Energy
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End-of-Life Management of Lithium-ion Energy Storage Systems

April 22, 2020

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Acknowledgements

This white paper was written by Marc Chupka, Vice President of Research & Programs at the U.S. Energy Storage Association (ESA). ESA wishes to thank members of the Corporate Responsibility Initiative who provided input and comments on several drafts of this paper, including Call2Recycle, Inc., Clearway Energy Group, Dimension Renewable Energy, Renewance, Inc., and Wärtsilä.

Acronyms

DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
EPC	Engineering, procurement, and construction
ESA	U.S. Energy Storage Association
ESS	Energy storage system
EV	Electric vehicle
GHG	Greenhouse gas
LFP	Lithium iron phosphate
Li-ion	Lithium-ion
LMO	Lithium manganese oxide
NCA	Nickel cobalt aluminum
NMC	Nickel manganese cobalt
NYSERDA	New York State Energy Research & Development Authority
OEM	Original equipment manufacturer
RBRC	Rechargeable Battery Recycling Corporation (now Call2Recycle)
RCRA	Resource Conservation and Recovery Act
SO_x	Sulphur oxides

Introduction

Energy storage is experiencing a period of rapid deployment growth, and even in the midst of an economic downturn, global analysts' projections indicate this trend is poised to continue due to increasingly attractive economics and the value storage provides from multiple grid services.[1] While many developers and owners are gaining experience deploying and operating grid-connected energy storage systems (ESS), few have yet to manage ESS facilities at the end of a system's life. But ESS owners, operators and developers may be able to apply some of the lessons learned from the auto industry's experience as it confronts the task of managing an increasing stock of used Lithium-ion (Li-ion) batteries from electric vehicles (EVs).

Both grid-connected ESS and EVs rely on Li-ion batteries, and the phenomenal growth in Li-ion applications creates stress along the entire value chain–from mining raw material inputs, such as lithium and rarer elements, to manufacturing and disposition of the batteries once they reach the end of their useful lives. This linear depiction of material and energy use in the economy – from extraction of natural resources to production, use, and disposal – may present significant environmental consequences as the volume of battery production increases. An alternative model has emerged that instead attempts to mimic nature in the way inputs are used in production of goods, which upon reaching the end of their useful lives are then reused and/or recycled as inputs again. Such "circular economy" concepts are prevalent in the debates surrounding how to best manage the Li-ion battery life cycle.

In April 2019, the U.S. Energy Storage Association (ESA) launched the Corporate Responsibility Initiative (CRI) with dozens of industry leaders to share advanced safety practices and develop educational materials and resources on safety, emergency preparedness, and lifecycle management. This paper focuses on the end-of-life management of Li-ion batteries, offering a review of options from the circular economy perspective. A related forthcoming CRI track will look at supply chain issues, which represents another arc along the circular economy, one which may increasingly rely on materials recovered after the end of (first or subsequent) life application.

[1] In this paper, ESS primarily refers to "Front-of-the-Meter" (FTM) battery storage systems connected to the grid at the transmission or distribution system level. However, the concepts and end-of-life pathways identified are also relevant for "Behind the Meter" (BTM) customer systems.

Why Focus on Li-ion?

While there are many other energy storage technologies and several battery chemistries, Li-ion currently commands the bulk of the market for electric vehicle and stationary grid-connected systems. Its use in both applications is expected to grow at a rapid pace. According to Wood Mackenzie Power & Renewables, 99% of stationary energy storage deployments in 2019 used Li-ion technologies.[2] Moreover, the vast majority of lead acid batteries (predominantly automotive batteries) are already recycled, and other battery chemistries are not expected to gain significant market shares in EV or ESS applications in the near term.

Circular Economy and Li-ion Batteries

The primary objective of the circular economy framework is to promote a sustainable economic system by minimizing material and energy used to provide economic goods and services. Some of these principles are expressed in shorthand slogans, such as "reduce, reuse, recycle," and frequently are congruent with greenhouse gas (GHG) reductions objectives. However, *given current technology and markets*, not all production and waste can be brought into a circular economy with beneficial results. For some goods, more energy would be used in collecting and recycling activities than is used to produce virgin materials, or the costs of reuse or recycling are prohibitive compared with relatively benign disposal options. Life-cycle analysis (LCA) can help identify these factors and may identify challenges and opportunities that can lead to improved technologies and more effective markets. Indeed, the current constraints and limitations to beneficial reuse or recycling within the Li-ion battery value chain have already prompted recent initiatives and new programs to address these barriers as discussed later in this document.

Circular economy reasoning generally superimposes a loose hierarchy on end-of-life options, with reuse (in the original application or some other less demanding application) taking precedence over recycling, and recycling all, or at least some, of the material inputs preferred over disposal. These paths are shown for EV batteries in Figure 1, with green and blue arcs representing environmentally-sustainable flows. This hierarchy is a reasonable way to frame end-of-life management options for Li-ion batteries —

[2] Wood Mackenzie Power & Renewables and Energy Storage Association, *U.S. Energy Storage Monitor 2019 Year in Review*, March 2020.

though, again, the desirability of any specific end-of-life management pathway on costs, emissions, or other measures depends on technologies, systems and markets. Circular economy principles even apply at the start, in designing products for more economic refurbishment or recycling, or for a longer service life that reduces the need for energy and material inputs for manufacture of new products.

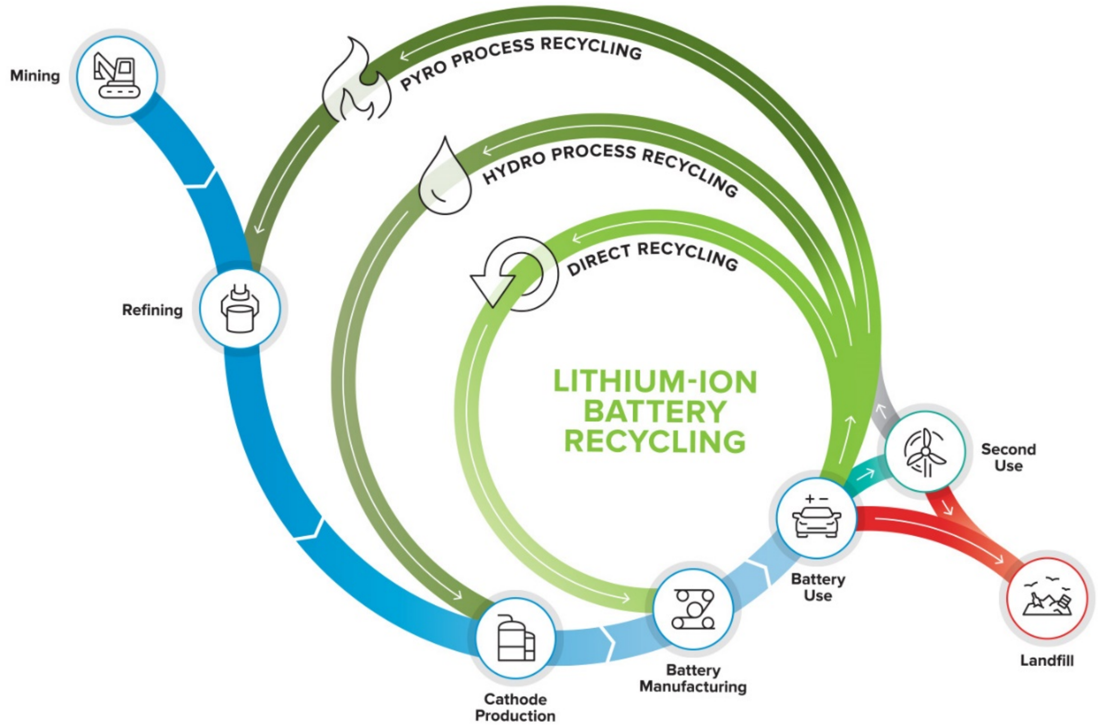

Figure 1:
Circular Economy Pathways for EV Batteries
Source: ReCell; Argonne National Laboratory

While this paper addresses stationary ESS, much of the information and experience with Li-ion end-of-life management is derived from the increasing management of spent EV batteries around the world. While ESS and EV Li-ion batteries have different applications, they share many material inputs and thus have similar reuse and recycle opportunities. Some of the practices that evolve to reuse and recycle EV batteries will influence, and sometimes determine, the end-of-life requirements and management practices applicable to stationary ESS batteries. Finally, the substantial number of EV batteries that will end service during this period as stationary ESS deployments rapidly increase has sparked research and commercial interest in the reuse and refurbishment of EV batteries for “second life” applications in stationary ESS, further linking the two applications.

Energy Storage System End of Life

For the vast majority of stationary ESS installations, the end of life represents a planning decision rather than an unexpected moment. Operating a Li-ion battery ESS under prudent safety guidelines and adhering to codes and standards helps prevent significant accidents or failures and thus extends its useful life. In the absence of catastrophic failure, owners generally have discretion on when to remove a Li-ion battery ESS from service.

The effective lifespan of the ESS can also sometimes be extended with enhanced maintenance and replacement activities. Li-ion battery-based ESS are inherently modular, being composed of individual battery cells assembled into modules (packs, trays or assemblies), arrayed in racks, connected into various control systems and enclosed in containers. Individual cells, modules and even entire racks can be replaced as needed (when, for example, one degrades unusually quickly compared to other components that maintain performance). Where economic, overall ESS performance can be maintained at acceptable levels by selectively refreshing individual components, thus extending the overall economic lifetime and deferring the retirement of the facility. Currently, the validation to ensure that a mixture of old and new battery cells or modules can work together effectively can be costly, although those costs will likely fall as operating experience accumulates. Extending the effective lifetime of a durable asset is consistent with circular economy benefits as it reduces both virgin material input requirements as well as potential waste, although at some point performance, safety and economic considerations will dictate decommissioning.

Decommissioning

As with any other asset within the power sector, the decommissioning process involves dismantling the ESS and removing it from the site in compliance with applicable federal and local rules that govern the safe transport and disposition of used equipment or waste. A primary issue in end-of-life planning is who bears the legal and financial liability for the equipment once a facility shuts down and components are moved offsite. Even if an engineering, procurement, and construction (EPC) or an operating contract assigns decommissioning cost responsibilities to another party,[3] the used Li-ion batteries will be

[3] Renewance estimated costs for dismantling, shipping, and recycling the batteries for a 10 MWh facility at over $474,000, or almost $50/kWh. See Renewance, Inc., "Commercial Liability Considerations for End-of-Life Industrial Batteries," 5.

classified as hazardous waste and thus the owner will be considered a hazardous waste generator liable for proper disposal under the Environmental Protection Agency (EPA) rules under the Resource Conservation and Recovery Act (RCRA).[4]

Decommissioning obligations, processes, and costs for stationary storage were not always considered in earlier installations and remain to some extent discretionary, in part due to currently limited standards and ambiguous regulatory frameworks. Long before owners face actual decommissioning decisions, they should understand and evaluate the options and develop a decommissioning plan, considering current and future potential regulations. And because the options to consider in eventual decommissioning continue to evolve, the plan should be capable of adapting to new information to take advantages of emerging opportunities.

It is becoming more common for contract language to specify that system decommissioning responsibilities and their costs lie with the operations and maintenance provider or EPC contractor, even though the EPA deems the owner liable for proper treatment of removed equipment. Under such arrangements, the contractor identified as responsible typically provides all decommissioning services (including restoration of the site to original state if required, and removal of the equipment). However, the details of how decommissioning is to be done, or what happens to the decommissioned battery, have not commonly been specified in the contracts.

State agencies and utilities are also encouraging or requiring the development of energy storage decommissioning plans at project inception. For example, utilities such as Portland General Electric in Oregon are now making decommissioning responsibilities explicit in requests for proposals. The New York State Energy Research and Development Authority (NYSERDA) published *New York Battery Energy Storage System Guidebook for Local Governments,* which includes a model rule for localities that specifies that applicants for new energy storage projects must have a decommissioning plan and a decommissioning fund.[5] The NYSERDA model rule states that applicants must have a narrative description of the decommissioning process, the estimated life of the energy storage system, details

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[4] The characteristics of Li-ion batteries determine their classification as hazardous waste, and a waste generator means "any person, by site, whose act or process produces hazardous waste…or whose act first causes a hazardous waste to become subject to regulation." (40 CFR § 260.10) and "a used battery becomes waste becomes a waste on the date it is discarded (e.g., when sent for reclamation)" (40 CFR § 273.2(c)(1)).

[5] See New York State Energy Research and Development Authority, *New York Battery Energy Storage System Guidebook for Local Governments,* 2019.

about the estimated cost of decommissioning and plans for ensuring its funding, and contingency plans for removal of damaged batteries.

The actual scope of decommissioning depends on project-specific conditions, the type of system, and the disposition pathway chosen, such as whether some or all of the ESS will be reused or recycled.[6] In some cases, the battery modules are removed, while the balance of the system (controls, enclosures, etc.) remain and are re-used with new battery modules. In other cases, the full systems are replaced as integrated packages. If the site itself is being entirely decommissioned (no future energy storage or similar infrastructure will occupy it), contractual agreements govern the final state of the site (e.g. resulting in remediated land, residual foundations, gravel, etc.).

Once a used battery is removed from service and diverted toward end-of-life management, it is designated as "Universal Waste," a special category of hazardous waste under EPA regulations.[7] These rules generally require recordkeeping, labeling, and storage methods that keep material out of the environment, and they outline approved recycling or disposal pathways. Damaged cells, e.g., where the cell casing has been breached, may face additional requirements than those imposed under Universal Waste rules.[8] A battery intended for refurbishment and reuse is not considered "waste" under RCRA, because it is not discarded.[9]

Although this paper addresses the end-of-life management of batteries, the balance of plant can represent a significant quantity of materials, including concrete pads, steel enclosures, cabling, and an array of electronics that are part of the entire energy storage system package. Concrete and steel are readily recyclable, and many enclosures can be reused, particularly if a site is being repowered with new batteries at the end of old equipment's lifespan. Inverters, control systems, and other electronic equipment share many of the challenges of e-waste more broadly, but useful materials can often be recovered. Some of the dismantled equipment from an ESS can be reused with minimal processing. For

[6] Strictly speaking, the ESS decommissioning applies to the battery-related elements of an ESS. The site itself, including interconnection facilities, could be reused with a new ESS, much like generating facilities can be "repowered" and thus re-commissioned with new generating equipment. However, the existing battery components would be dismantled and removed, thus becoming available for re-use, recycling or disposal.
[7] See 40 CFR § 273.
[8] See U.S. Environmental Protection Agency, "May a handler of universal waste manage broken or damaged batteries as universal wastes?" for a discussion of damaged battery classification.
[9] For material to be classified as hazardous waste, it first must be considered solid waste, and material "used or reused as effective substitutes for commercial products" is exempt from solid waste designation (40 CFR § 261.2(e)(1)(ii)).

example, rack systems can be reused in new or existing ESS facilities or returned to original equipment manufacturers (OEMs) for spare parts inventory.

Transport of Batteries

After dismantling and removal from the site, the old batteries are transported to facilities for refurbishment, recycling, or disposal. Moving Li-ion batteries can pose a fire risk if still-energized batteries short circuit or their containers are damaged. Transport of batteries, whether new or used, is governed by U.S. Department of Transportation (DOT) regulations that treat batteries as "Class 9" miscellaneous hazardous material and specify packaging and materials containment to mitigate the risk of accidental activation or reaction of the batteries during transport.[10] All batteries must be packed in a strong outer package which prevents short circuits or accidental activation, prevents the release of any hazardous materials, ensures no leakage, and inhibits any combustion, and damaged batteries are subject to additional packaging and labeling requirements.[11] However, Li-ion batteries shipped by motor vehicle to a permitted storage or disposal facility, or to a recycling facility, are exempted from certain labeling, marking, testing and record-keeping requirements.[12]

Both shippers who package battery waste and carriers (e.g., trucking firms and drivers) who haul the waste batteries must comply with training and certification requirements for hazardous materials transport. The packing, labeling, and training regulations are fairly detailed, and a lack of significant experience with the exact requirements that apply to transporting large-format Li-ion batteries may make carriers and/or individual drivers reluctant to accept loads where they lack regulatory experience.

Transport regulations generally apply to both individual Li-ion cells as well as battery modules; decommissioned ESS will generally yield battery modules for shipment. Batteries may be completely discharged prior to shipment to a recycling facility, while batteries destined for refurbishment and reuse will maintain some charge in transport (and while placed in temporary storage after transport). For reuse in particular, ensuring that the batteries are not damaged or further degraded is important (*e.g.,* leaving them exposed to weather or in a fully-discharged state can harm later reuse). The growing stockpiles of spent EV batteries may not become available for eventual refurbishing and reuse if not

[10] These rules are implemented and enforced by the Pipeline and Hazardous Materials Safety Administration and are found at 49 CFR § 173.185.
[11] See 49 CFR § 173.185(f).
[12] See 49 CFR §173.185(d). The exemptions relate to requirements found in UNECE, UN standard 38.3.

properly protected. The duration of time stored between transport and processing also raises liability issues for Universal Waste. Temporary storage must keep the decommissioned equipment in a safe state, shielded from fire risk, protected from risk of pollution and from safety hazards caused by trespassers.

Refurbishment and Reuse: "Second Life"

Where economically feasible, reusing battery systems and other components is more environmentally sound than recycling constituent materials. As batteries degrade over time, they may be less useful for their originally intended purpose, but still valuable for other applications. For example, backup power systems or batteries coupled with renewables to power remote irrigation systems may not need the same performance characteristics as commercial grid systems. These "second life" applications can substitute for newly-manufactured battery energy storage systems and in some cases expand the role of stationary energy storage, such as when new systems may be prohibitively expensive, but a lower cost refurbished system can meet the desired performance requirements.

There is increasing attention placed on reusing EV batteries for less exacting stationary service, and where energy density (Wh/kg) does not pose a significant design constraint. Projections of EV deployment indicate an immense and growing number of Li-ion battery systems will soon face end of life in their vehicle applications. Reconditioning EV batteries, either by original equipment manufacturers (OEMs) or third parties, is an active area of research and emerging commercial opportunity. Once EV batteries degrade to 70-80% of their original rated capacity they are typically retired, although future EV owners may retain their vehicle or original battery longer (even with degraded range) if it continues to serve their specific needs.[13] And while the current level of second-life battery deployment is very small in North America (10 MWh) and Europe (100 MWh), China had re-deployed almost 1 GW of used batteries by 2018, primarily as back-up power at telecommunication facilities.[14]

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[13] EV range increases could also lower that retirement threshold somewhat, as batteries at roughly 60% of their capacity could meet most driving needs (with charging at work). Even at 30% of their capacity, LBNL anticipates most (55%) of US driving needs could be met. See Lawrence Berkeley National Laboratory, V2G-Sim.

[14] See Melin, Hans Eric, "The lithium-ion battery end-of-life market – a baseline study," Global Battery Alliance. The figures from China likely reflect the impact of government mandates to assess for second life opportunities and subsidies.

Refurbishing or reconditioning batteries for second use is a significant undertaking. First, a processor must conduct tests to determine the condition or "state of health" of used batteries. The batteries must then be assembled into modules suitable for stationary service. Coupling batteries of varying states of health can require more advanced control systems, as the control hardware and software that interacts with original batteries to ensure optimal – and safe –operation is usually proprietary and designed for the original battery application. Developing new controls and software to convert older batteries into use for new applications remains a significant challenge.

The cost savings must be significant enough, and the performance of second-life batteries high enough, to make refurbishing appealing compared to new batteries. The discounted cost of reconditioned batteries relative to new ones must offset increased integration costs and reduced performance relative to new ones for a robust market for second-use batteries to develop. Declining prices and improved performance of new batteries may limit the demand for use of reconditioned EV batteries in stationary energy storage projects. As costs for new batteries continue to fall, it may become harder to convince manufacturers and users to refurbish and use old ones. Designing for reuse at the outset could reduce refurbishment cost substantially and increase the commercial viability of this path.

Second-life battery system applications in the U.S. are currently limited to pilot demonstrations and small projects. Several companies and academic institutions are investigating the reuse of EV batteries for stationary applications, and this research likely will be useful and broadly applicable to second-life use for stationary batteries. The codes and standards that apply to refurbished batteries also continue to evolve. UL recently finalized its standard 1974 for Evaluation of Repurposing Batteries, which seeks to establish consistent processes and metrics for assessing batteries destined for second-life applications.[15]

The State of U.S. Recycling of Li-ion Batteries

The primary loop for spent Li-ion batteries to reenter the economy remains some form of recycling. Ultimately this becomes the only alternative to disposal for of all batteries: even if second life

[15] "This standard covers the sorting and grading process of battery packs, modules and cells and electrochemical capacitors that were originally configured and used for other purposes, such as electric vehicle propulsion, and that are intended for a repurposed use application, such as for use in energy storage systems and other applications for battery packs, modules, cells and electrochemical capacitors." UL, Standard 1974 for Evaluation of Repurposing Batteries, Edition 1 (2018).

applications become prevalent, at some point batteries can no longer perform useful service. Therefore, recycling is currently the only viable long-term path to manage spent Li-ion battery waste consistent with circular economy principles.

Beyond enhancing stationary energy storage market sustainability, increasing the volume of batteries that are recycled rather than disposed may also improve supply chain economics. Recycling reduces solid waste streams and allows for the recovery of valuable materials from batteries to reduce reliance on raw material mining that imposes inherent energy and environmental burdens. Many of the materials in lithium-ion batteries such as cobalt and nickel are valuable; reinjecting these domestic resources into the supply chain can reduce costs and reduce imports of raw materials.[16]

Recycling materials has been practiced for decades in consumer waste streams (such as paper, bottles and cans) and commercial recycling (such as scrap metal). However, recycling Li-ion batteries, particularly from large stationary applications, is a relatively new industry.[17] It lacks stable markets for the collection, transport, and recovered resource sales, and applicable federal and state regulations are not always consistent or clear to market participants. As economic, safety and environmental issues are intensifying interest in battery recycling options, related business practices in different stages of project development, operation and decommissioning are still evolving. Some battery recycling methods exist and are well understood. Yet significant research & development (R&D) efforts to improve recycling processes and make them applicable to Li-ion batteries are underway, which will drive new commercial opportunities, regulatory frameworks and best practices. In order to make Li-ion battery recycling commercially viable, innovations (particularly in automated processes) must reduce the cost of collecting, managing, and recycling batteries, and market demand for the recovered materials must support prices to maintain profitability.

At present, no facility in the U.S. fully recycles Li-ion batteries, *i.e.*, renders used batteries into constituent materials and sells or otherwise reintroduces all the resultant material back into commodity markets, although several U.S.-based companies will accept and treat batteries to some degree. However, market demand for recovered materials is likely to strengthen as domestic Li-ion battery

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[16] Mayyas, Ahmad et. al. present a comprehensive overview of Li-ion battery recycling in "The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries," *Sustainable Materials and Technologies*, Volume 19 (April 2019): e00087.

[17] Recycling li-ion EV batteries began approximately a decade ago in the U.S.; see Taylor, Phil, "When an Electric Car Dies, What Will Happen to the Battery? Can millions of lithium ion batteries be recycled?" *Scientific American*, (September 14, 2009).

production capacity is poised to grow substantially in the next few years.[18] Thus, the industry has a narrowing window of time to establish best practices at the outset, encourage the development of an effective recycling market, and implement efficient recycling processes at scale.

Recycling Processes

Sorting recovered batteries is a critical first step to ensure that same-chemistry batteries are being fed into the system. This is less of a concern for ESS and EVs than it is for collections of heterogenous consumer electronic batteries, given the relative large size and low volumes of the former currently sent to recycling facilities.[19] The recycling facilities ensure that the correct type of batteries flow into a given recycling process, including separating different types of lithium-based chemistries, such as lithium iron phosphate (LFP) versus lithium nickel manganese cobalt (NMC). For this reason, labeling cells and batteries with chemistry information is critical during manufacturing to ensure accuracy, using a consistent, standard labeling approach. Japan has developed labeling requirements that use color coding and material data labeling to aid recycling efforts, in addition to a pre-existing color coding of basic battery chemistries (Ni-Cd, Ni-MH, Li-ion, Pb) for quick visual identification.[20]

The recycling process begins with dismantling electrically discharged batteries. The current diversity of Li-ion battery types, sizes, and chemistries makes this process difficult to automate, so it must largely be done manually. The steps consist of removing the battery casings, separating the connectors, disassembling modules from packs, separating cells from modules, and removing the electrolyte. In addition to manual separation, some recyclers employ ultrasound and/or mechanical agitation to remove cathode material. After shredding, or milling and pre-treatment, the cells undergo the recycling process.

Today, there are two primary commercial pathways for recycling batteries: the most common being pyrometallurgical processes (*i.e.*, smelting), and emerging hydrometallurgical processes that include chemical methods such as precipitation, solvent extraction, ion exchange and electrowinning.

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[18] U.S. Li-ion battery manufacturing capacity is projected to surge from 47 GWh currently to almost 160 GWh by the end of 2023. See Business Council for Sustainable Energy and Bloomberg New Energy Finance, *2020 Sustainable Energy in America Factbook* (February 2020): 104.

[19] Conventionally-recycled materials such as plastics, copper, and steel are readily separated without specialized sorting facilities or complex labeling.

[20] Battery Association of Japan, "Program to Make the Portable Secondary Battery Recycle Mark an International Standard." While the Japanese system does not yet indicate Li-ion sub-chemistries, BAI has proposed augmenting the current system with cathode material information. See Battery Association of Japan, "Revised Guideline for Recycle Marking on Li-ion Batteries for the Japanese Market."

Pyrometallurgy is based on 100-year old technology; the primary advantage of pyrometallurgy is that the smelters can easily handle battery cells of mixed chemistries.[21] Hydrometallurgical recycling processes reduce cells to elemental products using leaching techniques, which dissolve the metallic fraction and recycled metal solutions for separation and recovery. Leaching agents include organic and inorganic acids, and ammonia-ammonium salt systems. The main advantage for hydrometallurgy is the ability to recover transition metals and lithium from the cathode.

A major new research and development effort is focused on a third process called "direct cathode recycling." Direct cathode recycling aims to recover relatively intact cathode materials for easier reinsertion into the battery manufacturing process and may provide a method to recover significant value from lithium iron phosphate (LFP) and lithium manganese oxide (LMO) cathodes. This direct recycling is expected to have lower energy costs than other processes and produce more reclaimed and readily reusable material when scaled commercially.[22]

Lessons from Lead-Acid Battery End-of-Life Management

Unlike Li-ion, every stage in lead-acid recycling is profitable, owing to fundamental differences between lead-acid battery and Li-ion recycling. First, it is illegal to dispose of lead-acid batteries without recycling them, creating an enforced closed-loop market. Lead-acid battery recycling is also far simpler than Li-ion, having fewer materials, less material complexity, and less system design complexity. Manufacturers of car batteries all use the same materials: lead, lead oxide, and sulfuric acid in a standard sized polypropylene case. Moreover, the designs are nearly identical so dismantling can easily be automated.

The more complex the input material and design, the more complicated and costly the recycling. Other than some cylindrical Li-ion battery cells of common sizes, there are no prevailing standards for size and design, particularly for EV batteries that are customized for a specific model chassis. The lead in lead-acid batteries is used to manufacture new batteries, but the materials in a Li-ion battery do not always have a substantial market value and the dealer may be charged a fee to dispose of such materials. Lead-acid processors also enjoy an economy of scale, given their ubiquity in most cars and trucks, as well as in other consumer applications and some stationary storage systems.

[22] Pyrometallurgical, hydrometallurgical and direct cathode recycling processes are depicted on Figure 1.

Recycling methods that reintroduce raw materials into cell production can also reduce overall environmental impacts of battery production; life cycle analysis generally finds that upstream raw material extraction and processing creates more environment and energy burdens than cell production and pack assembly. [23] For example, since cobalt, nickel and copper are produced from sulfide ores, their virgin production is not just energy-intensive but also results in high sulfur oxide (SO_x) emissions, which are avoided by recycling.[24] Hence recycling or reclamation can be an efficient strategy to reduce overall environmental impacts from using Li-ion batteries.

However, overall environmental benefits depend on the recycling methods and particular battery chemistries. For example, both hydrometallurgy and direct cathode recycling would reduce greenhouse gas (GHG) emissions for NMC and nickel cobalt aluminum (NCA) batteries, whereas using pyrometallurgy to recycle NMC and NCA batteries may actually increase GHG emissions. Variation in the energy intensity of virgin metals production relative to the recycling process can produce counterintuitive results; *e.g.*, recycling LFP batteries may actually increase emissions relative to production from virgin materials, even using direct cathode recycling methods.[25] This underscores the importance of R&D into improving the processes used in battery recycling, both to improve environmental outcomes and economic viability.

Economics of Recycling

Currently, high processing costs and insufficient demand (and related low market prices for some of the constituent materials such as battery-grade lithium carbonate) impede full U.S. recycling.[26] For recycling to be economically viable for stand-alone commercial processors, the recovered materials must have more market value than the costs of the obtaining and recycling the batteries. Economies of scale in recycling processes and automation are key to reducing recycling costs, although very few ESS batteries are being decommissioned, while larger quantities of spent EV batteries increase slowly.

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[23] Dai, Qiang et. al., "Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications," *Batteries*, 5 (2019): 48.
[24] Gaines, Linda et. al. "Key issues for Li-ion battery recycling" *MRS Energy & Sustainability: A Review Journal*, 5 (2018).
[25] Ciez, Rebecca, "Lithium-Ion Battery Recycling Processes: Environmental Impacts and Economics" ESA Webinar: *Decommissioning, End of Life and Recycling* (March 13, 2019).
[26] Standard battery-grade lithium carbonate (99.5% pure) represents one potential market, while applications requiring less refined grades of lithium compounds could also present sales opportunities.

The primary element working in favor of recycling economics is that the concentration of metals in scrap is much higher than in virgin ores. Under favorable commodities market conditions, and affordable costs for collection and recycling processes, using recycled materials can reduce the costs of production. The cost of materials comprises more than 50% of new cell cost, of which cathode materials comprise the most significant portion, so Li-ion recycling depends heavily on cost-effectively recovering cathode material. Pyrometallurgy yields cobalt and nickel metals which are valued at their commodity prices. In some instances, the value of cathode chemical material is actually greater than that of its constituent elements, so recovering a reusable cathode yields more revenue than recovery of individual elements. For example, one process cost analysis of direct cathode recycling estimates that if NMC cathode material can be recovered for $15/kg or less, then direct cathode recycling would be economically competitive with traditional NMC cathode manufacturing methods.[27] However, the promising economics of direct cathode recycling processes depend on a stable value of specific cathode formulations, which will decline as battery manufacturers move to newer chemistries and render old cathodes obsolete.

A significant barrier to investment in recycling processes is the evolution of Li-ion battery chemistry in response to market conditions. Li-ion batteries contain relatively low percentages of retrievable metals by weight, therefore recyclers get relatively low value from post-process commodities. Cobalt is one of the more valuable recoverable elements, but because of its high cost and supply chain challenges, battery manufacturers are already finding ways to use less cobalt, in turn reducing the demand for cobalt. Market volatility in cobalt and magnesium prices can significantly alter the economic viability of their recovery, and this uncertainty can impede long-term investment decisions in recycling facilities. Rapid technological advances also can challenge recyclers: a facility might invest in the equipment to recycle today's common battery chemistries and face stranded investments if chemistries change to reduce upstream input costs.

Many of the economic uncertainties surrounding investment in recycling R&D, technologies, and processes involve the time lag between initial deployment and end of life of Li-ion batteries in EV and ESS applications. For EVs, the lag between initial deployment and reclamation can be a decade or longer. ESS battery lifespans vary according to their use pattern and the number of discharge / recharge cycles, however 15 years of first use is not uncommon. As EV battery life improves and second life

[27] Ciez, ESA Webinar.

applications flourish, the quantity of EV batteries introduced into the recycling markets may decline somewhat from expected levels. Increasing the useful life of batteries can reduce environmental impacts from initial production, but conversely longer battery lives could also impede recyclers who might otherwise invest in Li-ion processing facilities, particularly in new technologies which need to scale in order to realize cost efficiencies. These impediments to expanding recycling could limit future opportunities for ESS Li-ion battery recycling.

Disposal

Where recycling facilities are unavailable or the recovered materials are uneconomic, batteries are disposed as waste. The management of disposed Li-ion batteries is governed by EPA Universal Waste rules that require waste handlers to separate hazardous materials for disposal under federal laws but allow the disposal of the remaining non-hazardous waste to comply with state and local requirements.

Proper collection, identifying battery chemistries, and fully de-energizing batteries are as important to a disposal site as to the recycling processes discussed above. Once rendered inert from fire risk (mechanically or chemically), non-hazardous materials not recovered for reuse or recycling can be disposed of through municipal waste streams. While some lithium chemistries are considered non-hazardous, many batteries have toxic constituents that require treatment as hazardous materials. The potential toxicity of Li-ion battery materials varies widely by chemistry; for example, where nickel, cobalt, or lead are present in battery chemistries in significant quantities, precautions must be taken at disposal or incineration sites in line with the hazards of those individual materials.

Small Li-ion batteries found in consumer electronics have proliferated in recent years, leading to state efforts to deter improper disposal and encourage recycling. However, even in states such as New York that have implemented rules against disposal, consumer batteries have improperly entered municipal waste streams. Although the experience of small consumer goods batteries is not a reliable predictor of the fate of large-scale Li-ion batteries, federal requirements promulgated decades ago did not contemplate the disposal of significant quantities of large Li-ion batteries, and no clear prospects for action at the federal level to strengthen the rules governing recycling or disposal have emerged. In response, some state and regional policies are emerging, such as California legislature creating an Advisory Group to consider approaches to effectively prohibit landfilling Li-ion EV batteries and incentivize reuse and recycling.[28] The ESS industry will also need to work with regulators to ensure that waste managers utilize safe disposal practices for Li-ion batteries.

Promoting Sustainable End-of-Life Management

Numerous international and U.S. initiatives have recently launched to promote sustainable practices in managing the disposition of used Li-ion batteries. The European Union has established goals for recycling and directed its member states to establish collection programs; industry is working on strategies to meet them. The Global Battery Alliance, a public-private partnership initiated by the World Economic Forum in 2017, issued a report on sustainable battery production and use in September 2019, and announced in January 2020 that 42 organizations had agreed to abide by ten guiding principles to promote the realization of that objective.[29]

The U.S. manufacturing and consumer electronics industries have also been proactive in establishing standards and guidelines. The Rechargeable Battery Recycling Corporation (RBRC), now known as Call2Recycle, established a consumer 'seal' that is formally recognized by EPA; fees collected for licensing the seal help to fund consumer battery collection and recycling efforts. Other initiatives are led by associations of companies such as battery manufacturers, users and recyclers, including the National Alliance for Advanced Technology Batteries (NAATBatt) and the Responsible Battery Coalition.

The U.S. Department of Energy (DOE) has also recently initiated new projects to push forward recycling technology and develop a domestic recycling industry for Li-ion batteries recovered from consumer products, EVs, and stationary ESS facilities.

The ReCell Lithium Battery Recycling R&D Center,[30] led by Argonne National Laboratory along with other national labs and universities, is pursuing several areas of recycling innovation:

- **Designing for recycling** that would make recycling easier and cheaper by planning for disassembly and recycling in the physical layout or chemistry of batteries.

[28] See Lithium-ion Car Battery Recycling Advisory Group in Additional Resources for information and materials.
[29] See World Economic Forum, *A Vision for a Sustainable Battery Value Chain in 2030: Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation* (September 2019), and Global Battery Alliance, "42 Global Organizations Agree on Guiding Principles for Batteries to Power Sustainable Energy Transition" (January 23, 2020).
[30] Argonne National Laboratory, "DOE launches its first lithium-ion battery recycling R&D center: ReCell" (February 15, 2019).

- **Direct cathode recycling** that would improve recovery of cathode material and enhance the value of lithium batteries in recycling.
- **Improving the recovery** of other materials to create more value from recycling.
- **Reintroduction** of recycled materials into new batteries.

In November 2019, ReCell and the Responsible Battery Coalition announced a partnership to jointly pursue advancements in Li-ion battery recycling. In addition, DOE's Li-ion Battery Recycling Prize, administered by the National Renewable Energy Laboratory, seeks to increase Li-ion recycling rates from consumer, EV, and stationary storage to 90% with $5.5 million in awards to improve collection, separating and sorting, safe storage and transportation, reverse logistics, and other areas.[31]

Other DOE-led efforts seek to reduce critical mineral dependence in Li-ion batteries, which will promote domestic recycling. Most recently, in January 2020, DOE announced the Energy Storage Grand Challenge, which includes a call to create "a secure domestic manufacturing supply chain that is independent of foreign sources of critical materials, by 2030." [32] Recent DOE workshop materials highlight the importance of materials recovered from domestic recycling efforts as critical to attaining that goal.[33]

Conclusion

Most U.S. grid-connected energy battery storage systems have only recently been installed and system lifetimes can span more than 15 years; therefore few storage systems in the U.S. have confronted end-of-life issues and undergone decommissioning.[34] Thus, end-of-life alternatives to disposal for ESS facilities have not yet developed into a consistently regulated and economically viable activity. However, the U.S. storage industry is preparing to develop responsible industry practices.

Used EV Li-ion batteries are increasingly being diverted from disposal pathways into a growing recycling industry and even reuse in stationary ESS applications. The lessons learned from used EV Li-ion batteries may help develop sustainable pathways for decommissioned ESS facilities. Not only can

[31] NREL, "Competition Spurs Transformative Lithium-Ion Battery Recycling Solutions" (February 28, 2019).
[32] U.S. Department of Energy, "U.S. Department of Energy Launches Energy Storage Grand Challenge" (January 8, 2020).
[33] Howell, David, "Lithium Battery Technology Discussion," Presentation at NREL (March 16, 2020).
[34] As of March 24, 2020, U.S. Energy Information Administration Form 860m data showed only 11 ESS systems (totaling 52.5 MW) retired to date.

recycling of Li-ion batteries be environmentally beneficial, it can be economically desirable given the right combination of materials, processes, and commodity market prices. Right now, commercial recycling does not yet exist at a scale sufficient to process today's used EV batteries or the forthcoming decommissioned ESS batteries. Significant R&D efforts and increasing investments in recycling capacity are needed to ensure that recycling at scale is economic and practicable. In the meantime, states and other jurisdictions are beginning to develop rules and processes regarding decommissioning, transportation, disposal, and reuse.

The U.S. Energy Storage Association continues to lead the U.S. storage industry and engage with key stakeholders to foster innovation and advanced practice guidelines in emergency preparedness, safety, supply chain, end-of-life and recycling issues. To learn more about how ESA is working proactively on these issues, visit the ESA's Corporate Responsibility Initiative webpage to obtain previously-published and forthcoming resources.

Additional Resources

1. Argonne Lab ReCell Center: https://recellcenter.org/
2. California Environmental Protection Agency Lithium-ion Car Battery Recycling Advisory Group homepage: https://calepa.ca.gov/climate/lithium-ion-car-battery-recycling-advisory-group/
3. Call2Recyle interactive map of recycling laws by state: https://www.call2recycle.org/recycling-laws-by-state/
4. NAATBatt "Laws, Regulations and Best Practices for Lithium Battery Packaging, Transport and Recycling in North America" https://naatbatt.org/lithium-recycling-laws/
5. NREL Lithium Ion Battery Recycling Prize: https://www.herox.com/BatteryRecyclingPrize
6. U.S. Department of Energy, Energy Storage Grand Challenge: https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge
7. U.S. Energy Information Administration Form 860m: https://www.eia.gov/electricity/data/eia860m/

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