Investigation of Battery Energy Storage System Recycling and Disposal

Industry Overview and Cost Estimates

3002023651

Investigation of Battery Energy Storage System Recycling and Disposal

Industry Overview and Cost Estimates

3002023651

Technical Update, May 2022

EPRI Project Manager

B. Westlake

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Together…Shaping the Future of Energy®

© 2022 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ENERGY are registered marks of the Electric Power Research Institute, Inc. in the U.S. and worldwide.

ACKNOWLEDGMENTS

The Electric Power Research Institute (EPRI) prepared this report:

Principal Investigators
B. Westlake
L. Millet
S. Shaw

EPRI would like to acknowledge the following individuals at the Los Angeles Department of Water and Power for their guidance and direction in this research.

- Matt Hone
- Kitsan Lai
- Arevik Petrosyan
- David Alba
- Eric Hill
- Dennis Hou

EPRI would also like to thank Retriev, Kinsbursky Brothers, Umicore, Renewance, Avalon, Omega Harvested Metallurgical, KTY Engineering, Pegex, Absolute Chiller Services, GCI Equipment Rental, Eagle Trucking and Crane, and Express Transpro for the valuable discussions and information to inform this investigation into energy storage system recycling costs.

This publication is a corporate document that should be cited in the literature in the following manner:

Investigation of Battery Energy Storage System Recycling and Disposal: Industry Overview and Cost Estimates. EPRI, Palo Alto, CA: 2022. 3002023651.

ABSTRACT

Battery energy storage systems (BESS), particularly lithium ion, are being increasingly deployed onto the electric grid at larger and larger scale to provide grid resiliency and reliability, and to support the increased deployment of renewables. It is important for BESS owners and operators to plan for the system end-of-life as a component of fiscal and environmental management practices and to properly assess the chance of any potential future risks. This report develops cost estimates for end-of-life management of two different BESS designs: (1) a large BESS (20MW, half hour) lithium ion system, and (2) a smaller mixed chemistry system incorporating both lithium ion (100kW/400kWh) and vanadium flow batteries (100kW/400kWh). The estimates were made through application and expansion of the methodology described in a 2017 EPRI report (3002006911) and include disposal and recycling of both the battery modules and balance-of-system materials. These end-of-life cost estimates were calculated based on 2030, assuming a 10-year BESS lifetime. The report also provides a snapshot of the current industry by summarizing the current regulations for battery end-of-life management, recycling processes, and ongoing research efforts in the battery recycling space. Building on the momentum created from early deployments of lithium battery or other emerging energy storage systems, it will be important to look beyond the initial capital and operational costs of a system when calculating the financial balance sheets. End-of-life costs, from site decommissioning to battery module recycling or disposal, should be included in those total life cycle costs and levelized costs of storage considerations.

Keywords
Battery disposal
Lithium ion battery
Vanadium flow battery
Recycling
Grid energy storage
Recycling regulatio

Deliverable Number: 3002023651

Product Type: Technical Update

Product Title: Investigation of Battery Energy Storage System Recycling and Disposal: Industry Overview and Cost Estimates

PRIMARY AUDIENCE: Electric utilities interested in or actively installing Battery Energy Storage Systems (BESS)

SECONDARY AUDIENCE: Battery system suppliers, manufacturers, recyclers, or those interested in the policies and regulations surrounding BESS end-of-life

KEY RESEARCH QUESTION

With the deployment of increasingly larger BESS on electricity grids, it is critical that end-of-life management is planned for at the point of facility design. This report investigates critical questions on the topic using a cost and system accounting methodology developed by EPRI. These key questions include: What is a reasonable expected cost of the complete disassembly and disposal of a grid-scale lithium ion energy storage system? What variables contribute most to the cost, and how can cost be expected to change with varying chemistries and systems? What regulations are currently in place in the US and abroad pertaining to the handling, transportation, and recycling of lithium ion systems, and how do they impact end-of-life cost estimates?

RESEARCH OVERVIEW

This research investigated the end-of-life processes and costs for two utility battery systems, (1) the large BESS (20MW, half hour) lithium ion system, and (2) a smaller mixed chemistry system incorporating both lithium ion (100kW/400kWh) and vanadium flow batteries (100kW/400kWh). Information was collected from industry participants and applied to develop a detailed removal and recycling process cost estimate, described in the report. For the larger system, these nickel manganese cobalt (NMC) module removal costs were compared to a replacement with an alternative LFP module chemistry to understand the effects of system energy density and disposal costs.

KEY FINDINGS

- Total decommissioning cost for the 20MW/10MWh large BESS is estimated at $1,185,000, as described in Section 5.
- Looking at the cost breakdown as shown in Table 5-3, roughly 70% of the cost is due to battery module removal, transportation, and recycling.
- Battery energy density is estimated to have a large impact on total decommissioning costs, due to both manual labor in dismantling and packaging, as well as increased transportation and recycling costs.
- Decommissioning and disposal costs for the smaller mixed chemistry BESS with lithium ion (100kW/400kWh) and vanadium flow batteries (100kW/400kWh) is estimated at $168,200, as described in Section 6.
- The flow battery decommissioning and recycling industry is not as developed as the lithium ion battery recycling industry, and extra effort may be required to identify qualified disposal and material handlers outside of the original vendors.

- For lithium ion systems, changes in battery chemistry type can affect the number and volume of modules needed for the same system energy rating. This, coupled with the recycling and disposal costs for battery modules with less recoverable metal, may greatly affect system disposal cost estimates. Section 7 includes an example comparison.
- Planning for the responsibilities and costs of managing end-of-life tasks should be incorporated early in the battery system project life, preferentially during the design and procurement phase.

WHY THIS MATTERS

End-of-life decommissioning can represent a significant cost for large-scale BESS, and hence must be taken into account when considering proposals for new installations. This overview of estimates and technology can be used as a framework to understand energy storage system costs with and without end-of-life disposal in a quantifiable way. It may also help identify how decommissioning responsibilities are directed in initial system contracts.

HOW TO APPLY RESULTS

This report describes the process and cost components involved in system end-of-life decommissioning, whether for a lithium or flow battery system. Cost estimates are based on conversations and publicly available information obtained in 2020, and considers price estimates for decommissioning of recently installed systems in the 10-year time frame. This work may inform total life cycle costs for systems at planning and procurement, and may inform project planning and scope of work development for system removal, recycling, and disposal at end-of-life.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Program 94 Energy Storage and Distributed Generation
- Program 197 Environmental Aspects of Fueled Distributed Generation and Energy Storage

EPRI CONTACTS: Brittany Westlake, Sr. Technical Leader, bwestlake@epri.com

PROGRAM: P197 Environmental Aspects of Fueled Distributed Generation and Energy Storage

© 2022 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ENERGY are registered marks of the Electric Power Research Institute, Inc. in the U.S. and worldwide.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Overview

Battery energy storage systems (BESS), particularly those of lithium ion chemistry, are being increasingly deployed onto the electric grid at larger and larger scale. These systems provide grid resiliency, reliability, and support the increased deployment of renewables. The traditional form of grid-connected energy storage is as pumped-storage hydroelectricity, but recent performance improvements and cost declines of lithium batteries have made it an economic option for front of the meter (i.e. grid-connected) or behind-the-meter deployments. Cost declines for stationary storage have resulted from manufacturing build-out for the electric vehicle market. A similar build-out of end-of-life battery logistics/handling, recycling and processing plant capabilities will be needed in the future when these systems reach end-of-life. An additional, and important motivation is the opportunity for recovering materials that may play a critical role in sourcing future battery components. To this end, a U.S. presidential executive order to develop a strategy to ensure secure and reliable supplies of critical minerals was issued on December 20, 2017 [1], with a follow-up from a different administration on February 24, 2021 [2].

Lithium ion batteries are classified by the U.S. Environmental Protection Agency as universal waste (a sub-classification of hazardous waste) and need to be handled responsibly throughout their life cycle, whether in intact or damaged form. The U.S. Department of Transportation also has regulations for transport of batteries. These requirements add to management cost and logistics. The processes and costs involved in decommissioning, disposing, and recycling the batteries and system components need to be understood so that they can be considered during the project planning and accounting stages of a project.

The end-of-life battery recycling industry is still in the early stages of development. This is due to few BESS deployed on the grid previous to today, and the 10-15 year delay from beginning of battery system life to the need for recycling. As a result, utilities, automotive manufacturers, researchers, battery recyclers, and the larger community are beginning to develop programs with which to create the end-of-life solutions the industry will need in the future.

Industry Developments and Drivers for End-of-Life Considerations

The expected scale of future volumes of battery material reaching end of its first life is driving the focus on battery collection and recycling. Material volume estimates are projected based on lithium ion manufacturing and raw material supply chain stream, as well as expected BESS lifetimes. Most of these projections demonstrate substantial end-of-life material streams, which are also a source of salvageable product, in 2030. While there is a time lag between deployment of BESS and when they reach end-of-life, currently a robust infrastructure to handle these materials does not yet exist. Thus, the reverse supply chain logistics and infrastructure needs to be developed now. Thus, a wide variety of research, logistics and policy development activities have been greatly expanded in the last two years to support development of an end-of-life industry. In the interim, manufacturing scrap and consumer batteries may be recycled as the industry grows to scale. While there is some uncertainty in the years when stationary or vehicle batteries will reach end-of-life due to lack of real-world experience with system degradation and aging rates, market growth predictions can inform the expected volume of batteries reaching end-of-life. Figure 1-1 shows the project battery market out to 2030 representing 65 billion pounds or the weight of 89 Empire State Buildings worth of batteries. Note in the figure that stationary is shown added to electric vehicle demand, highlighting that while we are seeing larger and larger grid scale systems, they are still just a fraction of what is expected to be deployed to the electric vehicle market.

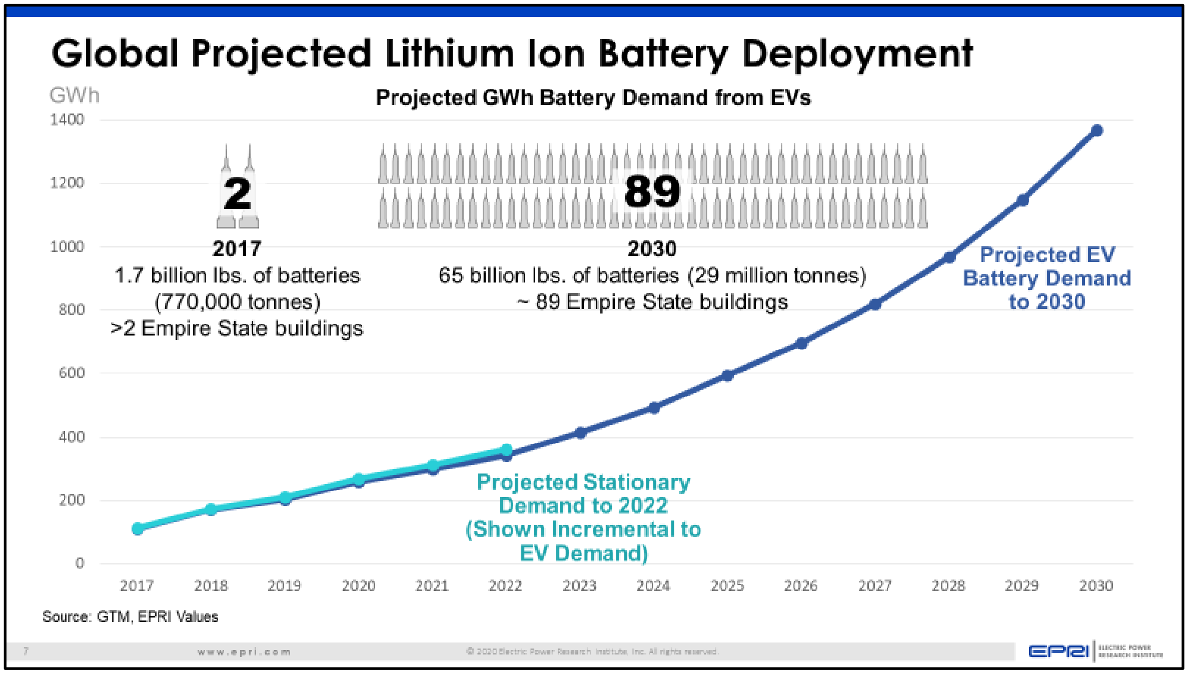

Figure 1-1
Global Project Lithium Ion Battery Deployment Calculated in Weights of Batteries Deployed.

For stationary storage systems, there is increasing interest in understanding end-of-life costs and responsibilities early in the project planning stage. This allows for planning and proactive collection of information to inform the decommissioning, removal, and recycling steps of a project. Contractual and financial agreements for prior BESS deployments did not include decommissioning plans or assessment of end-of-life options as a standard consideration. However, as the industry develops, more consideration is being given to the total ownership costs of a storage system beyond initial capital cost and installation. It is recommended that decommissioning plans are created at the point of BESS design and procurement moving forward.

Research Approach and Summary of Methods

This report expands on the methodology described in a prior EPRI report from 2017 and applies it to (1) the large BESS, a 20MW, half hour lithium ion system, and (2) a smaller mixed chemistry system with both lithium ion and vanadium flow batteries [3].

A combination of system information and parameter value estimates based on engineering judgement were used to create a bottom-up end-of-life cost estimate for a combination of disposal and recycling for the two systems, assuming a10 year lifetime ending in 2030. As with all future projections, there is uncertainty in future costs as markets develop and evolve and the industry scales.

The lithium ion cells in both the studied systems are comprised of nickel manganese cobalt (NMC). Recycling of this chemistry from a system installed in 2018 provides some salvage value from recoverable metal content (such as cobalt), which offsets a fraction of the recycling costs. As the industry shifts in the future to lower- or no-cobalt chemistries, the recycling costs and business case will adapt to the changing end-of-life material stream and cost estimation will need to be updated.

Content of the Report

This report provides an overview of the current regulations around battery end-of-life management, recycling processes, and ongoing research efforts in the battery recycling space to create a snapshot of the industry today. The regulatory overview is presented in Section 2, a description of end-of-life process steps and the relevant vendor and service provider communities in Section 3, and battery recycling processes and environmental considerations are discussed in Section 4. Subsequent sections of the report cover the decommissioning steps and costs for the case studies, with the larger BESS described in Section 5, and the smaller mixed chemistry BESS in Section 6. In Section 7, the larger BESS module removal and recycling costs are compared with a similar MWh amount of a Lithium Iron Phosphate (LFP) battery to illustrate the price dependence on the module and chemistry types. Conclusions and recommendations are in Section 8.

2

REGULATIONS AND POLICY

There are a variety of state and federal regulations that govern the disposal of battery and grid energy storage systems. At the federal level, regulations from the Environmental Protection Agency (EPA) classify batteries as universal waste (a type of hazardous waste) and regulations from the Department of Transportation (DOT) classify batteries as corrosive or flammable, depending upon the type of battery. Additionally, California state regulations classify batteries as universal waste.

The electric vehicle and stationary battery energy storage markets have developed quickly and become widespread over the past ten years, but an interest in developing safe, responsible, economic, and environmentally sustainable end-of-life pathways for these batteries is driving current discussions. Federal regulations and state of California regulations are described in this section, along with end-of-life and recycling efforts Europe and China.

Regulations in the US

Federal Regulations on Batteries

Environmental Protection Agency (EPA)

The principal federal law that governs the disposal of solid waste and hazardous waste in the US is the Resource Conservation and Recovery Act (RCRA), enacted in 1976 [4]. The RCRA regulations are contained within title 40 of the Code of Federal Regulations (CFR). The regulatory applicability to batteries is determined in 40 CFR 273, and a battery is defined by 40 CFR 273.9 as: [5].

> "Battery means a device consisting of one or more electrically connected electrochemical cells which is designed to receive, store, and deliver electric energy. An electrochemical cell is a system consisting of an anode, cathode, and an electrolyte, plus such connections (electrical and mechanical) as may be needed to allow the cell to deliver or receive electrical energy. The term battery also includes an intact, unbroken battery from which the electrolyte has been removed."

The definition section of 40 CFR 273.9 also classifies "Batteries as described in §273.2" as being "subject to the universal waste requirements." EPA defines that date upon which a used battery becomes waste, per 40 CFR 273.2, as "the date it is discarded (e.g., when sent for reclamation)." The generator of battery waste is defined in 40 CFR 273.9 as "any person, by site, whose act or process produces hazardous waste identified or listed in part 261 of this chapter or whose act first causes a hazardous waste to become subject to regulation." This subsection further includes a definition of a universal waste handler:

"Universal waste handler:

(1) Means:

(i) A generator (as defined in this section) of universal waste; or

(ii) The owner or operator of a facility, including all contiguous property, that receives universal waste from other universal waste handlers, accumulates universal waste, and sends universal waste to another universal waste handler, to a destination facility, or to a foreign destination."

Other applicable definitions under this subpart define a "destination facility" as one that "treats, disposes of, or recycles a particular category of universal waste." The generator or handler of batteries would arrange transportation of the waste to a destination facility for recycling or disposal.

Further clarity or legal consultation may be needed to determine whether a grid scale battery system at end-of-life would qualify as a universal waste generation site. The EPA website includes a table that breaks down the size categories and distinctions for universal waste handlers [6]. The distinction between large quantity and small quantity handlers is based on the total quantity (weight) of accumulation on site and any one time and does not seem to envision a stationary system reaching end-of-life with a large quantity of batteries that require a one-time disposal [7]. Though outside of universal waste regulations, 40 CFR 262.232 "Conditions for a generator managing hazardous waste from an episodic event" may be of interest to universal waste handlers as one-time battery disposal events become more common [8].

The universal waste regulations limit to one year from the date of generation, the length of time that batteries can be accumulated prior to transportation for recycling or disposal, if the receiving facility does not store the waste prior to recycling. Generators may accumulate waste for periods longer than one year under certain circumstances, however the burden is placed upon the generator to prove that the special circumstances apply, as described in 40 CFR 273.15 and 273.35.

The federal code also outlines employee training requirements (§273.36) that "a large quantity handler of universal waste must ensure that all employees are thoroughly familiar with proper waste handling and emergency procedures, relative to their responsibilities during normal facility operations and emergencies."

To ensure safe and proper handling of hazardous waste, there are several permit application requirements for a facility that treats, stores, and disposes of hazardous or universal waste. These can be found on the EPA website in a summary chart covering the general requirements as well as the permit application requirements [9].

Department of Transportation

Additional regulations regarding transportation of the batteries can be found in the Title 49 Transportation section of the CFR [10]. Classification of the DOT hazard class for various battery types is established in 49 CFR 172.101 Hazardous Materials Table. Vanadium electrolyte and lead acid batteries are both defined as Class 8 corrosives for transportation, while lithium ion batteries are classified as a miscellaneous Class 9 hazard [11-13].

The DOT regulations cover both new and end-of-life batteries and have a section covering "Lithium cells and batteries" specifically (49 CFR 173.185) [14]. This section includes packaging guidelines to prevent "short circuits, damage caused by movement or placement within the package, and accidental activation of the equipment." Beginning January 1, 2022, transportation of batteries manufactured after January 1, 2008, will require the manufacturer make available a test summary including information described in 49 CFR 173.185(a)(3). However, 49 CFR 173.185(d) states that "Lithium cells or batteries shipped for disposal or recycling" and transported by motor vehicle to a permitted storage facility or disposal site, or for purposes of recycling, "is excepted from the testing and record keeping requirements of paragraph (a) and the UN performance packaging requirements in paragraphs (b)(3)(ii), (b)(3)(iii) and (b)(6) of this section, when packed in a strong outer packaging conforming to the applicable requirements of subpart B of this part."

For cells or batteries that are "damaged, defective, or recalled," there is a description of additional packaging requirements to enable safe transport in section 49 CFR 173.185(f). These batteries must be enclosed in rigid, large packaging and are limited to transport by highway, rail or vessel only.

In addition to the detailed federal code, the DOT website provides resources and information related to transporting lithium batteries [15]. UPS also provides guidance for safely packaging and shipping batteries [16].

California State Regulations

The major battery legislation in California, passed in 2005, was the California Rechargeable Battery Recycling Act (AB1125, 2005) [17-18]. It set guidelines for rechargeable batteries in a variety of products, highlighting the need for legislation on battery technologies beyond lead acid cells. The timeline of California legislation related to batteries, shown in Figure 2-1, illustrates the market penetration and evolution of batteries over the 15 years since AB1125 was enacted.

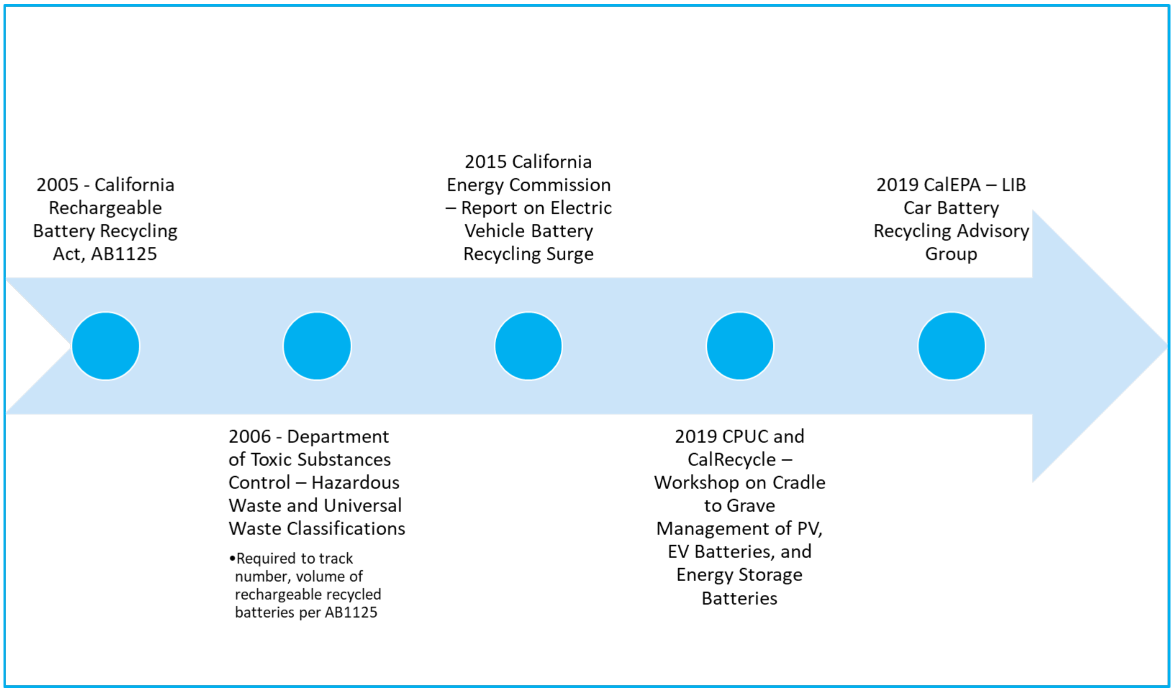

Figure 2-1
California Battery Recycling Legislation Timeline

Following the passage of AB1125, the Department of Toxic and Substances Control (DTSC), required survey tracking of the number and volume of rechargeable batteries in California, and collects this information annually on July 1 to be posted on the DTSC website. Data from 2019 is shown in Table 2-1, and highlights that even with the recent deployment of lithium ion batteries, they represent less than 10% of the batteries collected for recycling in California [19].

Table 2-1
Quantities of Rechargeable Batteries Collected in California in 2019

Battery Type	Pounds	Percent of Total Volume
Lithium ion Batteries (Li-ion)	436,135	8%
Nickel Cadmium Batteries (Ni-Cd)	390,703	7%
Nickel Metal Hydride Batteries (Ni-MH)	1,102,629	21%
Small Lead Acid Batteries (SS Lead Acid)	3,362,910	64%
Total Battery Weight	5,292,377	

Source: [19]

California is also looking ahead at future electric vehicle end-of-life and lithium ion recycling. In 2015 the California Energy Commission published a report titled "Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America" [19]. This report summarized the current and projected battery-operated vehicle market and outlined best practices and technologies to support management of those batteries at end-of-life. It also identified that while early electric vehicles were dominated by nickel metal hydride batteries, a larger proportion were expected to be lithium-based in the future.

In 2018, the California Public Utilities Commission (CPUC) and CalRecycle signed a Memorandum of Understanding (MOU) "to partner on developing consistent approaches to waste generated by photovoltaic panels, electric vehicle batteries, energy storage batteries, and related equipment" [21]. To support this effort, they held a joint public workshop in April of 2019 with industry and stakeholder participants on the end-of-life topics of collection, handling, and reuse or recycling. The recording, presentations, and agenda from this workshop are available on the CPUC website [22].

The CalEPA, in partnership with DTSC and CalRecycle, in 2019 created a lithium ion Car Battery Recycling Advisory Group [23]. The group was convened in accordance with AB 2832 requiring the group to "advise the Legislature on policies pertaining to the recovery and recycling of lithium ion vehicle batteries sold with motor vehicles in the state" [24-25]. While AB2832 focuses on lithium ion vehicle batteries, much of the infrastructure, best practices, and regulations developed may be applicable to the collection of stationary batteries for reuse, recycling, or disposal. The group recently completed a final draft of their policy recommendations and released it for public comment. Key recommendations were the need to clearly define responsibility for the coordination and payment for recycling in cases where the LIB is unwanted or costs presents a burden to the owner, as well as the formation of manufacturer take back policy. A final report is expected later in 2022.

Within the California Code of Regulation (CCR), Section 22 CCR 66261.2 Definition of Waste, defines waste as: [26].

> "Waste" means any discarded material of any form (for example, liquid, semi-solid, solid or gaseous) that is not excluded by section 66261.4(a) or section 66261.4(e) or that is not excluded by Health and Safety Code section 25143.2(b) or Health and Safety Code section 25143.2(d).

California characterizes batteries as hazardous waste due to "the metals and/or toxic or corrosive materials they contain," per the CalRecycle website, and continues "hazardous waste regulations designate a category of hazardous wastes called "universal wastes"" [27]. Current regulations, subject to future legislation or changes, can be found in the California Code of Regulations. Batteries are included in 22 CCR 66261.9 (a)(1) of the requirements for universal waste section of the code, specifically included as "Batteries, as described in section 66273.2, subsection (a)" [28].

Review of CCR Sections 66261.4(a) and 66261.4(e), and the Health and Safety Code Sections 25143.1(b) and 25143.2(b) would be needed for a final determination as to whether lithium ion or vanadium batteries are excluded from the universal waste requirements [29-30]. For the purpose of this cost analysis, it is assumed that they can be treated and handled as universal waste.

The DTSC website provides guidance defining a generator with respect to managing hazardous waste [31]. It describes a generator as "any person, by site, whose act or process produces hazardous waste identified or listed in Chapter 11 of the hazardous waste regulations or whose act first causes a hazardous waste to become subject to regulation." The CCR Chapter 11 Identification and Listing of Hazardous Waste includes Section 66161, referenced above. Chapter 11 further clarifies that "by site" refers to "where the hazardous waste is generated", and that "act" clarifies that to be a generator, "a person" does not necessarily have to produce the hazardous waste." An example is given that the cleaning service that removes residue from a storage tank, provides the "act" to produce the waste subject to regulation and advises that "by mutual agreement, these two parties may determine who is responsible for the hazardous waste."

The DTSC website also states that universal wastes do not count towards generator status, so if the batteries can be classified as universal waste, generator status would not be affected by the volume of batteries accumulated. Legislation passed in 2015, SB 612, added Health and Safety Code (HSC) Section 25158.1, that clarified when generators were calculating status, the generator "shall include all hazardous waste that it has generated in any month, except for universal wastes…" [32-34].

International Regulations and Developments

As Section 1 showed with the increased demand for electric vehicles and stationary batteries, material recovery from end-of-life batteries for reuse in new batteries will play an important role in material supply calculations and resources as battery manufacturing scales up. Looking abroad for examples of how other countries and regions are addressing battery end-of-life challenges and opportunities provides two interesting approaches, from Europe and China.

Regulations in Europe

Europe addresses battery end-of-life through the Battery Directive 2006/66/EC [35-36]. This Directive prohibits "disposal of automotive and industrial batteries by leaving in landfills or by incineration" thus driving requirements towards recycling and materials recovery. It additionally creates the development of "financing schemes [that] should help to achieve high collection and recycling rates and to give effect to the principle of producer responsibility" for batteries produced or imported into European countries. Proposed revisions to this directive were created in 2020, which "notably encompass end-of-life and sustainability requirements" [37]. In addition to expanding the types of batteries managed, collection and recycling rates, the revisions included rules on carbon footprint declarations, labelling, and requirements to adhere to standards of responsible material sourcing. Initial approval of the revisions was made in February 2022, moving the updated regulation closer to final approval, which is expected later in 2022, and subsequent implementation.

Several of the large battery companies developing manufacturing capabilities in or near the EU have also established recycling plants to support material recovery and reuse directly back into the production process [38]. This trend may inform future research or analysis on whether regulations or material supply recovery economics drive the colocation of recycling and manufacturing facilities that occurs in the lead acid battery industry as the lithium ion industry matures.

Regulations in China

China has also taken action related to battery recovery and recycling. In 2018, they published rules that held the makers of electric vehicles responsible to collect and recycle their batteries, specifically calling for “a network for the collection and recycling of used batteries” [39]. The following year, they established new requirements that mandated facilities be created that could “collect, sort, store, package and ship used-up electric car batteries, but are not allowed to disassemble these, except for inspection purposes” [40]. This essentially created a regional collection network for batteries and builds the foundation for a logistic network with additional requirements that the facilities must “trace and collect data on their inventory and to communicate this data to the manufacturers, who in turn have to make a report on the inventory data.”

3
PARTICIPANTS IN THE RECYCLING SPACE

End-of-Life Process Overview

Recycling a stationary system requires several steps, sometimes with multiple vendor participants playing a role to safely recycle and dispose of the system. Figure 3-1 walks through the potential pathway.

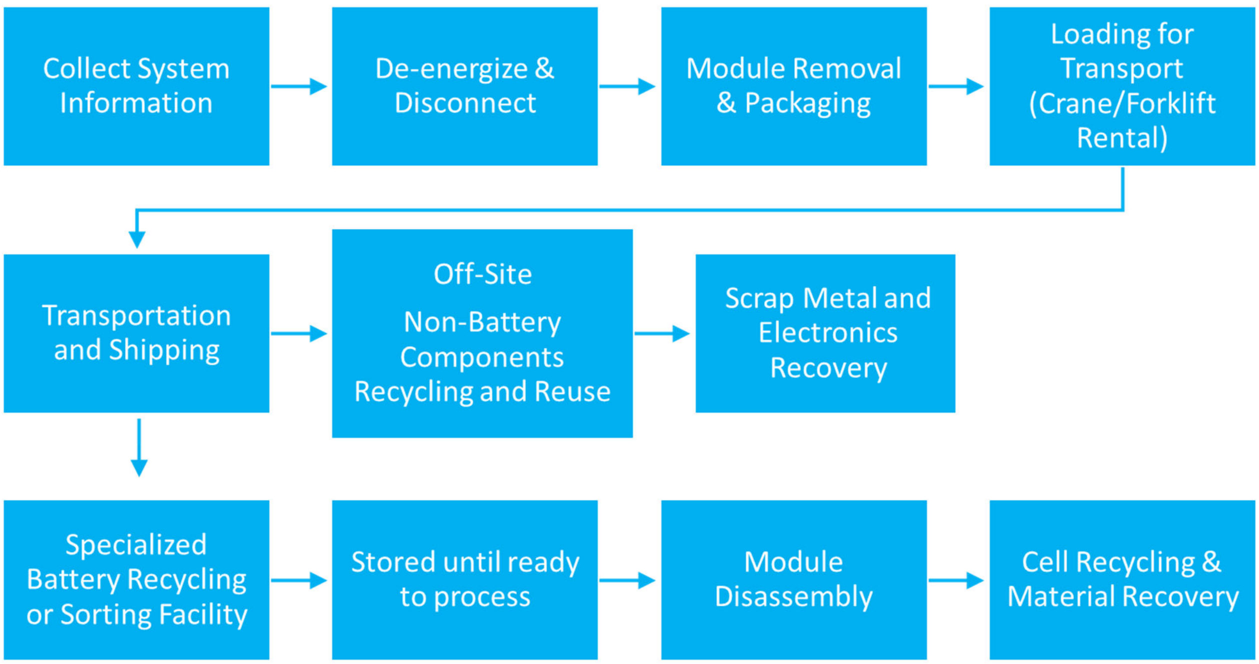

Figure 3-1
Example Recycling Process Pathway

Collect System Information: A first step in any end-of-life project should include a collection of system information to accurately identify which components or system parts need to be recycled. It is recommended that safety data sheets (SDS) and system inventory lists from procurement and site acceptance testing be stored in a manner that supports this information collection at end-of-life. Additionally, a site walkthrough could identify changes to topology or surrounding equipment that may inform safety or process steps around crane use or removal of the equipment. For systems that have not been recently operational or monitored, it is also recommended that a visual inspection of system condition be done to identify any degraded equipment.

De-Energize and Disconnect: Once decommissioning planning has been completed, the next step is to de-energize and disconnect the energy storage system and balance of system. The system disconnection step involves both electrical and physical disconnection, including all grounding and communication ties. The timing of disconnection relative to system removal should be considered from a safety monitoring perspective for thermal management of the cells.

Reducing the batteries' state of charge level is often recommended for safety during transportation, and guidelines may be available within vendor specifications for the particular chemistry and model system being decommissioned. Batteries are designed to store and discharge power, meaning that even with reduced state of charge they should be handled with electrical safety procedures in place.

Battery Module Removal and Packaging: For systems that cannot be transported with the battery modules left installed, due to highway weight restrictions[1] or system build design, a preliminary step to disconnect and remove the individual battery modules will be needed. For the large lithium ion system detailed in Section 5, this represents more than 3,200 battery modules each weighing approximately 120 lbs.[2] Each must be removed and packaged onto a pallet for safe transportation to a specialized battery recycling or sorting facility in a later step. The labor and time involved in this step should be considered in the overall decommissioning planning to ensure it can be done safely without worker or battery unit injury and so that delays do not affect later project timelines.

Loading for Transport: Site and system parameters will change for each project, but many energy storage systems may require forklift or cranes to remove equipment or to load the units onto trucks for transport. These costs and logistics are important in project resource, schedule, and budget estimations and planning.

Transportation and Shipping: Trucking and transport logistics are another important part of battery end-of-life. Battery modules may require travel over long distances to specialized battery sorting or recycling facilities. Additional costs should be anticipated for transportation distance and because batteries are classified as universal waste which increases costs due to safety considerations and training, see Section 2 for more details on regulations related to battery classification and transport. For the remaining more common balance of plant components, it is anticipated they are able to use local scrap and material recovery facilities, requiring less trucking distance.

Off-Site Non-Battery Component Recycling and Reuse: Local scrap and metal handling companies can break down the non-battery components. In addition to collecting scrap metal and electronics waste to be sent to local collection streams, several specialty items would need to be processed and directed to local reuse, disposal, and recycling areas. These include the refrigerant from the HVAC units, the undischarged fire suppression agent tank, and the fire control system may contain small lead acid back-up batteries that would require recovery and recycling.

Scrap Metal and Electronics Recovery: Final scrap metal and electronics recycling of system components can go to local handlers for recovery, reuse, and recycling.

Specialized Battery Recycling or Sorting Facility: Facilities that collect, process, and recycle quantities of batteries and universal waste are classified as small quantity or large quantity

---

[1] Overweight trucks are classified as above 80,000 pounds gross vehicle weight per 23 CFR 658.17. To accommodate the truck, trailer, and fuel weight a standard load is generally 40,000-45,000 lb to avoid the overweight classification. https://ops.fhwa.dot.gov/freight/sw/permit_report/index.htm

[2] Follow relevant OSHA guidelines for lifting weights over 100 pounds.

handlers of universal waste. More information around the definitions and guidelines for these facilities can be found in the regulatory EPA portion of Section 2.

Stored until Ready to Process: Batteries need to be stored safely while awaiting processing to avoid fire incidents. Staff at the storage facility need appropriate training for handling and safety best practices. This may be a larger concern for vehicle batteries that are aggregated at a vehicle scrap yard to optimize full truck loads than for stationary systems at specialized facilities but remains important across the industry to ensure worker safety and high industry safety standards. Additional general or facility permitting guidelines may introduce timeline limits for how long batteries may be stored before being processed.

Battery Module Disassembly: Larger form factor battery modules and packs may need to be broken down to fit within the recycling equipment. Dismantling should be done by trained staff with appropriate tools and personal protective systems and gear in place.

Cell Recycling and Material Recovery: Final recycling process to recover metals and reusable materials from the batteries. Section 4 provides additional details on current common and novel processes used.

In addition to ensuring safe equipment transfer for the outlined steps across the process, it is important to clearly outline responsibility and safety issues along the chain and to verify proper system disposal at the completion of the steps. Many recycling disposal management companies already have or are developing the expertise to support this process from site to final disposal and paperwork close out, ensuring all laws and regulations are properly followed for safe system disposal.

Established Battery Recycling Companies

As the industry expands, taking a closer look at traditional metal recycling and material recovery companies with decades of experience helps to understand the industry today as it ramps up with innovative solutions for the future. Section 4 dives deeper into the recycling processes that are mentioned here.

Retriev, now combined with Heritage Battery Recycling, is a battery recycling and management company, with locations in a Lancaster, Ohio and Trail, British Columbia [41]. It is a subsidiary of Kinsburksy Brothers, Inc. (KBI), a metal recycling company with over 40 years of experience, headquartered in Anaheim, CA. Retriev, formerly named Toxco, was awarded over $9 million "in a cost-sharing agreement in 2009 to facilitate construction and operation of the Next-Generation Lithium Ion (Li-Ion) Battery Recycling Facility" [42-43]. Retriev combines a hydrometallurgical process with material separation steps to recover metal solids and a metal-enriched liquid that can be solidified with filtering to undergo further metal purification. Using this process, large format packs are first dismantled. The smaller battery cells and small battery modules are then fed onto a conveyor to an automated crusher. This process has been automated to improve safety. During the crushing step, liquid solutions are used to prevent emissions and to reduce electrolyte reactivity. In addition to the metal products mentioned above, this process produces plastic fluff that can be recycled for fuel, it is often landfilled.

While plastic fluff from batteries is not yet a large volume market, the automotive market produces millions of tonnes annually of a similar automotive shredder residue. Work is underway, particularly in Europe, to recycle or recover value from this waste stream that may be applicable to battery recycling processes in the future [44-45].

Umicore is a global materials technology and recycling company headquartered in Brussels, Belgium founded in 1989 with the merger of four industrial companies in the mining and smelting industry. In addition to recycling and energy materials, Umicore also has business lines that produce catalyst and performance materials. Their U.S. efforts are centered in Raleigh, NC, with a network of collection and logistics partners throughout the country.

Umicore's recycling method combines both pyrometallurgical and hydrometallurgical processes, enabling the recycling of multiple types of lithium ion and Nickel Metal Hydride (NiMH) batteries. The mixed process allows for increased metal recovery. A direct battery feed reduces the battery cell and module dismantling needed. The batteries first undergo the pyrometallurgical step, producing an alloy (containing cobalt, nickel, and copper), slag fraction, and exhaust air that undergoes a cleaning process before release. The metal alloy produced undergoes a hydrometallurgical process to separate the alloy into its constituent metals. The slag fraction, which contains lithium, can be recycled and used in construction or integrated into standard lithium recovery processes. Research efforts are underway to develop processes to recover more metal and organic components from the slag [46].

List of Vendors Related to End-of-Life

Battery Recyclers

- Retriev Technologies (https://www.retrievtech.com/)
- Umicore (http://csm.umicore.com/en/recycling/battery-recycling/)
- Omega Harvested Materials http://www.ohm-inc.com
- American Manganese, Inc. (https://americanmanganeseinc.com/)
- Lithion (https://www.lithionrecycling.com/)
- Li-Cycle (https://li-cycle.com/)
- Battery Resourcers (https://www.batteryresourcers.com/)
- Blue Whale Materials (https://bluewhalematerials.com/)
- SungEel MCC Americas (https://www.smccrecycling.com/)

Recycling Disposal Management Companies

- Renewance (http://www.batterystewardship.com/)
- Safety-Kleen (https://www.safety-kleen.com/), A Clean Harbors Company (https://www.cleanharbors.com/)
- Heritage Environmental Services (https://www.heritage-enviro.com/)

Crane and Trucking Services

- Eagle Trucking and Crane (https://www.eagletruckingbakersfield.com/)
- GCI Equipment Rental (http://www.gciequipmentrental.com/)
- Express Transpro – Trucking and Logistics (http://expresstranspro.com/)

Processing, Second Use, and Lifecycle Management Companies

- Spiers New Technologies (http://www.spiersnewtechnologies.com/)
- Everledger (https://www.everledger.io/)
- Global Battery Solutions, LLC (https://globalbatterysolutions.com/)

Balance of Equipment Recyclers and Engineering Project Management Services

- Absolute Chiller Services, Inc – EPA Certified Refrigerant Reclaimer (http://www.acsrefrigerant.com/)
- PEGEX Hazardous Waste Experts – Hazardous Waste Disposal, Chemical Disposal, and Environmental Remediation (https://pegex.com/)
- KTY Engineering (http://ktyengineering.com/)

4

RECYCLING PROCESSES, ENVIRONMENTAL IMPLICATIONS, AND TECHNICAL ADVANCES

Processes for Lithium Ion Battery Recycling

In this section of the report, current processes related to battery recycling and material recovery will be reviewed, as well as the research and development efforts ongoing to advance future options.

Most stationary lithium ion battery modules or electric vehicle packs must first be dismantled to remove the smaller cells for recycling. In some system designs this step can be labor intensive due to wide variation in module designs, multiple fastener types used in a single module, and attachment/construction components intended to last for long lifetimes. As the end-of-life management industry develops, systems may be designed to simplify dismantling for easier component reuse or recycling in the future. We also anticipate the development of automated dismantling processes or to allow the recycling processes to input larger format batteries directly into the process, although that may increase the number of process steps downstream needed to separate the metals and valuable components [47-48]. Additionally, there are hazards associated with dismantling, and it should be carried out with insulated tools, and by staff trained in handling high voltage equipment, to prevent electric shock or short circuits.

Once the cells have been removed from the module, the recycling and material recovery process can begin. A mechanical processing step is next, which can vary by vendor but usually includes shredding, crushing, and/or cutting to expose the cell components [49]. This step includes procedures to capture gas emissions from release of the cell electrolytes. The mechanical processing step may also include separation steps utilizing screening, shake tables, magnetic separation, and even supercritical CO_2. This step releases the cell components and prepares the system for the next processing steps.

Hydrometallurgical

The hydrometallurgical process uses water-based solvents to recover metals from ores and recycled materials [50-51]. The process includes leaching steps followed by separation and purification steps. The main recovery products from lithium ion batteries are lithium carbonate and metal oxides; both of these can be reused in cathode production and other aspects of the battery industry [49]. Secondary products that can be recovered include steel, copper, and aluminum; these can be reused in the metals industry. The electrolytes, plastics, and graphite are lost in the process.

The solvents used in hydrometallurgy are dependent upon battery chemistry, and often use caustic chemicals. However, they can often be recovered and reused with established industry processes.

Pyrometallurgical

The pyrometallurgical process uses a variety of thermal processes for extraction and purification of the metals in the battery cells. These thermal processes can include:

- Roasting – heating in air to turn metal ores into metal oxides
- Smelting – process used in blast furnaces to produce molten phase products
- Calcining – thermal decomposition of the material
- Refining – removing impurities and unwanted elements

These are established industrial processes and can handle larger format cells with less dismantling than hydrometallurgy. However, they are energy intensive due to the requirement for crushing and mixing at extreme temperatures. The fumes and gases released from the process must be scrubbed before release, and the high temperatures burn off graphite and plastic components preventing their recovery [49].

Mixed Recycling

Mixed recycling involves processes steps that utilize a mixture of both hydrometallurgic and pyrometallurgic steps. Combining the processes can increase material recovery, but the extra steps needed, energy required, and environmental and health impacts of that energy, need to be balanced against the value of recovered material perspective. Commodity market prices or environmental sensitivities may affect this decision making or the economics involved.

Direct Recycling

While the raw cell materials (e.g. lithium and cobalt) certainly have value if recovered, a substantial amount of additional value in end-of-life batteries is in the embedded manufacturing and processing of the cathode and anode materials. Direct recycling methods are being developed to recover and recondition the battery cathode material "whole", in order to preserve the manufactured value from that component [52]. These processes are at the early research and development stages but have "the potential to reduce emissions and be economically competitive" [52].

Comparison with the Lead Acid Industry

One successful example is the lead acid battery recycling industry in the United States; 98% of these batteries are recycled [53]. However, it's important to understand the differences between lead acid and lithium ion battery recycling to appreciate why the lithium ion battery recycling may be more difficult. One major factor is that as a mature industry, lead acid recycling benefits from cost reductions at scale. A second major difference is the variety of lithium ion chemistries and form factors on the market compared to a more uniform type of lead acid battery, which simplifies the optimization of processing steps for high efficiency. In contrast, the lithium ion battery recycling industry may have to manage input streams from a number of battery chemistries, which may also have different plastic casing and material components. Each may require independent process optimization for maximum material recovery. These factors allow for a more consistent recycling and recovery process for lead acid, including breaking and separating the battery to recover the plastic case and the electrolyte and then a reduction and smelting step to recover the lead that can be re-used in new lead acid battery production.

Handling of Damaged Cells

Damaged batteries, or those suspected to be damaged, must be handled with care to ensure safety at their original project site location, during transportation, and at the endpoint of disposal or recycling. The type of actual or suspected damage is important: guidelines for dropping (mechanical failure), thermal damage, flame, vent, leakage, and often handling of modules may be found in O&M guides from vendors. Additional guidelines on transport and packaging of damaged, defective, or recalled cells or batteries can be found in 49 CFR 173.185 (f), although those descriptions may be more applicable to smaller consumer product batteries rather than those from EV or stationary platforms.

As the stationary storage market develops, there has been increasing interest in understanding how to manage damaged modules or stranded energy in the case of a battery fire or safety incidents. EPRI has several research efforts underway to better understand components of battery safety. Additionally, companies are emerging to address industry needs in this space, including planning for, or responding to, emergency events [54]. Further research is needed to develop standard processes and precautions for removing stranded energy from grid-scale storage systems. System battery modules did have to be carefully removed and discharged to remove stranded energy in the system following the McMicken battery energy storage system event [55]. Depending on the type of incident or cell and module damage, recycling may no longer be a safe option and other disposal avenues for the batteries may be needed.

Industry Efforts on Recycling

In recent years, the battery and storage system industries have taken a proactive look at handling batteries at end-of-life. In the U.S. the Energy Storage Association (ESA) created a Corporate Responsibility Initiative that brought its battery vendor, system suppliers and other industry representatives together to address end-of-life issues. They have published two white papers covering the topics of End-of-Life Management and Guidelines for End-of-Life [56-57].

Another industry association, NAATBatt International, with membership including battery manufacturers, vehicle OEMs, and electric utilities, has been hosting workshops on lithium ion battery recycling since 2016. They have several committee and subcommittee groups working on issues like tracking, supply chain, and manufacturing. Their website includes an overview of "Laws, Regulations and Best Practices for Lithium Battery Packaging Transport and Recycling in North America" [58].

Research Directions

The anticipated volume of lithium ion battery deployment has driven efforts to improve existing hydrometallurgical and pyrometallurgical recycling processes, and well as develop new approaches to increase battery recycling material recovery and efficiency [59]. Universities in the U.S. and abroad are also driving discoveries in areas related to battery recycling and solvent recovery [60-61].

With the goal of substantially advancing the capability of direct recycling methods to recover manufactured value, the Department of Energy (DOE) announced the creation of the ReCell Center in 2019 [62]. ReCell's "goal is to create profitable methods to dramatically improve recycling rates and improve national security by reducing a foreign reliance on supplies of critical battery materials such as lithium and cobalt." ReCell researchers are targeting several approaches as shown in Figure 4-1, from direct cathode recycling and other battery cell material recovery, to investigating new cell designs for improved recycling, as well as a modeling and analysis to inform industry efforts going forward. The benefits of recovering both materials and manufacturing value that went in to producing the cathode, are shown in the circular process diagram in Figure 4-2.

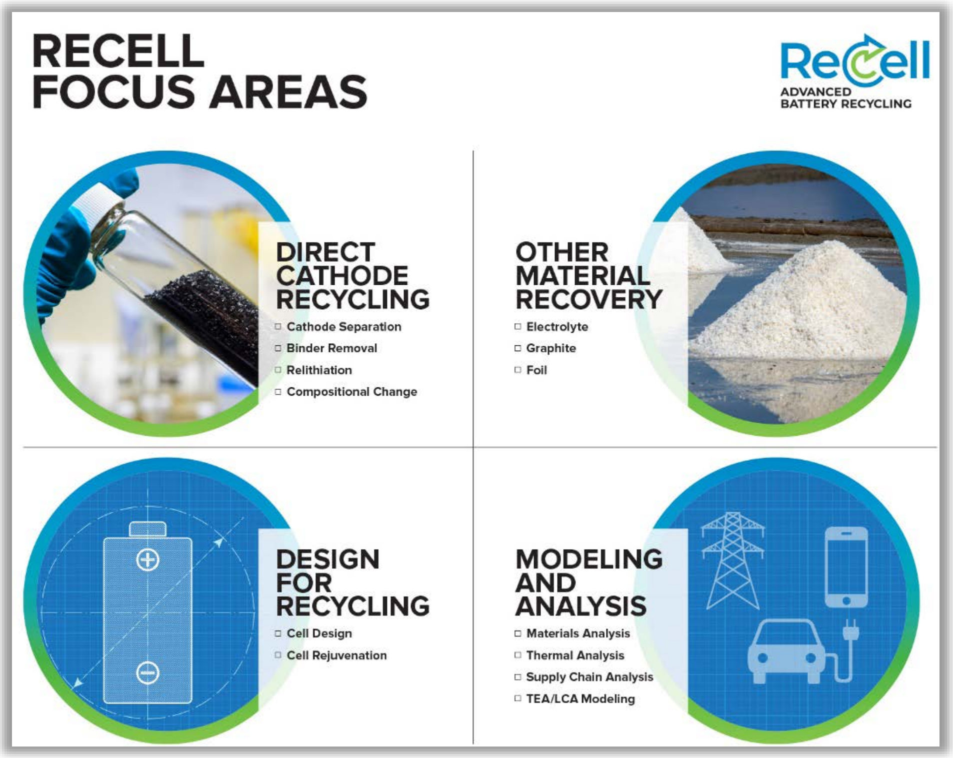

Figure 4-1
DOE's ReCell Lithium Ion Battery Recycling Focus Areas
Source: DOE

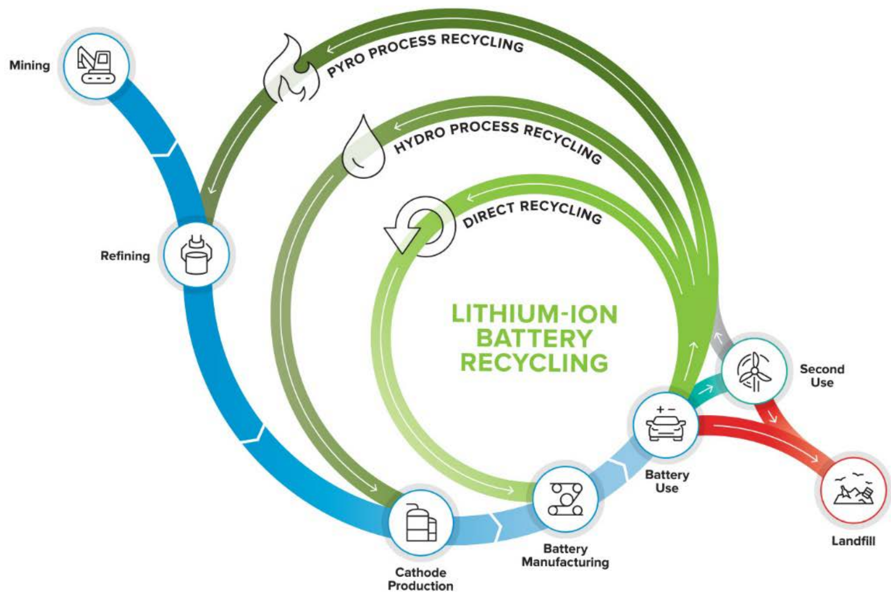

Figure 4-2
DOE's Lithium Ion Battery Recycling Overview Diagram
Source: DOE

Recycling Prize

Beyond the research described above, DOE is hosting a Lithium Ion Battery Recycling Prize[3] to encourage industry development and novel ideas to address broad range of technical and logistical challenges. The prize has awards for categories including collecting, sorting, storing, and transporting spent and discarded lithium ion batteries, as well as an open "other ideas" category to encourage creative solutions across the space.

The Prize spans three phases illustrated in Figure 4-3 below. The first involved teams proposing ideas for concept development and incubation. Phase 1 awards were announced in 2019, awarding 15 winners an award of $67,000 to submit a business model and technology plan. Phase 2 involves prototype development and partnering with other entities in the value chain and will award up to 10 winners to develop an end-to-end recycling solution. Phase 3, the final phase, involves pilot scale validation, and has awarded 6 winners who will design a real-world pilot of their technology. More information on the awards and project teams can be found on the recycling prize website.

---

[3] Lithium Ion Battery Recycling Prize Website: https://americanmadechallenges.org/batteryrecycling/

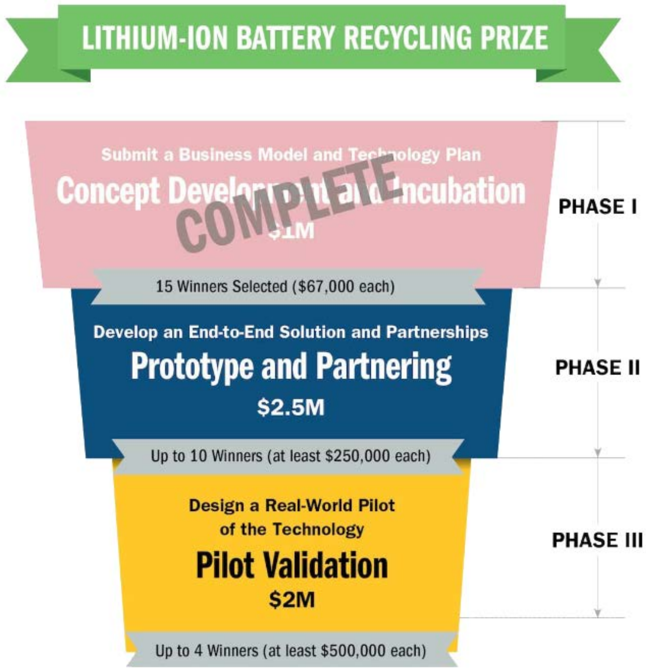

Figure 4-3
DOE's Lithium Ion Battery Recycling Prize overview.
Source: DOE

5
COSTS AND ECONOMICS OF A LARGE LITHIUM SYSTEM

In order to generalize end-of-life costs for any system, it is first necessary to outline and estimate weights of components of the systems and to identify how certain variables may affect the overall cost. For this analysis, we utilize a previously developed methodology and apply it to a larger lithium ion battery system [3]. The first system modeled in this report is a 20MW / 10MWh large BESS lithium ion system located next to a solar plant. The full system is described below, and forward cost estimates are calculated for disposal of the separate components of the system, as well as the various processes that decommissioning entails for each component and the site.

The analysis in this report assumes an end-of-life disposal of the entire energy storage system, including balance of plant equipment. In reality, individual system components may reach end-of-life at different time points. Further research is needed to determine expected component life, and contractual or system operational considerations will inform what constitutes “end-of-life" for a system.

System Overview

The large BESS is composed of 13 modular units each containing a battery container, power conversion system (PCS), and Medium Voltage Transformer mounted on concrete pads. A site overview of the entire system is shown in Figure 5-1. This shows the layout of the site and may inform equipment staging for end-of-life removal activities.

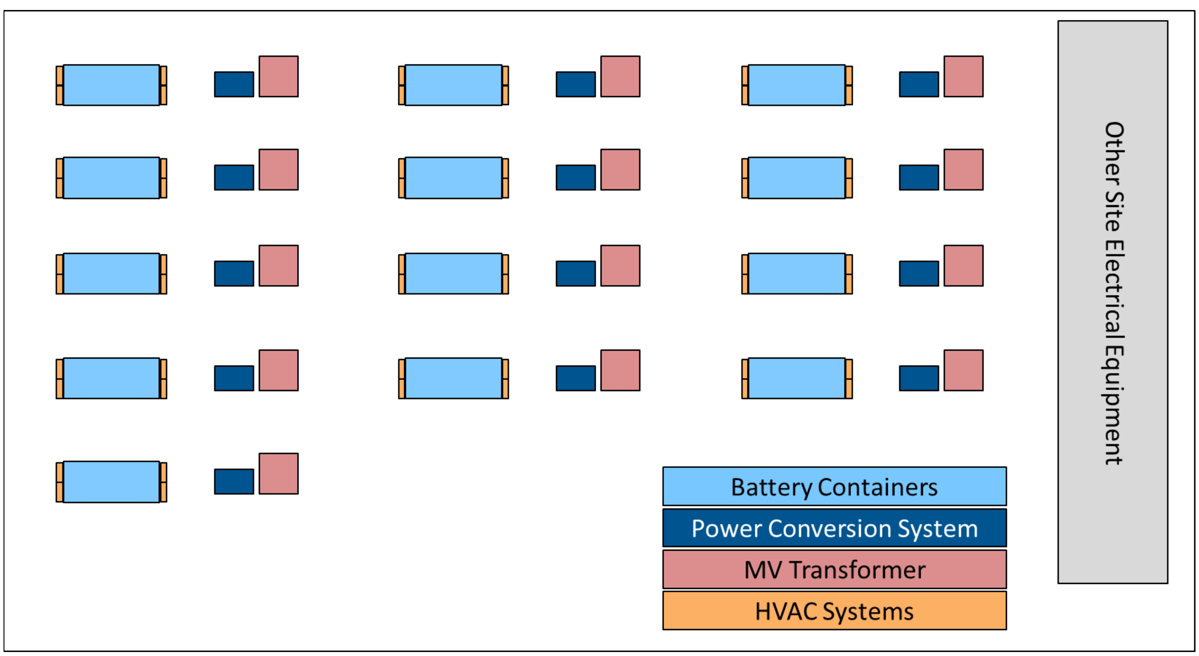

Figure 5-1
Battery Energy Storage System Site Diagram
Source: EPRI

A breakdown of what is contained in the modular battery units is shown in Figure 5-2. This depicts the various component categories in a modular unit and may be used as a reference to the system weight estimations described later in the Section.

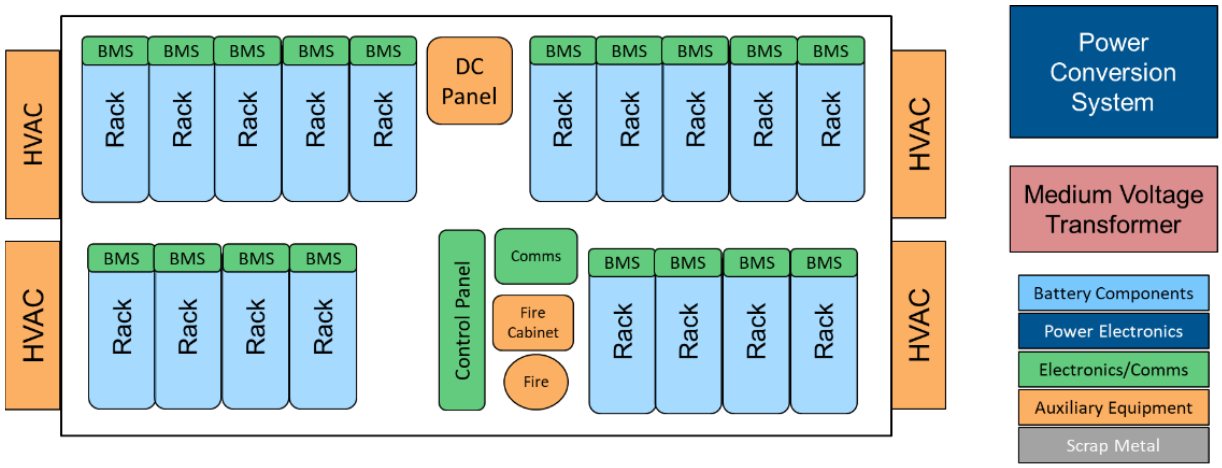

Figure 5-2
Modular Battery Block Component Diagram
Source: EPRI

The battery container units are 20-foot shipping containers with reinforced concrete walls. They each contain 19 racks of nickel manganese cobalt (NMC) Samsung battery modules. Each rack has 13 battery modules, a battery management system, and cabling to connect the battery modules electrical and communications systems. The remaining balance of system components include the power conversion system, medium voltage transformer, systems controls and communications, HVAC thermal management system, fire suppression system, and all additional equipment (including breakers, fuses, cable connectors, and the main switch).

Summary of System Weight Estimates

A bottom-up accounting method was used to estimate the modular battery block system weight. This information is summarized in Table 5-1 with high-level descriptions and weight estimates for a modular battery energy storage system block unit depicted in Figure 5-2.

The weight of the 20MW/10MWh system was calculated by multiplying these block unit weights by 13 to represent the entire system site. Shown in Table 5-2, this estimate approximates the total weights of each category for disposal. A more detailed description of system components as well as the information and assumptions used to calculate weights will be discussed later in the section.

Table 5-1
Single Battery Container Unit Weight Estimates

Estimated System Weight Components for One Battery Energy Storage Container Unit (One Container, PCS, MV Transformer)		
Item (Description)	**Weight (lb)**	**Weight (kg)**
Module Removal (to be removed and transported separately)		
Battery Modules (Based on 6.35 kWh modules, 13 modules in each of 19 racks in the system)	30,000	13,500
Power Conversion System (PCS)		
PCS Equipment (Standalone outdoor rated unit.)	7,500	3,400
Medium Voltage Transformer		
Transformer System (Medium voltage transformer and oil containment)	9,200	4,200
Balance of Lithium Container (Racks, BMS, HVAC, Fire Suppression, etc.)		
Container Enclosure (Built Concrete Enclosure)	50,000	22,700
Modifications (Lighting, flooring, venting, etc.)	1,000	450
Battery Racks (Estimated weight based on 82.5 kWh Rack, with 19 racks per container)	2,900	1,330
Battery BMS (19 BMS units, one per rack.)	840	380
Battery Connector Cables (Estimated Weight)	570	260
HVAC Equipment (Four 5-ton systems for redundancy.)	2,000	900
Refrigerant (Requires Special Handling and Removal)	50	22
Storage Management System (Master Computer, Communication Hardware, and any metal housing.)	100	45
Fire Suppression System Controls (Sensor and response box.)	30	14
Fire Suppression Tank and Agent (FM 200 Tank)	100	45
Piping Dispersion System (Metal piping for dispersion.)	50	23
Additional Equipment (Main Switch, Cables, Breakers, Fuses, etc.)	300	135
Total Estimated Unit Weight	**104,640**	**47,404**

Source: EPRI Estimates

Table 5-2
Entire Large BESS (13 Container Units) Weight Estimates

Estimated System Weight Large BESS System (13 Container Units)		
Item (Description)	**Weight (lb)**	**Weight (kg)**
Module Removal (to be removed and transported separately)		
Battery Modules (Based on 6.35 kWh modules, 13 modules per rack, and 19 racks per unit)	390,000	175,500
Power Conversion System (PCS)		
PCS Equipment (Standalone outdoor rated unit.)	97,500	44,200
Medium Voltage Transformer		
Transformer System (Medium voltage transformer and oil containment)	119,600	54,600
Balance of Lithium Container (Racks, BMS, HVAC, Fire Suppression, etc.)		
Container Enclosure (Built Concrete Enclosure)	650,000	295,100
Modifications (Lighting, flooring, venting, etc.)	13,000	5,850
Battery Racks (Estimated weight based on 82.5 kWh rack, with 19 racks per container)	37,700	17,290
Battery BMS (19 BMS units per container.)	10,920	4,940
Battery Connector Cables (Estimated Weight)	7,410	3,380
HVAC Equipment (Four 5-ton systems for redundancy.)	26,000	11,700
Refrigerant (Requires Special Handling and Removal)	650	286
Storage Management System (Master Computer, Communication Hardware, and any metal housing.)	1,300	585
Fire Suppression System Controls (Sensor and response box.)	390	182
Fire Suppression Tank and Agent (FM 200 Tank)	1,300	585
Piping Dispersion System (Metal piping for dispersion.)	650	299
Additional Equipment (Main Switch, Cables, Breakers, Fuses, etc.)	3,900	1,755
Total Estimated System Weight	**1,360,320**	**616,252**

Source: EPRI Estimates

Future Cost Projections and Assumptions

Planning for end-of-life battery disposal, is by design a forward-looking exercise. This large BESS has an expected life of 10 years, so disposal costs are projected in 2030 dollars. The battery site is in a remote location, near Mojave, CA, approximately 100 miles North of Los Angeles or 60 miles southeast of Bakersfield. Given the remote location, we assumed labor costs for a 12-hour day and included a per diem cost of $200/day to support mileage, food, and lodging. For onsite labor we assumed a 2030 labor cost of $150/hour fully loaded rate, unless specific rates were provided from vendors.[4] This gave an estimate of $2,000/per day per person for the onsite labor involved in decommissioning. For the offsite container dismantling, we assume that local trained, non-specialized labor will be able to complete the work and used a 2030 labor cost of $60/hour fully loaded rate. For a 12-hour per day shift, that gave an estimate of $720/day per person for the offsite labor involved in dismantling the battery container. For other costs that were only available in 2020 dollars, we utilized a 2.5% inflation rate to estimate 2030 costs for this analysis.

Summary of System Disposal and Recycling Costs

The system description and weights in Table 5-2 were then used to determine the total costs of system disposal and recycling. These costs, summarized in Table 5-3 include separate cost estimates for equipment recycling, labor and supplies for dismantling and packaging, as well as transportation costs for the equipment. As the table sums costs for system disposal, any estimated salvage value is represented as a negative number and subtracted from the subsystem total and the full system total.

It is important to note, the cost estimate in Table 5-3 does not include an Electrical Safety Observer (ESO). When a decommissioning project and task plan is developed for the site, this additional labor cost should be added to the total to ensure the appropriate number of ESO's are scheduled and budgeted across any needed days and project task areas where required.

[4] Hourly rates were adjusted for 2.5% inflation over ten years. For example, the $150/hour labor rate was estimated based on the following assumptions: A fully burdened California labor rate of $120/hour for 2020, projected with 2.5% inflation rate to grow to $150/hour in 10 years. Note – based on www.ssa.gov, the Average Wage Index increase was approximately 2.6% from 2000-2016.

Table 5-3
Large BESS Disposal Cost Estimates[5]

Estimated System Cost Components for the Large NMC Energy Storage System (Costs displayed as positive numbers, end-of-life values are displayed as negative numbers)				
Item (Description)	On-Site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	Subsystem Total
Preparation for Removal				**$40,000.00**
System Disconnection (Initial system disconnection in preparation for disposal.)	$40,000.00			
Battery Module Removal				**$814,000.00**
Battery Modules (Based on 6.35 kWh modules, in 19 racks with 13 modules per rack design)	$244,000.00	$160,000.00	$390,000.00	
Forklift (Two forklifts rented for two weeks.)		$20,000.00		
Balance of Plant at Site				**$142,512.50**
PCS Equipment (Standalone outdoor rated unit.)	$16,000.00	$8,000.00	-$487.50	
Medium Voltage Transformer (Medium voltage transformer and oil containment)	$16,000.00	$28,000.00	$65,000.00	
Small Crane (Small crane for 2 days to remove PCS and MV Transformer.)		$10,000.00		
Balance of Lithium Battery System and Container				**$173,000.00**
Battery Container without Modules for Offsite Dismantling (Built Concrete Enclosure with balance of lithium ion system and container.)	$16,000.00	$26,000.00	$91,000.00	
Large Crane (Large crane for 2 days to remove battery containers.)		$40,000.00		
Post-Site Work				**$16,000.00**
Post Removal Site Cleanup (Final site cleanup.)	$16,000.00			
Subtotals	$348,000.00	$292,000.00	$545,512.50	
Total Estimated System Disposal and Recycling Cost				**$1,185,512.50**

Source: EPRI Estimates

[5] Table cost estimate does not include an Electrical Safety Observer.

Detailed Description of the System Removal and Disposal

The following section describes the various steps and system equipment components in more detail and includes a discussion of any assumptions used in the calculations end-of-life recycling or disposal cost and value.

Preparation for System Removal

System Disconnection

Before the system, shown in Figure 5-3, can be dismantled or removed, it will need to be discharged, shut down, and disconnected from the utility system. This procedure may vary depending on the specific system technology, but at a minimum will include a final inspection of the system, system shut-down, and physical disconnection of the systems electrical components. This is estimated to take 4 workers 5 days to complete safely. At a cost of $2,000/day for 20 labor-days, this step is estimated to cost $40,000.

Figure 5-3
Battery System Site
Source: EPRI Photo

Battery Module Removal

Equipment and Description

The full system was calculated from the representative components in one container and expanded across all 13 containers, it is not based on the site nameplate rating for the system. Therefore, weights and energies for the system are a sum of reference values for the battery modules from specification sheets. Each battery system container houses 19 racks with 13 battery modules each, an example of four of these battery module racks are shown in Figure 5-4. The battery modules specify an energy of 6.4 kWh each, with the racks totaling to 82.5 kWh.

Figure 5-4
Four Battery Racks from the System
Source: EPRI Photo

To calculate the number of battery modules in the system, we can multiply the 19 racks times 13 battery modules per rack to determine there would be 247 battery modules in each battery container, or 3,211 battery modules for the entire battery system site. Each battery module weighs 54 kg (119 lb), so the total battery module weight for the entire system is calculated to be approximately 175,500 kg (390,000 lb). Given the 119 lb battery module weight, the system installation team designed a hoist system to lift the battery modules more easily into place. A reverse process for battery module removal is recommended for this end-of-life dismantling.

Recycling

Recycling of the battery modules accounts for the largest portion of system disposal cost. As earlier sections show, many battery recyclers are developing the capability to manage larger format packs and battery modules. For this costing exercise we communicated with some larger companies, Retriev and Umicore, to inform distance estimates for battery transport. Both are able to handle the disassembly required for grid-scale batteries. Retriev, now combined with Heritage Battery Recycling, has lithium ion battery recycling centers in British Columbia, Canada and in Lancaster, Ohio. Umicore's processing and recycling facilities are based in Europe, however they have battery collection staging areas across the U.S. These and other industry participants are discussed in Section 3.

As discussed in Section 4, before they are recycled, the battery modules must be disassembled. This disassembly can require a significant amount of time per battery module. Improved efficiency and designs that are easier to disassemble could reduce this in the future. After disassembly, the battery components are recycled. Interviews with battery recyclers gave a cost of $1/lb ($2.20/kg) as the recycling cost of Nickel Manganese Cobalt (NMC) lithium ion chemistry batteries for future receipt of installed systems in 2030. This cost is for batteries delivered to the recycling facility and represents the labor cost of battery module disassembly as well as the value of the metals recovered from the recycling process. For the estimated system weight of 175,500 kg (390,000 lb) NMC battery modules, this represents a battery module recycling cost of $390,000. It should be noted that these costs are reliant on recovered value and commodity pricing for battery materials and may vary as those prices fluctuate.

Dismantling and Packaging

Due to their heavy weight the battery modules will need to be removed and transported separately from the system container housing. Additionally, while most of the system components can be recycled through common methods (scrap metal, electronics, etc.), the battery modules must be sent to sites specifically capable of processing and recycling lithium ion batteries. It makes sense to limit the weight and components that are shipped longer distances that could otherwise go to a local recycler. Additionally, with the classification as universal waste or hazardous waste, batteries have to be transported with additional safety guidelines outlined in Section 2.

This system has an estimated 3,211 battery modules. Each of these battery modules weighs 54 kg (119 lb) and would need to be individually disconnected, have the electrode ends covered if needed to avoid shorts, be placed onto a wooden pallet and secured with shrinkwrap to secure the units. The pallets would need to have appropriate labels attached to denote the shipment of lithium ion batteries, which are hazardous materials. More details on the requirements surrounding lithium ion battery packaging can be found in Section 2 of this report. We estimate approximately 16 battery modules could be stacked per pallet, for a weight of approximately 864 kg (1,904 lb). For this system, it would take 200 pallets for shipping. We estimate a cost of $20,000 for pallets and packaging equipment for safely transporting the battery modules.

The time and labor involved in removing and packaging this number of battery modules is not insignificant. For a system this size, it was then estimated that it will take 8 people 14 days to remove and package the battery modules for shipment and to load the pallets onto the trucks for transport. At a cost of $2,000/day for 112 labor-days, this step is estimated to cost $224,000.

This value is highly dependent on the assumptions used. Processes to improve the efficiency of removing and packaging the battery modules, would reduce this cost, but safety should be considered for both the site handling, transport, and recycling center handling of the batteries. A reduction or increase in the minutes per battery module for removal time or the cost per hour of labor will affect this assessment.

Transportation

Once the battery modules are packaged and labeled, they will need to be transported from the system site to the battery recycling or processing facility. This could represent a significant distance of between 1,500 – 2,500 miles. With the estimate of 175,500 kg (390,000 lb) of battery modules on 200 pallets, it is estimated that it will take 10 truckloads to transport the battery modules. Estimating a cost of $8/mile for hazardous material over a distance of 2,000 miles, we estimate it will cost $160,000 for transportation of the battery modules to the recycling facility.

Forklift

To facilitate the disassembly, packaging, and placement of battery modules onto the pallets, and loading trucks for safe transport, it is estimated that two forklifts would be needed for 2 weeks. It is estimated that a forklift rental cost would be $20,000.

Balance of Plant at Site

The following section describes the balance of plant components that will be removed and recycled beyond the batteries and battery containers.

Power Conversion System

Equipment and Description

Another major electrical component of the energy storage system is the PCS, shown in Figure 5-5. For this system, it is an outdoor SMA Sunny Central Storage 2750-EV-US system. The unit's housing is made of gauged steel, and contains an LCD screen, communications and control equipment for the PCS, insulated gate bipolar transistors (IGBTs), and a cooling system. This system is air cooled; however, others may be liquid cooled with an ethylene glycol and water mixture. This PCS unit weighs 3,400 kg (7,500 lb). Across the site, there are 13 PCS units weighing 44,200 kg (97,500 lb).

Figure 5-5
Power Conversion System
Source: EPRI Photo

Recycling

The PCS units may be sent to a metal recycler for disposal, where they will be able to remove the IGBT and other power electronics for metal recovery. Based on the system weight of 7,500 lb and the rough guidelines for scrap metal value of one-half penny per pound, that there may be some value, approximately $500, obtained in equipment recycling.

Dismantling and Packaging

Dismantling and packaging of the PCS system used in this example is relatively straight forward. The unit would need to be placed onto the truck for transportation and pick-and-place for these PCS units are assumed under the container crane costs. We estimate disconnecting, preparing the unit for shipment and loading it onto the truck would take 4 people 2 days to complete. At a cost of $2,000/day for 8 labor-days, this step is estimated to cost $16,000.

Transportation

The PCS would need to be transported to a local metal recycler to be disassembled for recycling. We estimate that this would require 4 trucks for the short trip of approximately 400 miles, at a cost of $2,000 per truck we estimate, if partial trucks can be combined with other system transport needs, that the total cost for trucking the units would be $8,000.

Medium Voltage Transformer

Equipment and Description

In addition to the PCS each battery container has a medium voltage transformer, shown in Figure 5-6. This outdoor model is made of gauged steel and contains the transformer equipment and mineral oil and oil containment. This transformer unit weighs approximately 4,200 kg (9,200 lb). If ethylene glycol was used for liquid cooling in a similarly sized PCS, we estimate a weight of 45 kg (100 lb) of the coolant water mixture. Across the site, there are 13 medium voltage units weighing 54,600 kg (119,600 lb).

Figure 5-6
Medium Voltage Transformer
Source: EPRI Photo

Recycling

Estimates for transformer disposal costs of units this size and year model were estimated to be $5,000 per unit. The systems would be handled to remove and safely recover the oil in the transformer, as well as the transformer coils and unit housing for scrap metal. With 13 units, the total cost for disposal of the Medium Voltage Transformers is estimated to be $65,000.

Dismantling and Packaging

Dismantling and packaging of the transformer system used in this example is relatively straightforward. The unit would need to be placed onto the truck for transportation and pick and place for these transformer units are assumed under the container crane costs. We estimate disconnecting, preparing the unit for shipment and loading it onto the truck would take 4 people 2 days to complete. At a cost of $2,000/day for 8 labor-days, this step is estimated to cost $16,000.

Transportation

The transformers would need to be transported to a more specialized metal recycler to be disassembled for recycling. We estimate that this would require 7 trucks for a trip of approximately 800 miles, at a cost of $3,000 per truck we estimate, that the total cost for trucking the units would be $28,000.

Crane

The PCS and MV transformer equipment will require a small crane for loading onto truck trailers for transportation. There are 26 of these units, and it is estimated that it may take 2 days to pick and place them onto trucks for secure transport. It is estimated that a crane with operator and rigger would cost $10,000 for the three days. An image of the site and access area for the crane and loading is show in Figure 5-7.

Figure 5-7
System Site View for Crane and Loading Access
Source: EPRI Photo

Container Removal for Offsite Dismantling

We estimate that dismantling of the remainder of the lithium ion battery system, after the battery modules have been removed, will take place offsite.

Container

Equipment and Description

The system is comprised of 13 battery containers. They are approximately 20-foot concrete constructed containers with side access doors. These custom engineered containers, shown in Figure 5-8, are made from concrete and commonly used in the telecommunications industry. The concrete does add additional weight to the system, and each container is estimated to weigh 22,700 kg (50,000 lb), giving the total system container a weight of 295,100 kg (650,000 lb).

Figure 5-8
Battery System Container
Source: EPRI Photo

The container may also have additional components such as structural rails, vent baffling, and lighting installed to support both the personnel accessing the system as well as the batteries and equipment. These additional modifications are estimated to add an additional 450 kg (1,000 lb) to the container weight. This would add approximately 5,850 kg (13,000 lb) to the total system container weight.

Dismantling and Packaging

While no packaging will be necessary, the system housing container will require some preparation before shipment. All loose components will need to secure across the 13 units. The containers will need to be unbolted, or otherwise unsecured so that they may be lifted for transportation off site. These steps are estimated to take 4 workers 2 days to complete, assuming all other steps have been completed and the other listed materials have been disassembled. At a cost of $2,000/day for 8 labor-days, this step is estimated to cost $16,000.

Transportation of the Unit from the site

Given the weight of the concrete containers, they will require a specialized heavy-duty crane for removal and low-bed truck trailers for transport. Due to weight limitations, we estimate one container per trailer, requiring 13 truck trips to transport the containers to the offsite dismantling facility. It is assumed that offsite location can be found within 400 miles of the site, and truck costs are estimated to be $2,000 per truck trip. The total trucking costs to remove the containers is estimated to be $26,000.

Large Crane for Container Removal from site

The large equipment such as the battery containers, PCS units, and medium voltage transformer, will require a crane for loading onto truck trailers for transportation. There are 39 large systems, and it is estimated that it may take 3 days to pick and place them onto trucks for secure transport. It is estimated that a crane with operator and rigger would cost $40,000 for the two days. An image of the site and access area for the crane and loading is show in Figure 5-7.

Off-Site Dismantling of the Lithium Battery Container

For these process and cost estimates, we assumed the remaining battery container systems would be dismantled offsite. This reduces remote site travel and takes advantage of locally trained labor and third-party location sites with easier to scrap and recycling pathways for the balance of system components. As described in the beginning of the section, we assumed that work done at the offsite location would be at a lower labor rate of $60/hour for 12 hours at a cost of $720 per day and without per diem or site travel expenses. The costs for this offsite dismantling are shown in Table 5-4 and accounted in Table 5-3 under the “Battery Container without Modules for Offsite Dismantling” under the Equipment Recycling Column.

Table 5-4
Lithium Container Offsite Dismantling Cost Estimate (subset of costs in Table 5-3)

Estimated System Cost for Offsite Dismantling and Disposal of Balance of Lithium Battery System and Container (Costs displayed as positive numbers, end-of-life values are displayed as negative numbers)				
Item (Description)	On-Site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	Subsystem Total
Container Housing				**$26,085.00**
Base Container (Concrete built enclosure.)	$2,880.00	$6,500.00	$13,000.00	
Modifications (Lighting, Flooring, venting, etc.)	$2,880.00	$175.00	$650.00	
Battery System Components				**$17,962.00**
Battery Racks (Estimated based on 82.5 kWh Racks. 19 per unit with 247 total racks.)	$5,760.00	$500.00	-$188.50	
Battery BMS (19 per unit, for 247 total BMS units)	$2,880.00	$150.00	$5,460.00	
Battery Connector Cables (Electrical and Communication Cables.)	$2,880.00	$150.00	$370.50	
System Controls and Communications				**$20,935.00**
Storage Management System (Master Computer, Communication Hardware, Metal housing.)	$7,760.00	$175.00	$13,000.00	
HVAC Thermal Management System				**$12,220.00**
HVAC Equipment (Each unit has four 5-ton systems for redundancy.)	$2,880.00	$500.00	-$1,560.00	
Refrigerant (Requires special handling and removal.)	$0.00	$0.00	$10,400.00	
Fire Suppression System				**$6,666.75**
Fire Suppression System Controls (Sensor and response box.)	$1,440.00	$150.00	$0.00	
Fire Suppression Tank and Agent (FM 200 Tank)	$1,440.00	$500.00	$1,300.00	
Piping Dispersion System (Metal piping for dispersion.)	$1,440.00	$400.00	-$3.25	
Additional Equipment				**$5,030.00**
Additional Equipment (Main Switch, Cables, Breakers, Fuses, etc.)	$2,880.00	$200.00	$1,950.00	
Subtotals	$35,120.00	$9,400.00	$44,378.75	
Total Estimated System Disposal and Recycling Cost				**$88,898.75**

Source: EPRI Estimates

Battery Racks, BMS, and Connector Cables

Equipment and Description

As discussed above each battery container contains 19 metal battery rack frame structures that previously supported the battery modules. Across all 13 units, there would be 247 metal racks.

In addition to the rack frames, the system also contains a Battery Management System (BMS) and battery connector cables for both electrical and communication connections across the battery modules that would have been removed when the battery modules were disconnected. Each BMS electronic system is estimated to weigh 20 kg (45 lb). There is one per rack, for a total of 19 per unit for a total BMS weight of 380 kg (840 lb) per unit. For the total system, there are approximately 4,940 kg (10,920 lb) of BMS equipment for disposal. The metal rack units are each estimated to weigh 70 kg (154 lb) each, giving a total container weight for all 19 metal racks at 1,330 kg (2,900 lb), or a whole system weight of 17,290 kg (37,7000 lb). The cable connectors for each system were approximated to weigh 13 kg (30 lb) per rack unit, for a total container system cable weight of 360 kg (800 lb), or a whole system weight of 3,380 kg (7,410 lb).

Recycling

The metal racks can be reused for additional batteries or recycled as scrap metal. Based on conversations with metal recyclers, a general rule of thumb for scrap metal recycling value is one half penny per pound. Based on the approximated 17,290 kg (37,700 lb) weight for the metal racks, they are estimated to have a value of $200.

The BMS units contain the computer components that monitor and operate the battery modules, they along with the cable connectors can be recycled with the other electronic components in the system. As electronic recycling is a common practice to recover metal components, it is estimated that there will be only a small cost for recycling, 50 cents per pound. There are 247 BMS units weighing approximately 4940 kg (10,920 lb). The cost for disposal is estimated to be $5,460.

Dismantling and Packaging

The BMS can be removed for electronics recycling. The system will contain 19 BMS units per container. In total there are 247 BMS units in the system. We estimate that it would take 2 people 2 days to remove those units for recycling. At a cost of $720/day for 4 labor-days, this step is estimated to cost $2,880.

Additionally, the battery connector cables that were removed on site and stored in the container, would need to be collected for electronics recycling. The system will contain multiple cables per battery rack. We estimate that it would take 2 people 2 days to remove and package those units for recycling. At a cost of $720/day for 4 labor-days, this step is estimated to cost $5,760.

Finally, the metal racks may be removed to be reused or recycled as scrap metal. It is assumed that the scrap metal will be able to be transported without packaging in a truck or other container included in the transportation costs. However, it is estimated that it would take 2 people 4 days to unbolt and remove the 19 rack frames from the 13 battery containers. At a cost of $720/day for 8 labor-days, this step is estimated to cost $5,760.

As an alternative, the battery rack weight is low enough that it would be possible to ship them inside of the system container for removal at the salvage site.

Transportation

For the rack metal frames, BMS, and connector cables, we assume that a local recycler (within 100 miles of the offsite dismantling location) will be available that can process and recycle scrap metal, computer electronics, power electronics, and any additional components.

For the metal racks it is estimated that one truck will be needed to transport them from the dismantling site to the salvage handler at a cost of $500. Or they could be aggregated with other components to maximize transport to the end metal recycler from the dismantling site.

For the BMS units they are expected to need a partial truck load for local transportation for a cost of $1500 to transport the BMS units weighing 4,940 kg (10,920 lb) to a local electronic recycler. Similarly, for the battery connectors, we estimate a small transportation will represent a partial truck load and a cost of $150 to transport the connectors weighing 3,380 kg (7,410 lb) for electronic recycling.

System Controls and Communications

Equipment and Description

In addition to the BMS units located in each of the battery racks to monitor the individual battery modules, there will also be a master control computer and communication system to enable entire system control and coordination with the interconnected grid. These computer and hardware systems enable cell and battery module monitoring and communication with the system site controller and off-site monitoring for the system. These components are estimated to weigh 45 kg (100 lb) for each battery container unit, for a total weight of 585 kg (1,300 lb).

Recycling

This communications and control equipment may be reused or can be handled by a traditional metal or electronics recycler. The cost for this recycling or reuse is assumed to be $1,000 per unit, or $13,000 for the total system.

Dismantling and Packaging

It may be possible to leave the additional components inside of the system housing for removal, so that they may be transported and removed off-site by the metal recycler. If this is not an option, or if the components are to be reused, we estimate that it would take 2 people 4 days to remove the components. At a cost of $720/day for 8 labor-days, this step is estimated to cost $5,760. Packaging for the System Controls is estimated to cost $2,000.

Transportation

The additional equipment may be transported with other metal or electronic components. We estimate that it will take one quarter of a truck load and may add $175 to transportation costs for the system.

HVAC Thermal Management

Equipment and Description

For a large battery energy storage system, thermal temperature control is very important. These battery units each have four 5-ton HVAC systems to handle thermal cooling load during operation, two of these units are shown mounted onto the containers in Figure 5-9. These systems add redundancy to ensure back up in the case of one unit's failure. These units are estimated to weigh 225 kg (500 lb). With 4 units per each of the 13 containers, there are 52 HVAC unit on the site, giving a total weight of 11,700 kg (26,000 lb).

Figure 5-9
HVAC Units
Source: EPRI Photo

These HVAC systems use Refrigerant 22 or a similar agent in their cooling process. This chemical is also known as chlorodifluoromethane and is a gas. It has both ozone depleting potential and global warming potential and should be properly handled and disposed of to minimize unnecessary release. We approximate that each unit contains 5.4 kg (12 lbs) of coolant, and that across the 52 HVAC 5-ton cooling systems on the site, there would be a total of 286 kg (650 lb) of Refrigerant 22 coolant.

Recycling

While the HVAC systems may be sent to a metal recycler for breakdown and recovery, the refrigerant must first be removed. Removal of the refrigerant from the HVAC system must be done by a certified refrigeration technician and requires specialized equipment. Once recovered the refrigerant can be purified and reused. Refrigerant removal will cost approximately $200 per unit. For 52 units, the cost or refrigerant removals is estimated to be $10,400. For the remaining drained unit, the metal recycling value is assumed to be $30/unit, for a value of $1,560 for the 52 units.

Dismantling and Packaging

The refrigerant will need to be removed by a certified refrigerant technician as described in the previous section. The units are externally attached to the container, they would need to be removed after the refrigerant has been removed for scrap metal recycling. We estimate it would take 2 people 2 days to remove the units. At a cost of $720/day for 4 labor-days, the step is estimated to cost $2,880.

Transportation

Once the refrigerant has been removed, the HVAC units may be transported with other metal components. We estimate that they would require one short truck trip shipment at a cost of approximately $500.

Fire Suppression System

Equipment and Description

The fire suppression device for the battery containers includes metal tanks containing the suppression agent, a metal piping dispersion system, and the fire monitoring and alarm hardware. The metal piping system serves two purposes, to secure the gas tanks, and to spread the suppression agent across the protected area in the case of a fire. The metal in the piping and frame are estimated to weigh 45 kg (100 lb). The fire detection control box, shown in Figure 5-10, contains some electronics that may be sent with other system components. They also contain two small lead acid backup batteries, black boxes in the figure. Across the site there would be 26 small lead acid batteries that would need to be collected and directed to a local recycling collection center for recycling.

The Fire suppression tank, shown in Figure 5-11 contains a common suppression agent FM 200. This is a gaseous waterless fire suppression agent manufactured by The Chemours Company, a spin-off of DuPont. Chemically FM 200 is heptafluoropropane, which while it has zero ozone depleting potential, it does have a global warming potential, and must be handled to prevent unnecessary release. Each of the 13 containers is equipped with a tank of suppression agent, which would be filled with the calculated amount to suppress flames based on the container size. Each tank is estimated to weigh approximately 140 kg (300 lb) when full, for a total weight of all 13 tanks of 1,768 kg (3,900 lb).

Figure 5-10
Fire Detection Control Box
Source: EPRI Photo

Figure 5-11
Fire Suppression Tank
Source: EPRI Photo

Recycling

The fire suppression agents have an infinite shelf life if stored properly. At the end of the BESS lifetime, if the tanks have not been discharged, they may be returned to the supplier to be reused. In the event of tank discharge, the empty tank or pressure vessel should also be returned to the supplier, for proper handling of any remaining agent and so that the tank may be reused. A small cost of $100 per tank for return is assumed, for a total cost of $1,300.

The metal piping may be reused or recycled as scrap metal. While scrap metal does have a small recycling value, the gas dispersion system weight would not yield a significant return.

Dismantling and Packaging

The fire suppression system controls will need to be collected and disposed with the electronics recycling. We estimate that it would take 2 people 1 day to remove the controls. At a cost of $720/day for 2 labor-days, this step is estimated to cost $1,440.

The tanks of fire suppression agent, however, will need to be removed and returned to a qualified supplier for reuse. We estimate that it would take 2 people 1 day to remove those units and organize their transportation to an appropriate supplier. At a cost of $720/day for 2 labor-days, this step is estimated to cost $1,440.

The metal piping and tank rack may be reused or scrapped along with other metal components of the system. If done on site, we estimate that it would take 2 people 1 day to remove the metal piping and components. At a cost of $720/day for 2 labor-days, this step is estimated to cost $1,440.

Transportation

The fire suppression system control unit may be transported with other electronics, it is anticipated to add $150 to the transportation costs. The metal piping and rack can be transported with other metal components. Piping may take one quarter of a truck load for an estimated cost of $400. The tanks of fire suppression agents are high pressure vessels and will need to be secured according to best gas tank handling practices for transportation. Even with those requirements, we estimate a transportation cost of $500 for the tanks of suppression agent.

Empty Container

Equipment and Description

The container is described above and depicted in Figure 5-8.

Recycling

As these containers are very sturdy and built for multiple uses, there may be a market for secondary use. However, as a conservative estimate, and due to transportation limits from the heavy weight, we estimate a cost to dispose or recycle these units of $1,000. For thirteen units, the cost is estimated to be $13,000.

The modifications to the container if removed at end-of-life would also need to be disposed of. It is estimated to take 2 people 2 days to remove and dispose of the reinforcements, vent baffling, floor, and any additional components that are added to the base container. The total cost to remove and dispose of the container modifications is estimated to be $720/day for 4 labor-days for a total cost of 2,880.

Dismantling and Packaging

After the systems have been dismantled at the offsite location, we estimate it will take an additional 2 people 2 days to load and send the units for final disposal or reuse. At a cost of $720/day for 4 labor-days, this step is estimated to cost $2,800.

Transportation of the Empty Unit

Even after removal of all other components, the concrete container will still be very heavy. It is assumed the offsite location has capabilities for loading the unit onto a truck for final transport. The containers may still need to be transported independently due to weight, requiring 13 truck trips to transport the containers to the final disposal site. It is they would need to travel a short distance of 100 miles, and truck costs are estimated to be $500 per truck trip. The total trucking costs to remove the containers is estimated to be $6,500.

Additional Equipment

Equipment and Description

In addition to the components detailed above, the energy storage system would also contain a main switch, cables, breakers, fuses, and other metal or electrical components. These components may add approximately 230 kg (500 lb) per battery modular unit and could represent 2,990 kg (6,500 lb) across the entire system site.

Recycling

This additional equipment may be reused or can be handled by a traditional metal recycler. The cost for this recycling or reuse is assumed small, approximately $1,950. However, the scrap metal and cable materials do have a recycling value, a quote from a metal recycler would be needed to estimate residual value based on quantity and recoverable valuable materials.

Dismantling and Packaging

The battery module cable connectors will be removed as part of the battery module disassembly process but will need to be collected and packaged for transported and removed off-site by the metal recycler. We estimate that it would take 2 people 2 days to remove or collect and package the switch, cables, breakers, fuses, and other metal or electrical components. At a cost of $720/day for 4 labor-days, this step is estimated to cost $2,880.

Transportation

The additional equipment may be transported with other metal components. We estimate that it will take one quarter of a truck load and may add $200 to transportation costs for the system.

Project Closure and Post Site Work

Post Site Removal Cleanup

Following removal of the system, the remaining site will need be cleaned and potentially restored. Most battery systems will be placed on concrete slabs with electrical connections to utility or site grids. We anticipate in most cases that leaving the concrete platform in place to be sufficient. However, some personnel time will be needed to clean the area and secure and remove any remaining cables or connections that are no longer needed without the battery equipment present. This is estimated to take 4 workers 2 days to complete. At a cost of $2,000/day for 8 labor-days, this step is estimated to cost $16,000.

Disposal Paperwork

For asset management records or tracking, there may be paperwork verifying the removal and proper disposal of the utility asset. Specifically, the battery modules and transformer due to their hazardous waste and universal waste classifications. However, review of current utility practices for computer and other asset management should be undertaking to identify necessary reporting steps. Some paperwork, like Certificates of Disposal for the battery modules, will not be available until after they have gone through the recycling process, so it is important to factor that step into project timeline planning.

Conclusions

The total decommissioning cost for a large lithium ion BESS was summarized on a component-by-component basis. These cost estimates include salvage values for heavy equipment and scrap metal transportation and removal. The battery modules represent the largest weight and recycling costs of the system, and although recycling of lithium ion battery modules is still being developed on a commercial scale, most of the other components already have well established recycling procedures. For this estimated 20MW/10MWh energy storage system, it was estimated to cost roughly $1,185,000 for disposal and recycling at end-of-life in 2030 dollars.[6]

[6] This total does not include Electrical Safety Observers (ESO) who may be needed on the project site.

6

COST AND ECONOMICS OF A SMALL MIXED TECHNOLOGY SYSTEM

The same methodology used to estimate end-of-life costs for larger systems in the previous section can also be applied to smaller mixed technology systems. This chapter describes the anticipated procedure and estimated costs for the smaller mixed chemistry BESS comprised of a 100kW/400kWh lithium ion battery system coupled with a 100kW/400kWh vanadium flow battery system. The full battery system is described below, and forward cost estimates are calculated for the disassembly, recycling and disposal of the separate components of the system, as well as the overall site.

The analysis in this report assumes an end-of-life disposal of the entire BESS at one time in 2030 for easier comparative analysis. However, the vanadium flow battery has a 20-year performance expectation, so may not reach end-of-life until closer to 2040. The descriptive procedural steps envisioned here, would still be applicable, but the final costs would require adjustment.

As an emerging technology type, and without the additional scale from electric vehicle applications as exists for LIB recycling, there is no established market for the decommissioning of vanadium flow batteries beyond the original vendors. Third party waste disposal experts certainly have the capabilities but may need additional information on the products to enable end-of-life recycling and processing. As scale increases, a market could certainly develop to support end-of-life recovery of the vanadium electrolyte, but the uncertainty around that development is represented with conservative cost estimates based on currently available information.

System Overview

The smaller mixed chemistry BESS is composed of one lithium ion battery cabinet and 15 vanadium flow battery units along with balance of system equipment. A site overview of the entire system is shown in Figure 6-1. This shows the layout of the site and road access beyond and may inform equipment staging for end-of-life removal activities.

The lithium battery container, shown in the far left of the figure is coupled with four small HVAC units for thermal management, a fire suppression system, PCS, and H_2 sensor. In front of the lithium unit, on the lower pad are the Eaton cabinets that contain the switchgear and computer interface for the entire system. On the higher concrete pad are the 15 flow battery units, each with a small inverter attached. There is an additional communication unit to interface with the flow battery units. More details on the systems and equipment can be found in the respective detailed description sections below.

Figure 6-1
Battery Energy Storage System Site
Source: EPRI Photo

Summary of System Weight Estimates

A bottom-up accounting was used to estimate the weights for the system and its components. Table 6-1 includes the major components and weight estimates for one vanadium flow battery unit. The total system weight estimation below will include the weights of all 15 units. A more detailed description of system components as well as the information and assumptions used to calculate weights will be discussed later in the section.

Table 6-1
Mixed Chemistry System Vanadium Flow Battery Unit Weight Estimate

Estimated Vanadium Flow Battery Unit Weight		
Item (Description)	**Weight (lb)**	**Weight (kg)**
Electrolyte (1.6M Vanadium Electrolyte)	4,200	1,900
Inverters (Based on HiQ True String XL 480V Inverter.)	30	15
Tubing and Tank (Polypropylene and vulcanized plastic.)	60	30
Pumps (Circulating pumps.)	60	30
Reaction Stack (Stacks with carbon felt, plastic, and ductile iron.)	200	90
Enclosure (Outdoor container)	2,000	900
Total Estimated Unit Weight	**6,550**	**2,965**

Source: EPRI Estimates

This weight estimate was also done for the lithium ion unit, including battery modules and racks within the unit, as well as the auxiliary components necessary for safe operation and monitoring of the system. This system in shown in Table 6-2. As recycling and disposal experts deal in weights and volumes, these tables may also serve to inform quotes at time of system disposal.

Table 6-2
Mixed Chemistry System Lithium Ion Battery Unit Weight Estimate

Estimated Lithium Ion Battery Unit Weight		
Item (Description)	**Weight (lb)**	**Weight (kg)**
Battery Modules (Based on 9.0 kWh energy modules, in 8 racks with 9 modules per rack design)	8,500	3,900
Battery Racks (Metal rack)	900	400
Battery BMS (One unit per rack.)	360	160
Battery Connector Cables (Estimated Weight)	240	100
Container Enclosure (Metal Cabinet enclosure)	2,500	1,100
HVAC Equipment (Four systems for redundancy.)	1,000	450
Refrigerant (Requires Special Handling and Removal)	40	18
Fire Suppression System Controls (Sensor and response box.)	45	20
Fire Suppression Tank and Agent (FM 200 Tank)	100	45
Piping Dispersion System (Metal piping for dispersion.)	20	9
Additional Equipment (Cables, H2 Sensor, etc.)	250	115
Total Estimated Unit Weight	**13,955**	**6,317**

Source: EPRI Estimates

Finally, the entire system and supporting site hardware weight estimate is shown in Table 6-3. This includes 15 of the vanadium flow battery units, the lithium unit, and balance of system components.

Table 6-3
Total Mixed Chemistry BESS System Weight Estimates

Estimated System Weight for Battery Energy Storage System		
Item (Description)	**Weight (lb)**	**Weight (kg)**
Vanadium Flow Battery		
Flow Battery Containers (15 units) (Based on 10 kW, 30 kWh units)	99,000	45,000
Network Communications Unit (System communication system)	60	30
Lithium Ion Battery System		
Lithium Battery Cabinet with Modules (Standalone outdoor rated unit with 8 racks and 72 modules.)	14,000	6,350
Power Conversion System (Based on the Dynapower MPS250-800)	3,500	1,600
Balance of System		
Eaton Switchgear Cabinets (Computer Interface, Switches)	6,000	2,700
Battery Connector Cables (Estimated Weight)	480	220
Total Estimated Unit Weight	**123,040**	**55,900**

Source: EPRI Estimates

Future Cost Projections and Assumptions

Planning for end-of-life battery disposal, is by design a forward-looking exercise. This mixed chemistry BESS has two timelines for its major components. The lithium ion system has an expected life of 10 years, while the vanadium system has an expected lifetime of 20 years. Given the uncertainty out 20 years in general and specifically for the development of a vanadium battery recycling industry, the disposal costs for this system are only projected for 10 years to 2030 dollars.

The battery site is in an urban location, in downtown Los Angeles. This location may present challenges with traffic or surrounding construction or activity and should be considered in end-of-life planning and costs. Given the location, we assumed labor costs for a 12-hour day but did not include a per diem in the cost estimate. For onsite labor we assumed a 2030 labor cost of $150/hour fully loaded rate, unless specific rates were provided from vendors.[7] This gave an estimate of $1,800/per day per person for the onsite labor involved in decommissioning. For the offsite container dismantling, we assume that local trained, non-specialized labor will be able to complete the work and use a 2030 labor cost of $60/hour fully loaded rate. For a 12-hour per day shift, that gave an estimate of $720/day per person for the offsite labor involved in dismantling the battery container. For other costs that were only available in 2020 dollars, we utilized a 2.5% inflation rate to estimate 2030 costs for this analysis.

Summary of System Disposal and Recycling Costs

The system description and weights in Table 6-1, Table 6-2, and Table 6-3 were then used to determine the total costs of system disposal and recycling. These costs, summarized in Table 6-4 include separate cost estimates for equipment recycling, labor and supplies for dismantling and packaging, as well as transportation costs for the equipment. As the table sums costs for system disposal, any estimated salvage value is represented as a negative number and subtracted from the subsystem total and the full system total.

From the table below, more information on the Flow Battery Container (15) Equipment Recycling cost of $49,500 can be found later in this report section in the detailed cost description subsection in Table 6-5. Similarly, more detailed information for the lithium battery cabinet with modules equipment recycling cost of $24,000 can be found in the detailed cost description subsection for that technology in Table 6-6.

It is important to note, the cost estimate in Table 5-3 does not include costs that may be important at utility sites like an Electrical Safety Observer (ESO). When a decommissioning project and task plan are developed for a site, it will be important to include any additional labor costs, such as ESOs, for the needed days and project task areas where they may be required.

---

[7] Hourly rates were adjusted for 2.5% inflation over ten years. For example, the $150/hour labor rate was estimated based on the following assumptions: A fully burdened California labor rate of $120/hour for 2020, projected with 2.5% inflation rate to grow to $150/hour in 10 years. Note – based on www.ssa.gov, the Average Wage Index increase was approximately 2.6% from 2000-2016.

Table 6-4
Mixed Chemistry BESS Estimated System Battery Disposal Costs

Estimated System Cost Components for the Mixed Chemistry Battery Energy Storage System (Costs displayed as positive numbers, end-of-life values are displayed as negative numbers)				
Item (Description)	On-site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	Subsystem Total
Preparation and Crane Cost				**$66,000.00**
System Disconnection (Initial system disconnection in preparation for disposal.)	$21,600.00	$0.00	$0.00	
Crane for System Removal (Crane for 1 days to remove battery containers.)	$14,400.00	$30,000.00	$0.00	
Vanadium Flow Battery				**$56,350.00**
Flow Battery Containers (15 units) (Based 10 kW, 30 kWh units)	$7,200.00	$15,000.00	$33,150.00	
Network Communications Unit (System communication system.)	$900.00	$0.00	$100.00	
Lithium Ion Battery Unit				**$35,150.00**
Lithium Battery Cabinet with Modules (Standalone outdoor rated unit with 8 racks and 72 modules.)	$3,600.00	$1,200.00	$24,000.00	
Power Conversion System (Based on Dynapower MPS250-800)	$3,600.00	$750.00	$2,000.00	
Balance of System				**$7,100.00**
Eaton Switchgear Cabinets (Computer Interface, Switches)	$3,600.00	$1,500.00	$2,000.00	
Post-Site Work				**$3,600.00**
Post Removal Site Cleanup (Final site cleanup.)	$3,600.00	$0.00	$0.00	
Subtotals	$58,500.00	$48,450.00	$61,250.00	
Total Estimated System Disposal and Recycling Cost				**$168,200.00**

Source: EPRI Estimates

Detailed Description of the System Removal and Disposal

The following section describes the various steps and system equipment components in more detail and includes a discussion of any assumptions used in the calculations of end-of-life recycling or disposal cost and value.

Preparation for System Removal

System Disconnection

Before the system can be removed it will need to discharged, shut down, and disconnected from the electric grid. Vendor specifications for optimal state of charge for both the lithium batteries and the vanadium systems should be used as guidelines for safe charge levels during transport. Additionally, the system will need to be electronically and physically disconnected from the local grid and site. This includes disconnecting or cutting the electrical and communications lines and disconnecting the grounding cables from the concrete pad so that they can be removed. Figure 6-2 depicts some of the ground connections and concrete bolting that will need to be removed in this step. This procedure should include a final inspection of the system, system shut-down, and electrical disconnection of the system. This is estimated to take 4 workers 3 days to complete safely. At a cost of $1,800/day for 12 labor-days, this step is estimated to cost $21,600.

Figure 6-2
Battery System Site
Source: EPRI Photo

Crane for Site Removal of Equipment

Due to the locational topography and weight of the systems, a crane will be needed to pick and place the units onto truck trailers for transportation. Major components include the 15 vanadium flow battery units, the lithium ion cabinet, lithium ion PCS, the Eaton switchgear cabinets. There are approximately 20 of these units, and it is estimated that it may take 2 days to pick and place them onto trucks for secure transport. It is estimated that a crane with operator and riggers would cost $30,000 for the two days. Given the location and need to coordinate this effort with surrounding street traffic and monitoring, this is estimated to take an additional 4 workers 2 days. At a cost of $1,800/day for 8 labor-days, this step is estimated to cost $14,400. Figure 6-1 provides an overview of the surrounding parking area and street for access.

Vanadium Flow Battery Containers for Offsite Dismantling

For these process and cost estimates, we assumed the battery container systems would be dismantled offsite. This reduces site travel activity for specialized tasks like draining the electrolyte for recovery. It also takes advantage of locally trained labor and third-party location sites with easier access to electrolyte rinsing supplies, as well as scrap and recycling pathways for the balance of system components. As described in Section 5 and earlier in this section, we assumed that work done at the offsite location would be at a lower labor rate of $60/hour for 12 hours at a cost of $720 per day and without per diem or site travel expenses. The costs for this offsite dismantling for the vanadium flow battery units are shown in Table 6-5 and accounted in Table 6-4 under the "Flow Battery Containers" under the Equipment Recycling column.

Table 6-5
Mixed Chemistry System Vanadium 15 Unit Estimated Disposal Costs (subset of costs in Table 6-4)

Estimated Cost for Offsite Dismantling and Disposal of 15 Vanadium Flow Battery Units (Costs displayed as positive numbers, end-of-life values are displayed as negative numbers)				
Item (Description)	On-site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	
Electrolyte (1.6 M Vanadium Electrolyte)	$21,760.00	$20,000.00	-$28,350.00	
Inverters (Based on HiQ True String XL 480V)	$720.00	$50.00	$450.00	
Tubing and Tank (Polypropylene and vulcanized plastic.)	$4,320.00	$50.00	$450.00	
Pumps (Circulating pumps)	$2,880.00	$50.00	$0.00	
Reaction Stack (Stacks with carbon felt, plastic, and ductile iron.)	$2,880.00	$100.00	$6,000.00	
Enclosure (Outdoor Container)	$1,440.00	$500.00	-$150.00	
Subtotals	$34,000.00	$20,750.00	-$21,600.00	
Total Estimated System Disposal and Recycling Cost				**$33,150.00**

Source: EPRI Estimates

Vanadium Battery Unit Site Removal

Equipment and Description

The system contained 15 battery containers. They are approximately 6-foot by 4-foot metal enclosures with top access, as the enclosure base acts as a secondary containment unit for the battery electrolyte should there be a leak. One of these modular containers, is shown in Figure 6-3. For site transport, each loaded enclosure is estimated to weigh 2,965 kg (6,550 lb). Once the battery components have been removed as detailed later in this section, it is estimated that the enclosure would weigh 900 kg (2,000 lb), giving a total system vanadium battery enclosure weight of 13,500 kg (30,000 lb).

Figure 6-3
Vanadium Flow Battery Unit

Source: EPRI Photo

Dismantling and Packaging

While no packaging will be necessary, the system housing container will require some preparation before shipment. All loose components will need to secure across the 15 units. The containers will need to be unbolted, or otherwise unsecured so that they may be lifted for transportation off site. These final preparation steps to ensure the system are ready for the crane equipment and loading are estimated to take 2 workers 2 days to complete, assuming all other steps have been completed and the other listed materials have been disassembled. At a cost of $1,800/day for 4 labor-days, this step is estimated to cost $7,200.

Transportation of the Unit from the site

The battery enclosures may be loaded 3 per trailer, so it will take 5 tractor trailer trucks for transport, in addition to the crane for removal described earlier in this section. The offsite location for dismantling of these units, must be permitted or able to recover the vanadium electrolyte, it is assumed that an offsite location with those capabilities can be found within 400 miles of the site, and truck costs are estimated to be $3,000 per truck trip. The total trucking costs to remove the containers is estimated to be $15,000.

Electrolyte

Equipment and Description

The major component of the vanadium flow battery is the vanadium electrolyte. It is stored in tanks within a closed loop system to flow the reactant electrolyte through the system during battery operation. The enclosure acts as a secondary container beyond the polyethylene tank. The electrolyte is estimated to be approximately 80% water, 1.6 M vanadium, and 3.3 M Sulfuric Acid. As the electrolyte is acidic, there should be basic-acid neutralizing spill kits on site and during transportation of the systems. The electrolyte volume in one unit is estimated to be 1,900 kg (4,200 lb). The total electrolyte with recovery from all 15 units is estimated to be 28,500 kg (63,000 lb).

Recycling

At this stage in the vanadium battery market development, there is not a clear price signal for recovered vanadium from flow batteries. However, the electrolyte does not undergo dramatic degradation, so with light processing it could be reused in new vanadium batteries once recovered at end-of-life. At a minimum, the vanadium electrolyte solution could be sold to recover the vanadium metal with some purification as there is a market for vanadium in the steel processing industry. The commodity value for vanadium has been $5-6/lb, for this analysis we assume that the vanadium in this electrolyte solution would be valued at $2.5/lb to account for processing costs.

For a 1.6M vanadium solution with approximately 3.3M sulfuric acid, it is estimated that the vanadium would represent 18% of the electrolyte by weight. Therefore with 63,000 lb times 18%. There is an estimated 11,340 lbs of vanadium in this system. At a recovery value of $2.5/lb, this represents and end-of-life value of $28,350. As this represents an end-of-life value, rather than a cost, it is presented as a negative value in the cost accounting table in Table 6-5.

Dismantling and Packaging

Removal of the electrolyte from the system can be done using portable diaphragm pumps into an intermediate bulk container or “bird cage” for liquid shipping and storage. The electrolyte can be neutralized to avoid the risk of transporting acidic solutions. However, it is still classified as a hazmat Class 8 corrosive substance and would need to be transported with additional safety guidelines as outlined in Section 2. Estimating that each container holds about 1,000L, this system would need approximately 30 for transport containment. We estimate a cost of $16,000 for packaging.

For the labor costs at the off-site dismantling facility, we estimate it will take 2 people 2 days to pump transfer the electrolyte from the battery units to the transport containers for shipment and to load the pallet containers onto trucks for transport. At a cost of $7200/day for 4 labor-days, this step is estimated to cost $2,880.

The recovery value of the electrolyte will be dependent on the development of a vanadium flow battery market that would value the electrolyte for reuse, as well as the commodity price of vanadium for other industrial applications of the recovered vanadium metal.

Transportation

Once the electrolyte is neutralized and placed into the bird cage pallets with proper labeling, they will be ready for transport to a location that can reuse the vanadium electrolyte or utilize it for its commodity metal value. Given the development of this reuse space, it is estimated that transport distances could be 2,000 miles to a facility with those capabilities. To transport the estimated 30 pallets of electrolyte, it is estimated that it will take 2 truckloads. Estimating a cost of $5/mile for the Class 8 material over 2,000 miles, we estimate it will cost $20,000 for transportation of the electrolyte to a valuable reuse location.

Inverters

Equipment and Description

Each of the 15 vanadium units has an individual inverter. For the mixed chemistry BESS they are HiQ Solar True String XL 480V Energy Storage Inverters capable of 10kW 3 phase. Figure 6-4 shows a picture of the inverter mounted on the end of one of the vanadium flow battery units. Each individual inverter weighs 15 kg (30 lb), or for all 15 inverters from the system a total weight of 225kg (450 lb).

Figure 6-4
Vanadium Unit Inverter and Cabling

Source: EPRI Photo

Recycling

The inverters can be recycled as e-Waste [63]. We estimate a small fee of $30 per unit for recycling. For all 15 units, the cost for recycling disposal is estimated to be $450.

Dismantling and Packaging

The inverters are simply bolted to the exterior of the container, so once the cables have been disconnected can be unbolted for disposal. We estimate that it would take 2 people a half day to remove those units for recycling. At a cost of $720/day for 1 labor-day, this step is estimated to cost $720.

Transportation

It is assumed that the inverters can go to a local e-waste recycler along with other components. We estimate a small transportation fee to cover the partial truck load and a cost of $50 to transport the Inverters for electronic recycling.

Tubing and Tanks

Equipment and Description

A flow battery stores the electrolyte inside tanks, using pumps and tubing to flow the electrolyte from the anode and cathode side of the battery for mixing in the reaction stack within the battery cell. After the electrolyte has been drained from the unit, the remaining system should be flushed with water to rinse remaining electrolyte. The tank, tubing, and pump system can then be dismantled. The tanks are polyethylene plastic and can be recycled or repurposed once cleaned of residual electrolyte. The tubing is a vulcanized plastic that can also be reused or recycled after it has been rinsed. The plastic tubing and tank for each unit are estimated to weigh 30 kg (60 lbs), giving a total weight across all 15 flow battery units of 450 kg (900 lb).

Recycling

As described above the plastic in the tanks and tubing can be reused or recycled via local plastic recyclers. We estimate a small cost for recycling, 50 cents per pound. For approximately 450 kg (900 lb), the cost for disposal is estimated to be $450.

Dismantling and Packaging

Once the electrolyte has been drained, the tubing and tanks will need to be flushed to rinse out electrolyte residue. Then the system should be disconnected to remove it from the container; an additional rinse step may be needed. After that the plastic tank and tubing components are ready for reuse or recycling and no specialized packaging is needed. We estimate that it would take 2 people 3 days to complete those rinse and removal steps to recover the plastic for reuse or recycling. At a cost of $720/day for 6 labor-days, this step is estimated to cost $4,320.

Transportation

It is assumed that the plastic tanks and tubing can go to local salvage or recyclers along with other components. We estimate a small transportation fee to cover the partial truck load and a cost of $50 to transport the tanks and tubing for plastic recycling.

Pumps

Equipment and Description

As described in the subsection on tanks and tubing, the flow battery utilizes magnetic coupled drive pumps to flow the electrolyte throughout to support charging and discharging within the system. The pump cases are cast plastic. Once rinsed of electrolyte residue, the pumps can be refurbished for reuse or recycled. The pumps for each unit are estimated to weigh 30 kg (60 lbs), giving a total weight across all 15 flow battery units of 450 kg (900 lb).

Recycling

As described above the pumps refurbished and reused or recycled via local recyclers. We estimate a small cost for recycling, 50 cents per pound. For approximately 450 kg (900 lb), the cost for disposal is estimated to be $450.

Dismantling and Packaging

Once the electrolyte has been drained, the pumps can be removed and may need to be rinsed to remove any remaining electrolyte residue. Like the previous equipment, no specialized packaging is needed. We estimate that it would take 2 people 2 days to complete those rinse and removal steps and collect the pumps from all of the 15 vanadium units for reuse or recycling. At a cost of $720/day for 4 labor-days, this step is estimated to cost $2,880.

Transportation

It is assumed that the pumps can go to local salvage or recyclers along with other components. We estimate a small transportation fee to cover the partial truck load and a cost of $50 to transport the tanks and tubing for plastic recycling.

Reaction Stack

Equipment and Description

The power portion of a flow battery is the reaction stack where the electrolytes flow together to charge and store power or to discharge and release it. Once the cell is removed from the unit, it can be dismantled for disposal. The cell stack is made of a ductile iron frame bolted together around the plastic polypropylene internal components. Within the cell, the reactive surface is a carbon felt, made of extruded carbon.

Each of these Gen 2 30 kWh units has two cell reaction stacks. Not enough information is available to approximate individual component weights, but the two stacks in a single vanadium flow battery unit are estimated to weigh 90 kg (200 lbs), giving a total weight across all 15 flow battery units of 1,350 kg (3000 lb).

Recycling

Following the equipment description above, the ductile iron, which is already made from 100% recycled scrap iron and steel, is fully recyclable [64]. The plastic polypropylene components from the cell stack can also be recycled using traditional plastic recyclers. Finally, the carbon felt in the reactive cell can be rinsed and disposed of.

Due to the dismantling steps needed for the reaction cell, we estimate a cost for recycling of $200/unit. For the 30 reaction stacks across all 15 vanadium battery units, the cost for disposal is estimated to be $6,000.

Dismantling and Packaging

The reaction stacks will need to be unbolted from the battery enclosure and removed. If the stacks are being sent for dismantling, they may require packaging or pallets for transport. If dismantled with the units, the iron should be sorted with scrap metal, the plastics with like, and the carbon felt rinsed and disposed of. We estimate it will take 2 people 2 days to collect the 30 reaction stacks from the 15 vanadium units for further dismantling. At a cost of $720/day for 4 labor-days, this step is estimated to cost $2,880.

Additional dismantling as described above would increase the labor costs but may balance in savings from the estimated recycling disposal cost.

Transportation

The reaction stacks would need to be further dismantled with the flow battery units or sent to a location to do that next dismantling step. We estimate a small transportation fee of $100 to cover either the stack transportation or the component transportation of iron and plastic if dismantled.

Enclosure

Equipment and Description

The container is described above and depicted in Figure 6-3.

Recycling

The flow battery enclosures are sturdy and suitable for reuse; however, the specialized shape may make finding appropriate applications for the enclosures tricky. We estimate they may have a small, half a penny per pound, scrap metal value for recycling. For 15 units weighing a total of 13,550 kg (30,000 lb), we estimate a scrap value of $150.

Dismantling and Packaging

After the other battery components have been removed, the enclosures will need to be cleaned off, prepared for shipment to a scrap metal recycler, and loaded onto a truck for transport. We estimate it will take 2 people 1 day to complete these final steps. At a cost of $720/day for 2 labor-days, this is estimated to cost $1,440.

Transportation of the Empty Unit

It is assumed these containers can be recycled with a local scrap metal recycler. We estimate a transportation fee of $500 to cover this step.

System Controls and Communications

Equipment and Description

The vanadium flow battery system utilizes a communications unit to connect the vanadium battery controls to the larger system controller. It can be recycled with e-Waste. This unit is estimated to weigh 30 kg (60 lb).

Recycling

This communications and control equipment may be reused or can be handled by a traditional metal or electronics recycler. We estimate a cost for this recycling or reuse is assumed to be $100 for the unit.

Dismantling and Packaging

No special packaging is needed for the NEXTracker unit, and it can be collected and sent with other e-Waste materials. The unit will need to be disconnected from the site for disposal. We estimate that it would take 1 person a half day to remove the unit. At a cost of $1,800/day for a half labor-day, this step is estimated to cost $900.

Transportation

This single unit can be transported with other metal or electronic components. We do not estimate any additional cost for this single unit.

Lithium Ion Battery Cabinet with Modules for Offsite Dismantling

The lithium ion portion of the mixed chemistry BESS is a modular battery cabinet design that can be removed with the batteries contained for easier dismantling at an off-site location. Given access and site topology, this reduces labor involved in system dismantling, and can take advantage of scrap and metal recycling collection for balance of system components. As described in the beginning of the section, we assumed that work done at the offsite location would be at a lower labor rate of $60/hour for 12 hours at a cost of $720 per day and without per diem or site travel expenses. The cost breakdown estimates for this offsite dismantling are shown in Table 6-6 and accounted in Table 6-4 under the “Lithium Battery Cabinet with Modules” under the equipment recycling column.

Table 6-6
Mixed Chemistry System Lithium Ion Battery Cabinet Estimated Disposal Costs (subset of costs in Table 6-4)

Estimated Cost for Offsite Dismantling and Disposal of Lithium Ion Battery Unit (Costs displayed as positive numbers, end-of-life values are displayed as negative numbers)				
Item (Description)	On-site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	
Battery Modules (Based on 9.0 kWh energy modules in 8 racks with 9 modules per rack design)	$4,880.00	$4,000.00	$8,500.00	
Battery Racks (8 metal racks)	$720.00	$250.00	$0.00	
Battery BMS (One unit per rack, total of 8 BMS units)	$720.00	$0.00	$180.00	
Battery Connector Cables (Electrical and Communication Cables.)	$720.00	$0.00	$120.00	
Container Enclosure (Metal Cabinet Enclosure)	$0.00	$0.00	-$12.50	
HVAC Equipment (Four systems for redundancy)	$720.00	$0.00	-$5.00	
Refrigerant (Requires Special Handling and Removal)	$0.00	$0.00	$800.00	
Fire Suppression System Controls (Sensor and response box.)	$720.00	$0.00	$22.50	
Fire Suppressant Tank and Agent (FM 200 Tank)	$0.00	$0.00	$100.00	
Piping Dispersion System (Metal piping for dispersion.)	$720.00	$0.00	$0.00	
Additional Equipment (Cables, H2 Sensor, etc.)	$720.00	$0.00	$125.00	
Subtotals	$9,920.00	$4,250.00	$9,830.00	
Total Estimated System Disposal and Recycling Cost				**$24,000.00**

Source: EPRI Estimates

Lithium Ion Battery Unit Site Removal

Equipment and Description

The lithium battery cabinet system, shown in Figure 6-5, is a single battery unit on a transport skid, it is bolted to a smaller skid containing the power conversion system. Above the cabinet are the 4 HVAC units for system thermal management. Exterior to the cabinet is a fire monitoring and suppression system as well as an H_2 sensor. The cabinet fully loaded with battery modules, racks, and other equipment is estimated to weigh 6,350 kg (14,000 lb). Once dismantled as described below, the cabinet is estimated to weigh 1,100 kg (2,500 lb).

Figure 6-5
Lithium Ion Battery Cabinet, HVACs, and PCS
Source: EPRI Photo

Dismantling and Packaging

As can be seen in Figure 6-5, the transport skids are bolted together and will need to be separated for transport. Units will also need to be unbolted from the concrete platform. Loose cabling or external elements will need to be secured or removed for transportation off site. These steps are estimated to take 2 people 1 day to complete, assuming all other steps in the site disconnection process have been completed. At a cost of $1,800/day for 2 labor-days, this step is estimated to cost $3,600.

Transportation of the Unit from the Site

The battery cabinet and PCS skids will require a crane to pick and place them onto a truck trailer for transport. This step can be done in concert with the flow battery units as described in the crane for system removal step above. These units will represent a partial truck load and can be transported with other site equipment, such as the Eaton switchgear cabinets. It is assumed that offsite location for battery unit dismantling can be found within 600 miles of the site, and truck costs are estimated to be $1,200 for the battery system portion of the trip.

Battery Modules

Equipment and Description

The smaller mixed chemistry BESS lithium cabinet contains 8 racks with 9 battery modules per rack. This gives a total of 72 battery modules. The weight calculations are based on the Samsung energy battery modules that specify an energy of 9.0 kWh per battery module. Each battery module weighs 54 kg (119 lb), so the total battery module weight for the entire system is calculated to be approximately 3,900 kg (8,500 lb). As the battery modules weigh ~119 lb, they may be lifted by 2 -3 people, but utilizing a hoist or lift system to remove and transport them to the pallet for packaging would make that step easier.

Recycling

As described for the large lithium ion system in Section 5, these batteries will need to be recycled at a specialized battery recycling center that is equipped to handle universal waste and recover the materials. To estimate the cost of recycling for these NMC batteries, we use the $1/lb ($2.20/kg). As before, this cost is for batteries delivered to the recycling facility and represents the labor cost of battery module disassembly, as well as the value of the metals recovered from the recycling process. For the estimated system weight of 3,900 kg (8,500 lb) NMC battery modules, this represents a battery module recycling cost of $8,500. As noted above, these costs are reliant on recovered value and commodity pricing for battery materials and may vary as those prices fluctuate.

Dismantling and Packaging

Each of the 72 battery modules in this system weighs 54 kg (119 lb) and would need to be individually disconnected, have the electrode ends covered if needed to avoid shorts, be placed onto a wooden pallet and secured with shrink-wrap to secure the units. The pallets would need to have appropriate labels attached to denote the shipment of lithium ion batteries, which are hazardous materials. More details on the requirements surrounding lithium ion battery packaging can be found in Section 2 of this report. We estimate approximately 16 battery modules could be stacked per pallet, for a weight of approximately 864 kg (1,904 lb). For this system, it would take

5 large pallets for shipping. We estimate a cost of $2000 for pallets and packaging equipment for safely transporting the battery modules.

The time and labor involved in removing and packaging the battery modules is estimated to 2 people 2 days. At a cost of $720/day for 4 labor-days, this step is estimated to cost $2,880.

Transportation

Once the battery modules have been removed from the cabinet, they should be packaged onto a pallet or shipping container for transport to the recycling facility. Since these batteries represent a partial truck load, they may be stored until a full truck load is available to optimize shipping costs. In the case of storage, it should be done safely, following recommend best practices and regulatory requirements.

Transport of the battery modules from the dismantling site to the battery recycling or processing facility, could represent a significant distance of between 1,500 – 2,500 miles. As a partial truck load that is aggregated with other batteries for recycling, we estimate of transportation cost of $4,000.

Battery Racks, BMS, and Connector Cables

Equipment and Description

The battery cabinet contains 8 metal racks, each one would have a BMS for rack management. And like the configuration in Figure 5-4, each battery module would have both communication and electrical cable connections across the battery modules that would have been removed when the battery modules were disconnected. For the cabinet that represents 8 metal racks, 8 BMS units, and approximately 100 kg (240 lbs) of battery cabling.

The metal rack units are each estimated to weigh 50 kg (110 lb) each, giving a total scrap metal rack weight of 400 kg (900 lb) for the cabinet. Each BMS electronic system is estimated to weigh 20 kg (45 lb), so the weight of 8 BMS units is estimated to be 160 kg (360 lb) for the entire cabinet.

Recycling

The metal racks can be reused for additional batteries or recycled as scrap metal. Based on conversations with metal recyclers, a general rule of thumb for scrap metal recycling value is one half penny per pound. But based on small volume of approximately 400 kg (900 lb) for the metal racks, they are only estimated to have a value of $5.

The BMS units contain the computer components that monitor and operate the battery modules, they along with the cable connectors can be recycled with the other electronic components in the system. As electronic recycling is a common practice to recover metal components, it is estimated that there will be only a small cost for recycling of 50 cents per pound. There are 8 BMS units weighing approximately 160 kg (360 lb) and cabling estimated to weigh 100 kg (240 lb). The cost for disposal is estimated to be $180 for the BMS units and $120 for the cabling.

Dismantling and Packaging

The BMS can be removed for electronics recycling. The system will contain 8 BMS units. We estimate that it would take 2 people a half day to remove those units for recycling. At a cost of $720/day for one labor-day, this step is estimated to cost $720.

Additionally, the battery connector cables that were removed to during the battery module recover step, would need to be collected for electronics recycling. The system will contain multiple cables per battery rack. We estimate that it would take 2 people one half day to remove and package those for recycling. At a cost of $720/day for one labor-day, this step is estimated to cost $720.

Finally, the metal racks may be removed to be reused or recycled as scrap metal. The units will need to be unbolted and placed with scrap metal recycling for transport. It is estimated that it would take 2 people one half day to unbolt and remove the 8 rack frames from the cabinet. At a cost of $720/day for one labor-day, this step is estimated to cost $720.

Transportation

For the rack metal frames, BMS, and connector cables, we assume that a local recycler (within 100 miles of the offsite dismantling location) will be available that can process and recycle scrap metal, computer electronics, power electronics, and any additional components. For a partial truckload of these materials, it is estimated to cost $250. We estimate the remaining scrap metal components of the system would be included in this transportation cost.

Cabinet Enclosure

Equipment and Description

The container is described above and depicted in Figure 6-3.

Recycling

The lithium battery cabinet is sturdy and suitable for reuse. We estimate it may have a small, half a penny per pound, scrap metal value for recycling. For the cabinet weighing only a 1,1000 kg (2,500 lb), we estimate a scrap value of $12.50.

Dismantling and Packaging

After the other battery components have been removed, the enclosure can be sent for reuse or to a scrap metal recycler.

Transportation of the Empty Unit

It is assumed these containers can be recycled with a local scrap metal recycler and can be aggregated with the other scrap metal from the unit as described for the battery racks above.

HVAC Thermal Management System

Equipment and Description

Thermal temperature control is very important for any lithium ion battery energy storage system. This smaller mixed chemistry BESS battery cabinet has four small HVAC units for redundancy and to handle thermal cooling load during operation, these units can be seen on the roof of the battery cabinet in the photo in Figure 6-5. These units are estimated to weigh 113 kg (250 lb). With 4 units in the cabinet, we estimate a total weight of 450 kg (1,000 lb).

These HVAC systems use Refrigerant 22 or a similar agent in their cooling process. This chemical is also known as chlorodifluoromethane and is a gas. It has both ozone depleting potential and global warming potential and should be properly handled and disposed of to minimize unnecessary release. We approximate that each unit contains 4.5 kg (10 lbs) of coolant, and that across the 4 HVAC units, there would be a total of 18 kg (40 lb) of Refrigerant 22 coolant.

Recycling

While the HVAC systems may be sent to a metal recycler for breakdown and recovery, the refrigerant must first be removed. Removal of the refrigerant from the HVAC system must be done by a certified refrigeration technician and requires specialized equipment. Once recovered the refrigerant can be purified and reused. Refrigerant removal will cost approximately $200 per unit. For 4 units, the cost or refrigerant removals is estimated to be $800. For the remaining drained unit, the metal recycling value is assumed to its scrap metal value of a half penny per pound, the value of the 4 units weighing only 450 kg (1,000 lb) would be $5.

Dismantling and Packaging

The refrigerant will need to be removed by a certified refrigerant technician as described in the previous section. The units are externally attached to the top of the cabinet, they would need to be removed after the refrigerant has been removed for scrap metal recycling. We estimate it would take 2 people a half day to remove the units. At a cost of $720/day for one labor-day, the step is estimated to cost $720.

Transportation

Once the refrigerant has been removed, the HVAC units may be transported with other metal components. It is assumed these units can be recycled with a local scrap metal recycler and can be aggregated with the other scrap metal from the unit as described for the battery racks above.

Fire Suppression System

Equipment and Description

The fire suppression device for the battery cabinet includes metal tanks containing the suppression agent, some metal piping for dispersion, and the fire monitoring and alarm hardware. The metal piping system serves two purposes, to secure the gas tanks, and to spread the suppression agent across the cabinet area to suppress oxygen and limit combustion opportunity in the case of a fire. The metal in the piping and frame are estimated to weigh 9 kg (20 lb). The Fire detection control box, shown in Figure 6-6, contains some electronics that may be sent with other system components. They fire detection control box would also contain a small lead acid back up battery that would need to be recycled safely.

Figure 6-6
Fire Suppression Controller
Source: EPRI Photo

The fire suppression tank contains a common suppression agent FM 200, which is a gaseous waterless fire suppression agent manufactured by The Chemours Company, a spin-off of DuPont. Chemically FM 200 is heptafluoropropane, which while it has zero ozone depleting potential, does have a global warming potential and must be handled to prevent unnecessary release. The tank of suppression agent would be filled with the calculated amount to suppress flames based on the cabinet size. The tank, with suppression agent, is estimated to weigh approximately 45 kg (100 lb) when full.

Recycling

The fire suppression agents have an infinite shelf life if stored properly. At end of system life, if the tanks have not been discharged, they may be returned to the supplier to be reused. In the event of tank discharge, the empty tank or pressure vessel should also be returned to the supplier, for proper handling of any remaining agent and so that the tank may be reused. A small cost of $100 is estimated for tank recycling return.

The metal piping may be reused or recycled as scrap metal or recycled as scrap metal. While scrap metal does have a small recycling value, the gas dispersion system weight would not yield significant return.

Dismantling and Packaging

The fire suppression system controls will need to be collected and disposed with the electronics recycling. The tanks of fire suppression agent, however, will need to be removed and returned to a qualified supplier for reuse. We estimate that it would take 2 people a half day to remove the controller and tank. At a cost of $720/day for one labor-day, this step is estimated to cost $720.

The metal piping and tank rack may be reused or scrapped along with other metal components of the system. We estimate that it would take 2 people a half day to remove the metal piping and components. At a cost of $720/day for 1 labor-day, this step is estimated to cost $720.

Transportation

The fire suppression system control unit may be transported with other electronics from the system and the metal piping can be transported with the other scrap metal components.

Additional Equipment

Equipment and Description

In addition to the components detailed above, we anticipate additional equipment such as system coupling cables, and H_2 sensor, and metal cabinets and brackets used to secure the skids together and to anchor them in place. We estimate this additional equipment may add approximately 115 kg (250 lb) of weight to the battery container system.

Recycling

This additional equipment may be reused or can be handled by a traditional metal recycler. The cost for this recycling or reuse is assumed a small fee of 50 cents per pound, or approximately $125. If reuse options are available, the bolts and metal brackets may have a reuse value.

Dismantling and Packaging

The additional equipment may be collected and aggregated in the process of completing the outlined steps above, but to ensure it is completed and sent to its respective reuse or recycling location we estimate that it would take 2 people a half day to remove or collect and package the additional equipment and other metal or electrical components. At a cost of $720/day for one labor-days, this step is estimated to cost $720.

Transportation

The additional equipment may be transported with other scrap metal components.

Power Conversion System

Equipment and Description

Another major electrical component of the lithium energy storage portion or the smaller mixed chemistry BESS is the PCS, shown in Figure 6-7. For this system, it is an outdoor Dynapower MPS-250 800V system. The unit’s housing is made of gauged steel, and contains an LCD screen, communications and control equipment for the PCS, insulated gate bipolar transistors (IGBTs), and a forced air-cooling system. This PCS unit weighs 1,600 kg (3,500 lb).

Figure 6-7
Power Conversion System for Lithium Battery Cabinet
Source: EPRI Photo

Recycling

The PCS units may be sent to a metal recycler for disposal, where they will be able to remove the IGBT and other power electronics for metal recovery. We estimate a disposal cost of $2,000 for the unit.

Dismantling and Packaging

Dismantling and packaging of the PCS system used in this example is relatively straight forward. The unit would need to be placed onto the truck for transportation using the crane discussed in previous sections. We estimate disconnecting, preparing the unit for shipment and loading it onto the truck would take 2 people one day to complete. At a cost of $1,800/day for 2 labor-days, this step is estimated to cost $3,600.

Transportation

The PCS would need to be transported to a local metal recycler to be disassembled for recycling. We estimate that this would require a partial truck load and could be transported with other site components. We approximate the transportation costs for this equipment to be $750.

Balance of System

Eaton Switchgear Cabinets

Equipment and Description

The site includes three large Eaton cabinets that house the system switchgear, and on-site computer control unit. The units are shown in Figure 6-8. These components may add approximately 2,700 kg (6,000 lb) weight to the total system estimate. One of the switchgear panels is shown in Figure 6-9.

Figure 6-8
Eaton Cabinets with System Computer Interface and Switchgear
Source: EPRI Photo

Figure 6-9
Eaton Switchgear Panel
Source: EPRI Photo

Recycling

The Eaton cabinets with switchgear and computer components may be sent to a metal recycler for disposal, where they will be able to remove the electronic waste and power electronics for metal recovery. We estimate a disposal cost of $2,000 for the unit.

Dismantling and Packaging

Dismantling and packaging of the Eaton cabinets is straightforward. The system will need to be physically disconnected from electrical and communication cables. The units will need to be unbolted from the concrete pad and each other. Like the other units in the system, the switchgear cabinets would need to be placed onto the truck for transportation using the crane discussed in previous sections. We estimate disconnecting, preparing the unit for shipment and loading it onto the truck would take 2 people one day to complete. At a cost of $1,800/day for 2 labor-days, this step is estimated to cost $3,600.

Transportation

The switchgear and computer cabinet would need to be transported to a local metal recycler to be disassembled for recycling. We estimate that this would require a partial truck load and could be transported with other site components. We approximate the transportation costs for this equipment to be $1,500.

Project Closure and Post-Site Work

Post Site Removal Cleanup

Following removal of the system, the remaining site will need a final clean up. It is anticipated that the concrete platform will be left in place. To account for any needed cable or conduit management to ensure that the site is cleaned up, we estimate it will take 2 people 1 day to complete. At a cost of $1,800/day for 2 labor-days, this step is estimated to cost $3,600.

Disposal Paperwork

Similar to the large BESS, the mixed chemistry BESS, for asset management records or tracking, may have paperwork for verifying the removal and proper disposal of the utility asset. Review of current utility practices for computer and other asset management should be undertaking to identify necessary reporting steps. Some paperwork, like Certificates of Disposal for the battery modules will not be available until after they have gone through the recycling process, so it is important to factor that step into project timeline planning.

Conclusions

The cost of total system recycling for this mixed chemistry battery energy storage system on a component-by-component basis was summarized. These cost estimates represent the combining of heavy equipment and off-site dismantling to optimize skills and tools needed to dismantle the individual units and to reduce some of these costs. The 15 vanadium flow battery units represent the largest weight and recycling costs of the system. For this estimated 100kW/400kWh vanadium flow battery and 100kW/400kWh lithium battery hybrid system, it was estimated to cost roughly $168,200 for disposal and recycling at end-of-life in 2030 dollars.[8]

---

[8] This total does not include Electrical Safety Observers (ESO) who may be needed on the project site.

7
COST COMPARISON WITH OTHER LITHIUM CHEMISTRIES

Comparison with other Lithium Ion Chemistries

While this section primarily represents a comprehensive bottom-up cost exercise for system disposal. It is sometimes helpful to also do higher level cost estimates to enable comparison across different systems or chemistries. Table 7-1 shows estimated recycling costs for other battery chemistries, as obtained from interviews with battery recyclers. These prices assume delivery of the battery units to the recycler at their processing or collection facilities.

These cost numbers reflect the material recovery value of the battery chemistry types deployed today. As chemistries like Nickel Manganese Cobalt Oxide (NMC) go to higher nickel and lower cobalt blends in the future, these costs may change.

Table 7-1
Recycling Cost Estimates by Lithium Ion Chemistry

	Estimated Recycling Costs	
Chemistry	**Price per pound**	**Price per kilogram**
NCA – Nickel Cobalt Aluminum Oxide	$1.00	$2.20
NMC – Nickel Manganese Cobalt Oxide	$1.00	$2.20
LMO – Lithium Manganese Oxide	$2.50	$5.50
LFP – Lithium Iron Phosphate	$2.50	$5.50
LTO – Lithium Titanate	$1.00	$2.20

Source: [3, Conversations with vendors][9]

For an example comparison of end-of-life costs for NMC and LFP chemistries, we make the following assumptions. To recreate the energy density in kWh from the 3,211 battery modules of 6.35kWh NMC batteries it would take 3,862 battery modules of 5.28kWh LFP battery modules. However, battery module weight and total weight are better metrics for comparing costs of recycling, transportation, and labor for dismantling and packaging. Table 7-2 shows the weight calculations based on public specification sheets for 5.28kWh LFP battery modules weighing 165 lbs.

[9] Battery Recycling costs represent 2018-2019 installed system batteries reaching end-of-life for recycling in approximately 2030.

Table 7-2
Weight Comparison of NMC Battery Modules and LFP Battery Modules

NMC vs LFP Battery Module Weight Comparison (Comparing the kWh of the Large BESS NMC battery modules with equivalent LFP battery modules)		
Item (Description)	**Weight (lb)**	**Weight (kg)**
NMC Modules (Based on the Large BESS System)		
Battery Modules (3,211 Modules/System) (Based on 6.35 kWh modules, in 19 racks with 13 modules in each of the 19 racks in each container unit)	382,000	173,000
LFP Modules		
Battery Modules (3,862 Modules/System) (Based on 5.28 kWh modules weighing 165 lbs, to match the total energy of the NMC modules)	637,000	289,000

Source: EPRI Estimates

These calculations give a quantified comparison as a function of chemistry and energy density. The LFP modules weigh 40% more than the NMC modules, and with the lower energy in kWh per module you need an additional 20%. Those metrics combine to estimate that for similar total kWh nameplate rating, you would have 67% more pounds of LFP batteries than NMC batteries.

Following our methodology from Section 5, we made similar cost estimations to compare the NMC and LFP module disposal costs. Table 7-3 shows a summary of those calculations with estimates across the three categories of on-site dismantling and packaging for shipment, transportation, and equipment recycling.

Table 7-3
Cost Comparison of NMC Modules and LFP Modules

Estimated Cost Comparison for disposal of NMC vs LFP Battery Modules (Comparing the kWh of the Large BESS NMC battery modules with equivalent LFP battery modules)				
Item (Description)	On-site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	Subsystem Total
NMC Battery Module Removal (Based on the Large BESS System)				**$786,000.00**
Battery Modules (3,211 Modules/system) (Based on 6.35 kWh modules, in 19 racks with 13 modules in each of the 19 racks in each container unit)	$244,000.00	$160,000.00	$382,000.00	
LFP Battery Module Removal				**$2,160,500.00**
Battery Modules (3,861 Modules) (Based on 5.28 kWh modules weighing 165 lbs, to match the total energy of the NMC modules)	$312,000.00	$256,000.00	$1,592,500.00	

Source: EPRI Estimates

For the on-site dismantling and packing costs, it was estimated that 30% more time and labor would be needed to remove the larger quantity of heavier batteries. Due to the LFP modules being 75 kg (165 lb) per unit with a total of 3,862 modules. Compared to the 3,211 modules for NMC weighing 55 kg (119 lb). The increase in transportation costs represent the additional 40% of battery module weight freight that requires shipping to a battery recycling facility at end-of-life.

The most noticeable increase in cost when comparing the NMC and LFP modules is for the equipment recycling. It is a simple calculation of the battery weight in Table 7-2 times the cost to recycle per pound for each chemistry in Table 7-1. The cost calculation of recycling 382,000 lbs of NMC batteries at a cost of $1/lb, gives you an estimate of $390,000. The cost calculation of recycling 637,000 lbs of LFP batteries at a cost of $2.5/lb, provides an estimate of $1,590,000.

These rough calculations and dramatic differences in decommissioning cost estimates highlight the need to make economic comparisons of BESS options on more than just installed capital expenditure. The best financial analysis would also incorporate decommissioning, as well as efficiency and other to determine a total cost of ownership for the energy storage system. [65]

8 CONCLUSIONS AND RECOMMENDATIONS

General Considerations

As energy storage deployments continue, utilities and storage system developers must increasingly include discussions on end-of-life processes and responsibilities in the project planning and procurement process along with performance metrics and operation and maintenance costs [66]. If left unaddressed, the potential exists for unexpected large costs or liabilities in the actual total cost of ownership of the storage system [65]. These early discussions could also identify key system and installation information that may help inform system decommissioning.

While a number of waste volume projections have been performed, there remains uncertainty on when and how BESS will reach end-of-life due to a limited amount of experience with real-world degradation and aging. Different operational profiles will affect battery lifetime and potential for reuse in similar or lower-powered applications, regardless of deployment in an EV or stationary platform. The lack of clarity around timing of the retired battery module supply available for recycling has thus far stymied investment in a robust recycling infrastructure. Additional questions include: What marks end-of-life for a stationary system – a warranty time period or capacity guarantee window? If determined by system performance, which metrics will be used, and how often will the system be evaluated? Is repair or partial replacement possible, or is a full facility exchange required?

Other considerations for the battery recycling industry involve the diverse set of battery products, including different chemistries, system sizes, and cell formats. This variety makes it harder to optimize recycling processes for recovery of valuable components, which are often present at low mass within a module. Thus, recyclers may need to develop technologies to sort, disassemble, and recover materials that can be differently optimized for the variety of battery types, materials, and sizes expected.

Future Opportunities

As with all growing industries, there is ample opportunity for battery reverse supply chain participants to develop methods with which to better address the need for economic and sustainable material recovery. Stakeholder engagement across the entire supply chain would increase the efficiency and efficacy of logistics and design considerations that are currently under development. This in turn may result in lower costs, improved estimates of environmental sustainability, and increased options to assess the viability of reuse (e.g. second life) for battery modules.

Another future research area that has the potential to simplify recycling and reuse is in “design for recycling”. Future battery cell and modules designs that are robust and long-lived in their first life but can be easily disassembled for repair and refurbishment to support potential reuse, need to be investigated and successfully demonstrated.

Future Research

There are many research avenues with the potential to advance both our understanding and the industry to manage energy storage at end-of-life. Some include:

- Quantifying energy and environmental effects of current recycling processes, as well as identifying opportunities for improvements in cost, environmental effects, and recycling efficiency.
- Creation of recycling processes, such as direct recycling, which can recover both the battery materials and manufactured value in the systems.
- Investigation of streamlined, yet safe, methods to collect and transport battery systems. This may include clearer delineation of process steps, labelling requirements, software tracking tools, or other improvements.
- Development of decommissioning plan example components and templates.
- Documented guidelines and procedures for safe handling and disposal of damaged or defective battery cells and modules.
- Widespread application of metrics with which vendors and service providers can demonstrate and verify disposal and recycling performance and adherence to safety and environmental standards.
- Determine the roles of electric power companies in developing and operating circular economies (such as influencing "design for recycling" options for BESS), and share lessons learned about how to practically implement circular economy principles into business operations. EPRI is forming a Circular Economy for Clean Energy Technologies Interest Group to discuss these topics [67].

9
REFERENCES

1. United States, Executive Office of the President [Donald J. Trump]. Presidential Executive Order 13817 on a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals. 20 Dec. 2017.
2. The United States Government. (2021, February 24). *Executive Order on America's supply chains*. The White House. Retrieved March 1, 2022, from https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/
3. *Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation*. EPRI, Palo Alto, CA: 2017. 3002006911.
4. Horinko, et. al. *Waste Management: A Half Century of Progress*. 2020.
5. *Standards for Universal Waste Management*, 40 C.F.R. §273 (2020).
6. *Differences Between Universal Waste and Hazardous Waste Regulations*. (2019, March 11). Retrieved October 04, 2020, from https://www.epa.gov/hw/differences-between-universal-waste-and-hazardous-waste-regulations
7. *Categories of Hazardous Waste Generators*. (2020, April 14). Retrieved October 04, 2020, from https://www.epa.gov/hwgenerators/categories-hazardous-waste-generators
8. *Standards Applicable to Generators of Hazardous Waste*, 40 C.F.R. §262 (2020).
9. *Summary Chart of Hazardous Waste Permitting Regulations*. (2019, March 12). Retrieved October 04, 2020, from https://www.epa.gov/hwpermitting/summary-chart-hazardous-waste-permitting-regulations
10. *Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements*, 49 C.F.R. §172 (2020).
11. *Class 8 Dangerous Goods Corrosive* Substances. (n.d.). Retrieved October 04, 2020, from https://www.chemsafetypro.com/Topics/TDG/Class_8_Dangerous_Goods.html
12. *HAZMAT Class 8 Corrosive substances*. (2019, May 23). Retrieved October 04, 2020, from https://en.wikipedia.org/wiki/HAZMAT_Class_8_Corrosive_substances
13. PRBA: The Rechargeable Battery Association, *Batteries in Transport: Applicable U.S. Hazardous Materials Regulations and International Dangerous Goods Regulations*. (2017). [Fact sheet]. https://www.prba.org/wp-content/uploads/Overview-of-Battery-Transport-Regulations.pdf
14. *Shippers – General Requirements for Shipments and Packagings*, 49 C.F.R. §173 (2020).
15. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). *Transporting Lithium Batteries*. Retrieved October 04, 2020, from https://www.phmsa.dot.gov/lithiumbatteries
16. UPS. (2019, May). *How to safely pack and ship batteries*. Retrieved October 04, 2020, from https://www.ups.com/assets/resources/media/en_US/pack_ship_batteries.pdf
17. A.B. 1125, Chapter 572, 2005-2006 Regular Session, (California 2005).

18. California Department of Toxic Substances Control. (2020). *AB 1125: Rechargeable Battery Recycling Act*. Retrieved October 04, 2020, from https://dtsc.ca.gov/fs-ab1125/
19. California Department of Toxic Substances Control. (2020). *How is California Doing with Recycling Rechargeable Batteries?* Retrieved October 04, 2020, from https://dtsc.ca.gov/universalwaste/how-is-california-doing-with-recycling-rechargeable-batteries/
20. CEC. 2015. *Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America*. Montreal, Canada: Commission for Environmental Cooperation. 103 pp.
21. *Memorandum of Understanding Between the California Public Utilities Commission and the California Department of Resources Recycling and Recovery for the purpose of cooperatively developing consistent approaches to waste generated by photovoltaic panels, electric vehicle batteries, energy storage batteries, and related equipment, such as invertors*. (2019). Available at: https://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/Utilities_and_Industries/Energy_-_Electricity_and_Natural_Gas/CPUC%20%20CalRecycle_MOU_Fully%20Exctd_1-8-19.pdf
22. "CPUC and CalRecycle Partner on Disposal of PV Panels and Batteries for Storage and EVs2021." *CPUC and CalRecycle Partner on Disposal of PV Panels and Batteries for Storage and EVs*, 2021. https://www.cpuc.ca.gov/recycle/
23. California, State of. "Lithium-Ion Car Battery Recycling Advisory Group." *CalEPA*, 2021. https://calepa.ca.gov/climate/lithium-ion-car-battery-recycling-advisory-group/
24. California Legislative Information: *AB-2832 Recycling and Reuse: Lithium-Ion Batteries* (2018). Available at: http://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB2832 (accessed December 2020).
25. California, State of. "Lithium-Ion Car Battery Recycling Advisory Group." *CalEPA*. Accessed June 3, 2021. https://calepa.ca.gov/climate/lithium-ion-car-battery-recycling-advisory-group/lithium-ion-car-battery-recycling-advisory-group-meeting-materials-11-4-19-background/
26. Identification and Listing of Hazardous Waste, *Title 22 California Code of Regulations Chapter 11*, https://govt.westlaw.com/calregs/Document/IA1C01820D4BA11DE8879F88E8B0DAAAE?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)&bhcp=1&ignorebhwarn=IgnoreWarns
27. California CalRecycle, *Batteries*" Accessed June 3, 2021. https://www.calrecycle.ca.gov/reducewaste/batteries#:~:text=Batteries%20are%20considered%20hazardous%20waste,both%20rechargeable%20and%20single%2Duse.&text=Batteries%20are%20considered%20hazardous%20because,or%20corrosive%20materials%20they%20contain
28. Cal. Code Regs, Title 22, Division 4.5, Chapter 11 Section 66261.9 - Applicability - Batteries, *Title 22 California Code of Regulations §66273.2* https://govt.westlaw.com/calregs/Document/IA1C01820D4BA11DE8879F88E8B0DAAAE?

viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)

29. Cal. Code Regs, Title 22, Division 4.5, Chapter 11 Section 66261.2 – Definition of Waste. https://govt.westlaw.com/calregs/Document/IA1C01820D4BA11DE8879F88E8B0DAAAE?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)&bhcp=1&ignorebhwarn=IgnoreWarns
30. California Miscellaneous Health and Safety Provisions, Division 20, Chapter 6.5 *California Health and Safety Code §25143.2* http://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=HSC&sectionNum=25143.2
31. California Department of Toxic Substances Control, "Managing Hazardous Waste, Generators," Updated January 1, 2016. https://dtsc.ca.gov/generators/
32. California Legislative Information: SB 612, Chapter 452, 2015-2016 Regular Session, "Universal Waste Regulations & Generator Status," (California 2015) https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB612
33. California Miscellaneous Health and Safety Provisions, Division 20, Chapter 6.5, California Health and Safety Code §25158, https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=HSC&division=20.&title=&part=&chapter=6.5.&article=5
34. California Department of Toxic Substances Control, "Universal Waste Regulations and Generator Status (SB 612)," https://dtsc.ca.gov/regs/universal-waste-regulations-generator-status-sb-612/
35. European Union Parliament, "DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC," (2006) *Official Journal of the European Union*, L266, p. 1. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:266:0001:0014:EN:PDF
36. European Union, "REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, on the implementation and the impact on the environment and the functioning of the internal market of Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC." Brussels, April 9, 2019. https://op.europa.eu/en/publication-detail/-/publication/ac52b2ed-5ab2-11e9-9151-01aa75ed71a1/language-en
37. EUWID Recycling and Waste Management. "EU Battery Directive to Be Revised in Q4 2020." *EUWID Recycling and Waste Management*. Accessed June 3, 2021. https://www.euwid-recycling.com/news/business/single/Artikel/eu-battery-directive-to-be-revised-in-q4-2020.html
38. "Northvolt launches recycling program targeting 50 percent recycled material in new cells." Press Release. Accessed June 3, 2021. https://northvolt.com/newsroom/Announcing-Revolt
39. Nora Manthey, "China requires EV makers to recycle batteries," *Electrive.com*, February 26, 2018, https://www.electrive.com/2018/02/26/china-requires-ev-makers-recycle-batteries/

40. Chris Randall, “China releases battery recycling regulations,” *Electrive.com*, November 11, 2019, https://www.electrive.com/2019/11/11/china-releases-battery-recycling-regulations/
41. *Retriev Technologies Combines with Heritage Battery Recycling, Creating the Largest Lithium-Ion Battery Recycler in North America*. (2021, October 6). Retrieved March 1, 2022, from https://www.prnewswire.com/news-releases/retriev-technologies-combines-with-heritage-battery-recycling-creating-the-largest-lithium-ion-battery-recycler-in-north-america-301393666.html
42. Toxco, Incorporated, “Final Environmental Assessment for Toxco, Incorporated Electric Drive Vehicle Battery and Component Manufacturing Initiative Application.” Lancaster, Ohio (April 2010) U.S. Department of Energy, National Energy Technology Laboratory. https://www.energy.gov/sites/prod/files/nepapub/nepa_documents/RedDont/EA-1722-FEA-2010.pdf
43. PhilTaylor, “Recyclers Craft End-of-Life Solutions for EV Batteries,” *New York Times, Energy & Environment*, September 14, 2009. https://archive.nytimes.com/www.nytimes.com/gwire/2009/09/14/14greenwire-recyclers-craft-end-of-life-solutions-for-ev-b-47835.html
44. Fiore, S; Zanetti, M C (April 2012). “Automobile Shredder Residues in Italy: Characterization and valorization opportunities.” *Waste Management*. 32 (8): 1548–1559. doi:10.1016/j.wasman.2012.03.026. Archived from the original on 2015-06-01.
45. Savanna Cooper. “Recycling Auto Shredder Residue.” *Waste Advantage Magazine,* September 23, 2014. https://wasteadvantagemag.com/recycling-auto-shredder-residue/
46. Georgi, Tim & Friedrich, Bernd. (2007). *Investigation of a slag system for a Li-ion battery recycling process in the EAF*. 10.13140/RG.2.1.2756.3121.
47. Li, L. et. al. Disassembly Automation for Recycling End-of-Life Lithium-ion Pouch Cells. *JOM* 71, 4457-4464 (2019).
48. “DeMoBat Project Developing Robot-Assisted Dismantling for EV Batteries and Motors.” *Green Car Congress*, March 2, 2020. https://www.greencarcongress.com/2020/03/20200302-demobat.html
49. Velazquez-Martinez, O.et. al. A Critical Reivew of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective. *Batteries* 5, 68 (2019).
50. Gaines, L. Lithium-ion battery recycling processes: research towards a sustainable course. *Sustain. Mater. Technol*. 17, e00068 (2018).
51. Larouche F, Tedjar F, Amouzegar K, Houlachi G, Bouchard P, Demopoulos GP, Zaghib K. Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond. *Materials (Basel)*. 2020 Feb 10;13(3):801. doi: 10.3390/ma13030801. PMID: 32050558; PMCID: PMC7040742.
52. Ciez, R.E., Whitacre, J.F. Examining different recycling processes for lithium-ion batteries. *Nat Sustain* 2, 148–156 (2019). https://doi.org/10.1038/s41893-019-0222-5
53. Fix Ref - https://www.waste360.com/Recycling_And_Processing/lead-acid-batteries-most-recycled-product-200904
54. ESRG Energy Safety Response Group. Accessed June 3, 2021. https://www.energyresponsegroup.com/end-of-life

55. DNVGL, "McMicken Battery Energy Storage System Event Technical Analysis and Recommendations." (Section 2.4) 10209302-HOU-R-01. Available at: https://www.aps.com/en/About/Our-Company/Newsroom/Articles/Equipment-failure-at-McMicken-Battery-Facility
56. Energy Storage Association, "End-of-Life Management of Lithium-ion Energy Storage Systems," April 22, 2020.
57. Energy Storage Association, "ESA Corporate Responsibility Initiative: Guidelines for End-of-Life and Recycling of Lithium Ion Battery Energy Storage Systems," August 27, 2020.
58. NAATBatt International. (2020, October 05). Laws, Regulations and Best Practices for Lithium Battery Packaging, Transport and Recycling in North America. Retrieved November 05, 2020, from https://naatbatt.org/lithium-recycling-laws/
59. Jacoby, M. (14, July 2019). It's Time to Get Serious About Recycling Lithium-Ion Batteries." (Volume 97, Issue 28). *Chemical and Engineering News*.
60. Tran, M.K., Rodrigues, MT.F., Kato, K. et al. Deep eutectic solvents for cathode recycling of Li-ion batteries. *Nat Energy* 4, 339–345 (2019). https://doi.org/10.1038/s41560-019-0368-4
61. Harper, G., Sommerville, R., Kendrick, E. et al. Recycling lithium-ion batteries from electric vehicles. *Nature* 575, 75–86 (2019). https://doi.org/10.1038/s41586-019-1682-5
62. "DOE Launches Its First Lithium-Ion Battery Recycling R&D Center: ReCell: Argonne National Laboratory." DOE launches its first lithium-ion battery recycling R&D center: ReCell | Argonne National Laboratory. Accessed June 3, 2021. https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell
63. "Recycling & End-of-Life Considerations for Photovoltaics." *SEIA*. Accessed June 3, 2021. https://www.seia.org/initiatives/recycling-end-life-considerations-photovoltaics
64. "Sustainable Products." Sustainable Products | McWane Ductile. Accessed June 3, 2021. https://www.mcwaneductile.com/corporate-responsibility/environment/sustainability-for-generations/sustainable-products/
65. *ESIC Energy Storage Cost Template and Tool (ESIC Cost Tool) Version 2.0.* EPRI, Palo Alto, CA: 2018. 3002013529.
66. *Guidelines for Assessing End-of-Life Management for Renewable and Battery Energy Storage Technologies*. EPRI, Palo Alto, CA: 2021. 3002020594.
67. *Circular Economies for Clean Energy Technologies Interest Group*. EPRI, Palo Alto, CA: 2021. 3002023087.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

© 2022 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ENERGY are registered marks of the Electric Power Research Institute, Inc. in the U.S. and worldwide.

3002023651

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com