spent Li-ion batteries must be discharged to prevent spontaneous combustion and short-circuiting which is typically achieved by drenching the spent batteries in a salt solvent, or the process should be done in anoxic or inert environment.

Pre-treatment processes are essential for discharging and safe separation of Li-ion batteries. These processes include mechanical size reduction methods, solvent pre-treatment and thermal operations (Figure 10). Each method has its advantages and downsides, and proper selection of the technology could have consequences on scalability and cost of commercialization (Bae and Kim, Source: Chen et al., 2019.

The pyrometallurgical process is a high-temperature smelting process, which typically involves burning and subsequent separation of materials. This process treats the battery as if it were ore and repeats all of the same processing steps as would be done for virgin material. The general steps are described below.

- Batteries are fed into a high-temperature furnace with little to no pretreatment. The exception is EV batteries, which may be dismantled into modules. Some smelters process on the electronic waste comprising crushed and shredded battery cell (also called black mass) as feed stock.

- The organic materials (anode material such as graphite, electrolyte, separator plastics) burn and supply the heat for the process.
- The most valuable metals – cobalt, nickel, copper – reduce into a mixed alloy.
- The mixed metal alloy is processed (typically via the hydrometallurgy process) to recover pure, separated metals for reuse. Only cobalt, nickel, and copper are recovered; whereas the lithium and aluminum are typically left entrained in the process slag because they are not economically feasible to recover.
- The main waste by-product is a slag, which is landfilled in parts of the world.

The pyrometallurgical process is the most mature Li-ion battery recycling technology and is commercially available in North America and Europe. The process economics depend on the recovery of cobalt, which to date has been the most valuable element (in terms of market price) in the battery. Market trends, however, are moving towards less or no cobalt cathodes, which increases business model uncertainty. Innovation is needed to adapt business models to emerging generations of low to no cobalt Li-ion batteries. Increasing market price for lithium may make recovery technologically feasible for recycling using this process, but the cost-effectiveness is to be determined.

The **hydrometallurgical process** relies on aqueous chemistry via leaching in acids or bases and subsequent concentration and purification. The general steps are described below.

- Batteries are shredded separating plastic cases.
- Copper and aluminum metal foils are screened out for recovery.
- Active material powders are generally treated with acid through leaching to extract the metal ions from the cathode structure. Leaching processes include alkali leaching, acid leaching, and bioleaching.

The leachate undergoes further treatment through various precipitation and solvent extraction methods (ion exchange, solvent extraction, chemical precipitation, co-precipitation, electrolysis) to separate the metals and remove impurities. The salts can be used as raw material inputs for new cathode materials. The electrolyte and anode carbon are generally not recovered.

Hydrometallurgy is the most used method for Li-extraction to obtain Li+ solution in acidic medium where heat and oxidant such as hydrogen peroxide (H_2O_2) are used to assist metal leaching. The hydrometallurgical process is commercially available primarily in China and South Korea, but less so in the U.S. due to higher labor costs. The process is economically viable, particularly for cathodes high in cobalt and nickel; however, the business model is not as good as pyrometallurgy because the process reduces the cobalt content of the cathode materials. Hydrometallurgy offers a less energy-intensive alternative and lower capital costs (Jung et al., 2021). Recovery of the electrolyte and anode does not typically occur because they have low market value. The low pH operations can result in the emission of harmful gases for Cl_2, and NOx, that have environmental and health impacts.

The **direct recycling process** directly harvests and recovers active cathode materials while retaining their original compound structure so they can be reused in new battery production. Direct recycling is considered an emerging technology and has mostly been performed at lab and pilot scale. Recovery is focused on the cathode material because cathode production is a major energy-intensive step in battery manufacturing; thus, avoiding the energy-intensive refining and synthesis is desirable. Other materials are also recovered for reuse with direct recycling.

The general steps for direct recycling are described below.

- Pretreatment includes discharging to prevent thermal runaway; dismantling to produce useable materials streams; and electrolyte recovery to separate liquids from solids in the cells.
- Battery constituents are separated using physical separation methods such as magnetic separation, and moderate thermal processing to avoid chemical breakdown of the active materials.
- The active materials are purified and both surface and bulk defects are repaired by re-lithiation or hydrothermal processes.

The best-case business model for direct recycling consists of batteries with a consistent and known chemistry. Because Li-ion batteries consist of many different materials, and cathodes may be mixtures of more than one active material, separating each material out may not be economically or technically feasible. Direct recycling is challenging due to the different battery chemistries and appears to be better suited for small-scale recyclers, or for battery manufacturers to adopt for recycling electrode scrap. OnTo Technology (Bend, Oregon) recycles cathode materials directly through a hydrothermal process and additional heat treatment. This process is primarily at lab scale, but life cycle analyses and process-based cost models have revealed that direct recycling potentially has both economic benefits and greenhouse gas emission reductions compared to the pyrometallurgical and hydrometallurgical processes (Bai et al., 2020). The direct recycling process can be economical on a smaller scale compared to the pyro and hydro processes even if the cobalt content is low. Additionally, other cell components including the anode carbon and electrolyte solvents and salts can also be recovered, which reduces waste disposal costs. One technical obstacle whose impact is to be determined is ensuring both the quality and consistency of the regenerated material to meet changing and increasing battery industry requirements in energy density and cycle life (Bai et al., 2020).

Biohydrometallurgy, or bioleaching, is an emerging branch of hydrometallurgy that uses leaching agents that are biologically produced by microorganisms to recover metals from ores, concentrates, and recycled or waste materials in the aqueous extractive metallurgy. The microbe-assisted bioleaching process converts the insoluble metal composition into water-soluble metals by bio-oxidation, and the microbe gains energy by rupturing the ores or wastes into their component metals (Roy, Cao, and Madhavi, 2021). Because bioleaching is still at lab-scale, the process is not discussed further in this report.

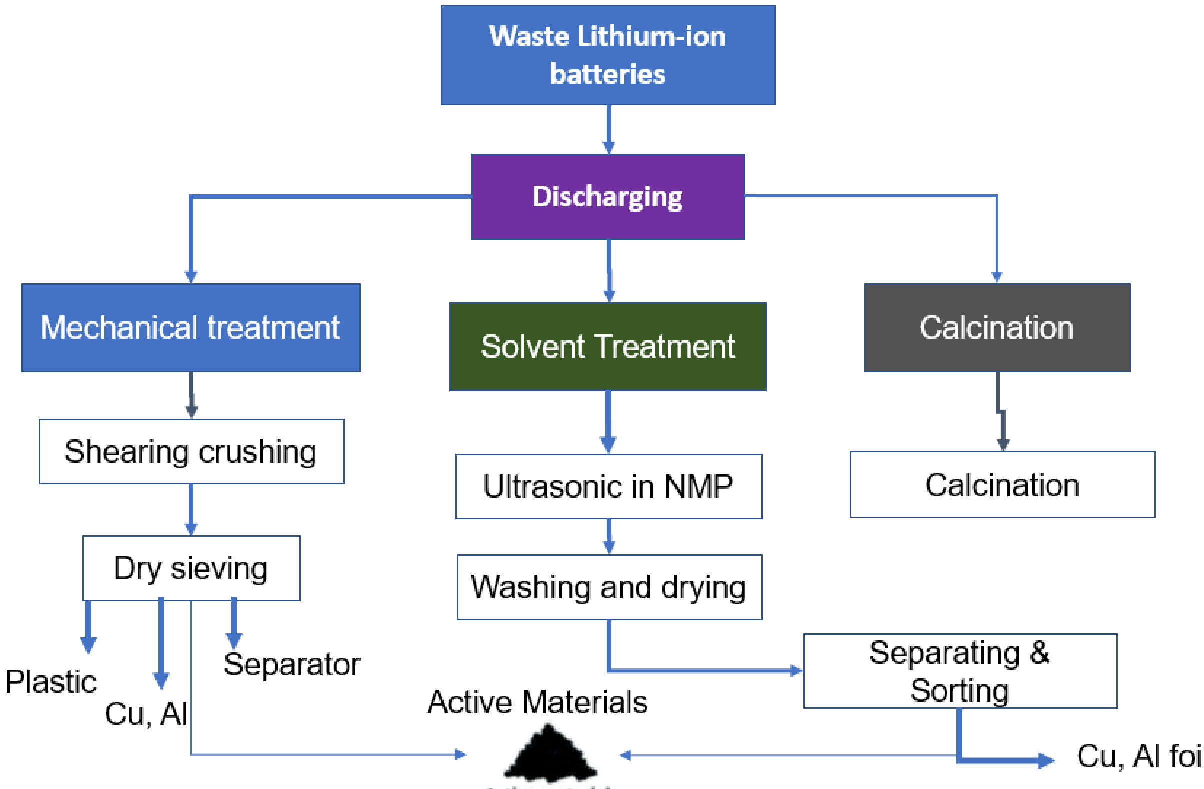

Figure 11. Li-ion recycling pre-treatment technologies and processes

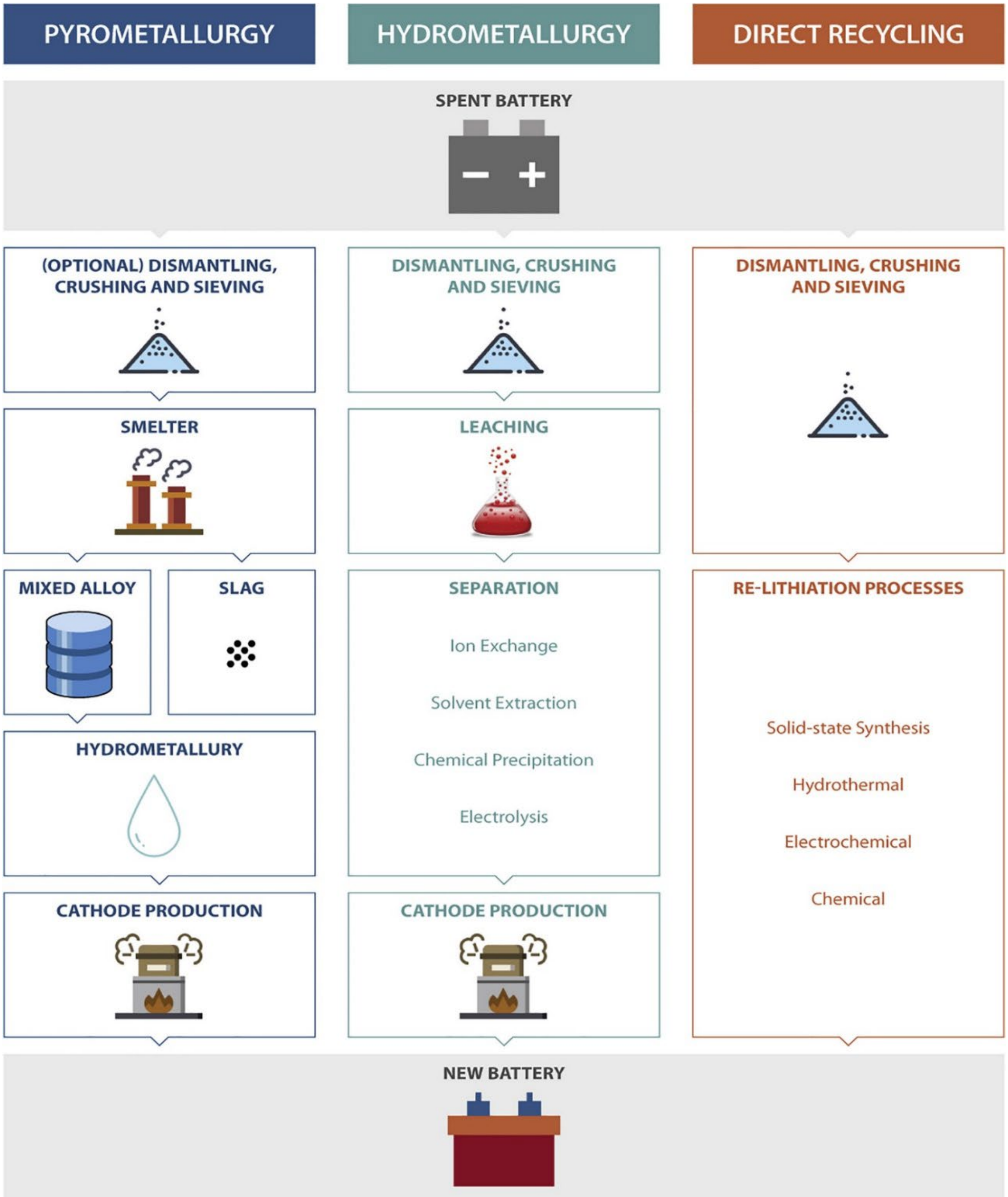

Figure 12. Three Major Li-Ion Battery Recycling Processes – Pyrometallurgy, Hydrometallurgy, and Direct Recycling (Chen et al., 2019)

Table 6. Main Advantages and Disadvantages of Li-Ion Battery Recycling Processes

Recycling Process and Description	Advantages	Disadvantages
Pyrometallurgy A high-temperature smelting process, which typically involves burning and subsequent separation of materials.	▪ A simple and mature process; most widely used process by recycling facilities. ▪ Sorting and size reduction are not necessary—a mixture of Li-ion battery and NiMH batteries can be recycled. ▪ The output consists of basic, elemental "building blocks" that can be used in synthesizing new cathode materials of many different chemistries.	▪ CO_2 generation and high energy consumption during the smelting process. ▪ The alloy requires further processing, which increases the total recycling cost. ▪ Many of the materials in LI-ION BATTERIESs are not recovered (e.g., plastics, graphite, and aluminum, Li, Mn)—the process recovers Co and Ni from the cathode materials and Cu from the anode current collector, which only account for ~30 weight percent in LI-ION BATTERIESs for electronics. ▪ Li remains in the slag as a compound and is hard to be recovered by pyrometallurgy due to its high melting and boiling point. ▪ Business model uncertainty as the battery industry is moving toward reduced Co or, ultimately, Co-free cathode materials.
Hydrometallurgy Material recovery is achieved using aqueous chemistry, via leaching and subsequent concentration and purification.	▪ High purity materials can be generated. ▪ Most LI-ION BATTERIES constituents can be recovered. ▪ Uses low temperature operation, resulting in lower CO_2 emissions compared to the pyrometallurgical process.	▪ Requires sorting, which may increase storage space and adds to cost and complexity. ▪ Challenge of separating some elements (Co, Ni, Mn, Fe, Cu, and Al) in the solution, due to their similar properties, which can lead to higher processing costs. ▪ Requires specialized wastewater treatment with associated costs.

Recycling Process and Description	Advantages	Disadvantages
Direct Recycling A recovery method proposed to directly harvest and recover active materials of LI-ION BATTERIESs, while retaining their original compound structure.	▪ A relatively simple process when battery chemistry is known. ▪ Active materials can be directly reused after regeneration. ▪ Significantly lower emissions and less secondary pollution, in comparison with pyrometallurgy and hydrometallurgy.	▪ Requires rigorous sorting and pre-processing, based on exact active material chemistry. ▪ Challenging to guarantee consistent high purity and pristine crystal structure, which may not meet standards required by the battery industry. ▪ Primarily exists at lab and pilot scale. ▪ Significant sensitivity to input stream variations. ▪ Inflexible process: what goes in comes out, and thus the process may not be appropriate to meet the reality of changing cathode chemistry (active materials recovered at EoL will be "old technology" and may no longer be relevant).

Sources: Chen et al., 2019; Kam and Doeff, 2017.

Waste By-Products from the Recycling Process

Li-ion battery recyclers tend to have patented recycling processes, but the general waste by-products created are generally understood and discussed in the literature (Brückner, Frank, and Elwert, 2020).

The primary by-products from the pyrometallurgical process include:

- Plastic and metal solid waste from dismantling
- Co-, Cu-, and Ni-bearing spent catalyst agents, electroplating sludges, filter dusts, and ashes from the smelter
- Co-, Cu-, and Ni-containing alloy (metallic phase) or matte (sulfidic phase)
- Al-, Mn-, and Li-containing slag (oxidic phase); and
- Fly ash.

The alloy/matte and slag can be treated by hydrometallurgy to recover the individual metals but is not conducted by all facilities and usually ends up being landfilled. The fly ash is also typically landfilled.

The hydrometallurgical process generates:

- Plastic and metal solid waste from dismantling

- Transition metal salts
- Metals (Co, Ni, Cu)
- Leaching residue (can be reused in the leaching process to the extent possible), wastewater.

No mention of waste by-products created from the direct recycling process were identified in the literature reviewed.

3.6 Landfill Disposal

Landfill is the destination for most solid waste generated in the United States (EPA, 2020). Although, some landfills sort waste and remove Li-batteries from landfill, many batteries are likely ending in landfills crushed and compressed. Damaged batteries may start fires in landfills, using the surrounding waste as fuel. In addition to the fire hazard because of their tendency to ignite, when Li-ion batteries end up in landfills, they release environmental contaminants, including toxic heavy metals like Co, Ni or Mn.

Li-ion batteries may meet the definition of hazardous waste under the Resource Conservation and Recovery Act (RCRA) if they exhibit characteristics of hazardous waste such as ignitability, reactivity, or toxicity when disposed. With respect to businesses, the EPA recommends managing Li-ion batteries under the federal Universal Waste regulations (40 CFR part 273).

With the exception of households, Li-ion generators such as small commercial consumers must dispose of Li-ion batteries at a household hazardous waste or e-waste collection point (if allowed), or at a battery recycling location (EPA, 2021b). Residential and commercial consumers should not dispose of Li-ion batteries directly in the trash or recycling bins, but it does happen, specifically when a consumer does not know a product contains a Li-ion battery, when a consumer is not aware of fire and other hazards associated with improper handling, and potentially when taking the battery/product to a certified electronics recycling or collection point is not convenient or available. No estimates of the quantity of Li-ion batteries that were directly disposed in the garbage were identified in the literature reviewed for this report; however, numerous examples of battery fires resulting from thermal runaway during MSW collection and disposal were identified (U.S. EPA, 2021b).

4 Policy Landscape for EoL Management

This section presents the state-level policy landscape for EoL management of Li-ion batteries (**Section 4.1**) and identifies organizations and working groups involved in Li-ion battery research and advocacy for sustainable EoL management (**Section 4.2**). The Bipartisan Infrastructure Law is funding various project for reintegration of used batteries into the supply chain to meet increased demand and self-reliance for critical materials.

4.1 State Battery Policies

Battery stewardship has become more common in the US. As of 2023 ten US states, California, Colorado, Maine, Maryland, Oregon, New Jersey, New York, Vermont, Washington and Florida -plus Washington D.C. have enacted extended producer responsibility (EPR) or similar laws for batteries. New York is the has enacted a law requiring battery manufacturers to develop and finance state approved plans for collecting and recycling batteries at no expense to the consumer or retailer. Vermont's EPR laws share the cost of recycling and safe materials management between consumers and producers and increase collection and recycling rate of covered products. Noncompliance with these requirements is subject to potential civil penalties of up to five thousand dollars. Several other states, shown in green in **Figure 13,** have landfill disposal bans for household batteries, primarily lead-acid, nickel-cadmium (Ni-Cd), and nickel metal hydride (Ni-MH) batteries. Some of these state regulations also specifically mention Li-ion batteries as part of the disposal ban.

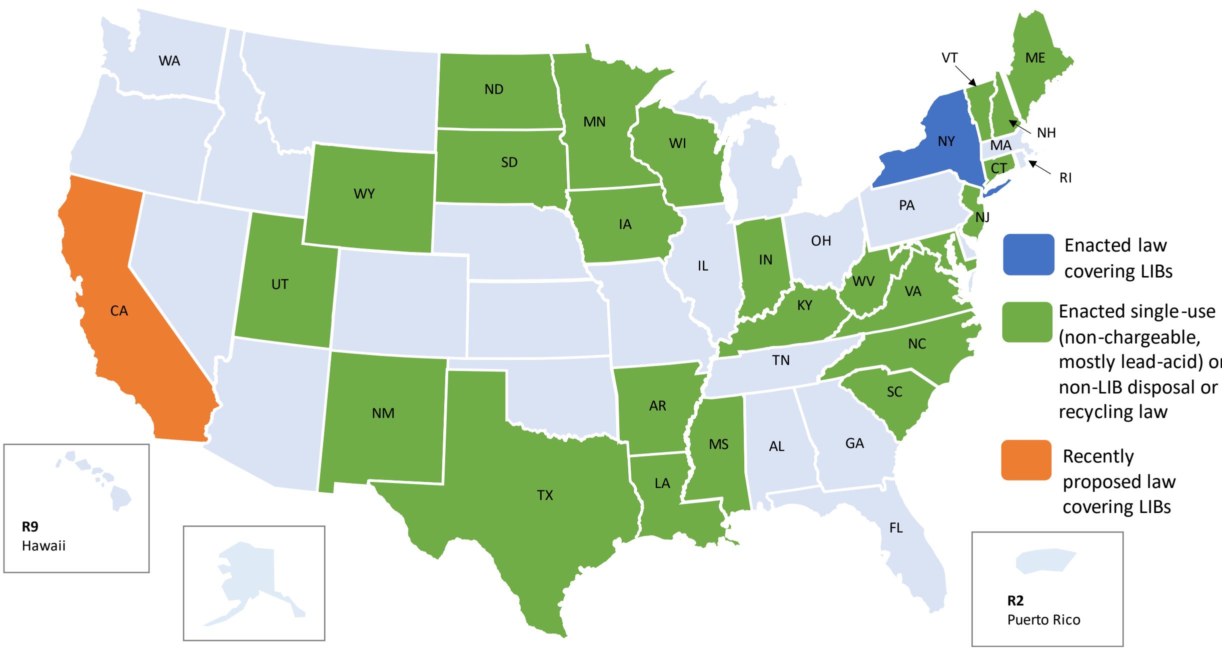

Figure 13. States with a Battery Recycling Law (*California, Washing and District of Columbia have passed EPA laws, 2023*)

New York

Rechargeable Battery Law (Article 27, Title 18 of the Environmental Conservation Law) – was signed into law on December 10, 2010. Retailers that sell rechargeable batteries are required to collect used batteries of the same type from customers for recycling and post a sign on their premises indicating they do so. The law covers most dry cell, non-vehicular rechargeable batteries weighing less than twenty-five pounds, regardless of chemistry. Disposal of rechargeable batteries as solid waste also is prohibited after December 5, 2011. Battery manufacturers are responsible for developing state approved plans for collecting and recycling batteries at no expense to the consumer or retailer.

The law requires battery collection by both local retailers and direct sellers of rechargeable batteries (i.e., catalog, telephone, or internet sales). Smaller food stores that sell rechargeable batteries explicitly are not required to collect used batteries. Non-compliance with these requirements is subject to potential civil penalties of up to five thousand dollars.

The following battery chemistries are covered by the law:

- Nickel Cadmium (Ni-Cd)
- Nickel Metal Hydride (Ni-MH)
- Lithium Ion (Li-Ion)
- Small Sealed Lead Acid (SSLA/Pb)
- Any other such dry cell battery capable of being recharged
- Battery packs containing any of the above-mentioned batteries.

Consumers are prohibited by a disposal ban from throwing their used rechargeable batteries into the trash. Consumers should make every effort to return their unwanted rechargeable batteries to a retailer that sells rechargeable batteries.

California

The Rechargeable Battery Recycling Act of 2006 (AB 1125), effective July 1, 2006, prohibits many retailers from selling rechargeable batteries in California unless they have a system in place for collecting used rechargeable batteries from consumers. This law provides a convenient, cost-free opportunity for consumers to return, recycle, and ensure the safe and environmentally sound management of used rechargeable batteries. A retailer is not subject to the requirements for the sale of rechargeable batteries that are contained in or packaged with a battery-operated device, meaning the law does not cover all instances of rechargeable batteries sold in the state.

In 2019, AB 1509, titled the "LITHIUM-ION BATTERY FIRE PREVENTION ACT," was introduced in the Assembly, but was not passed by the Senate. The bill would have required establishment of a used lithium ion battery stewardship program by manufacturers and retailers. The bill was intended to address the fire safety problems purportedly facing municipal recycling programs from the collection of used batteries.

The Responsible Battery Recycling Act of 2022 requires battery stewardship by producers, either individually or through the creation of one or more stewardship organization, for the collection and recycling of covered batteries. Li-ion batteries are also banned from disposal in California.

4.2 Select Organizations and Working Groups

Several organizations and working groups are involved in EoL management of products including Li-ion batteries and e-waste. The major players and their relevant focus areas are briefly described below.

Call2Recycle® is the country's first and largest non-profit consumer battery stewardship and recycling program. Founded in 1994, Call2Recycle brings together thousands of partners, including retailers and government municipalities, to manage battery recycling efforts. The organization works on behalf of stakeholders to provide its turnkey consumer battery recycling program to consumers across the U.S. through more than 16,000 public drop-off sites.

SERI is a multi-stakeholder, collaborative nonprofit organization focused exclusively on minimizing the environmental and health risks posed by used and EoL electronics while also maximizing the social and economic value presented by this equipment. SERI is an ANSI-accredited Standards Development Organization and developed the R2 Standard, which is the world's most widely adopted standard for responsible practices for used electronics.

DOE's Argonne National Laboratory has conducted lithium-ion battery research for decades and operates the **Materials Engineering Research Facility** (MERF). Using state-of-the-art equipment and instrumentation, MERF researchers apply emerging manufacturing technologies to develop scalable and economically viable manufacturing processes with the circular economy in mind, including processes to recycle batteries. The MERF work is helping to bridge the gap between materials discovery and technology commercialization.

DOE's ReCell Center is a national collaboration of industry, academia, and national laboratories working together to advance recycling technologies alone the entire battery life-cycle for current and future battery chemistries. ReCell was launched in 2019 with a $15 million investment and is headquartered at Argonne National Laboratory. Research is focused on longer-term projects, including direct cathode recycling, and plans to demonstrate a cost-effective method for recycling cathode powders in 2021/2022.

DOE's Lithium-Ion Battery Recycling Prize focuses on identifying innovative solutions for collecting, sorting, storing, and transporting spent and discarded Li-ion batteries from EVs, consumer electronics, and industrial and stationary applications for eventual recycling and materials recovery. The Battery Recycling Prize is a $5.5 million phased prize competition, announced in January 2019, to specifically incentive American entrepreneurs to develop and demonstrate processes that, when scaled, have the potential to profitability capture 90 percent of all discarded or spent Li-based batteries in the U.S. for eventual recovery of key materials for re-introduction into the U.S. supply chain. The Bipartisan Infrastructure Law has added $10 M to this prize. The program completed Phase III, in 2023 and the seven Phase II winning teams are eligible to implement a pilot validation of their end-to-end solutions developed in Phase I and expanded upon in Phase II. The program has received an additional $10 M in the 2023.

Electronics Recycling Coordination Clearinghouse (ERCC) is a public-private association managed by National Center for Electronics Recycling and the Northeast Recycling Council. The ERCC maintains an on-line resource of state regulations focused on small format, electronics recycling at https://www.ecycleclearinghouse.org.

National Center for Electronics Recycling (NCER) is a non-profit organization formed in 2005 that is dedicated to the development and enhancement of a national infrastructure for the recycling of used electronics in the U.S. through 1) the coordination of initiatives targeting the recycling of used electronics in the U.S., 2) participation in pilot projects to advance and encourage electronics recycling, and 3) the development of programs that reduce the burden of government through private management of electronics recycling systems.

Northeast Recycling Council **(NERC)** is a non-profit organization that conducts research, hands-on projects, training, and outreach on issues associated with source reduction, recycling, composting, environmental preferable purchasing, and decreasing the toxicity of the solid waste stream. They provide webinar trainings and numerous resources on their 11 state members (from Maine to Maryland).

5 Assessment of the Li-ion Battery Recycling Network

Recycling of spent Li-ion batteries increases sustainable EoL management options for consumers, can provide cost-effective sources of materials for new battery manufacturing, may lead to job creation, and reduces energy consumption and greenhouse gas emissions associated with mining virgin materials and battery manufacturing from new materials. This section identifies Li-ion battery recycling in the U.S. and internationally (**Section 5.1**), interesting recycling-related research and planned recycling facilities (**Section 5.2**), and discusses the drivers, barriers, and enablers to increase a recycling and the circular economy for Li-ion batteries (**Section 5.3**).

5.1 Recycling Facilities in the U.S.

Figure 13 shows the major Li-ion batteries recycling facilities worldwide as of 2022 as compiled by Chen et al. (2019). Most recycling facilities are concentrated in China, western Europe (France, Switzerland, Germany), and the east and west coast of the United States. Collection and transfer stations are required to collect enough batteries to transport them to a battery recycling facility in the U.S. or internationally. As mentioned previously, Call2Recycle facilitates more than 16,000 collection and drop-off locations across the U.S. and Canada and claims that 86 percent of Americans live within a 10-mile radius of a Call2Recycle drop-off site[2], although this is likely not representative of those living in central U.S. states or those in rural areas.

[2] As noted in the Call2Recycle 2020 Annual Report, available at https://www.call2recycle.org/annualreport/.

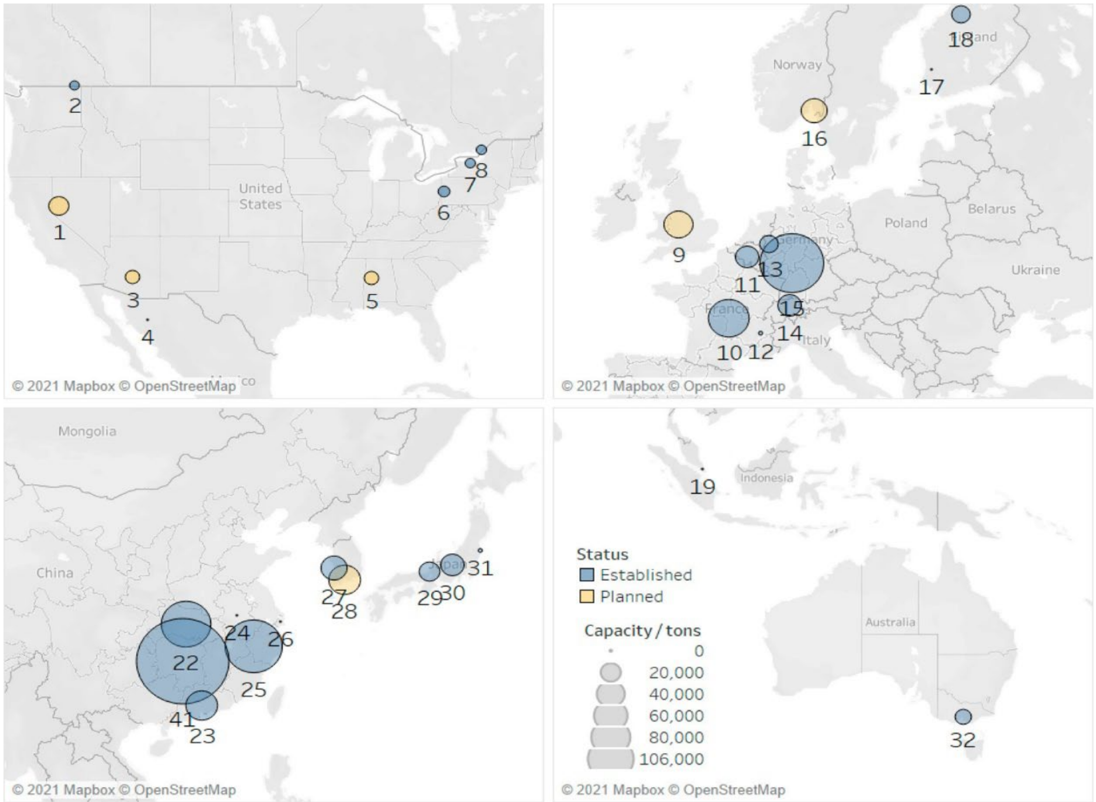

Figure 14. Established and planned global Li-ion battery recycling facilities as of November 2021. (Baum et al., 2022)

Source: Chen et al., 2019
Figure note: This map does not include recycling plants at pilot-scale and other lab-scale recycling technologies.

The infrastructure needs and logistical costs of collection and transport have not been examined in detail with respect to spent battery generation in the U.S., but Call2Recycle and others' collection sites presumably could handle the amount of spent Li-ion batteries generated annually in the U.S. The costs for collection and transport are voluntarily covered by producers for members of Cal2Recycle and paid for by recycling entities and then recouped through the sale of recovered materials. For example, Call2Recycle, North America's most comprehensive cellphone, and rechargeable recycling network, has hundreds of industry stewards and charges set fees[1] by battery type per gram for collection. Suppose Li-ion battery manufacturers are required to take back or generally collect spent Li-ion batteries. In that case, a 2014 study estimated that it would cost them approximately $1,120 per ton based on the assumption that collection costs represent approximately 40 percent of variable costs (Wang et al., 2014). Wang et al. (2014) conducted a cost optimization analysis and estimated that manufacturers could have a profit of $240 per ton of spent Li-ion batteries if they collected and recycled spent Li-ion batteries versus disposing of them in a landfill. The probabilities of those scenarios follow the distribution illustrated in **Figure 15**. The costs of recycling Li-ion batteries involve high-order of fluctuation uncertainty due price of raw material supply of Li and Co, and the cost of transportation of collected batteries due to the hazardous nature of Li-ion batteries. Unlike landfill disposal, recycling requires a certain amount of investment but could bring an overall financial gain. Although these numbers differ by location and time, recycling is viewed as a lever that can potentially decrease the cost of future batteries and energy use, lessen pristine material use and reduce reliance on imported materials (Chen et al., 2019).

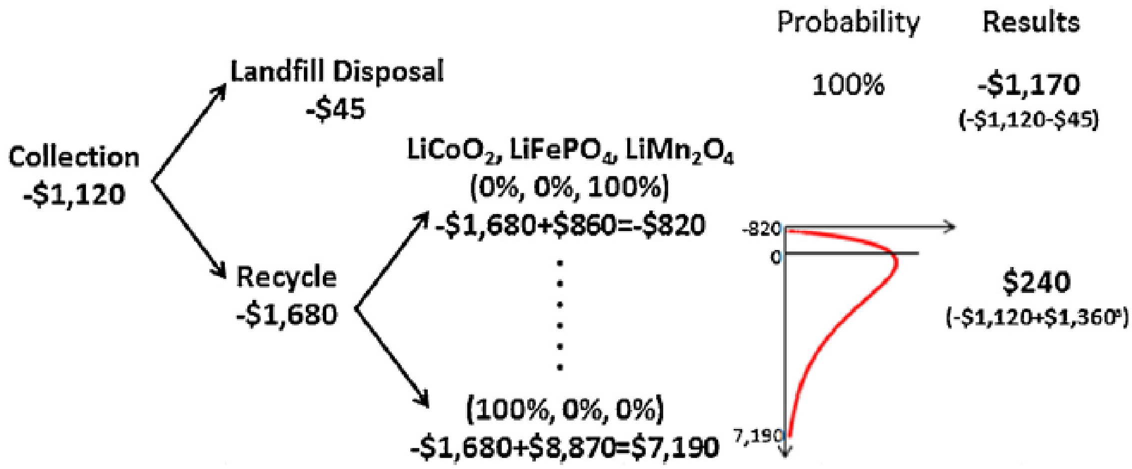

Figure 15. A Decision Tree for Spent Li-Ion Battery Management by a Manufacturer Required to Collect Spent Li-Ion Batteries (Wang et al., 2014)

Note: Numbers are calculated for one ton of spent Li-ion batteries

5.2 Battery Recycling Projects to Watch

This following is a list of battery recycling companies and organizations involved in promising Li-ion battery recycling research and development, and planned recycling facilities (e.g., LiCycle). Currently, most of anode and cathode components of batteries used in North America have to be imported. A new manufacturing corridor from the Michigan to Georgia, also know as “Battery Belt” is where the capacity for GWh battery production is being built.

North America

Cirba Solutions (Battery Management and Materials): This is a pioneer battery recycling business that has been in existence for over 30 years in North America and is currently processing EOL of Li-ion batteries across many chemistries. With head office in Wixom, Michigan, and plants in Ohio, Arizona, and South Carolina, Cirba Solutions takes end-of-life batteries, processes them to extract critical materials, and sells them to the supply chain. Cirba Solutions offers comprehensive circular services that solve battery collection programs, second-life applications, cathode production, extract materials, and supply materials that return to the supply chain. Cirba Solutions has plants in Wixom, Mich., near Detroit; Anaheim, Calif.; Mesa, Ariz.; British Columbia, Canada; and Lancaster and Baltimore, Ohio, near Columbus

American Battery Technology Company (ABTC): ABTC, formerly American Battery Materials, Inc. is focused on a clean-technology platform that provides more effective production of metals used in EVs, grid storage and electronics batteries. Its green battery-production platform seeks to enable a circular economy that provides sustainable sourcing of critical battery materials. It plans to open a battery-metals recycling plant in Fernley, Nevada with an eventual capacity of 20,000 metric tons of scrap materials and EoL batteries per year. The final grading permit was awarded in June 2021 and construction will begin on the pilot plant shortly. It is unknown when a full-scale plant will be in place. In addition to the battery recycling plant, ABT is building a universal waste storage facility in Fernley and a hazardous waste storage facility in nearby McCarran, Nevada.

Ascend Elements: The former **Battery Resourcers:** This Worcester, Massachusetts startup, a spin-off of Worcester Polytechnic Institute, is focused on making new cathode powders for Li-ion batteries from postindustrial scrap. They synthesize NMC cathode materials from spent Li-ion batteries from any battery chemistry and the process can recover more than 90 percent of all materials from the batteries. The battery made from recycling materials in a pilot project had a 32 percent longer life cycle than the reference battery produced by industry. Ascend Elements Hydro-to-Cathode™ process spent Li-ion battery materials to recover valuable elements and deliver precursor and finished cathode materials.

Li-Cycle: The Canadian Li-ion resource recovery company begin constructing the largest Li-ion battery recycling plant with a capacity of 66,000 metric tons of spent input material equating to 120,000 electric vehicle batteries in Rochester, N.Y. in late 2021. The plant will use hydrometallurgical recycling and is expected to recover 95 percent or more of the cobalt, nickel, lithium, and other valuable elements through the company's zero-wastewater, zero-emissions process. The plant is scheduled began operations in 2022 and will be the largest domestic source of Ni and Li, and the only source of Co in the U.S. (Jacoby, 2019). Li-Cycle operates by a "spoke and hub" model where the spokes are facilities that handle preliminary processing of spent batteries and scrap, which are then transferred to a centrally located hub for final processing into battery-grade materials. One spoke is in Kingston, Ontario (near Toronto) and a second spoke just opened in Rochester. The new recycling plant in Rochester will be the recycling hub Li-Cycle Corp has opened new facilities in Gilbert, AZ, Tuscaloosa, Alabama and Kingston, Ontario Canada, which are part of the company's original plan to construct 20 spokes globally by 2025 (INFO@LI-CYCLE.COM). LI-Cycles are opening a new plant in 2023, in Norway with the joint venture operation with Norwegian companies Morrow Batteries and Eco Stor.

ReCell Center: Funded through a 3-year, $15 million grant from the U.S. Department of Energy's Vehicle Technologies Office, this research center is focused on longer-term methods such as direct cathode recycling.

Redwood Materials: Cofounded in 2017 by former Tesla CTO J.B. Straubel, the Carson City, Nevada, startup has positioned itself as a raw-materials supplier and will recycle electronic waste generally. The company uses hydrometallurgical metal refining to remanufacture anode and cathode battery components. It is among five initial recipients of Amazon's $2 billion Climate Pledge Fund. The company has a multibillion-dollar deal with Tesla and Panasonic to meet battery recycling for the rapidly growing EV market. Redwood has a production of anode copper foil in Nevada already. It aims to support the production of more than 1 million EVs annually. Redwood Materials is building, recycling, refining, and manufacturing anode and cathode components outside Charleston, South Carolina.

Europe

Northvolt: This Swedish battery startup, founded by former Tesla executives in 2016, already has an experimental recycling plant up and running and, with aluminum company Hydro, plans to open an 8,000-metric-ton-per-year recycling plant in Norway this year. ECO STOR is partnering with Li-Cycle Holding Corp., and Morrow Batteries AS is to open Li-ion battery recycling facility.

ReLI-ION BATTERIES: Comparable to the U.S. ReCell Center, this R&D collaboration based at the Faraday Institution in Birmingham, England, is focused on improving the efficiency of EV battery recycling in the United Kingdom.

Umicore: A leading materials recycler with 11,000 employees worldwide, Umicore has since 2017 focused on "clean mobility," including the recycling of all components of electric vehicles. Its Hoboken, Belgium, plant can handle 7,000 metric tons of Li-ion batteries a year.

East Asia

Brunp Recycling Technology Co.: A subsidiary of the leading Li-ion battery maker CATL, Brunp is the largest recycler of those batteries in Asia (and therefore the world). Its new plant in China's Hunan province reportedly can recycle 100,000 metric tons of lithium-ion battery scrap per year.

Ganfeng Lithium: The Chinese Li-ion battery maker plans to build a battery-recycling plant in Mexico, to sell minerals to electric-vehicle makers and suppliers, including Tesla and South Korea's LG Chem.

Green Li-ion: The Singapore startup will open its second recycling plant in early 2021, which focuses on recycling Li-ion battery cathodes that are "99.9 percent pure."

Primobius: This joint venture of Australia's Neometals and Germany's SMS Group will demonstrate Neometal's proprietary recycling method with plans to scale up commercially in Europe.

SMCC Recycling: A joint venture of South Korea's SungEel HiTech Co., a battery recycler, with Business-to-Business operation. As of 2023 SMCC Recycling has not raised any funding rounds yet.

Tesla: For the past couple of years, Elon Musk has hinted that the EV maker will recycle its own batteries. Now it has reportedly begun doing so in China, where phase 2 of its Shanghai Gigafactory is wrapping up.

5.3 Drivers, Barriers, and Enablers

Li-ion battery recycling is not yet a universally well-established practice because of technical constraints, economic barriers, logistical issues, regulatory gaps, and lack of consumer knowledge. Hydrometallurgy processes are more common outside the US. While pyrometallurgical and hydrometallurgical recycling processes are commercially available, their business models depend heavily on the high cobalt concentration in Li-ion batteries, recovery of nickel, and high market prices for both metals. Data collected by the Consortium for Battery Innovation indicates that the volume of Li-ion battery production is relatively low in North America, which indicates the recovered materials from spent Li-ion batteries in North America may need to be exported to a country such as China where production is high and recovered materials have a greater chance of finding a buyer. Additionally, future changes in battery chemistry and design will require recycling facilities to manage all types of Li-ion batteries, which may increase sorting and disassembly costs (due to the variety of designs) and potentially increase business model uncertainty for the handful of Li-ion battery recycling facilities currently operating in the U.S.

Several drivers and enablers have been identified and have potential for increasing Li-ion battery recycling in the short term (5 to 10 years) in areas located near a free of charge battery collection site, and/or when massive amounts of Li-ion batteries start entering the waste stream. As noted above, it generally accepted that a large portion of battery waste is shipped to China for recycling and that Li-ion battery recyclers in the U.S. may not have the spent battery supplies to make their business models profitable. However, that may change in the next 5 to 10 years as EVs and solar power storage systems reach their expected end of life since these items tend to be larger and less likely to be hidden in normal household trash.

The most encouraging enablers and drivers include the increased federal research and development funding and the DOE's ReCell center and collaborative research platform, planned facilities such as the Li-Cycle recycling hub in Rochester, New York, and the existing consumer spent battery drop-off network (operated by Call2Recycle and others). Existing regulation covering battery disposal in select states could also be amended to include Li-ion batteries, or new laws requiring Li-ion battery collection and recycling could be proposed, which may also drive and incentivize battery recycling. Additionally, while not necessarily a driver, the prevalence of fires originating from Li-ion batteries may push local governments and MSW collectors and landfill owners and operators to enforce compliance of consumer disposal practices more strictly.

These and other barriers, drivers, and enablers to promoting a circular economy, and specifically recycling, of EoL Li-ion batteries are presented in this section.

For context, the terms of drivers, barriers, and enablers are defined below.

- **Drivers** are opportunities that motivate actors to adopt a desired behavior and typically benefit specific stakeholders or the public interest. Federal, state, and industry policy can either enable or inhibit a particular opportunity or benefit. Economic and environmental drivers are presented in **Table** 7.
- **Barriers** are factors that may hinder a desired behavior or outcome. Federal, state, and industry policy can inhibit a particular opportunity, benefit, or desired outcome. Identifying the major barriers associated with Li-ion battery recycling may help policymakers formulate policy solutions to overcome future challenges. A variety of barriers are presented in **Table** 8.

- **Enablers** are solutions or ways to overcome a barrier that inhibits a desired behavior or outcome. Federal, state, and industry policy can enable a desired behavior or outcome. The main enablers are presented in **Table** 9.

The stakeholders that may be impacted from the removal or implementation of each driver, barrier, and enabler are also identified.

Table 7. Drivers to a Circular Economy for Li-ion Batteries

Driver	Description	Manufacturer	Consumer	Drop-off Sites, Logistics	Recycler	Government	MSW Collectors	Landfill Operator
Financial support for research and development	U.S. federal funding and dedicated research centers are pushing technology and involving a variety of stakeholders (academia, private sector).	x	x	x	x	x	x	x
Increasing knowledge of the potential for thermal runaway and battery fires	Increasing consumer awareness about fire hazards may prompt consumers to properly manage spent batteries through collection events and recycling versus disposal with household garbage.	-	x	x	x	x	x	x
Reduced resource constraints	Recycling aims to conserve high-value materials, prevent resource constraints, and reduce import demand for raw materials.	x	-	-	-	-	-	-
Global supply of lithium and other key metals	Demand for lithium is expected to outweigh supply as the world decarbonizes transportation and the energy supply according to market analyses. Additionally, China has a larger control over the global lithium supply compared to the U.S.	x	x	x	x	x	-	-
Cost savings and increased profits	Reduce manufacturing costs and achieve additional revenue streams; afford decrease project costs. Market prices for two common cathode metals, cobalt and nickel, are expensive and could yield a large re-sale value if market prices remain high and stable. In many types of Li-ion batteries, the concentrations of these metals, along with those of lithium and manganese, exceed the concentrations in natural ores, making spent batteries akin to highly enriched ore (Jacoby, 2021).	x	x	x	x	-	-	-
Enhanced competitiveness incentivizing circularity	Appealing to circular economy carries a transformational potential that increase a business's green or environmentally responsible image and increase consumer trust when using recycled Li-ion battery constituents, particularly in relation to the social and environmental damages associated with mining virgin materials.	x	x	-	x	x	-	-

Driver	Description	Manufacturer	Consumer	Drop-off Sites, Logistics	Recycler	Government	MSW Collectors	Landfill Operator
New and expanded market and employment opportunities	Recycling may provide opportunities for new and expanded markets and job creation.	x	-	x	x	x	-	-
Reduction in negative environmental impacts	Recycling reduces waste, the generation of greenhouse gases and other air pollutants, and electricity consumption during manufacturing and additional resource use and environmental impacts from mining raw materials, transport, refining, and manufacturing of products.	x	x	-	x	x	-	x

Table 8. Barriers to a Circular Economy for Li-ion Batteries

Barrier	Description	Manufacturer	Consumer	Drop-off Sites, Logistics	Recycler	Government	MSW Collectors	Landfill Operator
Fluctuations in market price for recovered materials	Fluctuations in market pricing for metals and valuable minerals may increase challenges to recycling business models. The prices of two common cathode metals, cobalt and nickel, the most expensive components, have fluctuated substantially in recent years. Current market prices for cobalt and nickel stand at roughly $27,500 per metric ton and $12,600 per metric ton, respectively. In 2018, cobalt's price exceeded $90,000 per metric ton.	x	x	x	x	-	-	-
Lack of innovation and information exchange between individual recycling companies	Patented technologies and company policy typically do not support information exchange between manufacturers and recyclers to promote design for easy disassembly and more efficient and environmentally friendly recycling processes.	x	x	-	x	x	-	-
Lack of economic incentives for small-scale Li-ion battery recycling	Limited economic incentives exist to promote design for recycling, or for the collection, transport, and recycling of Li-ion batteries from household consumers.	x	x	x	x	x	x	x
Variety of Li-ion battery chemistry, size, and shape of batteries; and variety of products using Li-ion batteries	Li-ion batteries are compact, complex devices, come in various shapes and sizes, and are not designed to be disassembled. They also contain a wide variety of ever-evolving materials, which makes sorting, disassembly, and recycling challenging. Quickly identifying and removing Li-ion batteries facilitates recycling.	x	-	x	x	-	x	x
Evolving battery chemistry	With cobalt being the most economically valuable metal on the market, the move to low or no cobalt designs may challenge recycling business models.	-	-	-	x	-	-	-
Lack of consistent state policies and regulations	Very few states have enacted regulations or policies to encourage Li-ion battery recycling.	x	x	x	x	x	x	x
Lack of data about Li-ion battery repair and refurbishment for reuse	Limited information is available on repair and refurbishment processes, services, and costs; and volume of retired Li-ion batteries with potential for repair and refurbishment.	-	x	x	x	x	-	-

Table 9. Enablers to a Circular Economy for Li-ion Batteries

Enabler	Description	Manufacturer	Consumer	Drop-off Sites, Logistics	Recycler	Government	MSW Collectors	Landfill Operator
Increasing investment in research and development	Identifying more efficient methods for recycling could reduce market uncertainty and investment risk for recyclers and for emerging recycling processes such as direct recycling (and how to separate more efficiently the cathode material) and bioleaching.	-	-	x	x	-	-	-
Increased and publicly available information and information exchange	Public awareness campaigns about proper EoL management, drop-off centers and collection events, and recycling could decrease landfill disposal and help reach economies of scale for recycling.	x	x	x	x	x	x	x
Clearly defined laws and regulations	Clearly defined regulatory requirements and restrictions can reduce uncertainty and risk associated with Li-ion battery recycling, specifically in states requiring recycling and those that do not. MSW collectors divert batteries from the recycling stream.	x	x	x	x	x	x	x
Statutory and regulatory schemes that support Li-ion battery recycling and resource recovery efforts	Federal and state policies can require or incentivize recycling such as those that require manufacturer take-back programs, include compliance strategies and financial penalties for landfill disposal.	x	x	x	x	x	x	x
Better labeling of products and Li-ion batteries	Better product labeling of products that contain Li-ion batteries with a recommendation to recycle would help consumers understand proper EoL management. Recycling facilities normally receive EoL Li-ion batteries without knowing the interior chemical constituents; proper labeling by battery manufacturers would improve the efficiency of battery sorting based on chemistry.	x	x	x	x	-	x	x
Scale of recycling facilities	Increases the difficulty of achieving economies of scale and may require businesses to expand their service area, which may increase collection and transport logistics and cost. Large-scale facilities are recovering electrolyte and anode carbon, while direct recycling could be economical on a smaller scale even if the cobalt content is low.	-	-	x	x	-	-	-

6 Conclusion

With the increased use of battery technologies, the volume of used and decommissioned Li-ion batteries presents end-of-life management concerns. It could also be a source for resource recovery and secondary market opportunity. Li-ion battery-based clean technology could promote the transition to a circular economy by increasing the use of renewable energy, reducing waste and pollution, and keeping products and materials in use. Thus, recycling Li-ion batteries can reduce negative environmental impacts associated with the unsafe management of batteries, reduce resource constraints, and increase supply chain securities of precious and crucial materials.

Technical, economic, social, and regulatory factors have been barriers to achieving a circular economy of batteries. The current standard practices of manual disassembly will be automated. There are technical gaps for efficient sorting and grading processes and designing batteries for recycling to assist in the easy disassembly of cells. Disassembling is followed by many approaches for recovering materials, including pyrometallurgy, hydrometallurgy, short-loop, and direct. Furthermore, the state of different companies in EOL management of batteries, the state of barriers, and enablers are presented.

The scope of this report is limited to current EOL management practices of Li-ion batteries, including recycling drivers, barriers, and enablers in the United States. However, the report may have partial information on the state-of battery management due to the fast pace of technological changes, regulatory landscape, and policy that have incentive reuse and recycling and sustainable management practices.

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