ELECTRIC POWER RESEARCH INSTITUTE

Recycling and Disposal of Battery-Based Grid Energy Storage Systems

A Preliminary Investigation

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Technical Update, December 2017

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ABSTRACT

Battery-based grid energy storage systems—particularly systems based on lithium ion batteries—are in greater use by electric utilities. As a result, better strategies and infrastructure are needed to address the removal, disposal, and recycling of these stationary lithium ion batteries. The development of these strategies is needed by 2025 when the batteries begin to reach end-of-life. This technical update reports on the characteristics of lithium ion batteries as well as existing options for and challenges to removing, reusing, and recycling these types of systems and associated electronic and auxiliary parts. Also examined is the potential impact of evolving state and federal safety and environmental regulations on end-of-life battery management.

In an effort to identify feasible, cost-effective recycling and disposal options, the update draws upon recycling practices from other battery manufacturing industries. Ownership and services are assessed based on scenarios for residual value or liability associated with battery-based grid energy storage systems. An approximate system framework and cost estimate for the decommissioning of a 1-MWh lithium nickel manganese cobalt oxide (NMC) battery-based grid energy storage system is outlined. Such information is crucial as energy storage becomes part of the utility asset base, and reclamation of parts and materials on a large scale may fiscally impact decision making in terms of battery system recycling and/or disposal processes.

Keywords
Batteries
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EXECUTIVE SUMMARY

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Product Title: Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation

PRIMARY AUDIENCE: Electric utilities interested in or actively installing battery energy storage systems

SECONDARY AUDIENCE: Battery manufacturers and recyclers

KEY RESEARCH QUESTIONS

What is a reasonable expected cost of the complete disassemble and disposal of a grid-scale lithium ion battery energy storage system? What variables contribute the most to cost, and how can cost be expected to change with varying battery chemistries and systems? What regulations are currently in place in the United States and abroad pertaining to the handling, transportation, and recycling of lithium ion systems, and how do regulations impact end-of-life estimates?

RESEARCH OVERVIEW

A survey of publicly available information on large-scale battery systems was conducted. From this, an approximate system framework and cost estimate for the decommissioning of a 1-MWh lithium nickel manganese cobalt oxide (NMC) battery-based grid energy storage system was outlined. That estimate was extrapolated to include various lithium ion chemistries, including lithium nickel cobalt aluminum oxide (NCA), lithium iron phosphate (LFP), lithium manganese oxide (LMO), and lithium titanate (LTO) on the modular level. Key regulatory structures are summarized, and a brief description is provided on possible allocations of end-of-life responsibility.

KEY FINDINGS

- Total decommissioning cost for a 1-MWh NMC lithium ion battery-based grid energy storage system is estimated at $91,500.
- Cost breakdowns are as follows: Roughly 40% of cost accrues to on-site dismantling and packaging, 30% to transportation costs, and 30% to recycling costs.
- Battery energy density is estimated to have a large impact on total decommissioning costs as a result of manual labor in dismantling and packaging as well as increased transportation and recycling costs.
- Module decommissioning costs range from $50,000–$150,000 depending on energy density and battery chemistry.
- U.S. federal regulations provide only for the transportation and correct packaging and labeling of lithium ion batteries, while state regulations vary.
- New York, California, and Minnesota have the most comprehensive battery recycling regulations, with battery manufacturers being largely responsible for battery collection and for provision of an accessible pathway for responsible disposal and recycling.
- Responsibility for managing end-of-life tasks should be consistent with various opportunities for increased efficiencies and reduced overhead depending on the capabilities of the parties involved.

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WHY THIS MATTERS

End-of-life disposal can represent a significant cost for large-scale battery energy storage systems and therefore must be taken into account when considering proposals for new installations. The estimate provided in this update can be used as a framework to compare energy storage system costs with and without end-of-life disposal in a quantifiable way. It may also help to identify how disposal responsibilities are directed in initial system contracts.

HOW TO APPLY RESULTS

Cost estimates are based on publicly available 2015 product specifications for module weight and energy density. Price estimates are based on decommissioning of recently installed systems over a 10–15 year time frame. The original analysis was based on California labor rates, which were assumed to be $175/hour for this future scenario (given a fully burdened California labor rate of $125/h for 2015 projected with 2.5% inflation rate to grow to $175/h in 15 years). While labor rates can change significantly from place to place, the amount of labor necessary to dispose of a certain number of modules should not change with scale; therefore, much of this report can be extrapolated to larger systems.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Program 94 Energy Storage and Distributed Generation

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PROGRAM: P94 Energy Storage and Distributed Generation

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1 INTRODUCTION

Disposal of a Storage System

Electrochemical energy storage (ESS) systems, particularly lithium ion, are being increasingly deployed as grid-scale solutions to rising variability due to renewables integration. Through providing services like peak shaving, off-peak loading, frequency regulation, and reserve capacity, such battery systems have demonstrated their flexibility and have quickly risen in production, with the global total exceeding 21.6 GW rated power in June 2016 and projected to increase [1]. Crucially, as more battery systems come online at such a large scale, more will eventually (within ten to twenty years) be decommissioned. This massive increase in potentially hazardous – and potentially valuable – electrochemical waste requires a commensurate investment in the infrastructure necessary to process and dispose of such systems properly.

While the disposal of a battery system can be less complicated than other industrial systems, end of life processing can represent a significant cost; yet it is often missing in system cost analyses or Research and Development focus. In producing any industrial-scale system such as this, accounting for responsible end-of-life disposal is necessary for both environmental stewardship and the economic bottom-line of the organizations involved.

Recycling Costs

The lithium ion battery market is extremely diverse, and involves cells of all shapes and sizes with numerous different intercalation chemistries that can effect both the disposal and recycling costs. Such a lack of standardization in battery chemistries and form factors have made the capital costs associated with recycling lithium ion batteries challenging. In addition, there has been limited research and development of lithium ion battery recycling processes within the United States. However, as more large scale systems come online in the coming years, demand for cathodic raw materials such as cobalt or nickel is projected to outweigh supply significantly. For example, the price of cobalt has almost doubled since the beginning of 2017, in part due to political instability in the DRC, where over 50% of cobalt is mined [2]. As production is heavily dependent on the geopolitics of unstable areas, shortages have the potential to make recovering raw materials from spent batteries more economically appealing. Sufficient policy measures may also incentivize the development of lithium ion recycling plants, and have already done so in parts of Europe. AEA technologies (UK), Accurec GmbH (Germany), and Batrec Industry (Switzerland) have all developed methods of recycling due to policy changes.

Research Approach and Summary of Methods

This study is meant to provide a technical backdrop against which utility members can frame their analyses regarding end-of-life economics, as well as an introduction to the current regulatory and legal climate surrounding decommission. First, we present a case study for a typical 1 MW system using specifications from Manufacturer 1, outlining the processes involved in decommission and associated costs. Data was taken from publically available information using 2015 modules/racks, a full system was approximated based on Manufacturer 1's technology as it was the most complete system information.[1] Apart from publically available information, discussions with advisory resources from battery manufacturing and recycling industries greatly informed this paper. Limited preliminary information was also gathered from members of the automobile and mobile phone manufacturing sectors, where small form factor lithium ion batteries are in widespread use and industries are working to identify cost-effective recycling strategies.

Lithium ion battery chemistries currently on the market involve many distinct chemistries, the differences between which can complicate the development of a coherent recycling infrastructure (Table 1-1). We therefore extrapolated the study to account for variations in physical and electrochemical characteristics due to different technologies. However, comparably detailed data was not publically available for example systems of the alternate chemistries, and so the analysis was limited to data on the module scale.

Table 1-1-1
Typical Lithium Ion Intercalation Chemistries, As Well As Major Market Players that Utilize Them

Technology/Chemistry	Current Users/Manufacturers
Lithium Nickel Cobalt Aluminum Oxide – NCA (LiNiCoAlO2)	Tesla (Panasonic)
Lithium Nickel Manganese Cobalt Oxide – NMC (LiNiMnCoO2)	2nd Generation EV Batteries, LG Chem, Kokam, Samsung
Lithium Manganese Oxide – LMO (LiMn2O4)	1st generation EV batteries, Chevrolet Volt (Samsung), Nissan Leaf (NEC)
Lithium Iron Phosphate – LFP (LiFePO4)	NEC, BYD, Sunwoda
Lithium Titanate – LTO (Li4Ti5O12)	Toshiba, Altairnano, Sunwoda

As with any other industrial process, regulation surrounding disposal and decommissioning can have a large impact on cost estimations. Thus, a survey of the current regulatory environment in the US and abroad, as well as discussion on considerations for framing end-of-life responsibilities are presented, before a brief conclusion and perspectives going forward.

[1] The data used in this report was generated from publicly available information as of November 2015, and is intended to be representative of industry prices at large. This data has been anonymized to avoid the appearance of promotion or disparagement of individual companies and technologies.

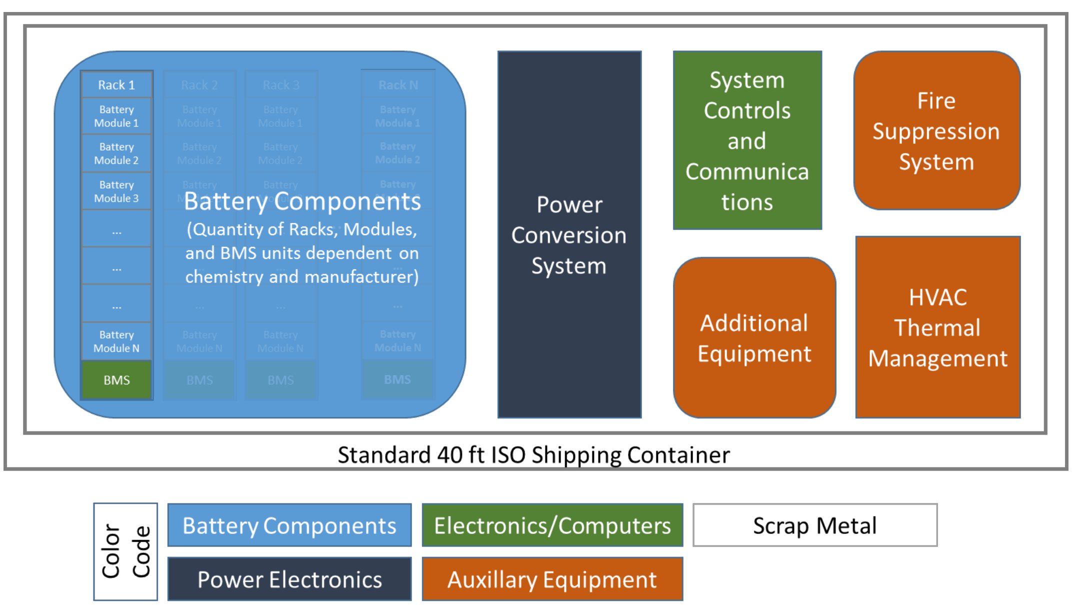
2 DECOMMISSIONING AND RECYCLING COST ESTIMATION FOR A 1 MWh BATTERY ENERGY STORAGE SYSTEM

In order to generalize end-of-life costs for any system, it is first necessary to outline and estimate how certain variables can affect the overall cost. Herein we provide a framework and case study estimation of the end of life costs for a container based modular 1 MWh system consisting of Manufacturer 1's modules and racks, chosen based on the availability of public information. Cost estimates are calculated for the separate components of the system, as well as the various processes that decommissioning entails for each component.

The analysis in this report assumes an end-of-life disposal of the entire energy storage system. In reality, individual system components may reach end-of-life at different time points. Further research is needed to determine expected component life, as well as what constitutes 'end-of-life' for a system.

Estimated 1 MWh NMC Battery System (Manufacturer 1)

The following specifies recycling and disassembly costs, including transportation for a 1 MWh lithium ion battery system housed in a standard 40 ft. ISO shipping container with NMC modules (Manufacturer 1). This example system, shown in Figure 2-1, is divided into two parts, components dependent on the battery chemistry and the remaining balance of system components.



Source: EPRI Estimates

Figure 2-1
Estimated Components of a 1 MWh Lithium Ion Energy Storage System

Components dependent on the specific chemistry or manufacturer include the battery modules, the metal rack frames housing the battery modules, and the rack level BMS system. This dependence is due to the variation in size and energy density of different types of battery modules and battery rack systems. In this example, the 1MWh systems from Manufacturer 1, would require 19 of the 54.4 kWh rack components. Each rack contains 17 battery modules, 1 battery management system (BMS), and all of the connectors required to operate the system.

The remaining balance of system components are assumed to be relatively independent of the chemistry or battery manufacturer. These components include the system container housing, power conversion system, systems controls and communications, HVAC thermal management system, fire suppression system, and all additional equipment (including breakers, fuses, cable connectors, and the main switch) as well as the initial system disconnection and post site cleanup labor.

Summary of System Weight

Based on the general system identified in Figure 2-1, information on example equipment and components was collected to build a more detailed example system. This information is summarized in Table 2-1 with high-level descriptions and weight estimates for a 1 MWh energy storage system. 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.

Summary of System Disposal and Recycling Costs

The system description and weights in Table 2-1 were then used to determine the total costs of system disposal and recycling. These costs, summarized in Table 2-2 include separate cost estimates for equipment recycling, labor and supplies for dismantling and packaging, as well as transportation costs for the equipment.

Labor costs were calculated using a $175/hour loaded rate.[2] In situations where specialized hazardous materials handling training is required, it may affect the labor cost for those activities.

[2] The $175/hour labor rate was estimated based on the following assumptions: A fully burdened California labor rate of $125/hour for 2015, projected with 2.5% inflation rate to grow to $175/hour in 15 years. Note – based on www.ssa.gov, the Average Wage Index increase was approximately 2.6% from 2000-2016.

Table 2-1
Estimated Weight of Components in a 1 MWh Lithium Ion NMC Energy Storage System

Estimated System Weight Components for an 1 MWh NMC Lithium Ion Energy Storage System		
Item (Description)	Weight (lb)	Weight (kg)
Container Housing		
Base Container (Standard 40 ft ISO Container)	8,600	4,000
Modifications (Steel Reinforcement, insulation, lighting, etc.)	5,000	2,300
Battery Components		
(For a 1 MWh system using Manufacturer 1 NMC Modules in a 54.4 kWh Rack Unit there would be 19 racks containing 17 battery modules, 1 BMS, and 19 Battery Connector Cables.)		
Battery Modules (Based on 3.2 kWh modules)	25,000	11,000
Battery Racks (Estimated weight based on Rack 54.4 kWh)	6,300	3,000
Battery BMS (Estimated to weigh 50 lb (24 kg))	1,000	450
Battery Connector Cables (Estimated Weight)	800	360
Power Conversion System (PCS)		
PCS Equipment	8,800	4,000
System Cooling Liquid (If the unit contains ethylene glycol/water as a cooling agent.)	100	45
Systems Controls and Communications		
Storage Management System (Master Computer, Communication Hardware, and any metal housing.)	100	45
HVAC Thermal Management System		
HVAC Equipment (Two 5 ton systems for redundancy.)	1,000	450
Refrigerant	25	10
Fire Suppression System		
Tanks and Suppression Agents	600	270
Piping Dispersion System	400	180
Additional Equipment		
Additional Equipment (Main Switch, Cables, Breakers, Fuses, etc.)	500	230
Total Estimated System Weight	58,000	26,250

Source: EPRI Estimates.

Table 2-2
Estimated Disposal Costs of a 1 MWh Lithium Ion NMC Energy Storage System

Estimated System Cost Components for an 1 MWh NMC Lithium Ion 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 Post-Site Work				**$2,800.00**
System Disconnection (Intitial system disconnection in prepration for disposal.)	$1,400.00			
Post Removal Site Cleanup (Final site clean up.)	$1,400.00			
Container Housing				**$1,400.00**
Base Container (Standard 40 ft ISO Container)	$1,400.00	$1,000.00	-$1,500.00	
Modifications (Steel Reinforcement, insulation, lighting, etc.)	$0.00		$500.00	
Battery Components (For a 1 MWh system using Manufacturer 1 NMC Modules in a 54.4 kWh Rack Unit there would be 19 racks containing 17 battery modules, 1 BMS, and 19 Battery Connector Cables.)				**$75,350.00**
Battery Modules (Based on 3.2 kWh modules)	$25,400.00	$20,000.00	$25,000.00	
Battery Racks (Estimated weight based on 54.4 kWh Racks)	$2,800.00	$0.00	-$50.00	
Battery BMS (Estimated to weigh 50 lb (24 kg))	$350.00	$500.00	$0.00	
Battery Connector Cables (Estimated Weight)	$850.00	$500.00	$0.00	
Power Conversion System (PCS)				**$6,100.00**
PCS Equipment (Crane may be required to load for Transportation)	$700.00	$5,000.00	-$50.00	
System Cooling Liquid (If the unit contains ethylene glycol/water as a cooling agent.)	$350.00	$0.00	$100.00	
Systems Controls and Communications				**$350.00**
Storage Management System (Master Computer, Communication Hardware, and any metal housing.)	$350.00	$0.00	$0.00	
HVAC Thermal Management System				**$2,100.00**
HVAC Equipment (Two 5 ton systems for redundancy.)	$1,400.00	$500.00	$0.00	
Refrigerant	$0.00	$0.00	$200.00	
Fire Suppression System				**$1,700.00**
Tanks and Suppression Agents	$350.00	$500.00	$0.00	
Piping Dispersion System	$350.00	$500.00	$0.00	
Additional Equipment				**$1,700.00**
Additional Equipment (Main Switch, Cables, Breakers, Fuses, etc.)	$1,200.00	$500.00	$0.00	
Subtotals	**$38,300.00**	**$29,000.00**	**$24,200.00**	
Total Estimated System Disposal and Recycling Cost				**$91,500.00**

Source: EPRI Estimates.

Detailed Description of System Parts and Assumptions

The following section describes the various 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.

Container

Equipment and Description

This report assumed the 1 MWh energy storage systems was housed in a standard 40 ft. ISO shipping container. These general purpose containers, are made of durable corrugated steel, and measure 40 ft. long, 8 ft. wide, and 8.5 ft. tall. The plain container weighs 3,900 kg (8,600 lb) without modifications.

For a standard shipping container to house a grid-scale battery system, modifications would be necessary. The container would need additional steel reinforcements to support the battery weight as well as insulation, flooring, 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 2,300 kg (5,000 lb) to the container weight.

Recycling

As these containers are very sturdy and built for multiple uses, there is a market for secondary use. Currently, online websites (including ebay), show similar units for sale starting at $1,500. The steel in the container, also makes metal recycling an option for end of life, however the process is very energy intensive, making repurposing or reusing used shipping containers an increasingly popular option.

The modifications to the container if removed at end of life would also need to be disposed of. It is estimated to cost $500 to remove and dispose of the reinforcements, insulation, lighting, floor, and any additional components that are added to the base container.

Dismantling and Packaging

While no packaging will be necessary, the system housing container will require some preparation before shipment. Any external additions such as stairs or railings will need to be removed. All loose components will need to secured as well. 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 2 workers half a day to complete. At a cost of $175/hour for 8 hours, this step is estimated to cost $1,400.

Due to container shipping weight limits, the heavy system components such as batteries, the Power Conversion System (if housed internally), and the HVAC units will need to be removed prior to shipment. The time and cost for removal of these components is calculated under each respective category and is not included in the estimate for container dismantling and packaging.

Transportation

After removal of the heavy components and equipment, the shipping container should be relatively easy to transport. The remaining container will weigh between 13,000-23,000 lb, but is a standard shipping form factor. It is estimated that removal of the shipping container will cost $1,000.

Batteries

Equipment and Description

The 1 MWh system approximated as an example for calculations was based on Manufacturer 1's NMC chemistry. Information on the weights and energies of both the battery modules and rack systems was publically available, making it possible to estimate a realistic grid scale system for this NMC chemistry.

The system rack unit contains 17 modules. The modules specify an energy of 3.2 kWh, and the racks 54.4 kWh. A 1 MWh system using these units would require 19 racks with 17 modules each for a total of 1033.6 kWh. (Note this represents an additional 3% sizing of the system. For accurate comparison in Section 3, module numbers are calculated for a system 3% over 1 MWh as well.)

To calculate the number of modules in the system, we can multiply the 19 racks times 17 modules per rack to determine there would be 323 modules in this example system. Each module weighs 34 kg (77 lb), so the total battery module weight for the entire system is calculated to be approximately 11,000 kg (25,000 lb).

In addition to the 17 battery modules, the rack unit also contains a Battery Management System, approximately 19 battery connector cables, and the metal housing for the rack unit. Each BMS electronic system is estimated to weigh 23 kg (50 lb). There is one per rack, for a total of 19 with a total BMS weight of 450 kg (1,000 lb). The metal rack units are each estimated to weigh 150 kg (330 lb), giving a total system weight for all 19 metal racks at 3,000 kg (6,300 lb). The cable connectors for each system were approximated to weigh 18 kg (40 lb) per rack unit, for a total system cable weight of 360 kg (800 lb).

The detailed information available on both module and racks enabling the calculation of system size and to estimate individual component weight (BMS, metal rack, and connectors) was only available for this one technology from Manufacturer 1, and could not be found for the other lithium chemistries or manufacturers in 2015. Therefore, Section 3, which compares recycling costs for different battery chemistries and manufacturers only uses module level data.

Recycling

Recycling of the battery modules accounts for a large portion of system disposal cost. While many battery recyclers exist due to the high volume of consumer electronic batteries, many do not have the capabilities to handle larger format module sized batteries found in grid-scale energy storage systems or the battery packs used in electric vehicles. While researching this report, two companies, Retriev and Umicore, were contacted for estimates. Both are able to handle the disassembly required for grid-scale batteries. Retriev 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 in the U.S. in North Carolina.

Before they are recycled, the battery modules must be disassembled. This disassembly is currently done by hand and requires a significant amount of time per 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 NMC lithium ion chemistry batteries. This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 25,000 lb of NMC battery modules, this represents a battery module recycling cost of $25,000. 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.

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 6,300 lb weight for the metal racks, they are estimated to have a value of $50 as well as no transportation costs for removal.

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 no cost for recycling.

Dismantling and Packaging

Due to their heavy weight the battery modules will need to be removed and transported separately of 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.

The estimated system used for our calculation estimates would contain 323 of Manufacturer 1's 3.2 kWh modules. Each of these modules weighs 34 kg (77 lb) and would need to be individually disconnected, have the electrode ends covered to avoid shorts, and then stacked onto a wooden pallet with a cardboard box placed over the top. The boxes 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 4 of this report. We estimate approximately 7 modules could be stacked per pallet, for a weight of approximately 240 kg (530 lb). For a 1 MWh system with 323 modules, it would take 47 pallets for shipping. We estimate a cost of $3,000 for pallets and packaging equipment.

The time and labor involved in removing and packaging this number of modules is not insignificant. To estimate this cost involved it was assumed it would take 25 minutes per module. Multiplying this time estimate by the 323 modules in the system, it was then estimated that it will take 4 people 4 days to remove and package the modules for shipment. At a cost of $175/hour for 128 hours, this step is estimated to cost $22,400.

This value is highly dependent on the assumptions used. A reduction or increase in the minutes per module for removal time or the cost per hour of labor will affect this assessment.

Once the modules have been removed, the BMS may be removed for electronics recycling. The system will contain 19 BMS units, one per rack. We estimate that it would take 1 person 2 hours to remove those units for recycling. At a cost of $175/hour for 2 hours, this step is estimated to cost $350.

Additionally, the battery connector cables may be removed and collected for electronics recycling. The system will contain approximately 19 per battery rack, for a total of 350-400 cables. We estimate containers for collecting these cables will cost $500, and that it would take 1 person 2 hours to remove and package those units for recycling. At a cost of $175/hour for 2 hours, this step is estimated to cost $350.

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 2 days to unbolt and remove the 19 approximately 150 kg (330 lb) metal rack frames. At a cost of $175/hour for 16 hours, this step is estimated to cost $2,800.

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

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 25,000 lb of battery modules, classified as hazardous material, it will cost $20,000 for transportation.

For the remaining battery and system components, we assume that a local recycler (within 20-150 miles) will be available that can process and recycle scrap metal, computer electronics, power electronics, and any additional components. Any remote or difficult to reach battery sites may need to account for additional costs in transporting systems components at system end-of-life.

It is assumed that metal rack units will not require a transportation fee due to the value of the scrap metal. Additionally, the metal rack units could be shipped within the system container housing, allowing them to be removed at the metal recycling center, thus minimizing transportation steps.

For the BMS units a small transportation cost of $500 to transport the BMS units weighing 450 kg (1,000 lb) to a local electronic recycler can be used as an estimation. Similarly, for the battery connectors, we estimate a small transportation cost of $500 to transport the connectors weighing 360 kg (800 lb) for electronic recycling.

Power Conversion System

Equipment and Description

Another major electrical component of the energy storage system is the Power Conversion System (PCS). For this estimated system, an Outdoor PCS model was used as an example piece of equipment for calculations. 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 particular example system is air cooled, however others may be liquid cooled with an ethylene glycol and water mixture. This PCS unit weighs 4000 kg (8820 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.

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 8820 lb and the rough guidelines for scrap metal value of one half penny per pound, that there may be some value, approximately $50, obtained in equipment recycling.

If the system utilizes a liquid cooling system, the ethylene glycol water mixture would need to be drained before transporting the unit. Ethylene glycol, or antifreeze, is a commonly used coolant and there are many facilities available for recycling. We estimate that there may be a small disposal fee of $100.

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. We estimate disconnecting, preparing the unit for shipment and loading it onto the truck would take 1 person 4 hours to complete. At a cost of $175/hour for 4 hours, this step is estimated to cost $700.

If the system did contain a liquid cooling methods, the ethylene glycol and water would need to be drained and placed into containers for disposal prior to transporting the PCS unit. We estimate this step would take 1 person 2 hours to complete. At a cost of $175/hour for 2 hours, this step is estimated to cost $350 if necessary.

Transportation

The PCS would need to be transported to a local metal recycler to be disassembled for recycling. We estimate that this transportation would cost $2,000.

The ethylene glycol carries no special transportation guidelines, a pickup could be scheduled, or it could be transported in an ordinary truck or vehicle to the recycling or collection center that is able to accept it.

System Controls and Communications

Equipment and Description

In addition to the BMS units located in each of the battery racks to monitor the individual modules, there will also be a master control computer and communication system to enable entire system control and coordination with the interconnected grid. One example of such equipment is the control cabinet based on the commercially available modular concept. It is housed in a metal cabinet and contains a human machine interface, or computer, the system control units, the Ethernet switch, and the 24 V DC power distribution equipment. This system is estimated to weigh 100 kg (200 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 zero.

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 1 person 2 hours to remove the components. At a cost of $175/hour for 2 hours, this step is estimated to cost $350.

Transportation

The additional equipment may be transported with other metal or electronic components. We estimate that it should add no significant additional cost.

HVAC Thermal Management

Equipment and Description

For a large battery energy storage system, thermal temperature control is very important. For this estimated 1MWh system, a 5-ton unit should be able to handle thermal load. For redundancy, the system will need two such systems to ensure back up in the case of one unit's failure. An example of a 5-ton system that could meet these system cooling needs would be a Bard WA-Series wall mounted air conditioner. Each of these units weigh, 225 kg (500 lb) for a total HVAC system weight of 450 kg (1000 lb).

These HVAC systems use Refrigerant 22 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. For two 5 ton cooling systems, we approximate they would contain 10 kg (25 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.

The HVAC units may be sent to a metal recycler separately, or they may be sent with the housing container for disposal off-site at the recyclers.

Dismantling and Packaging

The refrigerant will need to be removed by a certified refrigerant technician as described in the previous section.

If the units are externally attached to the housing, they would need to be removed and placed inside the container for transport. We estimate it would take 2 people 4 hours to remove the units and place them inside the container or prepare them for shipping. At a cost of $175/hour for 8 hours, the step is estimated to cost $1,400.

Transportation

Once the refrigerant has been removed, the HVAC units may be transported with other metal components. We estimate that it should add no more that $500 to the cost.

Fire Suppression System

Equipment and Description

The fire suppression device for a 1 MWh energy storage system would include metal tanks containing the suppression agent and a metal piping dispersion system. 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 180 kg (400 lb).

Common suppression agents include FME 200 and FE 25. Both are gaseous waterless fire suppression agents manufactured by The Chemours Company, a spin-off of DuPont. Chemically FME 200 is heptafluoropropane and FE 25 is pentafluoroethane. While both chemicals have zero ozone depleting potential, they do have a global warming potential and must be handled to prevent unnecessary release. Two tanks of suppression agent would be needed for a 1 MWh battery system. Each tank is estimated to weigh approximately 70 kg (150 lb) empty, and 140 kg (300 lb) 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. The cost for this recycling or reuse is assumed to be zero.

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 yield a significant return.

Dismantling and Packaging

The metal piping and tank rack may be reused or scrapped along with other metal components of the system. At a maximum, we estimate that it would take 1 person 2 hours to remove the metal components. At a cost of $175/hour for 2 hours, the step is estimated to cost $350.

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 1 person 2 hours to remove those units and organize their transportation to an appropriate supplier. At a cost of $175/hour for 2 hours, this step is estimated to cost $350.

Transportation

The metal piping and rack can be transported with other metal components. Piping should add no more that $500 to the cost. 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.

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 should add no more than 120 kg (155 lb) to the total system weight.

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 to be zero. While scrap metal and cable materials do have a recycling value, the small amount of additional components may not yield a significant return. A quote from a metal recycler would be needed to estimate residual value based on quantity.

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 1 person 4 hours to remove the switch, cables, breakers, fuses, and other metal or electrical components. At a cost of $175/hour for 4 hours, this step is estimated to cost $700. If these components were to transported separately from the system to a metal recycler, we estimate that packaging would cost no more than $500.

Transportation

The additional equipment may be transported with other metal components. We estimate that it should add no more that $500 to the cost.

Preparation and Post Site Work

System Disconnection

Before the system can be dismantled or removed, it will need to be 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 2 workers half a day to complete. At a cost of $175/hour for 8 hours, this step is estimated to cost $1,400.

Post Site Removal Cleanup

Following removal of the unit, the remaining site will need be cleaned up. 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 any cables or connections that are no longer needed without the battery equipment present. This is estimated to take 2 workers half a day to complete. At a cost of $175/hour for 8 hours, this step is estimated to cost $1,400.

Conclusions

The cost of total system recycling on a component by component basis was summarized. Combining heavy equipment and scrap metal transportation and removal may consolidate and reduce some of these costs. The battery modules represent the largest weight and recycling costs of the system, and although the recycling of the lithium ion modules is still being developed on a commercial scale, most of the other components already have well established recycling procedures. For this estimated 1MWh energy storage system, it was estimated to cost roughly $91,500 for disposal and recycling at end-of-life.

3

EFFECT OF BATTERY CHEMISTRY ON MODULE RECYCLING COST

The energy storage system depicted in the previous section details the components of a particular battery chemistry from a specific manufacturer. While the balance of system components is appropriate for multiple chemistries, the costs to dismantle, ship, and recycle the battery components from a different chemistry for an equivalent 1 MWh energy storage system will vary. This section investigates the comparative cost of recycling, transportation, and system dismantling for five different lithium ion battery types, as well as for different battery manufacturers of NMC batteries.

The energy density inherent to each of the five lithium ion chemistries is shown in Table 3-1. Based on these theoretical energy density values it can be approximated that an LFP battery system may weigh twice as much as an NCA battery system with the same energy.

Table 3-1
Estimated Energy Densities for the Five Major Lithium Ion Chemistries

Abbreviation	Full Name (Chemical Equations)	Range of Energy Density (Wh/kg)
NCA	Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)	200-260
NMC	Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)	150-220
LMO	Lithium Manganese Oxide ($LiMn_2O_4$)	100-150
LFP	Lithium Iron Phosphate ($LiFePO_4$)	90-120
LTO	Lithium Titanate ($Li_4Ti_5O_{12}$)	70-80

Source: [3]

These theoretical values, however, are often much higher that the energy densities realized in cell and module designs and only apply to the battery portion of the system. System battery weight and recycling cost calculations in this report are based on publically available information on battery modules to better approximate real-world recycling costs.

Estimated Summary of Module Chemistry by Type and Manufacturer

Summary of Module Weights

We were able to find publically available module level data for five chemistries and six different manufacturers on which to base our system modules estimates, the results of which can be seen summarized in Table 3-2 for an approximated 1 MWh system.

Summary of Module Disposal and Recycling Costs

The module information and weights in Table 3-2 were then used to determine the total costs of the battery module disposal and recycling costs of the system. These costs, summarized in Table 3-3 include separate cost estimates for module recycling, labor and supplies for dismantling and packaging, as well as transportation costs for the battery modules.

Labor costs were calculated using a $175/hour loaded rate. In situations where specialized hazardous materials handling training is required, labor costs may be higher.

Table 3-2
Estimated Battery Module Weight for a 1 MWh Lithium Ion Energy Storage System

Estimated Battery Module Weight for an 1 MWh Energy Storage System		
Item (Description)	Weight (lb)	Weight (kg)
NMC - Manufacturer 1		
(For a 1 MWh system using Manufacturer 1 NMC modules there would be an estimated 323 modules.)		
Battery Modules (Weight calculated for 323 of the 3.2 kWh modules, each weighing 34 kg)	25,000	11,000
NMC - Manufacturer 2		
(For a 1 MWh system using Manufacturer 2 NMC modules there would be an estimated 93 modules.)		
Battery Modules (Weight calculated for 93 of the 11.1 kWh modules, each weighing 92.5 kg)	19,000	8,600
NCM - Manufacturer 3		
(For a 1 MWh system using Manufacturer 3 NCM modules there would be an estimated 369 modules.)		
Battery Modules (Weight calculated for 369 of the 2.8 kWh modules, each weighing 22 kg)	18,000	8,200
NCA - Manufacturer 4		
(For a 1 MWh system using Manufacturer 4 NCA modules there would be an estimated 574 modules.)		
Battery Modules (Weight calculated for 574 of the 1.8 kWh modules, each weighing 19 kg)	24,000	11,000
LMO - Manufacturer 3		
(For a 1 MWh system using Manufacturer 3 LMO modules there would be an estimated 356 modules.)		
Battery Modules (Weight calculated for 356 of the 2.9 kWh modules, each weighing 43 kg)	34,000	15,400
LFP - Manufacturer 5		
(For a 1 MWh system using Manufacturer 5 LFP modules there would be an estimated 196 modules.)		
Battery Modules (Weight calculated for 196 of the 5.28 kWh modules, each ESTIMATED to weigh 75 kg)	33,000	15,000
LTO - Manufacturer 6		
(For a 1 MWh system using Manufacturer 6 LTO modules there would be an estimated 398 modules.)		
Battery Modules (Weight calculated for 398 of the 2.6 kWh modules, each weighing 60 kg)	53,000	24,000

Source: EPRI Estimates.

Table 3-3
Estimated Battery Module Cost Components for a 1 MWh Lithium Ion Energy Storage System

Estimated Battery Module Cost Components for an 1 MWh Energy Storage System				
Item (Description)	On-site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	**Module Total**
NMC - Manufacturer 1				
(For a 1 MWh system using Manufacturer 1 NMC modules there would be an estimated 323 modules.)				
Battery Modules (Weight calculated for 323 of the 3.2 kWh modules, each weighing 34 kg)	$25,400.00	$20,000.00	$25,000.00	**$70,400.00**
NMC - Manufacturer 2				
(For a 1 MWh system using Manufacturer 2 NMC modules there would be an estimated 93 modules.)				
Battery Modules (Weight calculated for 93 of the 11.1 kWh modules, each weighing 92.5 kg)	$13,200.00	$20,000.00	$19,000.00	**$52,200.00**
NCM - Manufacturer 3				
(For a 1 MWh system using Manufacturer 3 NCM modules there would be an estimated 369 modules.)				
Battery Modules (Weight calculated for 369 of the 2.8 kWh modules, each weighing 22 kg)	$18,800.00	$20,000.00	$18,000.00	**$56,800.00**
NCA - Manufacturer 4				
(For a 1 MWh system using Manufacturer 4 NCA modules there would be an estimated 574 modules.)				
Battery Modules (Weight calculated for 574 of the 1.8 kWh modules, each weighing 19 kg)	$27,700.00	$20,000.00	$24,000.00	**$71,700.00**
LMO - Manufacturer 3				
(For a 1 MWh system using Manufacturer 3 LMO modules there would be an estimated 356 modules.)				
Battery Modules (Weight calculated for 356 of the 2.9 kWh modules, each weighing 43 kg)	$36,600.00	$30,000.00	$85,000.00	**$151,600.00**
LFP - Manufacturer 5				
(For a 1 MWh system using Manufacturer 4 LFP modules there would be an estimated 196 modules.)				
Battery Modules (Weight calculated for 196 of the 5.28 kWh modules, each ESTIMATED to weigh 75 kg)	$24,900.00	$30,000.00	$82,500.00	**$137,400.00**
LTO - Manufacturer 6				
(For a 1 MWh system using Manufacturer 6 LTO modules there would be an estimated 398 modules.)				
Battery Modules (Weight calculated for 398 of the 2.6 kWh modules, each weighing 60 kg)	$44,200.00	$40,000.00	$53,000.00	**$137,200.00**

Source: EPRI Estimates.

Detailed on Module Calculations and Assumptions

Overview of Assumptions

System Size

Battery recycling calculations for this report were based primarily on module level data that is publically available from technical specification sheets on the technologies. The Manufacturer 1 system used in Section 2, is based on module and rack level data as it was readily available. For this system, the rack sizing gives a system with 3% more energy than the 1 MWh size specified. To be consistent, and to ensure comparable results among all battery module numbers, weights, and costs were calculated for 1,030 kWh.

Cost to Recycle by Technology

Different battery chemistries also carry different recycling costs. Through interviews with battery recyclers we were able to obtain the following price estimates to use in our system cost calculations, Table 3-4. These prices assume delivery of the battery units to the recycler at their processing or collection facilities.

Table 3-4
Recycling Cost Estimates by Chemistry

	Estimated Recycling Costs	
Chemistry	**Price per pound**	**Price per kilogram**
NCA	$1.00	$2.20
NMC	$1.00	$2.20
LMO	$2.50	$5.50
LFP	$2.50	$5.50
LTO	$1.00	$2.20

Source: [4]

We were unable to obtain projected future costs due to increased scale, but it is expected that larger volumes would lead to lower future recycling and handling costs. These costs pertain to current module chemistries and would change if the composition or value of recoverable material changed enough to warrant an adjustment. It should also be noted that these costs are reliant on recovered value and commodity pricing for battery materials and may vary as those prices fluctuate.

Dismantling Time

The battery modules included in this report, vary in size and weight. The following guidelines in Table 3-5 were developed to consistently calculate the time to remove and package the individual battery modules across the multiple technologies.

Table 3-5
Estimated Time Per Battery Module for Removal, Packaging, and Preparation for Shipment Based On Module Weight

Module Weight Range		Estimated time for removal and packaging per module (mins)
Kilogram	Pounds	
10-30	22-66	15 mins
31-50	67-110	25 mins
51-75	111-165	35 mins
76-100	166-220	45 mins

Source: EPRI Estimates.

Packaging

Cost calculations were based on the batteries being wrapped to avoid possibility of a short, stacked, and secured onto a pallet with a cardboard box placed over the units for protection. It was assumed that each pallet could hold 240-300 pounds of battery modules. For some technologies, this limited the calculations to 3 modules per pallet, whereas for smaller, lighter module technologies, it was estimated that 14 modules could be packaged onto the pallet. It was assumed that it costs roughly $50 per pallet for packaging and labeling supplies.

Transportation

As discussed in Section 2, it is assumed that, lithium ion battery modules, even at end-of-life are classified as hazardous materials and must be transported following special guidelines. Additionally, these battery modules will need to be delivered to one of a few locations within the United States or Canada that processes or collects batteries for processing. Although many recyclers exist to accommodate the large volume of small format batteries, only a small number of battery recyclers are currently equipped with the manpower and expertise to disassemble and recycle larger format batteries.

Currently these limitations require that the batteries be transported to processing centers in Lancaster, Ohio or Trail, British Columbia, Canada where Retriev has facilities. Or to collection centers in North Carolina where Umicore prepares recyclable materials to be transported to their dismantling and recycling facilities in Europe. In any of the above scenarios, modules from battery systems in California will need to be shipped 1,500 – 2,500 miles from the installation site to the recycler. This accounts for a large portion of the recycling costs of the energy storage system.

Again, the module weights, size, and numbers will vary between technologies and manufacturers in a 1 MWh system. The estimated shipping costs in Table 3-6 attempt to scale the cost variance across different system weight estimates. These values were developed as estimates to approximate battery module recycling costs, for accurate project planning, individual quotes tailored to exact system specifications would be necessary.

Table 3-6
Estimated Shipping Costs Based On Battery Weight

Total Battery Module Weight Range		Estimated shipping costs
Kilogram	Pounds	
33,000 – 55,000	15,000 – 25,000	$20,000
55,001 – 88,000	25,001 – 40,000	$30,000
88,001 – 132,000	40,001 – 60,000	$40,000

Source: EPRI Estimates.

NMC – Manufacturer 1

Equipment and Description

For a 1 MWh system built with Manufacturer 1's chemistry, module estimates were based on 3.2 kWh modules. An example system using these would require 323 modules for a total of 1033.6 kWh. Each module weighs 34 kg (77 lb), so the total battery module weight for the entire system is calculated to be approximately 11,000 kg (25,000 lb).

Recycling

Recycling costs for the battery modules with Manufacturer 1 NMC chemistry are estimated by battery recyclers to be $1/lb ($2.20/kg). This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 25,000 lb of NMC battery modules, this represents a battery module recycling cost of $25,000.

Dismantling and Packaging

The Manufacturer 1 system would contain 323 modules weighing 34 kg (77 lb) per module. Each one will need to be individually disconnected, have the electrode ends covered to avoid shorts, and then be stacked onto a wooden pallet with a cardboard box placed over the top. We estimate approximately 7 modules could be stacked per pallet, for a weight of approximately 240 kg (530 lb). For a 1 MWh system with 323 modules, it would take 47 pallets for shipping. We estimate a cost of $3,000 for pallets and packaging equipment.

The time and labor involved in removing and packaging this number of modules is not insignificant. To estimate the cost we assumed it would take 25 minutes per module. Multiplying this time estimate by the 323 modules in the system, we calculate that it will take 4 people 4 days to remove and package the Manufacturer 1's modules for shipment. At a cost of $175/hour for 128 hours, this step is estimated to cost $22,400.

This value is highly dependent on the assumptions used in our calculations, a reduction or increase in the minutes per 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. We estimate that for 25,000 lb of battery modules, it will cost $20,000 for transportation.

NMC – Manufacturer 2

For a 1 MWh system built with Manufacturer 2 NMC chemistry and modules estimate. The modules have an energy of 11.1 kWh. An example system using these would require 93 modules for a total of 1032.3 kWh. Each module weighs 92.5 kg (204 lb), so the total battery module weight for the entire system is calculated to be approximately 8,600 kg (19,000 lb).

Recycling

Recycling costs for the battery modules with NMC chemistry are estimated by battery recyclers to be $1/lb ($2.20/kg). This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 19,000 lb of NMC battery modules, this represents a battery module recycling cost of $19,000.

Dismantling and Packaging

The Manufacturer 2 system would contain 93 modules weighing 92.5 kg (204 lb) per module. Each one will need to be individually disconnected, have the electrode ends covered to avoid shorts, and then stacked onto a wooden pallet with a cardboard box placed over the top. We estimate approximately 3 modules could be stacked per pallet, for a weight of approximately 280 kg (620 lb). For a 1 MWh system with 93 modules, it would take 31 pallets for shipping. We estimate a cost of $2,000 for pallets and packaging equipment.

The time and labor involved in removing and packaging the modules was calculated as follows. To estimate the cost we assumed it would take 45 minutes per module. Multiplying this time estimate by the 93 modules in the system, we calculate that it will take 4 people 2 days to remove and package the Manufacturer 2 modules for shipment. At a cost of $175/hour for 64 hours, this step is estimated to cost $11,200.

This value is highly dependent on the assumptions used in our calculations, a reduction or increase in the minutes per 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. We estimate that for 19,000 lb of battery modules, it will cost $20,000 for transportation.

NCM – Manufacturer 3

Equipment and Description

For a 1 MWh system built with Manufacturer 3 NCM chemistry and modules estimate. The modules have an energy of 2.8 kWh. An example system using these would require 369 modules for a total of 1033.2 kWh. Each module weighs 22 kg (48 lb), so the total battery module weight for the entire system is calculated to be approximately 8,200 kg (18,000 lb).

Recycling

Recycling costs for the battery modules with NCM chemistry are estimated by battery recyclers to be $1/lb ($2.20/kg). This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 18,000 lb of NMC battery modules, this represents a battery module recycling cost of $18,000.

Dismantling and Packaging

The Manufacturer 3 system would contain 369 modules weighing 22 kg (48 lb) per module. Each one will need to be individually disconnected, have the electrode ends covered to avoid shorts, and then stacked onto a wooden pallet with a cardboard box placed over the top. We estimate approximately 12 modules could be stacked per pallet, for a weight of approximately 260 kg (570 lb). For a 1 MWh system with 369 modules, it would take 31 pallets for shipping. We estimate a cost of $2,000 for pallets and packaging equipment.

The time and labor involved in removing and packaging the modules was calculated as follows. To estimate the cost we assumed it would take 15 minutes per module. Multiplying this time estimate by the 369 modules in the system, we calculate that it will take 4 people 3 days to remove and package the Manufacturer 3 modules for shipment. At a cost of $175/hour for 96 hours, this step is estimated to cost $16,800.

This value is highly dependent on the assumptions used in our calculations, a reduction or increase in the minutes per 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. We estimate that for 18,000 lb of battery modules, it will cost $20,000 for transportation.

NCA – Manufacturer 4

Equipment and Description

For a 1 MWh system built with Manufacturer 4 NCA chemistry, module estimates were based on the 1.8 kWh modules. An example system using these would require 574 modules for a total of 1033.2 kWh. Each module weighs 19 kg (42 lb), so the total battery module weight for the entire system is calculated to be approximately 11,000 kg (24,000 lb).

Recycling

Recycling costs for the battery modules with NCA chemistry are estimated by battery recyclers to be $1/lb ($2.20/kg). This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 24,000 lb of NCA battery modules, this represents a battery module recycling cost of $24,000.

Dismantling and Packaging

The Manufacturer 4 system would contain 574 modules weighing 19 kg (42 lb) per module. Each one will need to be individually disconnected, have the electrode ends covered to avoid shorts, and then stacked onto a wooden pallet with a cardboard box placed over the top. We estimate approximately 14 modules could be stacked per pallet, for a weight of approximately 260 kg (570 lb). For a 1 MWh system with 574 modules, it would take 41 pallets for shipping. We estimate a cost of $2,500 for pallets and packaging equipment.

The time and labor involved in removing and packaging the modules was calculated as follows. To estimate the cost we assumed it would take 15 minutes per module. Multiplying this time estimate by the 574 modules in the system, we calculate that it will take 4 people 4.5 days to remove and package the Panasonic modules for shipment. At a cost of $175/hour for 144 hours, this step is estimated to cost $25,200.

This value is highly dependent on the assumptions used in our calculations, a reduction or increase in the minutes per 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. We estimate that for 24,000 lb of battery modules, it will cost $20,000 for transportation.

LMO – Manufacturer 3

Equipment and Description

For a 1 MWh system built with Manufacturer 3 LMO chemistry, module estimates were based on the 2.9 kWh modules. An example system using these would require 356 modules for a total of 1032.4 kWh. Each module weighs 43 kg (95 lb), so the total battery module weight for the entire system is calculated to be approximately 15,400 kg (34,000 lb).

Recycling

Recycling costs for the battery modules with LMO chemistry are estimated by battery recyclers to be $2.5/lb ($5.50/kg). This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 34,000 lb of LMO battery modules, this represents a battery module recycling cost of $85,000.

Dismantling and Packaging

The Manufacturer 3 LMO system would contain 356 modules weighing 43 kg (95 lb) per module. Each one will need to be individually disconnected, have the electrode ends covered to avoid shorts, and then stacked onto a wooden pallet with a cardboard box placed over the top. We estimate approximately 6 modules could be stacked per pallet, for a weight of approximately 260 kg (570 lb). For a 1 MWh system with 356 modules, it would take 60 pallets for shipping. We estimate a cost of $3,000 for pallets and packaging equipment.

The time and labor involved in removing and packaging the modules was calculated as follows. To estimate the cost we assumed it would take 25 minutes per module. Multiplying this time estimate by the 356 modules in the system, we calculate that it will take 4 people 6 days to remove and package the Manufacturer 3 LMO modules for shipment. At a cost of $175/hour for 192 hours, this step is estimated to cost $33,600.

This value is highly dependent on the assumptions used in our calculations, a reduction or increase in the minutes per 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. We estimate that for 34,000 lb of battery modules, it will cost $30,000 for transportation.

LFP – Manufacturer 5

Equipment and Description

For a 1 MWh system built with Manufacturer 5 LFP chemistry, module estimates were based on the 5.28 kWh modules. An example system using these would require 196 modules for a total of 1034.9 kWh. Exact module weights for the Manufacturer 5 LFP modules could not be found, we estimate a weight of 75 kg (165 lb), so the total battery module weight for the entire system is calculated to be approximately 15,000 kg (33,000 lb).

Recycling

Recycling costs for the battery modules with LFP chemistry are estimated by battery recyclers to be $2.5/lb ($5.50/kg). This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 33,000 lb of LFP battery modules, this represents a battery module recycling cost of $82,500.

Dismantling and Packaging

The Manufacturer 5 system would contain 196 modules estimated to weigh 75 kg (165 lb) per module. Each one will need to be individually disconnected, have the electrode ends covered to avoid shorts, and then stacked onto a wooden pallet with a cardboard box placed over the top. We estimate approximately 4 modules could be stacked per pallet, for a weight of approximately 300 kg (660 lb). For a 1 MWh system with 196 modules, it would take 49 pallets for shipping. We estimate a cost of $2,500 for pallets and packaging equipment.

The time and labor involved in removing and packaging the modules was calculated as follows. To estimate the cost we assumed it would take 35 minutes per module. Multiplying this time estimate by the 196 modules in the system, we calculate that it will take 4 people 4 days to remove and package the Manufacturer 5 modules for shipment. At a cost of $175/hour for 128 hours, this step is estimated to cost $22,400.

This value is highly dependent on the assumptions used in our calculations, a reduction or increase in the minutes per 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. We estimate that for 33,000 lb of battery modules, it will cost $30,000 for transportation.

LTO – Manufacturer 6

Equipment and Description

For a 1 MWh system built with Manufacturer 6 LTO chemistry, module estimates were based on the 2.6 kWh modules. An example system using these would require 398 modules for a total of 1034.8 kWh. Each module weighs 60 kg (132 lb), so the total battery module weight for the entire system is calculated to be approximately 24,000 kg (53,000 lb).

Recycling

Recycling costs for the battery modules with LTO chemistry are estimated by battery recyclers to be $1/lb ($2.20/kg). This cost is for batteries delivered to the recycling facility, and represents the labor cost of module disassembly as well as the value of the metals recovered from the recycling process. For the estimated 1 MWh system with 53,000 lb of LTO battery modules, this represents a battery module recycling cost of $53,000.

Dismantling and Packaging

The Manufacturer 6 system would contain 398 modules weighing 60 kg (132 lb) per module. Each one will need to be individually disconnected, have the electrode ends covered to avoid shorts, and then stacked onto a wooden pallet with a cardboard box placed over the top. We estimate approximately 4 modules could be stacked per pallet, for a weight of approximately 240 kg (530 lb). For a 1 MWh system with 398 modules, it would take 100 pallets for shipping. We estimate a cost of $5,000 for pallets and packaging equipment.

The time and labor involved in removing and packaging the modules was calculated as follows. To estimate the cost we assumed it would take 35 minutes per module. Multiplying this time estimate by the 398 modules in the system, we calculate that it will take 4 people 7 days to remove and package the Manufacturer 6 modules for shipment. At a cost of $175/hour for 224 hours, this step is estimated to cost $39,200.

This value is highly dependent on the assumptions used in our calculations, a reduction or increase in the minutes per 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. We estimate that for 53,000 lb of battery modules, it will cost $40,000 for transportation.

4

CURRENT REGULATIONS AND RESPONSIBILITIES SURROUNDING LARGE-SCALE BATTERY DECOMMISSION

Regulating Lithium Ion Batteries: Hazards to Avoid

When dismantling and recycling battery systems, large amounts of batteries are grouped together for transport, and most of the batteries still carry residual charge. Incorrect disposal of lithium ion batteries in landfills or careless transportation can lead to fire, explosion, or environmental contamination. Dismantling thus requires appropriately trained staff and well defined safety regulations.

United States Federal Regulation

Federal regulation of lithium ion batteries is limited to transportation, and the United States takes care to maintain UN standards for international transportation. The federal government classifies lithium and lithium ion cells as Class 9 hazardous materials, which are required to maintain a certain standard of packaging and labeling. The dismantling and packaging of such hazardous materials are required to be performed by employees who have completed hazmat training that is described as general awareness/familiarization and function specific [5]. A hazmat employee is defined in 49 CFR §171.8 as "any person, who loads, unloads or handles hazardous materials… or who prepares hazardous material for transportation," [5 and 6]. Responsibility falls upon the employer (in this case, the utility company, battery manufacturer, or a recycling company) to provide hazardous materials training and to abide by all of the federal hazardous materials regulations, including post-removal site clean-up. If the dismantling and removal of end-of-life batteries cannot be done in-house by the utility company, professional resources are available to handle this type of requirement, including ensuring post-removal site safety [7 and 8]. A brief summary of the packaging and labeling requirements can be seen below.

Packaging and Labeling:

Lithium cells or batteries must be packaged in a manner to prevent short circuits, movement within the outer package, and accidental activation of the equipment. This often involves putting insulating tape or the original terminal covers over the positive and negative posts to protect the battery from heat and prevent electrical charges. For packages containing lithium cells or batteries offered for transportation, they must be placed in inner packaging that completely enclose the cells or batteries, and that separates the cells or batteries from contact with conductive materials. Each inner package offered for transportation must meet the following materials requirements (metal, wooden, fiberboard, plastic, and plywood). The outer package must be constructed of suitable material of adequate strength and design in relation to the capacity. Lithium batteries that weigh 12kg (26.5 lb) or more and have a strong, impact-resistant outer casing and assemblies, may be packed in strong outer package and protective enclosures [9].

For transportation by aircraft there are strict weight and package size limitations. If the "lithium metal cells or batteries are packed with or contained in equipment in quantities not exceeding 5 kg net weight" they are allowed to be transported by aircraft. Above that weight, labeling is required on the outer package stating "LITHIUM METAL BATTERIES - FORBIDDEN FOR TRANSPORT ABOARD PASSENGER AIRCRAFT," and are restricted to intracontinental transportation by rail, highway, or vessel [9].

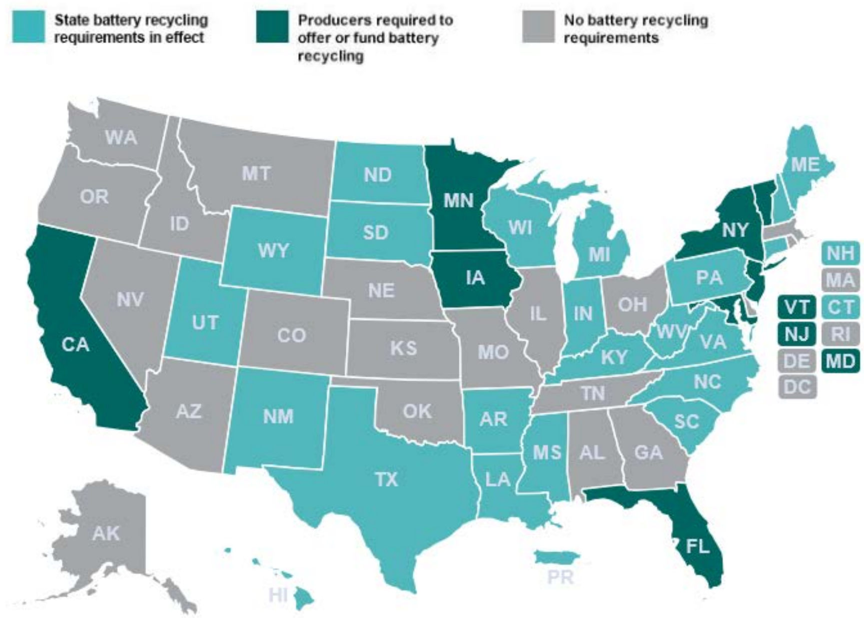
For transportation by highway or rail only, there are limitations on lithium content of the cell or battery. If content exceeds 5g for lithium metal cells, 25 g for lithium metal battery, 60 Wh for lithium ion cell, or 300Wh for lithium ion battery, then the outer packaging is required to be labeled: "LITHIUM BATTERIES-FORBIDDEN FOR TRANSPORT ABOARD AIRCRAFT AND VESSEL" [9].

Lithium cells or batteries that have been damaged or recalled by the manufacturer for safety reasons or those being returned to the manufacturer have potential of producing heat, fire, and short circuit must be transported by highway, rail, or vessel. Each cell or battery must be packaged individually, with non-metallic, non-combustible, non-conductive, and absorbent inner packaging. The outer packaged must be marked as "DAMAGED/DEFECTIVE LITHIUM ION BATTERY" [9].

Recently, the Department of Transportation updated the regulation in order to maintain compliance with UN standards; the complete update can be found in 82 FR 15796 [10]. Lithium ion batteries are to be labeled explicitly, rather than simply stating the presence of Class 9 hazardous materials.

Regulation by State

New York, Minnesota, and California have stewardship laws that cover lithium ion batteries [11, 12, 13, and 14]. As shown in Figure 4-1, 20 other states have lead acid battery law and 27 states do not require battery recycling [15]. For states with lithium ion battery disposal laws, they pertain to the return of end-of-life rechargeable batteries to manufacturers and retailers. The states laws intent are that the cost associated with the handling, recycling, and disposal of used rechargeable batteries be the responsibility of the producers and consumers, and not local government or their service providers, state government, or taxpayers. Lithium ion cells or batteries shall be shipped with others of a similar shape, size, and function to those being disposed of. Retailers shall take up as many such batteries per day from any person regardless whether such person purchases replacement batteries, and purchases from the retailer.



Source: [15]

Figure 4-1
Map of US Battery Recycling Regulations

California Regulations

California does not allow batteries to be disposed in the trash as they may contain toxic metals such as mercury, lead, cadmium, and nickel. In 2005, the governor signed California Rechargeable Battery Recycling Act, which requires retailers create a process to accept all rechargeable batteries (small, non-vehicular, rechargeable nickel-cadmium, nickel metal hydride, lithium ion, or sealed lead-acid battery) from consumers for recycling [16]. The law requires Department of Toxic Substances Control (DTSC) to post in its website a report by July 1st of each year on battery handling and/or recycling facilities, as well as the estimated amount, by weight, of each type of rechargeable battery returned for recycling [17]. The mission of DTSC is to make Californians aware of how to properly dispose of rechargeable batteries and protect the state from harmful effects of contamination from toxic substances. In chapter 11 of title 22, division 4.5, California Code of Regulations describes that the batteries must be discarded as a hazardous waste regardless of size and chemicals [18]. Moreover, owners of solid waste transfer stations, municipal landfills, and recycling centers, upon discovering batteries in the waste should remove and manage the batteries separately according to the regulations. The facilities that engage the removal of the batteries from the municipal solid waste must comply with the hazardous waste management regulations.

European Union Regulations

The European Union's Batteries Directive is designed to protect, preserve, and improve the quality of the environment [19]. For industrial batteries for electric cars, the producer has to accept for free - waste, reused, or secondary used batteries. In recent developments, the EU commission moved to require a stop to landfilling and sought to harmonize recycling and collecting of batteries. According to the Advanced Rechargeable and Lithium Batteries Association, recycling and reuse can soften the environmental impact of batteries to reduce the energy required for their production, minimize waste that is associated by the disposal of hazardous materials, reduce the environmental impact of extracting new materials, and recover materials. The EU legislation may encourage battery manufacturers to develop better recycling processes and end-of-life designs, which in the future may be incorporated in the United States and other countries.

Potential Allocation of Responsibility

As with any long term service contract, the delegation of end-of-life responsibility must be taken into account when comparing system proposals. The optimal distribution of responsibility for any project will depend on the system itself, the ownership structure of the ESS, the capabilities of the vendor or utility, and the logistics surrounding location and transportation. Total system recycling costs for each option may vary, given differences in overhead and cost structures for vendors and utilities involved. Project management costs, contracting procedures and other factors will contribute differently to overall battery disposal and recycling costs, but are difficult to estimate unless the specific parties and project parameters involved are clearly stated. The allocation of responsibilities between the utility and vendor can, however, result in the introduction of certain systematic benefits to the overall efficiencies and overhead costs of decommissioning. A few examples are outlined below.

Availability of trained labor familiar with the system

In section 2, the decommission cost for a 1 MW system was estimated to be about $91,500, a large proportion of which is due to skilled labor. Much of this labor is specific to the battery system involved, which can differ between manufacturers and technologies. The manufacturer, having trained staff specific to the equipment and safety standards involved, may have the best trained staff resources for actions specific to their unique product. In contrast, most auxiliary equipment such as scrap metals and electronic waste do not change significantly with the specific battery technology and manufacturer, and can thus be the responsibility of the utility or a local third party without incurring any significant overhead increase.

Contracting procedures and reduction of overhead

Decommissioning can also lead to synergies between the vendor/utility and external third-party recyclers. For example, battery manufacturers could negotiate a long-term contract with the battery recycler, providing a guaranteed stream of the same battery type (packaging and chemistry) and allowing for scale savings in dismantling and recycling processes. In contrast, utilities are more localized than battery manufacturers, and so can maintain active relationships with local scrapyards and electronics waste recyclers, saving on transportation and overhead.

In general, allocation of end-of-life responsibility will depend on the financial and operational capabilities of each party involved. It is, however, necessary to take into account potential system efficiencies such as those outlined above, as well as the differential costs of decommissioning outlined in section 2 and 3.

5
CONCLUSIONS AND RECOMMENDATONS

Currently the decommissioning of lithium ion battery systems is both expensive and time consuming. However, due to the increase in demand of lithium ion battery storage, both grid and consumer scale, there is increasing concern around mitigating the lifecycle impact of battery systems and a drive to understand and lower the costs and impacts involved. While the challenge of decommissioning battery systems on this large scale is still years away, it is imperative that we take steps now to mediate significant future economic and environment costs.

Developing a sustainable and effective recycling infrastructure around lithium ion batteries will require coordination and input from all stakeholders in the lithium ion battery value chain. Today there is not enough focus on end-of-life considerations for these batteries, and performance and manufacturing costs are prioritized during the development process. It is important for all stakeholders, including vendors, customers, and battery recyclers, to start thinking about the entire lifecycle of the battery, from pre-production to decommissioning. Lithium ion battery manufacturing designers need to further consider how to make recycling productive, even profitable, and the materials used in manufacturing must be considered for how they might be effectively and inexpensively used during life and after. Removal of the risks inherent in the raw materials markets through providing an alternate end-of-life stream of resources could provide the stability and sustainability necessary for a long-standing grid resource.

While the responsibility for decommissioning will be managed on a case by case basis, and will in most cases fall on the shoulders of the system owners, manufacturers can do much on the front end to simplify the process and facilitate recycling approaches. Some steps that can be taken include:

- Including labels or other distinguishing features to make sorting various chemistries faster and easier
- Using a minimal number of different materials
- Standardizing formats and materials
- Avoiding bad-actor materials (cadmium, arsenic, mercury, halogens)
- Enabling easy separation of parts [20].

In addition, the development of effective recycling and sustainable disposal may be highly influenced by the present regulatory regime. In other industries, such as lead acid, toxicity has driven development of comprehensive disposal regulation, resulting in 98% of all lead acid batteries being recycled in the United States. This occurred as a result of a consistent, comprehensive framework of regulations based on a system of penalties and incentives that promote recycling at scale. Currently no such federal regulations exist in the United States for lithium ion, although there are some examples of state-level programs.

6
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