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Program on Technology Innovation: Life Cycle Assessment of Lithium-ion Batteries in Stationary Energy Storage Systems

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Technical Update, September 2019

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ABSTRACT

Grid-connected stationary energy storage deployment is growing rapidly, with increasing numbers of facilities in the ground, and others in the procurement stage. As a result, it is increasingly important to understand the environmental issues associated with energy storage technologies. A small amount of literature on environmental life cycle assessments (LCAs) has examined relevant impacts for stationary battery energy storage systems. This is complemented by a larger number of studies on transportation applications, for which some life-cycle inventory data are also relevant for stationary battery LCAs. However, grid-scale stationary and transport applications have different packaging, operational profiles, and perhaps even different end-of-life phase needs. Additional LCA investigation of stationary grid-scale battery storage systems (predominantly lithium ion chemistries) is therefore needed.

This technical update presents the scope, inventory description, and results from a new LCA study of lithium ion battery energy storage systems undertaken by EPRI and EcoShift Consulting. This effort was unique as it considered a variety of realistic scenarios for battery designs (and balance of system materials), applications, and end-of-life management, based on eleven installation sites described in California's recent storage procurement mandate. The life cycle phases included were battery production (often called cradle-to-gate, including raw material extraction, cell and module manufacturing), use phase, and end of life. Transportation associated with commissioning and decommissioning activities was also included. Four battery chemistries were considered: NCM (Lithium-nickel-cobalt-manganese-oxide, Li-NCM); NCA (Lithium-nickel-cobalt-aluminum-oxide, Li-NCA); LFP (Lithium-iron phosphate, LiFePO4); and LMO (Lithium-manganese oxide, LiMnO2) in a variety of pack designs. Three stationary application scenarios were investigated – electric utility services, renewables support, and natural gas support. Several end-of-life scenarios were considered, including disposal; disposal with materials recovery; and disposal with materials recovery and cathode recycling. The use phase was characterized by dispatch profiles determined by EPRI's StorageVet tool, and battery degradation was estimated. Environmental impacts were characterized using the U.S. Environmental Protection Agency's (EPA's) Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) framework, and the results were reported for several functional units [e.g. per unit energy delivered (MWh); per installed capacity (kW); and per unit time in (service hours for frequency response)].

Keywords

Lithium ion battery
LIB
Life cycle assessment
LCA
Stationary energy storage system
Grid-scale energy storage

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PRIMARY AUDIENCE: Environmental and resource planning staff at power generation companies

SECONDARY AUDIENCE: Stakeholders interested in environmental assessments of energy storage technologies

KEY RESEARCH QUESTION

It is increasingly important to obtain an improved understanding of the relevant environmental impacts associated with energy storage technologies. While a few prior studies have performed environmental life cycle assessments (LCAs) for battery storage, most of these are not specific to stationary grid-scale lithium ion batteries, and instead focus on vehicle transportation battery applications. Thus, additional investigation is needed of the life cycle environmental impacts of stationary energy storage systems, such as those that utilities would install on transmission or distribution systems, or at renewable energy generation sites.

RESEARCH OVERVIEW

A variety of realistic scenarios for battery designs, applications, and end-of-life management were created, based on eleven installation sites described in California's recent storage procurement mandate. These scenarios incorporated information collected through literature reviews, discussions with specialists (e.g. battery manufacturers, energy storage operations experts, and waste management companies), LCA inventory databases, and modeling tools (i.e. EPRI's StorageVet tool for high time resolution economic storage operations simulations). Extensive sensitivity and scenario analysis comparing the various battery system designs and performance was completed. The U.S. Environmental Protection Agency's (EPA's) Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) framework for analyzing LCA results was used. Results were reported using several functional units [e.g. per unit energy delivered (MWh); per installed capacity (kW); and per unit time in (service hours for frequency response)].

KEY FINDINGS

- Operation, or use-phase, of LIB facilities is a significant driver of several categories of environmental impact, such as greenhouse gas emissions.
- Emissions associated with battery production were also a significant contributor to the impacts of LIB deployment on acidification, ecotoxicity impact, and non-cancerous human toxicology impact categories.
- While the choice of LIB chemistry is important for performance considerations, other factors (including site selection and end of life (EOL) management) can have greater impact on environmental endpoint results.
- The environmental impacts of recycling and transportation were both found to be significant. Creation of more efficient LIB recycling infrastructure, located closer to expected storage deployment sites, would help to reduce this impact.

- As LIB chemistries, designs and operational strategies for grid-scale energy storage systems are still evolving, the results of environmental assessments for LIBs are likely to be somewhat different in the future, and should continue to be re-assessed. For example, future LCA of stationary grid-scale LIB storage systems should reflect “value stacking” operational strategies used by asset owners.

WHY THIS MATTERS

Deployments of grid-connected lithium ion battery (LIB) energy storage systems are accelerating as costs continue to decrease. Large stationary LIB energy storage systems are becoming an increasingly cost-effective option for utility companies to meet a variety of grid needs. Environmental impact assessments of various types, including LCAs, can inform utility decision-making during resource planning, procurement requests, facility operations, and end of life management.

HOW TO APPLY RESULTS

The results of this study may be used to help evaluate the environmental impacts of grid-connected lithium ion battery (LIB) energy storage systems similar to those studied in this analysis, including:

- Potential environmental impacts of deploying grid-connected lithium ion battery (LIB) energy storage systems (including manufacture, use, and disposal),
- How these impacts are different for different grid service use cases, and
- How much these impacts would be reduced if it were possible to recycle the components of a LIB energy storage system.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Pellow, M., Ambrose, H., Mulvaney, D., Betita, R., Shaw, S. (2019) Research Gaps in Environmental Life Cycle Assessments of Lithium Ion Batteries for Grid-Scale Energy Storage Systems: End-of-Life Options and Other Issues. In press at *Sustainable Materials and Technologies*.
- Program 197: Environmental Aspects of Fueled Distributed Generation and Energy Storage

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ABBREVIATIONS

ADP	abiotic resource depletion potential
Ah	Amp-hour
BatPac	Battery Performance and Cost model
BMS	battery management system
BOS	balance-of-system
CAISO	California Independent System Operator
CAS	Chemical Abstract System
CED	cumulative energy demand
CERCLA	U.S. Comprehensive Environmental Response Compensation Liability Act
CO	carbon monoxide
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
CTG	cradle-to-gate
CTU	comparative toxic unit
DMC	dimethyl carbonate
DOD	depth of discharge
DOE	U.S. Department of Energy
eGRID	Emissions & Generation Resource Integrated Database
EIO	Economic Input-Output
EOL	end-of-life
EPA	U.S. Environmental Protection Agency
ESS	energy storage system
EV	electric vehicle
GESD	Global Energy Storage Database
GHG	greenhouse gas
GIS	geographic information system
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP	global warming potential
ICEV	internal combustion engine vehicle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization

kg	kilogram
kW	kilowatt
LCA	life cycle assessment
LCI	life cycle inventory
LCO	lithium cobalt oxide
LFP	lithium iron phosphate
LIB	lithium-ion battery
LMO	lithium manganese oxide
LTO	lithium titanate oxide
MJ	megajoule
MW	megawatt
MWh	megawatt hour
NiMH	nickel-metal hydride
NaS	sodium sulfur battery
NCA	nickel cobalt aluminum oxide
NMC	nickel manganese cobalt oxide
NiMH	nickel-metal hydride
NaS	sodium sulfur battery
NCA	nickel cobalt aluminum oxide
NMC	nickel manganese cobalt oxide
NMP	N-methyl-2-pyrrolidone
NO_X	nitrogen oxides
PDS	pack design scenario
PHEV	plugin hybrid electric vehicle
PM	particulate matter
PV	photovoltaic
SO_2	sulfur dioxide
T&D	Transmission & Distribution
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental impacts

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INTRODUCTION

1.1 Overview

Grid-connected energy storage system (ESSs) deployments are accelerating (Figure 1-1a), driven by a combination of factors. The underlying factors driving this trend – including the falling cost of lithium ion battery (LIB) systems, electricity market developments, and the continuing growth of wind and solar generation capacity – are likely to remain in place for several years to come. As the number and size of grid-scale ESSs continues to increase in coming years, a comprehensive and realistic understanding of their likely environmental impact will be increasingly important.

This acceleration in grid-scale deployments has been enabled by the dramatic decrease in the cost of LIB ESSs over the past decade (Figure 1-1b). As a result of this decrease, energy storage is therefore becoming increasingly cost-competitive with traditional grid assets (such as fossil-fueled power plants) for utility companies addressing bulk power and power quality needs. Utility companies and public utilities commissions are also exploring energy storage as an economical alternative to investing in transmission and distribution infrastructure. [1,2] Energy storage has potential to enhance the economic value of distribution-connected photovoltaic generation. LIBs are expected to see further cost reductions, which may lead them to become increasingly cost-effective for a variety of grid services. [3] This will likely lead to further growth in deployments of grid-connected LIB systems.

Utility-scale ESSs provide a number of services such as power ramping, reserve capacity, curtailment avoidance, voltage support, frequency regulation, black-start, and other ancillary services, making them flexible utility assets for electricity grid management. Technological advances and cost reductions are increasing the choices of electrochemical devices for utility-scale storage. LIBs are already the most common form of electrochemical energy storage in a variety of applications, including automobiles and stationary grid electricity storage. The various LIB cell configurations and battery chemistries currently entering the mass market offer performance differences, including cycle life, specific energy, and power densities, which will impact both the economic and environmental performance of these devices. Differences in chemical composition are based on active ingredients in cathode and anode materials, but these differences can subsequently affect the choice of battery management systems, cooling systems, and other components. [4]

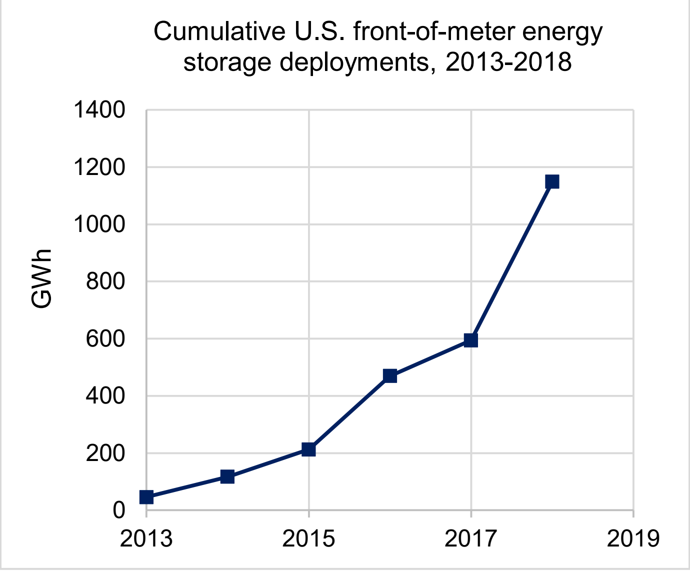


Figure 1a. Cumulative U.S. front-of-meter energy storage deployments. Data: GTM Research 2018b.

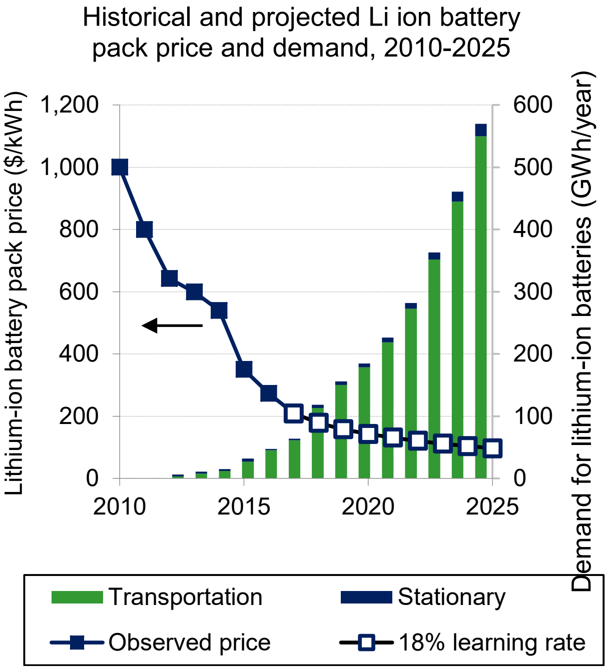


Figure 1b. Lithium ion battery pack-level costs, observed and projected (based on 18% learning rate); and projected Li ion battery demand. Data: BNEF 2017.

Figure 1-1
ESS Deployments and LIB Prices

As of January 2018, there were approximately 32.1 GW of installed utility-scale electricity storage capacity in the United States, about 90% of which is pumped hydropower (28.9 GW). [5] While new markets for energy services and regulatory mandates were expected to expand the use of a range of stationary technologies online, such as compressed air storage, flywheels, and various battery types [6], significant interest has followed the use of LIBs. Since 2013, more than half of all new stationary storage installations have been LIBs and in 2017, LIBs represented over 95% of the market. There were approximately 818 MW of LIBs in stationary grid-connected projects deployed by January 2018 (2.5% of total storage installed), according to the U.S. Department of Energy (DOE). With projects under construction or announced, this number is poised to rise significantly in the coming years. The scale of LIB cell manufacturing is also increasing rapidly, which will drive down the costs of LIBs. [7] Further cost reductions and increases in performance are also expected due to improving LIB electrode chemistries and cell designs, which will enable higher energy and power densities and longer service lifetimes. [8]

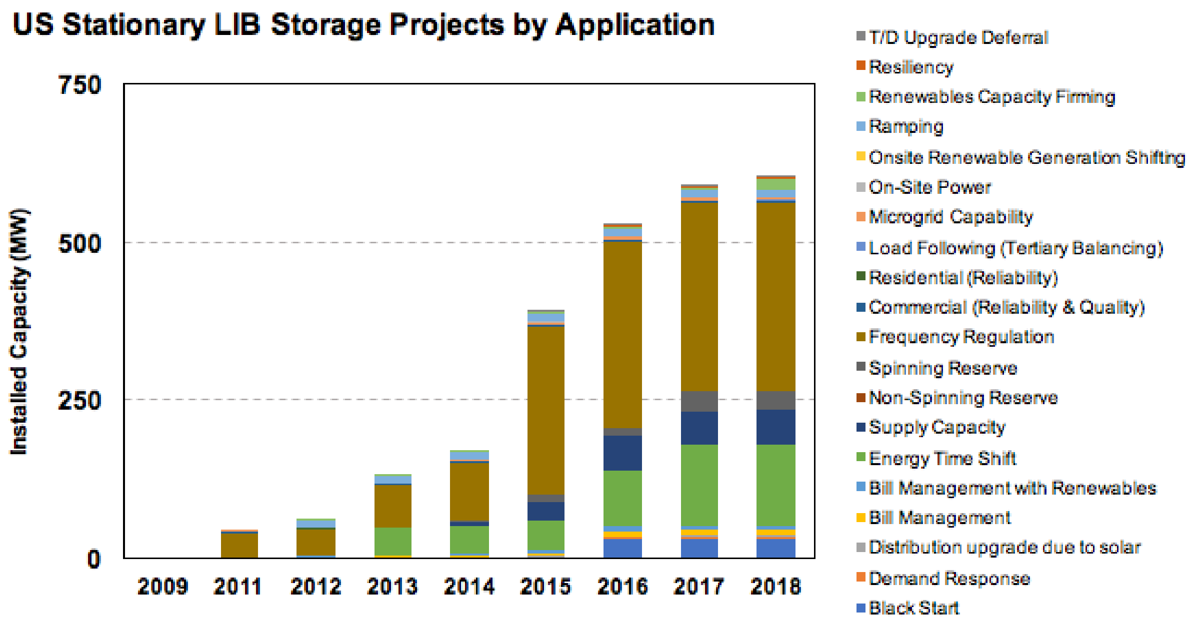


Figure 1-2
Operational Lithium electrochemical energy storage projects in the U.S., 2009-2018 [9]

Figure 1-2 illustrates the rapid growth in lithium ESS projects in the U.S. over the past ten years by application. While a variety of technologies are commercialized for grid-scale energy storage, LIBs are currently more mature than other options, with extensive deployments and well-established supply chains. LIB is unique among other storage technology options in that it shares the economies of large-scale production driven by a separate major market, electric vehicles (EVs). This is an important factor driving the dramatic cost declines for LIB in recent years. Key stakeholders in grid-scale deployments – utility companies, regulators, battery vendors, and system integrators – are now gaining significant working experience with LIB grid-scale ESS. LIB is therefore likely to continue as a dominant technology for both grid-scale and behind-the-meter applications in coming years. The scale by which many analysts suggest LIBs are poised to grow make them a critical topic for which to investigate environmental impacts using LCA.

Comprehensive environmental impact assessment of this new technology class has not received sufficient scientific inquiry. The majority of environmental research on LIBs has focused on traction batteries in electric vehicle (EV) applications, due to both the emphasis on market offerings of LIBs for mobile applications and projections for the size of the overall traction battery market. LIBs are used as traction batteries for EVs because they offer the high energy density, power density, and cycle lifetimes necessary for vehicle applications, although this response varies by LIB chemistry.

A prior report summarized prior life cycle assessment research on LIBs. [10] Studies have found that EVs have greenhouse gas benefits compared to conventional gasoline vehicles, but are dependent on the emissions from energy used to produce battery systems. [11] Research comparing LIBs to other electrochemical options such as nickel–metal hydride (NiMH) and lead–acid (PbA) also found LIBs to have lower toxicity and potentially pose fewer risks to human health. Owing to significantly higher energy densities, LIBs have lower material demands and subsequent impacts through mining and resource extraction. LIBs energy intensity per unit storage can be affected by manufacturing capacity and volumes due to energy required for cell assembly processes. The total throughput a battery can deliver is also strongly affected by the type of duty cycle the battery experiences (i.e. cycles, discharge depth, rate, and temperature), which complicates performance and impact estimation. [12]

There are far fewer studies focused on environmental assessments of LIBs in utility or grid-scale stationary applications. This is in part due to the rapid pace of the technology's development and deployment. The published literature primarily focuses on the technical performance of LIBs, new designs, production technologies, or simulation/optimization of application. Studies have also considered the effects on marginal and average carbon intensity of generation and the economics of grid services provided by storage. These studies tend to ignore impacts from battery production and end-of-life (EOL), and instead show that storage has mixed impacts on grid carbon intensity due to indirect changes in grid generation mix during the use phase. [13]

We identified four sets of services for which utilities might consider installing LIBs (Table 1-1). In general, different services have different requirements for energy storage and capacity. While the primary application of the LIB system could drive selection of the battery design, LIBs can offer a portfolio of simultaneous services depending on their capabilities (i.e. a blend of frequency and voltage support with arbitrage).

Table 1-1
Example Grid Services for Storage

Application	Duration (h)	Cycles Per Day	Energy Capacity	DOD	Description
Area and Frequency Regulation	0.25	> 30	20 - 30 MWh	~ 8%	Signal following, high frequency cycling
Support of Voltage Regulation	0.25	< 0.75	10 - 20 MWh	~16%	Signal following, low frequency average, high variation
Peak shaving and time shifting	8	1 - 2	50 - 100 MWh	80% / 90%	Daily economic arbitrage, charge off-peak or mid-day, discharge on- peak
T&D Investment Deferral	2	< 1	10 - 20 MWh	80% / 90%	Avoided infrastructure, less frequent cycling

Peak shaving and time shifting –LIBs in a large bulk storage scenario designed to flexibly meet daily and seasonal shifts in the mismatch between capacity and demand. This scenario encompasses applications to deal with the overgeneration risk commonly called the "Duck Curve" caused by intermittent renewable generation and inflexible baseload power. In this scenario, batteries are cycled each day, switching seasonally between evening and mid-day charging patterns.

Area and Frequency Regulation –LIBs providing local area firming or frequency regulation (up or down) service to contribute to grid optimization or help integrate renewables. This translates to a high cycle frequency, low DOD environment, and generally smaller system capacities (from an energy storage perspective), but can have high power ratings.

T&D Investment Deferral –LIBs are used to defer additional investment in the expansion of transmission or distribution lines. Batteries in the T&D scenario are used to meet short peaks in local demand. Batteries experience less than one cycle per day on average, but at a higher discharge rate than in the peak shaving scenario. They also see an aggressive DOD schedule (>80%).

Support of Voltage Regulation – Contrasts with the frequency and regulation by having lower daily cycling on average. LIBs have the potential to flexibly service multiple duty cycles when needed, including to meet intermittent high frequency voltage support, and offer occasion mid to deep cycle near peak ramping.

1.2 Common chemistries of lithium-ion batteries (LIBs)

The following different chemical configurations comprise nearly all LIBs in use and commercially available.

- **Lithium cobalt oxide (LCO)** is used mainly in the portable electronics industry because it typically has shorter life spans and degradation is more susceptible to failure under heat stress.

- **Lithium iron phosphate (LFP)** is the chemistry used in the majority of operational LIB storage technologies commercially available. This chemistry is relatively inexpensive and popularized by manufacturers A123 [14] and BYD. [15]

- **Lithium manganese oxide (LMO)** LIB chemistries ($LiMn_2O_4$) have low internal resistance and high current discharge capabilities, and are more widely used in traction batteries with blended NMC.

- **Lithium titanate oxide (LTO)** LIB chemistries provide long cycle lives and lower voltage potentials. One example is $Li_4Ti_5O_{12}$, but there are stoichiometric blends. LTO batteries are installed in storage projects that require shorter output durations. Toshiba is one manufacturer of LTO LIBs. [16]

- **Lithium nickel cobalt aluminum oxide (NCA)** is used by Tesla/Panasonic**, and like NMC,** are available with different proportions of nickel, cobalt, and aluminum. In general, as nickel content goes up, so does the energy capacity of the battery, but the stability also goes down.

- **Lithium nickel manganese cobalt oxide (NMC)** is used by several cell manufacturers and for several vehicle producers, such as Chevy, Nissan, and BMW. It is preferred for its high energy densities and favorable performance and stability under high temperatures. The stoichiometric ratio of nickel, manganese, and cobalt can vary, early production of even

(1:1:1) formulations, have given way to a focus on (6:2:2) and (8:1:1) formulations of (N:M:C), with lower cobalt content.

1.3 The life cycle of lithium-ion batteries (LIBs)

Life cycle assessment (LCA) is a standardized approach to assess the environmental impacts of a defined product or process. LCA considers the impacts resulting from inputs and outputs of a defined product system. A life cycle inventory (LCI) is collected to compile impacts that occur from each of the inputs and outputs. The life cycle of LIBs can be grouped into several stages; these include the extraction and refining of raw materials, cell production, module and pack assembly, use, and EOL. EOL options include reuse applications, recycling, or disposal. Environmental impacts can occur at each life cycle stage, but at different scales and in different impact categories. Here we describe these stages in more detail.

1.3.1 Raw material extraction

There are a number of different materials used in LIB manufacturing. Lithium for LIBs comes primarily from high grade lithium carbonate and lithium hydroxide, which are produced from both brine and hard-rock mineral sources. Brines dominate known reserves of Lithium, and approximately 50% of global production Lithium production are from brine deposits. [17] The extraction of lithium from evaporated brines also produces potash. Several precipitation and drying stages result in lithium carbonate salts (Li_2CO_3), or lithium hydroxide can also be produced from both rock and brine sources through hydrometallurgical processes. [18] Lithium is also obtained from tantalum and antimony mining.

For other metals contained in LIBs, each type involves different set of mineralization and refinement processes depending on whether they contain nickel, cobalt, copper, manganese, and/or aluminum. For instance, aluminum used in LIBs collector materials is a primary metal obtained from bauxite ores. The battery industry is the second largest consumer of manganese, which is obtained by primary ore mining and mainly used by the steel industry. Cobalt is obtained from mainly nickel ores, but also copper ores. Other raw materials used in lesser amounts are obtained from secondary mining processes.

1.3.2 Cell and module manufacturing

Cathode materials, made from lithium metal oxides and conductive binding agents, are prepared with an organic solvent such as N-methyl-2-pyrrolidone (NMP), and then sputtered or pressed onto conductive contacts (commonly aluminum); anode materials are made from carbon-based pastes (graphite) and conductive contacts like copper. The anode and cathode are physically isolated by a separator, and are commonly rolled or coiled before being trimmed and placed in an encapsulating material with the electrolyte. Prismatic pouch and large-format cells are filled with electrolyte, made of lithium salts dissolved in an organic solvent, and then sealed. The particular electrode configuration depends on the cell casing. The cells are finally charged in a temperature-controlled environment to form the structural electrolyte interface.

Cells are combined into modules, usually configured based on the desired voltage. Modules can have individual battery management systems (BMS), or be integrated at the pack level. In vehicles, LIB modules are constructed with aluminum or steel substructures and thermal management systems to create packs. These manufacturing stages are typically included in the system boundary of LCAs of LIBs.

1.3.3 Use phase

The impacts from LIB use phase often vary across different LCAs studies because of different system boundaries and use-case scenarios, a persistent challenge observed by even early studies on battery assessment. [19] Most investigators of LIBs find that use phase impacts dominate the life cycle impacts of LIBs in both traction battery and stationary grid storage applications. [20] The impacts of this phase are influenced by regional and temporal variability in energy generation sources on the electrical grid. [21]

As a result, though impacts occur at different life cycle stages of LIBs from cradle to gate (CTG) to EOL, the environmental performance of these devices is strongly tied to their use phase application. In addition to upstream impacts mentioned above, there are important effects of duty cycle on battery longevity and efficiency, as well as effects on normalization for reporting of life cycle impacts. While the normalization unit can be a unit of energy (e.g., kWh or MJ), for vehicle applications it can also be distance (e.g., km or miles traveled).

1.3.4 End-of-Life (EOL)

EOL for LIBs, whether in a reuse scenario, recycling, or landfill disposal, is generally considered in the context of forecasting or predicting future industrial systems for battery collection and recycling. Reuse in low power applications is being explored as a viable scenario for LIBs initially installed in high power applications (such as EVs). [22] Battery degradation in high power applications usually results in increases to internal resistance such that a considerable amount of storage capacity is unavailable for the short-time, constant discharge necessary to achieve vehicular acceleration. Any remaining capacity may therefore serve a “second-life” in a low-power application. Recycling usually describes both mechanical and metallurgical processes for material recovery. These processes are generally driven by economics in the absence of comprehensive policy; mixed chemistry waste streams and a move to cathodes with lower material costs are likely to complicate the economics of recycling. Few studies have considered EOL alongside other stages, but there is a significant body of literature focused solely on lithium recycling and the role it plays in overall environmental performance.

2
GOAL AND SCOPE

Life cycle assessment (LCA) is a framework that quantifies and characterizes the energy and material flows from production from raw materials acquisition up the supply chain, through manufacturing and use to EOL phases like recycling or disposal. [23] LCAs consider the potential impacts and benefits, which can be economic, environmental, societal, or otherwise resulting from all inputs and outputs of a defined product system.

The goal of this study is a comprehensive environmental LCA of lithium ion batteries employed in stationary, utility-scale grid applications. As described in guidance from International Organization for Standardization (ISO) 14040-44:2006, LCA can be divided into four key stages: goal and scope setting, collecting and/or calculating life cycle inventories (LCIs), assessing life cycle impacts, and interpreting results.

This study compares the environmental performance of energy storage devices on a life-cycle basis, which can be described as a cradle to grave accounting of significant inputs of energy and materials required to produce, install, operate, decommission, and dispose of a product. This need is driven in part by electricity system stakeholders in order to understand potential benefits and challenges and their drivers, and in part by public interest in reducing the environmental impacts of generating and delivering electricity. The intended audience for the study includes utilities, regulators, system operators, industry groups, and other stakeholders.

This LCA considers the relevant inputs and outputs of materials, energy, and emissions from production, installation, use, maintenance, and disposal of stationary, grid-tied, LIBs. Specifically, this study looks at several comparable lithium-ion battery designs relying on four different cathode chemistries:

- NCM - Lithium-nickel-cobalt-manganese-oxide (Li-NCM)
- NCA – Lithium-nickel-cobalt-aluminum-oxide (Li-NCA)
- LFP - Lithium-iron phosphate ($LiFePO_4$)
- LMO - Lithium-manganese oxide ($LiMnO_2$)

LCA results also have the potential to inform storage technology selection and integration decisions. Therefore, several parameter sensitivity analyses were performed as part of this study, including a range of assembly energy, use phase and EOL scenarios. This study considers uncertainty in impact estimation from production processes, product selection at the point of purchase, and management strategies for in-use products.

The scope of an LCA study needs to "ensure that the breadth, the depth and the detail of the study are compatible and sufficient to address the stated goal," (ISO 14040:2006). To provide that breadth, this study considers the relevant performance characteristics of the selected battery chemistries, as well as various operational strategies. Battery supply/production pathway scenarios, use-case application scenarios, and EOL/disposal scenarios are developed and described in this section.

The methods used to construct a process model of the battery life cycle are discussed in Section 3. A more detailed discussion of methods used to conduct scenario and sensitivity analysis is contained in the appendix.

2.1 Product system

2.1.1 Battery Components

This study considers LIB installed in stationary applications to provide value-added services. The primary function of the product is to provide electricity storage over short and long time-horizons, as well as grid services such as frequency regulation, load shifting, arbitrage, avoided curtailments, and renewables integration.

The LIB life cycle has several stages including raw material extraction and refinement, component manufacturing and assembly, cell and battery assembly, installation and use, and end of life (EOL). The battery's components include cells, packaging, and battery management systems (including cooling). Table 2-1 lists an inventory of components and materials in a typical LMO module. Manufacturing processes include production of the cathode active material, anode active material, binders, electrolyte, packaging and structural elements (plastics, insulation, etc.), and management systems (electronics/charge controllers). The environmental impacts resulting from the choice of materials generally scale with mass of material used. For LIBs, material production environmental impacts tend to be dominated by materials used for cathodes, collectors, foil pouches, and other structural elements.

Table 2-1
Inventoried Components of the LIB Pack

Inventoried Components	
Anode Active Material	Terminal Assembly
Cathode Active Material	Cell and Module Interconnections
Carbon Black	Cell Container
Binder	Insulation
Binder Solvent	Battery Jacket
Anode Solvent	Thermal Enclosures
Cathode Foil	Pack Enclosure
Anode Foil	Battery Management System
Separator	Active Thermal Management
Electrolyte	Bus Bars and Compression Plates

Production process for LIBs begins with raw material extraction of lithium ores and brines, mineralization and refinement of transition metals (nickel and cobalt), as well as copper and aluminum foil production. Cathode materials, made from lithium metal oxides and conductive binding agents, are prepared with an organic solvent such as N-methyl-2-pyrrolidone (NMP), and then sputtered or pressed onto conductive contacts (commonly aluminum). Anode materials are made from carbon-based pastes (graphite) and conductive contacts like copper. [24]
The anode and cathode are physically isolated by a separator, and are commonly rolled or coiled before being trimmed and placed in an encapsulant with electrolyte. Prismatic pouch and large-format cells are filled with an electrolyte made of lithium salts dissolved in an organic solvent, and then sealed. The particular electrode configuration depends on the cell casing.

After the cell casing is sealed, the cells are charged in a temperature-controlled environment to form the structural electrolyte interface. Cell formats range from a few amp-hours (Ah) capacities to almost 200 Ah. Cells are packaged into modules, usually configured based on the desired voltage. Collections of similarly configured modules are often referred to as packs, and several series of packs can be used to create MWh-scale storage applications. Both come in a wide range of formats depending on the intended application (Table 2-1).

2.1.2 Battery System Design and Site selection

A systematic approach was taken to determine the parameters that define the battery systems evaluated in this LCA. We created a list of stationary grid-scale storage projects from individual procurement plans proposed to the CPUC for installation by California IOUs. The California Public Utilities Commission (CPUC) has committed electric utilities to install 1.325 GW of electricity storage through a procurement mandate authorized by the legislature. [25] While the mandate includes a carve-out for customer sided electric storage, some of which may be owned by utilities, the majority is managed by the CAISO. [26]

Eleven installation sites were considered (Table 2-2). For each site, we simulate several LIB system designs to characterize a range of potential technical configurations. Three key design characteristics are used to simulate battery system designs: capacity (i.e. power capacity for charging and discharging; in MW), energy capacity (in MWh), and interconnection voltage level (transmission or distribution). Transportation distances between the site of installation and use and the site of EOL final disposition (see Section 3.4.1) are also estimated for each of the sites listed in Table 2-2 below.

Table 2-2
Sites for Stationary LIB Installations

Sites	Capacity (MW)	Energy Content (MWh)	Inter-connection Level	Location (City)
1	30	15	Transmission	Livermore
2	10	40	Transmission	Sebastopol
3	1	2	Distribution	Fresno
4	1	2	Distribution	Mendocino
5	0.5	2	Distribution	Browns Valley
6	100	400	Transmission	Long Beach
7	1.3	5.2	Distribution	Stanton
8	2.4	3.9	Distribution	Orange
9	30	80	Transmission	San Bernardino
10	7.5	30	Transmission	El Cajon
11	20	80	Transmission	Pomona

2.1.3 Product System Scenarios

The study uses scenario analysis to include parametric variability and quantify uncertainty in impact estimation. Scenarios were developed based on reasonable combinations of battery cell chemistries, cell formats, pack designs, duty cycles, siting and operating conditions, and end of life management practices. In total, 1584 scenarios were evaluated. Section 3 discuss how parameter values for each set of scenarios were developed; an overview of the scenarios is provided in Table 2-3.

Table 2-3
Description of Scenarios Considered in this Study

Installation Site and Duty Cycle	Pack Designs (PDS)	LIB Application	End of Life (EOL)
11 scenarios for installation sites representing variability in: • Dispatch profile • System Size • Installation/transportation • Climatic variation	12 scenarios for battery pack designs to reflect: • Different LIB cell chemistries • LIB pack configurations • Pack efficiencies	3 scenarios looking at different applications and patterns of utilization: • Electric Utility Services • Renewables Support • CCG Natural Gas Support	3 combined EOL scenarios: • Disposal • Disposal with Materials Recovery • Disposal with Materials Recovery and Cathode Recycling

2.2 Functional units

Three primary functional units for the LIB and reference flows from process outputs are used to capture battery impacts and product performance. Each impact category is reported in terms of the following functional units:

- per unit energy delivered (MWh)
- per installed capacity (kW)
- per unit time in (service hours for frequency response)

These were included to account for variability in system configuration, function, and operation conditions. To consider the potential increase in impacts for electricity delivered by a grid-tied battery system, impact scores are compared across the total throughput of the LIB system of its service life (in MWh). For comparison to siting other storage technologies, impacts are also presented by installed system capacity (kW). Finally, as there are many different use applications for the battery system, and the battery system can be providing value-added services when not being charged or discharged, impact scores are also presented divided by the total service hours delivered (in service hours for frequency response).

Total energy throughput of the battery during the service period is used as a normalization factor through the "*per unit energy delivered"* functional unit in this study. For every charge and discharge cycle, some energy is lost to inefficiencies in the battery system and to power thermal controls. In this study, the emissions associated with throughput energy losses are attributed to the battery system. Therefore, use-phase emissions (measured by any functional unit) reflect both the different efficiencies of the battery systems modelled, as well as the emissions associated with electricity generation.

2.3 System boundary setting

The study system boundary includes all life cycle processes included in raw material provision, refining, production, assembly, transport, installation, operation, maintenance, disposal, and potential recycling. Capital equipment and labor used in manufacture, disposal, transport, or to install LIBs are excluded from the system, as is typically the convention. Electricity generation and transmission infrastructure is also outside the system boundary. The system boundary for the study is depicted below. This study compares LIB chemistries; therefore, the system depicted focuses on battery production and assembly paired with appropriate use phase scenarios, including potential EOL management options and implications. The system boundary is shown in Figure 2-1.

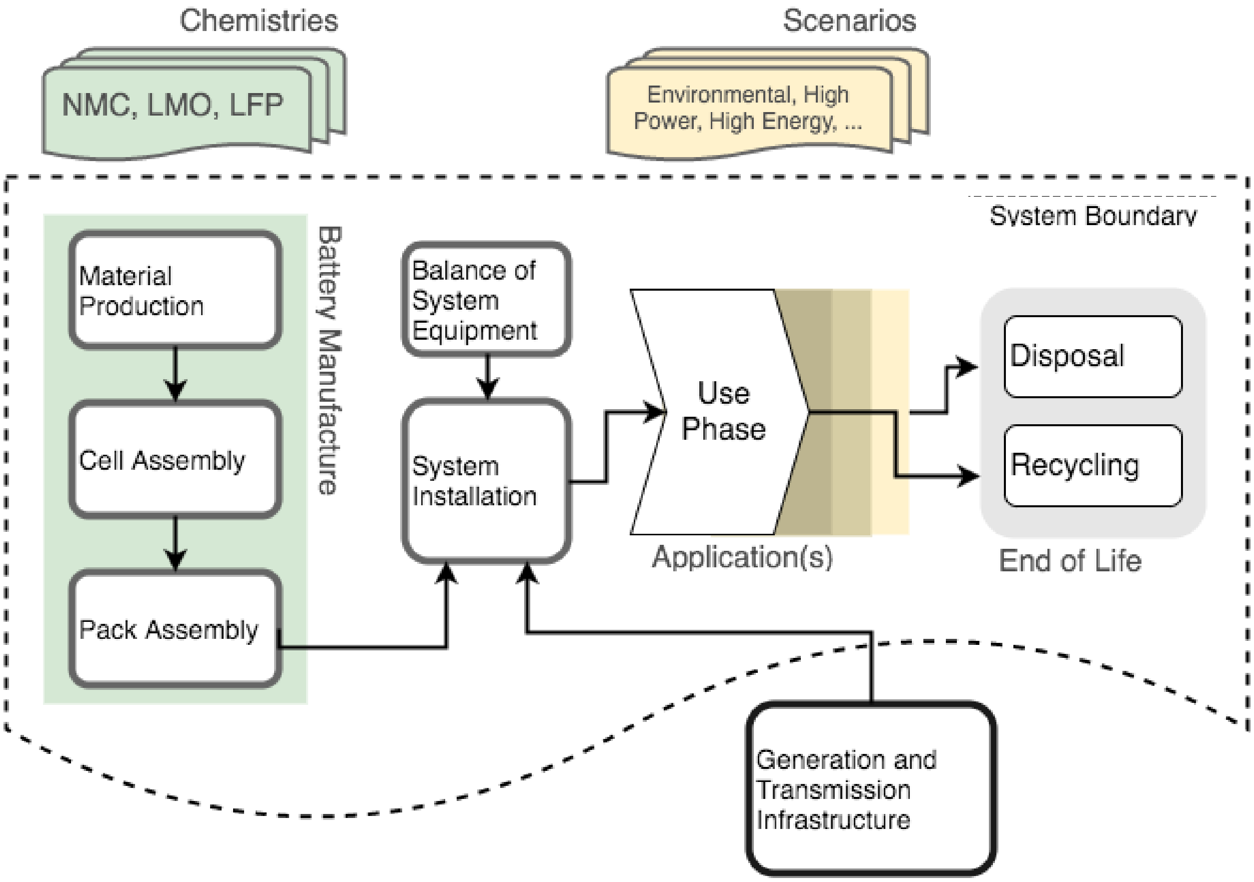


Figure 2-1
System boundary for this LCA

2.4 Allocation

For processes that are multifunctional - producing two or more products - consistent allocation rules are necessary to assign environmental burdens to those products. System expansion is the preferred approach to allocation in most energy LCA, including those used in public policy. System expansion can be used to allocate emissions by treating the co-products as substitutes to products in the market. System expansion involves considering the marginal alternative replaced by a co-product. When a co-product substitutes for a product in the market, that will result in avoided emissions from not producing the substituted product. In this study, allocation is used to attribute emissions that result from generating the electricity lost to round-trip efficiency. This energy loss is due to limits in the round-trip efficiency of the storage system, and is dependent on the storage duration, design, and other factors.

2.5 Impact assessment framework

Environmental impacts occur at each stage of production and the goal of LCA is to provide a full picture across all stages. A life cycle inventory (LCI) is prepared with data on material consumption and energy requirements. Once LCIs are complete, the impacts from each material in the inventory are compiled across all the materials and energy required. For example, if a battery contains lithium, cobalt, and aluminum, the GHG emissions from producing the specific amount needed for the device are compiled into a single GHG amount for the battery. Each input can have a number of environmental impacts to characterize, such as impacts to global warming, ozone depletion, freshwater pollution, or impacts to human health. Characterization is a process of normalization of impact to a standard unit, such as a CO_2 equivalent used for global warming potential (GWP). One widely used characterization method is the U.S. Environmental Protection Agency's (EPA's) Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI). [27] The impact category indicators provided by the TRACI framework allows every input in an inventory of a process to be characterized based on its impacts to various environmental media (air, seawater, freshwater, etc.). TRACI normalizes the impacts based on each input's relative contribution to the overall impact category. Changes in some environmental flows can have non-linear impacts on environmental impacts. TRACI indicators represent the following impact categories:

- **Global warming potential (GWP)** – mass of carbon dioxide (CO_2) equivalent emissions to air with the potential to contribute one unit of global warming. This combines emissions of CO_2, N_2O, CH_4, and other GHGs based on their relative contribution to radiative forcing on a 100-year time horizon

- **Acidification potential** – mass of emissions that contribute to acidic pollution expressed as equivalent hydrogen ions (H^+) from nitrogen and sulfur emissions to soil and water

- **Ozone depletion potential (ODP)** – mass of substances released to air that could deplete stratospheric ozone reported in chlorofluorocarbon-11 equivalents

- **Eutrophication potential** – mass of emissions to air and water that can enrich freshwater and coastal water bodies with nitrates or phosphates represented in nitrogen equivalents. These pollutants can accelerate biological productivity (growth of algae and weeds) and deplete oxygen in aquatic ecosystems

- **Photochemical smog formation potential** – mass of air emissions of NO_x, VOCs, and other ground level ozone forming chemicals reported in units of ozone equivalence. TRACI uses the maximum incremental reactivity method to estimate the likely tropospheric ozone smog formation potential from VOCs, which have several chemical fate pathways

- **Resource depletion** – mass of fossil fuel, volume of water, or area land use; context is critical to this indicator as different resources have different availabilities

- **Human health - particulate** – mass of air pollution emissions including particulate matter consisting of inhalable coarse particles between 2.5 and 10 microns ($PM_{10-2.5}$) in diameter and fine particles less than or equal to 2.5 microns ($PM_{2.5}$) and their precursors

- **Human health - cancer comparative toxicity unit** (CTU_{cancer}), human health non-cancer comparative toxicity unit ($CTU_{non-cancer}$), and ecotoxicity comparative toxicity unit (CTU_{eco}) – metrics that represent the emissions of known carcinogens and toxics to urban air, nonurban air, freshwater, seawater, natural soil, and agricultural soil based on a chemical fate model. Human health cancer aims to provide information about emissions known to cause human cancer. Human health non-cancer represents contributions to other kinds of toxicity. Ecotoxicity estimates freshwater or marine toxicity or damage.

Additional GWP characterization metrics and warming factors have emerged in the both government and academic literature. As an additional reference point, we also provide updated warming factors from the AR5, IPCC 5th Assessment, and time adjusted warming potentials that can capture the timing of emissions occurrence. [28]

2.6 Data requirements and collection methods

Previous LCA studies have identified large range of energy used during cell production and battery assembly, as well as a range of impacts under different use phase conditions. Data collection efforts focused on the second and third stages of battery production, namely: manufacturing and assembly, installation and use. We surveyed three groups of stakeholders—manufacturers, vendors, and utilities/integrators—for stationary LIBs to provide a clearer picture of key stages in the life cycle of LIBs.

Several options for data were explored in this research. The ideal data set would be a combination of supply chain data and LIB manufacturing data and bills of materials. Efforts to obtain bills of materials were unsuccessful despite extensive outreach efforts to LIB manufacturers. Primary information and data were initially sought from detailed surveys. A focused effort to identify survey subjects included correspondence with manufacturers, vendors, and electric utilities, as well as attendance at battery and storage conferences for in-person discussions. Three survey instruments and interview schedules were designed to collect data from battery cell manufacturers, third-party installers or system manufacturers, and utilities/integrators considering or employing LIBs respectively. A list of key contacts and players in the LIB industry across different segments of the value chain were compiled. Prospective respondents were identified from expert solicitation, industry membership, and company information. The team cultivated relationships with several LIB industry players through industry meetings and the teams' networks. Surveys were disseminated digitally through email and an online survey and data aggregation tool. Despite these efforts, and moving the process far along with several manufacturers and installers, most were, in the end, unwilling to share production data on batteries on the time scale needed, so we relied on secondary data sources for many of the materials in the inventory. The companies willing to share information were utilities and vendors of batteries. These data did not form a representative sample for our project, so survey data collection efforts were discontinued.

Fortunately, considerable LCI data for material inputs in LIB inventories are available. These material combinations can be refigured and scaled with the inventories for different battery chemistries. A life cycle inventory database was populated with information on environmental flows by obtaining relevant inventories for resources and energy flows. In some cases where data was unavailable or proprietary, proxy data was used, which is discussed further in Section 3.

LCIs for materials were sourced from the Ecoinvent database, Version 3.3. [29] Manufacturing energy inputs, cell performance characteristics, and material inventories were used to aggregate data into an LCI for each battery design scenario by chemistry. Mass balance information was used to scale material inventories, while process information was used to characterize energy flows. Sourcing information was used to distinguish potential geographically specific impacts, such as electricity generation mix, sourcing of reagents, or other consumable inputs. Data specification sheets from battery manufacturers were also used to gather general battery attributes.

Five interviews were conducted with two major e-waste recyclers, a reverse logistics company, a manufacturer, and a project integrator, to collect information and data about typical battery configurations and life cycle stages. These data helped inform the installation and EOL phases in particular, as these descriptions are lacking in the literature. These interview data complimented data obtained from battery manufacturer specification documentation. Data collection included information about material sourcing, production siting, product throughput, and process energy inputs for individual cell chemistries. Mass balance information, cycle life, capacity degradation, and general company information were also solicited. For the installation phase, the survey for retailers or third-party vendors focused on module and pack level performance characteristics, component sourcing, system lifetime data, and installation requirements (i.e. balance of system –BOS).

2.7 Limitations

The study's generalizability will be limited by the degree of primary data about battery production, performance characteristics, and composition that can be collected. As the use of these technologies in grid storage is still nascent, there are severe limitations on the amount of cycle life performance data available. This study addressed this need through the use of performance degradation modeling (see Appendix 2). LIB manufacturing scale is continuing to increase rapidly, and further changes to production systems are likely. This study is limited to consider only current technologies with minimal changes to background systems.

A key limitation of this study is that it does not consider feedbacks of deploying storage assets on the grid. Environmental impacts associated with the use of a grid-connected ESS depend on several factors. These include (1) the marginal generation mix used to charge the ESS, and that which would otherwise energize the grid during times of discharge, as well as (2) the round-trip ESS efficiency. The generation fuel mix, and the corresponding weighted average emissions intensity, vary with time of day. The times of day and frequency at which an ESS charges and discharges are therefore additional operational parameters that have significant implications for the use-phase environmental impact of the ESS. The extent to which ESS can displace generators at the margin, or traditional frequency or ancillary service generators from capacity markets, has been shown to be a potentially significant consequential impact of ESS and LIB use in utility systems. [30]

Where primary data is not available, and is the case for recycling processes, values were obtained from academic literature or other reporting. Due to the highly competitive nature of the LIB industry and the rapid growth in manufacturing, data on emerging processes and production is highly proprietary and despite several attempts, was not possible to obtain.

3

LIFE CYCLE INVENTORY ANALYSIS

This section describes the process model approach, battery production (i.e. Cradle-to-Gate) modeling, use-phase modeling and EOL management modeling used in this study. It closes with a summary of key assumptions used and their sources.

3.1 Process model approach

A process model describes a bottom-up approach to estimating the environmental flows resulting from different combinations of battery chemistry, product value chain, and use-phase application. For each sub-process in the product life cycle, inputs and production control decisions are modeled explicitly. Sub-process decisions are aggregated into an LCI, the summation of which is the estimate of the burdens for the product system as a whole. Sub-process uncertainty is treated through scenario analysis, which allows the study to support decision making by illuminating trade-offs.

Reference LCI data was obtained from the Ecoinvent database, Version 3.3. [31] Manufacturing energy inputs, cell performance characteristics, and material inventories were used to aggregate data into an LCI for each battery design scenario by chemistry. Mass balance information was used to scale material inventories, while process information was used to characterize energy flows. Sourcing information was used to distinguish potential geographically specific impacts, such as electricity generation mix, sourcing of reagents, or other consumable inputs. A full list of reference LCIs used in this study is provided in Appendix C.

3.2 Battery Production (Cradle-to-Gate) Modeling

Initial modeling and a review of published research revealed that battery lifetime, use application, round trip efficiency, and battery chemistry are important factors determining LCA outcomes in environmental assessments of stationary storage. [32] Other factors that contribute to production energy consumption include maintaining rigorously anhydrous assembly conditions, heating elements, and test cycling new cells to provide electrode interphase formation. [33]

For materials production, LCIs were compiled based on an inventory for each of the battery chemistries collected from the literature. Cell material composition was estimated using the Battery Performance and Cost Model (BatPaC 3.0), created by Argonne National Lab. For each pack design scenario, the percent composition by cell capacity is estimated and scaled with the system. Balance of system materials are expected to scale with system size, but with a non-linear or discontinuous (i.e. step wise) relationship to cell count.

To build the inventory up to the production gate, we first needed to assess battery system designs and estimate the corresponding mass and energy inputs for assembly. This study considers a range of potential cell sizes and types in order to quantify the effects of cell type on overall environmental impacts. A range of proprietary cell sizes and types are used to build stationary

LIB packs. For example, Tesla Motors, in partnership with Panasonic, has been developing cylinder format cells for use in both stationary and vehicle applications. The standard 18650 cell is one of the most widely produced lithium-ion batteries. With 3.2 to 3.4 Ah at 3.6-4.2 V, 18650s are scalable to a wide range of applications. The more recent 21700 cylindrical cell configuration have increased capacities by 25% (>5 Ah). NEC, like many other manufacturers, often employs large-format, prismatic pouch type cells. [34] There are a wide variety of formats for pouch type Li-polymer cells, owing in part to the fact that pouches can be cut and sealed to size almost any cathode configuration. Any given manufacturer can also employ a range of cell types in different pack configurations based on the desired performance. There are trade-offs in designing packs for high power output or long duration energy storage, and packs are traditionally configured primarily for one or the other application.

Depending on the chemistry of the electrodes, cell type, and dimensions, cells have different energy storage potential and nominal voltage. Based on assumptions about the electrochemical potential of cathode and anode couples, the composition of electrode binders and electrolyte, as well as dimensions of cell collectors, terminals, and enclosures, cell composition can be estimated. Table 3-1 details the assumptions used for this study to estimate cell composition, which were obtained from the BatPaC model.

Table 3-1
LIB Cell Chemistry Assumptions and Electrode Potentials from BatPac

	NCA-G	**NMC-G**	**LFP-G**	**LMO-G**
Cathode Capacity (mAh/g):	200	180	150	100
Anode Capacity, (mAh/g):	360	360	360	360
Positive Foil Material	Aluminum	Aluminum	Aluminum	Aluminum
Positive Foil Thickness (um)	20	15	20	20
Negative Foil Material	Copper	Copper	Copper	Copper
Negative Foil Thickness (um)	12	10	12	12
Cathode Active material (%)	95	95	95	95
Cathode Binder (%)	5	5	5	5
OCV at 20% SOC , V	3.551	3.565	3.246	3.826
Open circuit voltage at 50% SOC, V	3.68	3.75	3.282	3.954

Based on analysis of existing commercial offerings for stationary LIB systems, 12 pack design scenarios were selected to encompass a range of cell formats, module configurations, and cell chemistries. Table 3-2 summarizes technical information for each pack design scenario (PDS) that was used in this study. PDS 1-4 are based on cylindrical cells with a nickelate cathode material in a liquid cooled pack architecture. PDS 1-4 are also configured primarily for energy storage at the pack level, which we define as a power-to-energy ratio >1 hour. PDS 5—8 represent larger-capacity, prismatic pouch format cells relying on phosphate or manganese spinel cathode active materials. PDS 5-8 are configured for higher power densities and output. PDS 9-12, like PDS 5-8, are also composed of prismatic pouch cells using phosphate or manganese spinel cathode active materials, but are configured primarily for energy storage. PDS 5-12 also utilize an air-cooled system, as opposed to the liquid cooling thermal management in PDS 1-4. For PDS 1-4, each module has an active liquid cooling system to maintain operating temperature range. For PDS 5-12, the thermal management system includes passive module heat sinks and enclosures, with forced air circulation at the pack level. The liquid cooled system likely provides a more stable and narrow range of operating temperatures than the forced air circulation, but also requires additional materials and power requirements.

Table 3-2
LIB Pack Design Scenarios

Pack Design Scenario	Cell Size (Ah)	Cell Format	Cell Chemistry	Pack Energy to Power Ratio (Hours)	Pack Rated Power (kW)	Cells per Module	Cells in Parallel	Modules in Parallel	System Voltage (V)	Heat Transfer Fluid
PDS1	3.4	Cylindrical	NCA-G	4.2	50	1050	8	16	468.7	Ethylene Glycol
PDS2	5.1	Cylindrical	NCA-G	4.2	50	700	6	16	416.6	Ethylene Glycol
PDS3	3.4	Cylindrical	NMC-G	4.2	50	1050	8	16	468.7	Ethylene Glycol
PDS4	5	Cylindrical	NMC-G	4	50	700	6	16	417	Ethylene Glycol
PDS5	20	Pouch	LMO-G	0.3	136	56	2	1	785.5	Cool Air
PDS6	32	Pouch	LMO-G	0.3	136	36	1	1	811.7	Cool Air
PDS7	20	Pouch	LFP-G	0.3	136	56	2	1	785.5	Cool Air
PDS8	32.0	Pouch	LFP-G	0.3	136	36.0	1	1.0	811.7	Cool Air
PDS9	20.0	Pouch	LMO-G	2.0	52	62.0	3	2.0	811.7	Cool Air
PDS10	32.0	Pouch	LMO-G	2.0	52	40.0	2	2.0	1028.4	Cool Air
PDS11	20	Pouch	LFP-G	2	52	62	3	2	811.7	Cool Air
PDS12	32	Pouch	LFP-G	2	52	40	2	2	1028.4	Cool Air

Cell capacity is estimated as a function of pack and module configuration, given required pack energy storage and power output. The air-cooled systems (PDS 5 – 12) are assumed to have access to an air reservoir 5^{o}C cooler than the target performance temp and 15-20^{o}C cooler than effective average ambient temperature.

Table 3-3 shows the estimate mass composition for twelve different battery pack design scenarios obtained from BatPaC.

Table 3-3
Pack Design Scenario Mass Balances

Pack Design	Chemistry	Cathode	Aluminum	Graphite	Titanium	PVDF	Binder	Copper	Packaging	Electrolyte	Coolant	Plastics	BMS
PDS1	NCA	11%	24%	9%	0%	1%	1%	8%	36%	5%	2%	1%	1%
PDS2	NCA	14%	26%	12%	0%	1%	1%	10%	24%	7%	2%	1%	1%
PDS3	NMC	12%	24%	9%	0%	1%	1%	4%	37%	6%	3%	1%	1%
PDS4	NMC	12%	28%	14%	0%	2%	2%	5%	27%	5%	4%	2%	1%
PDS5	LMO	28%	32%	12%	0%	2%	2%	11%	1%	10%	0%	2%	1%
PDS6	LMO	30%	28%	13%	0%	2%	2%	11%	1%	10%	0%	2%	1%
PDS7	LFP	20%	34%	12%	0%	2%	2%	13%	1%	14%	0%	2%	1%
PDS8	LFP	21%	30%	13%	0%	2%	2%	14%	1%	15%	0%	2%	1%
PDS9	LMO	28%	31%	12%	0%	2%	2%	11%	1%	10%	0%	2%	0%
PDS10	LMO	30%	28%	13%	0%	2%	2%	11%	1%	10%	0%	2%	0%
PDS11	LFP	20%	34%	12%	0%	2%	2%	12%	1%	14%	0%	2%	0%
PDS12	LFP	22%	32%	13%	0%	2%	2%	12%	1%	15%	0%	2%	0%

Cell assembly is widely identified as an energy intensive process. Assembly processes were assessed based on two scenarios for probable ranges of cell throughput (low assembly, high assembly). Data on assembly energies and production wastes (i.e., cathode/anode trimming) were drawn from values published in the literature. [35] Table 3-4 shows the average assumed energy inputs across the pack design scenarios. Low assembly energy refers to a scenario where the efficiency of manufacturing throughput is high because it runs at high capacity. A high assembly energy scenario requires nearly double the energy per capacity of battery manufactured. In this scenario, he most significant energy inputs in the cell assembly process are attributable to drying and clean room requirements. The energy requirements for these two steps is significantly higher than in the low assembly scenario, while the energy requirement for other steps is similar across these two scenarios (Table 8). Pack assembly is assumed to require a small additional energy input from screwing, soldering, and other activities. It is assumed this contributes an additional 0.451 kWh/kWh of final pack weight. All assembly energy requirements are expected to be met with off-site generated electricity (e.g., no direct combustion of fossil fuels for heating).

Table 3-4
Estimated Assembly Energy Inputs (kWh / kWh capacity)

kWh / kWh	Mixing	Coating	Drying	Calendaring	Notching	Stacking	Welding & Sealing	Electrolyte Filling	Sealing	Charging	Dry room	Pack Assembly	Total
Low Assembly	0.952	1.557	5.382	3.288	6.143	6.663	2.163	5.105	0.865	1.163	3.375	0.451	37.11
High Assembly	0.952	1.557	26.910	3.288	6.143	6.663	2.163	5.105	0.865	1.163	16.873	0.451	72.13

Total assembly energy requirements estimated in Table 3-4 of 37 to 72 kWh/kWh of capacity fall towards the middle of published estimates in the literature, which varied from 18 to 760 kWh/kWh of capacity. Figure 3-1 provides a graphic representation of processes that contribute to cell assembly energy, and compares differences across cathode chemistries. For assembly energy, a market rate electricity inventory is used. Cell and pack assembly is assumed to occur in Asia or the US; reference LCI data was selected to represent the average industrial electricity generation sources for assembly energies. These inventories are listed in Appendix C.

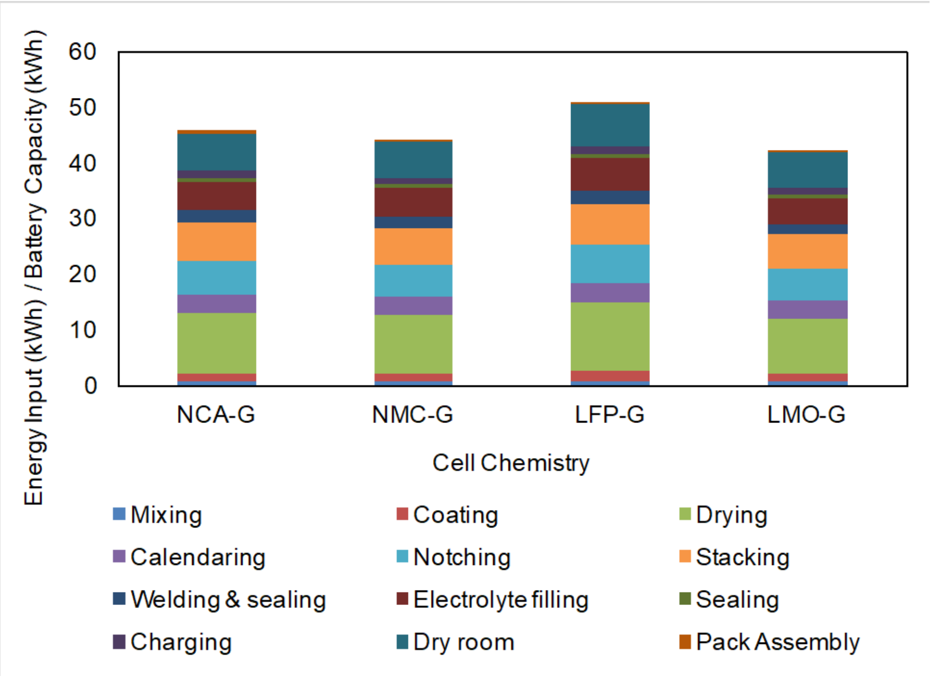


Figure 3-1
Cell Assembly Energy by Process

There is a wide range in estimates for energy requirements for LIB manufacturing, particularly for cell assembly. The key questions related to the accuracy of these results are onsite energy use and accuracy of inventories. The issue of the very wide range of estimated CED has been thoroughly reviewed by Peters (2018). This review highlights that “bottom-up” assessments produce lower estimates (<1.5 MJ/kWh), and the higher estimates come from top-down studies. This systematic discrepancy highlights the different value and methodological challenges that each approach provides. Bottom-up analyses are typically open and transparent, with the underlying data presented for review. However, these often can be incomplete, or require a number of assumptions where required data are not publicly available. Top-down analyses are typically opaque, with the underlying data that supports the final reported values not provided. The opacity of top-down analyses prevents detailed comparison to other analyses, and prevents other LCA practitioners from analyzing the reasons for the systematic difference between top-down and bottoms-up analysis. Therefore, both approaches should be used whenever possible, and the two scenarios selected in this study were chosen to represent each of these approaches respectively.

Based on the site specifications, we then estimate the number of packs and industrial inverters necessary for each installation site based on the site power requirements. Table 3-5 shows the estimated packs and inverters for each site by pack design scenario. 500 kW industrial inverters are assumed for each system site and included in the installation impacts.

Table 3-5
Pack Requirements by Site and Pack Design Scenario (PDS)

Pack Design Scenario	Packs Required										
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
PDS1 - 4	600	200	20	20	10	2000	26	48	600	150	400
PDS5 - 8	221	74	7	7	4	735	10	18	221	55	147
PDS9 - 12	577	192	19	19	10	1923	25	46	577	144	385
Inverters	60	20	2	2	1	200	3	5	60	15	40

3.3 Use Phase Modeling

3.3.1 Use phase scenario overview

The use phase portion of the assessment modeling provides estimates of battery lifetime, total throughput, and energy lost to charge and discharge cycles (i.e., allocation), as well as transportation to the installation cite and the balance of systems (including industrial inverters.

The use phase inventory includes:

- Installation and balance of systems components (i.e. inverters)
- Thermal management and operational housekeeping power
- Roundtrip energy loses to internal resistance

Storage can and is installed to meet a variety of grid services. Grid system operators are increasingly valuing services like ramping and frequency response and are developing markets in response. The intended grid service has an impact on the storage system design and duty cycle characteristics. The characteristics of the duty cycle will in turn affect the length of service in the use phase, as well as the estimates of environmental burdens by way of the functional unit. We define the duty cycle to be the number, frequency, and depth of discharge events experienced over the expected service life of the battery system.

As discussed in section 2.2, eleven installation sites were identified based on projects procured under the California Energy Storage Mandate. [36] Transportation and dispatch profiles were simulated for each site (Table 3-6). The next section discusses the duty cycle simulation in more detail.

The unit mass transport distance by mode was estimated to each of the installation sites from the sites for each pack design scenario (Table 3-6). Modal reference LCI data (i.e. ocean freight, rail, and on-road) was used to estimate impacts for each transportation link.

Table 3-6
Average Freight Installation Distance by PDS and Site

Pack Design Scenario	**Installation thousand ton-kilometer**										
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
PDS1 - 4	690	**285**	**15**	**35**	**15**	**25**	**2**	**4**	**137**	**56**	**55**
PDS5 - 8	138	**48**	**6**	**7**	**1**	**1118**	**13**	**24**	**281**	**87**	**194**
PDS9 - 12	318	**110**	**14**	**16**	**3**	**2578**	**31**	**56**	**648**	**200**	**447**

With the exception of ocean-going vessels, all transportation is assumed to occur by on-road, class 7-8 truck based on Ecoinvent 3.3 (Transport freight, lorry 16 – 32 tonnes (EURO4)). This corresponds to a class 8 truck meeting 2005 model/engine year emissions standards, with a cargo capacity of ~60,000 lbs.

3.3.2 Dispatch Model

The operation of the battery system was simulated using an economic dispatch model of electricity system operations. The EPRI Storage Value Estimation Tool (StorageVET). StorageVET is a publicly available, web based, energy storage simulation tool that allows for estimating the site-specific value of storage in the California ISO region. [37] The model solves for the optimal dispatch of storage assets given other generation assets, transmission infrastructure, local pricing, and demand. The StorageVET model was used to estimates bids for frequency regulation and spinning reserves, as well as the rate and duration of system dispatch for each site (Table 3-7).

The key inputs to StorageVET were the size and capacity of the battery systems, and the local marginal electricity prices for the nearest distribution nodes to the battery sites. Local marginal price data was retrieved from the California Open Access Same-time Information System (OASIS). [38] Locational marginal pricing (LMP) is a method for wholesale markets to reflect the spatially and temporally dynamic value of electricity. As LMPs vary throughout the year due to patterns of load, generation, and physical limits of transmission infrastructure, LMPs reflect the inherent variability in system operations and locational value of storage. Two representative months were selected to capture key climatic differences between summer and winter operation. The average LMPs for the two nearest nodes to each storage installation were obtained from the OASIS database for January and August of 2017.

Table 3-7
Description of StorageVET Simulation Outputs

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Capacity (MW)	30	10	1	1	0.5	100	1.3	2.4	30	7.5	20
Storage (MWh)	15	40	2	2	2	400	5.2	3.9	80	30	80
Winter Up/Down Frequency Bid (MWh)	1080	462	47	47	23	4606	60	114	1409	342	921
Winter Spinning Reserve Commitment (MWh)	0	16	1	1	1	188	2	2	37	15	38
Winter Dispatched (MWh/day)	38	56	4	4	3	563	7	8	142	45	112
Winter Cycles/day to 80%DOD	3	2	2	2	2	2	2	2	2	2	2
Winter Average C-Rate	0.10	0.45	0.30	0.28	0.45	0.45	0.45	0.23	0.37	0.49	0.45
Summer Up/Down Frequency Bid (MWh)	1058	422	43	43	21	4262	55	106	1314	309	851
Summer Spinning Reserve Commitment (MWh)	5	20	1	1	1	201	3	2	36	19	39
Summer Dispatched (MWh/day)	29	47	5	3	2	451	6	7	116	50	92
Summer Cycles/day to 80%DOD	2	1	3	2	2	1	1	2	2	2	1
Summer Average C-Rate	0.10	0.39	0.44	0.27	0.42	0.38	0.38	0.22	0.32	0.57	0.39

Table 3-6 describes the simulated operations for each system for each period of pricing data. The quantity of energy storage was assumed to be limited to 80% of the rated capacity of the LIB system to prevent excessive wear on the battery. Figure 3-2 also provides a graphical view of the simulated dispatch profile by site for each month. The right (y) axis's show inputs to or outputs of power by the battery system, while each facetted panel moving down corresponds with the 11 installation sites (S1 to S11), for each hour of the month.

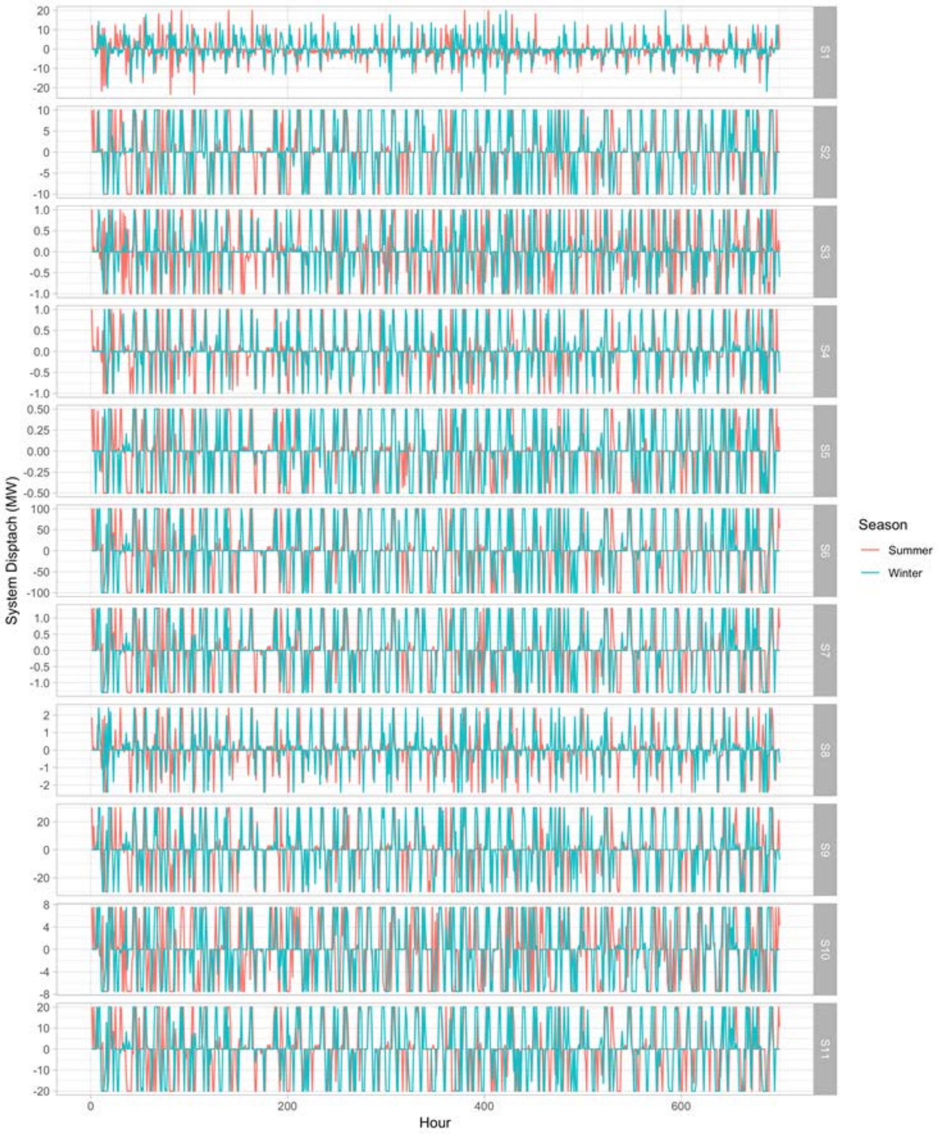


Figure 3-2
Simulated Dispatch Profiles by Installation Site and Season

Calendar aging effects also occur in LIBs due to storage at SOC and ambient temperature conditions. LIBs that experience higher temperatures during charge cycling or storage can see accelerated capacity degradation. Calendar ageing effects are less well understood, and accelerated testing usually exploits the effects of increased temperature. Calendar aging and cycle aging are highly correlated, and are almost impossible to disaggregate in operations. Constant discharge tests could yield a poor estimate of real world battery performance, where average discharge rates are low (<C/2, a battery that discharges half its capacity in one hour), but high power requirements occur at different intervals and frequency.

Battery degradation ultimately determines the effective service life of a battery, which in this context refers to the ability of the battery to meet a particular duty cycle. In this study, battery degradation is simulated based on energy throughput and calendar ageing affects. Battery capacity loss and impedance increase will eventually result in the need for removal or replacement. A linear model for battery decay is employed to capture both the increasing resistance, as well as the diminished capacity over the battery life. More information on the battery degradation model and battery degradation literature data is available in Appendix B.

Battery degradation and throughput were estimated for a service period of 10 years. Figure 3-3 shows the projected system capacity degradation by site and chemistry. In some cases, the battery capacity is significantly degraded by the end of the ten-year period.

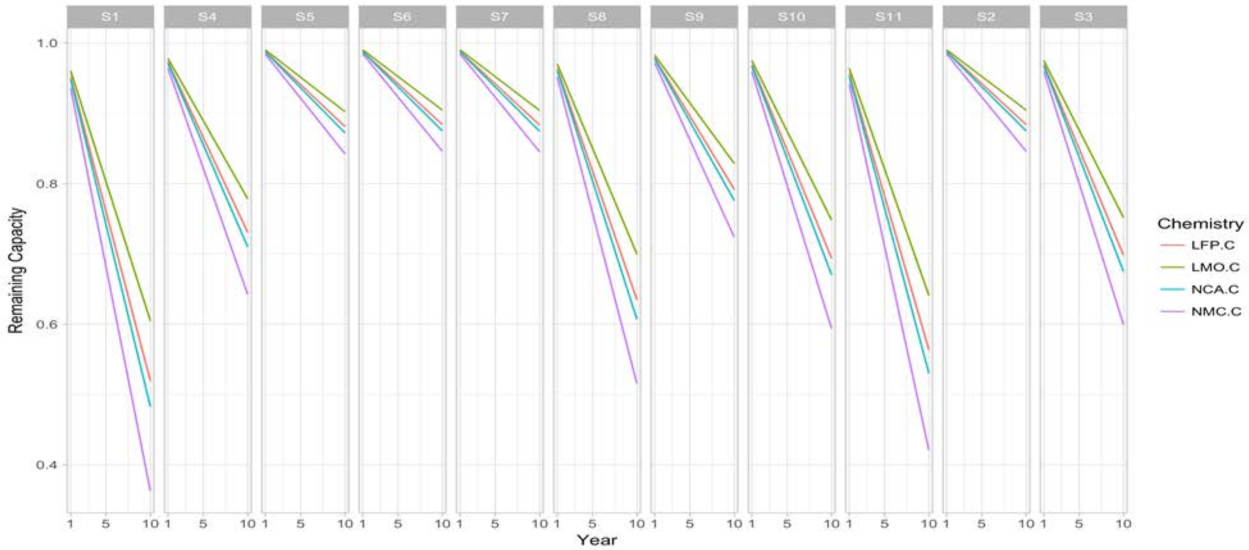


Figure 3-3
Estimated Battery Degradation by Site and Chemistry

Table 3-8 shows the average energy losses attributed to round trip energy efficiency by pack design scenario and cell chemistry. The inverse of these values represents the roundtrip energy efficiency of the LIB system, which on average we found to by 89%, in-line with literature values. [39] The total delivered energy and throughput losses are then estimated based on the remaining LIB battery capacity and average LIB system efficiency for each year of operations.

Table 3-8
Average Round-trip Energy Losses in MWh

Pack Design Scenario	Cell Chemistry	Average lifetime Throughput Losses (MWh/MWh)
PDS1	NCA	0.108
PDS2	NCA	0.108
PDS3	NMC	0.096
PDS4	NMC	0.096
PDS5	LMO	0.119
PDS6	LMO	0.119
PDS7	LFP	0.112
PDS8	LFP	0.112
PDS9	LMO	0.119
PDS10	LMO	0.119
PDS11	LFP	0.112
PDS12	LFP	0.112

3.4 EOL Management Modeling

The final stage we examine to provide a full picture of the full life cycle impacts is the EOL phase. LIBs taken out of service can be repurposed, remanufactured, recycled and/or sent to disposal. [40] Management pathways and processes considered for EOL LIBs are based on plausible outcomes identified in the literature and from information solicited from experts at EOL battery management companies, utilities, and battery equipment suppliers for the management. The focus of the present analysis is on materials recovery/recycling of LIBs in the EOL. We consider also consider the impacts of decommissioning and management of potential waste flows based on existing disposition routes.

The primary route for EOL management in this LCA model proceeds along the following pathway based on information collected through interviews with key waste management industry experts. More information on the interviewees is provided in an Appendix D. Decommissioning starts with either the (1) onsite disassembly or (2) removal of batteries to a disassembly site via reverse logistics to the supplier’s factory. Batteries are disassembled to the cell level, separating out plastics and metals used in the housing. After initial disassembly, metals and plastics recovered are sent to standard recycling facilities or waste transfer station for materials recovery and recycling. This initial disassembly is mainly with manual human labor.

Total system mass includes inverter and any cooling equipment. The total system mass is assumed to be transported offsite at EOL. Some disassembly occurs onsite, but only a portion of the system mass is passed on to shredding and smelting and ultimate recovery, due to separation of inverters and most (structural) enclosure materials. A standard unit mass distance LCI value from Ecoinvent 3.3 is used to estimate impacts for system delivery and transport (Transport freight, lorry 16–32 tonnes (EURO4)). This corresponds to a class 8 truck meeting 2005 model/engine year emissions standards, with a cargo capacity of ~60,000 lbs.

Once batteries are disassembled to the cell-level, cells are shredded into metals and plastic fluff. The shredding process, used in electronics scrap recycling, used electricity to power the equipment. Plastic fluff is sent to plastics recycling and the remaining metal parts of LIB cells are sent to a smelter for materials recovery or disposal at a waste facility. Table 13 shows the geographic locations modeled to estimate impacts from transporting EOL LIBs. Based on personal communications with experts in 2017, the geographic regions to which EOL LIBs are sent from California are the Pacific Northwest, the Northeast, and the Southeast regions of the US. We assume these sites are near port facilities and chose Trail, British Columbia, and Lancaster, Ohio, as the smelter locations, and Raleigh, North Carolina as the hub for export to Brussels, Belgium, where lithium can be recovered. There are no known recyclers or waste management companies able to process LIBs across the American Southwest, including none in California. This means that LIBs installed in California will travel significant distances in advance of investment in local recycling infrastructure.

The number and specific materials recovered at smelters varies spatially by region and temporally with changing prices and LIB material compositions. We assume four materials are recovered in all scenarios: nickel, cobalt, aluminum, and copper, based on both interview data and literature review. [41] We also consider manganese recovery in an alternative scenario. An economic screen is typically used to identify the range of materials that would be saleable in secondary markets, but the research literature points to only four to six metals recovered.

Inventory data on EOL management processes were drawn from values found in the literature and databases. Processes for LIB battery flows were reconstructed based on personal communications with electronic waste (e-waste) management experts. The process used in this study has three main steps:

1. Disassembly and decommissioning
    - onsite by waste management company
    - hauling to shredding facility
2. Shredding LIB cells to plastic fluff and metals
    - Hauling to plastic recycler
    - Hauling to Metal recycler
    - Energy for shredding

3a. Scrapping cells

- Energy for scrappage
- Burden for material disposal

3b. Smelting cells for metal materials recovery

- Energy for recovery of aluminum copper
- Credits for avoided primary metal us

3c. Smelting cells for precious metal recovery

- Energy for recovery of Cathode material
- Credits for recovered nickel and cobalt

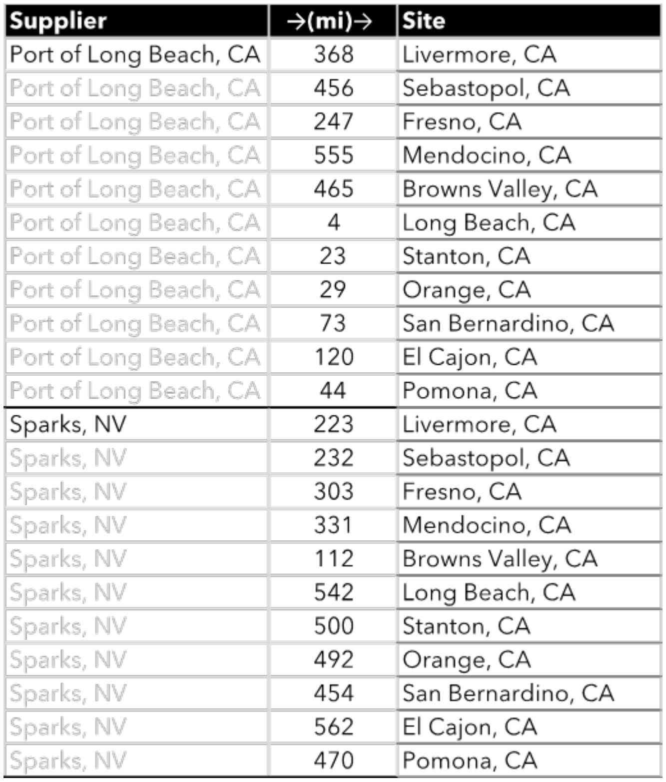
The reporting metrics for this phase of the LCA include cumulative energy demand, greenhouse gas emissions, acidification, smog formation, eutrophication, and several human health indicators (cancer, non-cancer, and criteria pollutants). We also compare economic value of recovered materials to cumulative energy demand. As LIB recycling and disposal systems have yet to scale to maturity, battery EOL was included primarily to document existing EOL practices.

3.4.1 Collection and hauling

This process describes all of the transportation activities of decommissioning, collection, and delivery of LIBs to final recovery or disposal sites. We assume that collection of utility-scale LIBs involves transport via heavy-duty truck. While rail would have fewer impacts, several accidents with EOL LIBs has led rail operators to avoid transporting LIBs. After disassembly, all materials require transportation to a final destination. The distances to those destinations are meant to reflect hypothetical route distances from California installations to disposal sites. Since there are no know smelters in California, LIBs are shipped to the northwest, southeast, and northeast. Relevant data is shown in Table 3-9.

Since EOL LIBs are regulated devices requiring strict adherence to hazardous waste management laws, we assumed all stationary storage was formally disposed of by the manufacturer, vendor, or a waste management company. Emissions factors were taken from GREET or Ecoinvent to model the emissions and energy use from heavy-duty truck transport. Embodied energy from sorting and hauling equipment and infrastructure is excluded. The inventories included here are energy for electricity, wastewater, and transportation fuels.

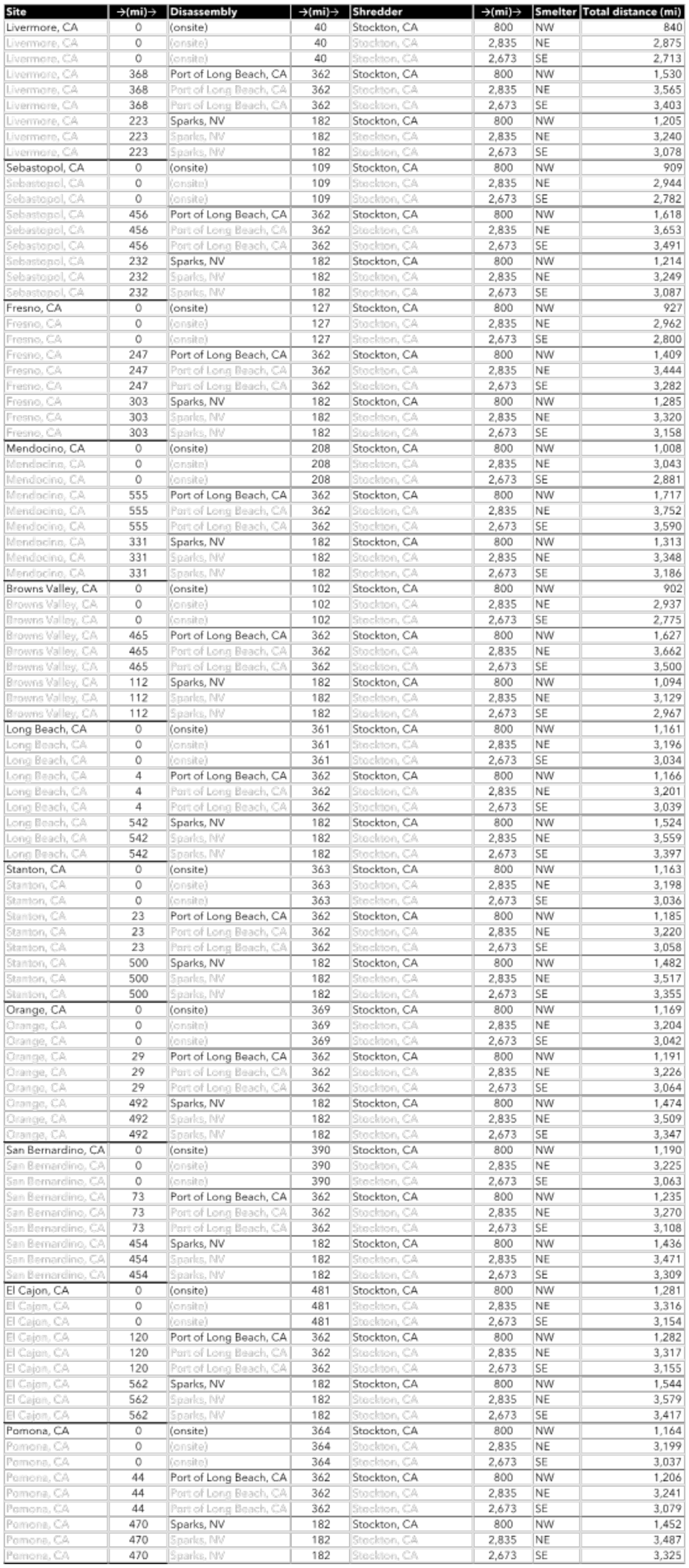
Table 3-9
Transport distance from Supplier to Installation Sites



Supplier	→(mi)→	Site
Port of Long Beach, CA	368	Livermore, CA
Port of Long Beach, CA	456	Sebastopol, CA
Port of Long Beach, CA	247	Fresno, CA
Port of Long Beach, CA	555	Mendocino, CA
Port of Long Beach, CA	465	Browns Valley, CA
Port of Long Beach, CA	4	Long Beach, CA
Port of Long Beach, CA	23	Stanton, CA
Port of Long Beach, CA	29	Orange, CA
Port of Long Beach, CA	73	San Bernardino, CA
Port of Long Beach, CA	120	El Cajon, CA
Port of Long Beach, CA	44	Pomona, CA
Sparks, NV	223	Livermore, CA
Sparks, NV	232	Sebastopol, CA
Sparks, NV	303	Fresno, CA
Sparks, NV	331	Mendocino, CA
Sparks, NV	112	Browns Valley, CA
Sparks, NV	542	Long Beach, CA
Sparks, NV	500	Stanton, CA
Sparks, NV	492	Orange, CA
Sparks, NV	454	San Bernardino, CA
Sparks, NV	562	El Cajon, CA
Sparks, NV	470	Pomona, CA

Transport at EOL is assumed to occur over three potential distances: to disassembly, to shredder, and to smelter. Table 3-10 shows the estimated travel distances for these EOL legs. The range of distances is from 4 miles in Long Beach, which is assumed to be close to a site of EOL management and export, to 555 miles in Mendocino where EOL LIBs must be hauled far distances before they can be eventually exported.

Table 3-10
EOL Transport Distances



Site	→(mi)→	Disassembly	→(mi)→	Shredder	→(mi)→	Smelter	Total distance (mi)
Livermore, CA	0	(onsite)	40	Stockton, CA	800	NW	840
Livermore, CA	0	(onsite)	40	Stockton, CA	2,835	NE	2,875
Livermore, CA	0	(onsite)	40	Stockton, CA	2,673	SE	2,713
Livermore, CA	368	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,530
Livermore, CA	368	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,565
Livermore, CA	368	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,403
Livermore, CA	223	Sparks, NV	182	Stockton, CA	800	NW	1,205
Livermore, CA	223	Sparks, NV	182	Stockton, CA	2,835	NE	3,240
Livermore, CA	223	Sparks, NV	182	Stockton, CA	2,673	SE	3,078
Sebastopol, CA	0	(onsite)	109	Stockton, CA	800	NW	909
Sebastopol, CA	0	(onsite)	109	Stockton, CA	2,835	NE	2,944
Sebastopol, CA	0	(onsite)	109	Stockton, CA	2,673	SE	2,782
Sebastopol, CA	456	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,618
Sebastopol, CA	456	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,653
Sebastopol, CA	456	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,491
Sebastopol, CA	232	Sparks, NV	182	Stockton, CA	800	NW	1,214
Sebastopol, CA	232	Sparks, NV	182	Stockton, CA	2,835	NE	3,249
Sebastopol, CA	232	Sparks, NV	182	Stockton, CA	2,673	SE	3,087
Fresno, CA	0	(onsite)	127	Stockton, CA	800	NW	927
Fresno, CA	0	(onsite)	127	Stockton, CA	2,835	NE	2,962
Fresno, CA	0	(onsite)	127	Stockton, CA	2,673	SE	2,800
Fresno, CA	247	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,409
Fresno, CA	247	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,444
Fresno, CA	247	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,282
Fresno, CA	303	Sparks, NV	182	Stockton, CA	800	NW	1,285
Fresno, CA	303	Sparks, NV	182	Stockton, CA	2,835	NE	3,320
Fresno, CA	303	Sparks, NV	182	Stockton, CA	2,673	SE	3,158
Mendocino, CA	0	(onsite)	208	Stockton, CA	800	NW	1,008
Mendocino, CA	0	(onsite)	208	Stockton, CA	2,835	NE	3,043
Mendocino, CA	0	(onsite)	208	Stockton, CA	2,673	SE	2,881
Mendocino, CA	555	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,717
Mendocino, CA	555	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,752
Mendocino, CA	555	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,590
Mendocino, CA	331	Sparks, NV	182	Stockton, CA	800	NW	1,313
Mendocino, CA	331	Sparks, NV	182	Stockton, CA	2,835	NE	3,348
Mendocino, CA	331	Sparks, NV	182	Stockton, CA	2,673	SE	3,186
Browns Valley, CA	0	(onsite)	102	Stockton, CA	800	NW	902
Browns Valley, CA	0	(onsite)	102	Stockton, CA	2,835	NE	2,937
Browns Valley, CA	0	(onsite)	102	Stockton, CA	2,673	SE	2,775
Browns Valley, CA	465	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,627
Browns Valley, CA	465	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,662
Browns Valley, CA	465	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,500
Browns Valley, CA	112	Sparks, NV	182	Stockton, CA	800	NW	1,094
Browns Valley, CA	112	Sparks, NV	182	Stockton, CA	2,835	NE	3,129
Browns Valley, CA	112	Sparks, NV	182	Stockton, CA	2,673	SE	2,967
Long Beach, CA	0	(onsite)	361	Stockton, CA	800	NW	1,161
Long Beach, CA	0	(onsite)	361	Stockton, CA	2,835	NE	3,196
Long Beach, CA	0	(onsite)	361	Stockton, CA	2,673	SE	3,034
Long Beach, CA	4	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,166
Long Beach, CA	4	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,201
Long Beach, CA	4	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,039
Long Beach, CA	542	Sparks, NV	182	Stockton, CA	800	NW	1,524
Long Beach, CA	542	Sparks, NV	182	Stockton, CA	2,835	NE	3,559
Long Beach, CA	542	Sparks, NV	182	Stockton, CA	2,673	SE	3,397
Stanton, CA	0	(onsite)	363	Stockton, CA	800	NW	1,163
Stanton, CA	0	(onsite)	363	Stockton, CA	2,835	NE	3,198
Stanton, CA	0	(onsite)	363	Stockton, CA	2,673	SE	3,036
Stanton, CA	23	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,185
Stanton, CA	23	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,220
Stanton, CA	23	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,058
Stanton, CA	500	Sparks, NV	182	Stockton, CA	800	NW	1,482
Stanton, CA	500	Sparks, NV	182	Stockton, CA	2,835	NE	3,517
Stanton, CA	500	Sparks, NV	182	Stockton, CA	2,673	SE	3,355
Orange, CA	0	(onsite)	369	Stockton, CA	800	NW	1,169
Orange, CA	0	(onsite)	369	Stockton, CA	2,835	NE	3,204
Orange, CA	0	(onsite)	369	Stockton, CA	2,673	SE	3,042
Orange, CA	29	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,191
Orange, CA	29	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,226
Orange, CA	29	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,064
Orange, CA	492	Sparks, NV	182	Stockton, CA	800	NW	1,474
Orange, CA	492	Sparks, NV	182	Stockton, CA	2,835	NE	3,509
Orange, CA	492	Sparks, NV	182	Stockton, CA	2,673	SE	3,347
San Bernardino, CA	0	(onsite)	390	Stockton, CA	800	NW	1,190
San Bernardino, CA	0	(onsite)	390	Stockton, CA	2,835	NE	3,225
San Bernardino, CA	0	(onsite)	390	Stockton, CA	2,673	SE	3,063
San Bernardino, CA	73	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,235
San Bernardino, CA	73	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,270
San Bernardino, CA	73	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,108
San Bernardino, CA	454	Sparks, NV	182	Stockton, CA	800	NW	1,436
San Bernardino, CA	454	Sparks, NV	182	Stockton, CA	2,835	NE	3,471
San Bernardino, CA	454	Sparks, NV	182	Stockton, CA	2,673	SE	3,309
El Cajon, CA	0	(onsite)	481	Stockton, CA	800	NW	1,281
El Cajon, CA	0	(onsite)	481	Stockton, CA	2,835	NE	3,316
El Cajon, CA	0	(onsite)	481	Stockton, CA	2,673	SE	3,154
El Cajon, CA	120	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,282
El Cajon, CA	120	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,317
El Cajon, CA	120	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,155
El Cajon, CA	562	Sparks, NV	182	Stockton, CA	800	NW	1,544
El Cajon, CA	562	Sparks, NV	182	Stockton, CA	2,835	NE	3,579
El Cajon, CA	562	Sparks, NV	182	Stockton, CA	2,673	SE	3,417
Pomona, CA	0	(onsite)	364	Stockton, CA	800	NW	1,164
Pomona, CA	0	(onsite)	364	Stockton, CA	2,835	NE	3,199
Pomona, CA	0	(onsite)	364	Stockton, CA	2,673	SE	3,037
Pomona, CA	44	Port of Long Beach, CA	362	Stockton, CA	800	NW	1,206
Pomona, CA	44	Port of Long Beach, CA	362	Stockton, CA	2,835	NE	3,241
Pomona, CA	44	Port of Long Beach, CA	362	Stockton, CA	2,673	SE	3,079
Pomona, CA	470	Sparks, NV	182	Stockton, CA	800	NW	1,452
Pomona, CA	470	Sparks, NV	182	Stockton, CA	2,835	NE	3,487
Pomona, CA	470	Sparks, NV	182	Stockton, CA	2,673	SE	3,325

3.4.2 Disassembly

Disassembly processes require human labor, fuel, and electricity needed to separate the cells from the rest of the device. The first stage in disassembly is to take apart the entire storage system (onsite or at a disassembly facility), down to the cell level, resulting in waste streams of plastics, metals, and LIB cells from connectors, wires, and structural elements. Before entering the recycling process lines, LIBs are drained of glycol chemicals if used as a coolant.

The second stage is to further shred battery cells into plastic fluff and metals. Materials that arrive at the collection site are typically sorted with manual labor, sometimes using a conveyance or conveyor belt at a separate sorting plant or a facility with all processes in place on site. Shredding involves sorting, breaking batteries to pieces, and using magnets to further sort out plastics, steel, and other metals. The next step sends materials through a hammermill, which involves breaking LIBs into smaller bits. From the hammermill the materials are sent through a filter press, where mixed metal oxides are recovered from the filter cake. These processes can separate LIBs into fluff (plastic compounds), copper cobalt, and economically valuable metals (cobalt, copper, aluminum, and nickel).

3.4.3 Processing for materials recovery

Formal management of EOL LIBs can result in (1) materials recovery using hydrometallurgical processes, (2) materials recovery using pyro-metallurgical processes, such as elemental recovery at smelting facilities, (3) disposal at hazardous waste disposal facilities, and (4) repurposing or remanufacturing for reuse. While all four are widely documented in prior research, our EOL scenario focuses on elemental recovery at smelting facilities because no other practices are currently in commercial operation according to our interviews with waste experts.

Recycling of cathode and anode materials can be done by hydrometallurgical recovery, which is common aqueous chemical approach to recycling batteries. Feedstock materials for hydro-metallurgical recycling processes include limestone, acid (citric acid or sulfuric), anti-foaming chemicals, and peroxide. Electricity, propane, natural gas, and water use (including hydrated lime and chemical solutions) were also considered on a per-mass processed basis. Waste products from this EOL management pathway include wastewater emissions (Co, Cu, Ni), emissions to air (SO_2, VOCs), and other solid waste disposal (paper and plastics). However, we determined this was not a pathway for current LIBs installed in California.

This process was considered but not included because there is no evidence it is a common practice. Direct reuse of some materials in EOL LIBs makes them candidates for recycling. For example, battery pack containers might warrant reuse. Repurposing, or second-life, is possible for some battery systems due to the unique characteristics of the battery degradation. Even with diminished capacity, some short cycle duration, low DOD applications could be appropriate. Given the falling cost of batteries, and the lack of a strong secondary market, this scenario was left outside of the scope of this LCA.

High value materials that can be recovered from LIBs at smelting facilities include cobalt, nickel, aluminum, manganese, and copper. The ability to recover materials depends on the characteristics of the waste stream and ultimately the economics of materials recovery. Researchers from Argonne National Labs suggest that cobalt recovery is the primary driver of

LIB recycling, although quantities contained in successive generations of battery designs may change this in the future as cobalt percentages go down. [42]

Some research points to the possibility of lithium recovery, but most analysts find the low concentrations to be uneconomical. However, Umicore commercially recovers lithium via a smelting process. Soda ash is used to precipitate lithium carbonate. Gaseous emissions are sent to a scrubber before being released to air. Data from Toxco suggest that recovery rates for LIBs using physical separation are around 60%. [43] Recovered materials can be of low quality due to contamination and co-mingling of different cathode materials, which can raise processing costs and lower economic motivators for LIB recycling. Low value materials that may be recycled from LIBs include plastics, coolant, thermal enclosure materials, and circuit boards.

The main EOL management pathway in this study is elemental recovery at a smelter. Also known pyro-metallurgy, it uses thermal approaches to materials recovery. Typically, after sorting, the first process would be pyrolysis. Waste gases are sent for filtration while the mass left behind is sent to an induction furnace, where some metals can be condensed. However, with the safety concerns around the flammability of LIBs, alternative approaches have been developed. This involves first crushing the batteries, then neutralizing them in solution. Wastewater emissions, heavy metals disposal, emissions to air, and other solid waste disposal are outputs considered in this LCA. The inventory for pyro-metallurgical approaches includes NaOH, water, and electricity. Outputs include iron and steel for recycling, cobalt powder, non-ferrous metals (aluminum), and manganese powder. Air emissions are particulate matter and SO_2. Wastewater effluents include Cl ions and SO_2. Plastic solid wastes were assumed incinerated.

Smelters are designed to recover elements and salts and are a likely destination for formally managed EOL LIBs. The high temperatures of the smelting process leads to the destruction or incineration of organic materials (plastics, solvents, and carbon electrodes) in the LIB, with some energy recovery for fuel. Key materials recovered in this route are nickel, copper, iron, and cobalt, which are granulated and sent to refineries for reprocessing into cobalt and nickel chloride solutions. [33] Lithium and aluminum recovered is contained in slag that is added to concrete, although hydrometallurgy may be used when prices and technological development warrant it. [44] Umicore claims a 93% recovery rate for LIBs (metals 69%, carbon 10%, plastics 15%). [45] Major emissions from smelting include those from energy use, and emissions of furans and dioxins. Bag filters on flue gases and high temperature processing mitigate most gaseous emissions in the smelter inventory. For this inventory, a proxy smelter inventory from a European facility is used.

3.4.4 Displaced production

We considered two fates for materials recovered: open-loop versus closed-loop. Closed-loop means that the materials feed back into the supply chain for LIBs, whereas open-loop implies that the recycled materials inventory is used across multiple industry sectors. It is assumed that cobalt recovered re-enters the supply chain as a salt. Lithium re-enters the supply chain as Li_2CO_3. Plastics and other metals used in the rack/module for the cells are recycled to similar products when removed during the disassembly phase.

The recycled content allocation approach is used as the default scenario and the EOL (avoided burden) recycling approach is used in a sensitivity analysis. Where secondary production results in the reduction of primary production and an "avoided burden," each material may not displace on a 1:1 basis, so each material is assigned a displacement factor. Where the displacement factor is < 1, this means that secondary production does not prevent all primary material and energy production.

Because most LIBs manufactured to date are in active service, there is little data characterizing the waste streams of dedicated or commingled LIB recycling schemes. System expansion (ISO 2006) is applied and environmental benefits and environmental impacts beyond the system boundary are quantified (e.g., using the EOL [avoided burden] recycling approach); these benefits and loads shall be reported separately. The benefits and impacts shall be quantified in relation to the net amount of surplus secondary materials or fuels leaving the product system (all outputs of a secondary material minus all inputs of that secondary material, see also EN 15804).

Table 3-11
Displacement factors for EOL materials

Secondary product	Displaced product	Displacement factor
Cobalt chloride		Cobalt sulfide
Nickel chloride		Nickel sulfide
Recycled Copper	Virgin copper	
Recycled Aluminum	Virgin aluminum	

Not all materials are considered to have economic value. For example, carbon black and graphite are considered low recycling priorities. All materials without an economic value are assigned a disposal cost.

4

LIFE CYCLE ASSESSMENT

In this section, we review the results of the environmental impact assessment. The first section provides the results for each functional unit. The second section focuses on the relative contribution to each impact category across life cycle stages. The subsequent sections describe the key findings from the scenario analyses.

4.1 Impacts by Functional Unit

The study considered three functional units of system performance:

- Kilowatts (kW) of installed capacity
- Megawatt-hour (MWh) energy delivered
- Service hours for frequency response

These were included to account for variability in system configuration, function, and operation conditions. The life cycle assessment model estimates the quantity of substances emitted to the environment. These are then input into the TRACI characterization model to generate environmental impact scores for different categories of environmental impact. To consider the potential increase in impacts for electricity delivered by a grid-tied battery system, impact scores are divided by the total energy delivered by the battery system over its service life. For comparison to siting other storage technologies, the impacts are divided by the installed capacity. Finally, as there are many different use applications for the battery system, and the battery system can be providing value-added services when not being charged or discharged, impact scores are divided by the total service hours the system delivers.

Table 4-1 shows the results for each functional unit and impact category averaged across the 11 study sites with the (minimum/maximum) scores in parenthetical. In Table 3-11, each category is displayed in the standardized units discussed in Section 2.5 of this report. A ten-year service life is assumed for all sites. On average, systems delivered the equivalent of 690 cycles to 80% of their capacity per year, with the most utilized system averaging 2.4 charge/discharge cycles per day, and the lowest the equivalent of 1.6 cycles, to 80% DOD. Total delivered energy (e.g., throughput) varied considerably by site and system size; from 952 MWh per year for the 0.5MW/2MWh Browns Valley site (S5), to 195,263 MWh per year for the planned 400 MWh Long Beach system (S6). Even when holding system size constant, impacts also varied by service provision. This is observed as all systems are assumed to deliver a constant service hours. The minimum impact values in Table 4-1 were near zero due to the influence of assumed recovery of key metals during recycling and crediting for displaced primary materials.

Impacts of battery use on emissions of greenhouse gases are of chief concern owing to the commonly invoked role of LIBs in supporting renewable electricity generation. When normalized to per MWh delivered, impact scores represent an estimate of the additional intensity for energy supplied back to the grid by the battery system.

Table 4-1
Average Final Impact Score by Functional Unit with (min/max)

TRACI	kW Installed	MWh Delivered	Service Hours	
Acidification	7.4 (0,26)	0.6 (0.1,2.5)	0 (0.1,0.6)	*kg SO2 eq*
Ecotoxicity	158.7 (0,494)	13.3 (2.9,63.9)	-0.1 (1.6,27.5)	*CTUeco×10²*
Eutrophication	14.2 (0,54)	1.1 (0.1,4.1)	0.2 (0.2,1)	*kg N eq*
GWP	1700.3 (0,6651)	123.6 (7.6,450.3)	30.2 (28.7,114.7)	*kg CO2 eq*
Humanpartic	5.6 (0,23)	0.4 (0,1.4)	0.1 (0.1,0.3)	*PM2.5 eq*
HumantoxCAN	0 (0,0)	0 (0,0)	0 (0,0)	*CTUcancer*
HumantoxNC	0 (0,0)	0 (0,0)	0 (0,0)	*CTUnoncancer*
ODP	0 (0,0)	0 (0,0)	0 (0,0)	*kg CFC-11 eq*
Resources	1396.8 (30,5341)	102 (6.2,347.3)	36.7 (23.4,114.6)	*kg fossil resource*
Smog	72.2 (0,257)	5.6 (0.5,22.8)	0.8 (1,6.2)	*kg O3 eq*

With a 95% confidence interval on the mean GWP emissions by site, the LIB system adds between 37 to 208 kg of CO_2e per MWh of energy delivered. This compares to an average greenhouse gas intensity of electricity used to charge battery systems from the California utility grid of 362 kg/MWh. This conclusion has important caveats, as it does not incorporate:

- Use of otherwise curtailed renewables that are enabled by storage;
- Avoided gas emissions (e.g., from avoided peaker startups)

And is based on a geographically and temporally specific region (e.g., California) and is likely to vary across regions due to the significant differences in electricity generation technologies and fuels utilized.

On the basis of installed capacity, we see that every kW of installed LIB capacity is associated with the emissions of approximately 70 kg of ozone equivalents, 5.5 kg of fine particulate aerosols, and 1.6 metric tons of CO_2 equivalents. This aggregation obscures a important differences in power to energy ratio for these systems which varied by up to a factor of 4.

Production of battery systems have significant impacts on acidification, ecotoxicity, and human health attributable to electrode materials. These impacts are driven by two sets of processes: raw material recovery and processing and sources of industrial heat and energy in cell assembly. Pollution impacts, including ecotoxicity and eutrophication, are also driven by the production of batteries and cathode materials. The production of virgin aluminum from bauxite for collector foils and packaging was a significant contributor to overall impact scores. We found the impacts of cathode materials were driven primarily by material refining processes, specifically hydrometallurgical processes assumed in the lithium carbonate reference data. The carbonate reference data primarily reflects production from brines, which also have limited mining impacts or activities. We also observe that particulate emissions are highly sensitive to the source of industrial energy generation for inputs of heat and electricity in cell assembly.

4.2 Contribution by Life Cycle Stage

The scope of this study covered: the cradle to gate (CTG) phase, including raw material acquisition, battery production, and assembly; the use-phase, including system installation and battery cycling; and the end of life (EOL), which includes decommissioning, disposal, and recycling. Due to the role of ESS and LIBs in emissions reductions policies, particularly climate emissions reduction goals and increased renewables integration, this section focuses on characterizing the emissions from LIB ESS use.

Figure 4-1 shows the relative contribution of each life cycle stage to the impact score per MWh delivered. Over the battery life cycle, the CTG phase is an important contribution to ecotox, humantox, and to a lesser degree acidification potential and smog potential. These impacts are primarily attributable to producing battery electrode materials, and to a lesser extent cell assembly process (~10%). The impacts of emissions of GHGs, ozone, smog, and particulate matter are more evenly due to CTG and use phases. CTG phase is dominant in many impact categories, but use phase is a substantial contributor to all categories. Use-phase emissions primarily depend on the generation technologies used to charge battery systems as compared to those displaced. The impacts varied considerably by system site depending on the functional unit used for evaluation. This was attributable to two primary factors:

- The service portfolio/duty cycle – the extent to which systems were utilized (e.g. dispatched) varied by site
- The system size – systems with the lowest energy capacities were dispatched less on average, and had lower throughput

The use phase impacts are relatively higher contributions for ¾ of the categories based on emissions GWP, human particulate, and ODP (Figure 4-1). Across the range of scenarios considered, approximately 75% of use-phase impact scores were associated with electricity generation emissions. Transportation to site, construction, and balance of system components, including industrial inverters contributed the remainder to use-phase burdens. While CTG burdens are significant, variation in impact scores across sites and EOL pathways was much larger than variability across cell chemistries or pack designs.

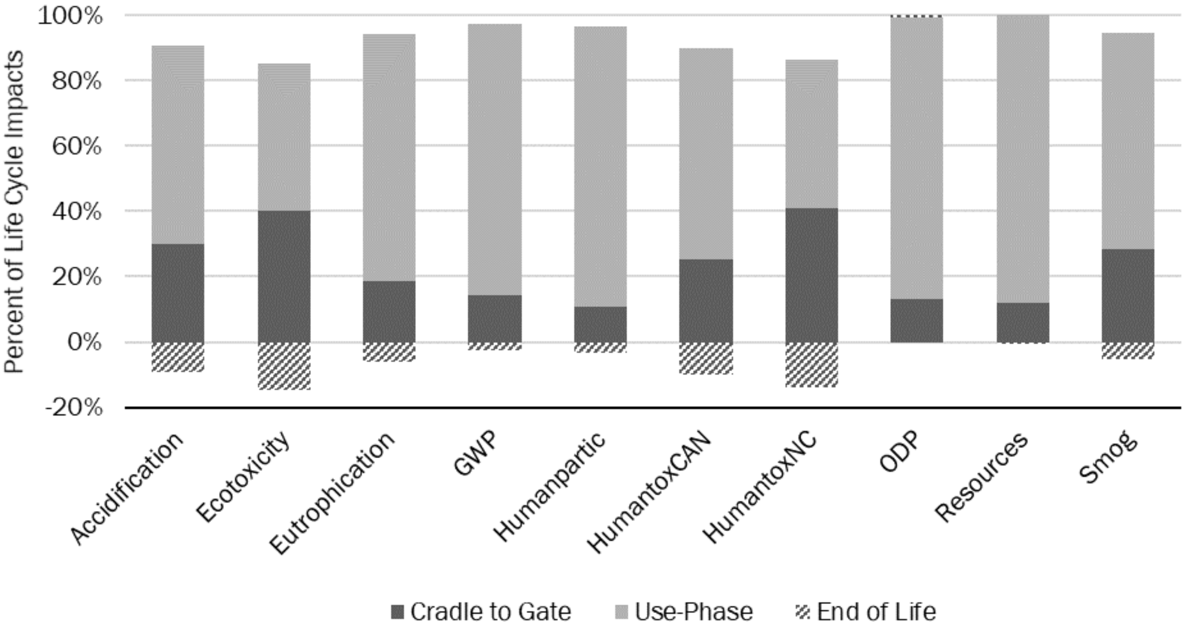


Figure 4-1
Relative Contribution to LCA Results by LCA Stage per MWh Delivered

The study considered two potential EOL pathways for battery systems: disposal with recycling, disposal with recycling and recovery of cathode materials. The study assumes that recycled and recovered materials displace virgin battery materials where appropriate, and assigns a displacement credit to the battery at the EOL stage. This results in a negative impact score for EOL processes in some cases, as reflected in Figure 4-1.

Table 4-2 shows the average EOL impacts for the disposal scenarios excluding any recycling processes. The opportunity for recycling to offset or reduce EOL impacts are in avoiding emissions associated with ecotoxicity and GWP impacts. Table 3-11 does not include any estimate of the impacts of landfilling or otherwise storing remaining battery components as waste indefinitely. As impacts of un-managed wastes could be significant, these values should not be construed as the worst case or default for management LIB systems at EOL. Rather, this speaks to the potential impacts of decommissioning, transporting, and preparing battery wastes for recycling or other formal waste management.

Table 4-2
Average Impacts by Functional Unit for LIB System Disposal (Without Recycling)

TRACI	per kW Installed	per MWh Delivered	per Service Hour
Acidification	0.0	0.00	0.01
Ecotoxicity	68.5	1.92	16.49
Eutrophication	0.0	0.00	0.00
GWP	21.4	0.60	5.16
Humanpartic	0.0	0.00	0.00
HumantoxCAN	0.0	0.00	0.00
HumantoxNC	0.0	0.00	0.00
ODP	0.0	0.00	0.00
Resources	16.2	0.48	4.10
Smog	1.0	0.03	0.25

Table 4-3 lists the impacts scores per kW of installed capacity by LC stage. The impact scores are relative proportions by life cycle phase. The EOL scenarios considered in the study resulted in a wide range of implied burdens. When recycling credits are not included, impacts from disposal are minimal (Table 4-2). The impact category with the biggest improvement due to recycling was ecotoxicity, which had benefits under both metals recovery and cathode materials recovery scenarios. Recycling had little effect on estimates for human health impacts, or ozone depletion potential. Emissions reductions potential from recycling is driven primarily by the displacement of copper and aluminum. Recovery of cathode materials are more chemically and energy intensive than production of primary resources. Therefore, the scenarios that included full cathode material recovery showed increased impacts in some categories, namely GWP and smog. We discuss this further in the section on end of life.

Table 4-3
Impact Scores per kW Installed by Life Cycle Stage

TRACI	Cradle to Gate	Use-Phase	End of Life	
Acidification	2.7	5.5	-0.8	*kg SO2 eq / kW Installed*
Ecotoxicity	90.2	101.8	-33.3	*CTUeco×10² / kW Installed*
Eutrophication	3.0	12.2	-1.0	*kg N eq / kW Installed*
GWP	254.6	1493.6	-48.0	*kg CO2 eq / kW Installed*
Humanpartic	0.6	5.2	-0.2	*PM2.5 eq / kW Installed*
HumantoxCAN	0.0	0.0	0.0	*CTUcancer/ kW Installed*
HumantoxNC	0.0	0.0	0.0	*CTUnoncancer/ kW Installed*
ODP	0.0	0.0	0.0	*kg CFC-11 eq / kW Installed*
Resources	167.7	1229.6	-0.6	*kg fossil resource / kW Installed*
Smog	23.0	53.5	-4.3	*kg O3 eq / kW Installed*

4.3 Cradle to Gate Impacts

The key contributions to impacts during the CTG phase include extraction and refining of raw materials, transportation, production of battery cathode materials and cells, as well as assembly of LIB systems. As observed in the literature, there are a wide range of estimates for energy required to assembly LIB cells. Therefore, the study considered a range of assembly energies based on a bottom up modelling of cell assembly processes. We find those energy inputs to range from 3.6 to 66 kWh of energy required for every kWh of pack capacity, with the most efficient cell assembly scenarios requiring 7.2 kWh/kWh on average.

Despite the wide range of cell assembly energies considered, impacts were primarily found to be driven by battery materials. Figure 8 shows the relative contribution of production and assembly processes versus materials to the burdens in each impact category. More than 50% of impacts on acidification, ecotoxicity, smog, and human toxicity on a per MWh of delivered electricity were attributable to emissions from the CTG phase. In addition, 25% of impacts on GWP per MWh were also attributable to the CTG phase. With the exception of ozone depletion (ODP), these impacts were driven almost entirely by battery electrode materials (~80%). The contribution of assembly to CTG and overall impacts is discussed further in section 5.

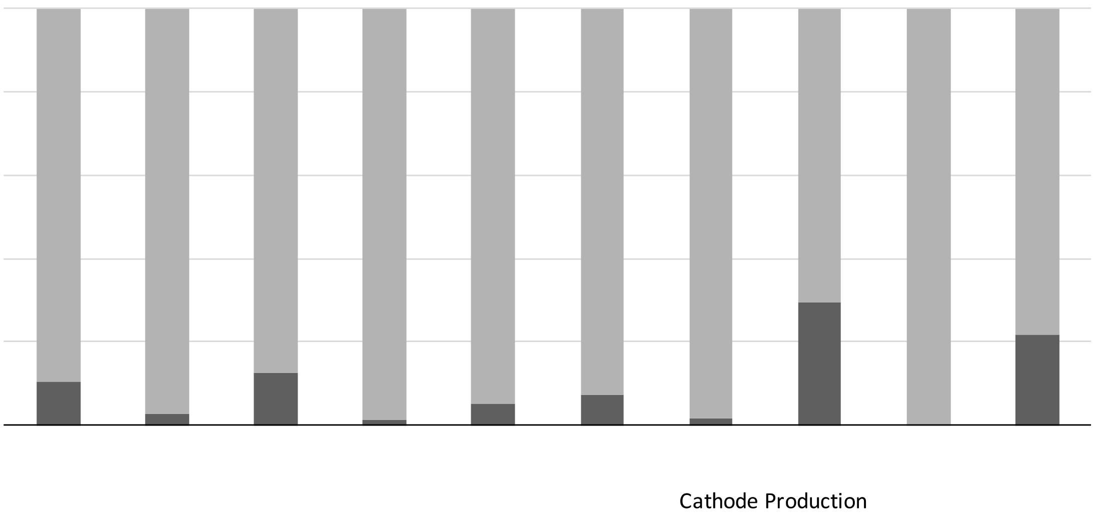


Figure 4-2
Materials vs. Cell Production and Assembly CTG Impacts per KWh installed

In other words, the contribution of assembly energies to either CTG emissions, or total impacts scores, were less than associated with battery materials and less than 10% on average of total burden (Table 4-4).

Table 4-4
Materials and Cell Production Contribution to CTG

	Contribution of Cell Production Energy to CTG Impacts	Contribution of Cell Production Energy to Total Impact Score
Acidification	6% - 11%	3% - 6%
Ecotoxicity	2% - 3%	1% - 2%
Eutrophication	7% - 13%	3% - 6%
GWP	1% - 2%	<1%
Humanpartic	3% - 6%	1% - 2%
HumantoxCAN	4% - 9%	2% - 4%
HumantoxNC	1% - 3%	~ 1%
ODP	19% - 30%	6% - 12%
Smog	13% - 22%	6% - 12%

4.4 Use-Phase Impacts

Across the range of scenarios considered, emission associated with electricity generation were more than 75% of use-phase impact scores. Therefore, use-phase emissions, and in some cases overall impacts, are associated with the generation technologies used to provide electricity for charging battery systems vs displacement. This also means that overall emissions profile can vary strongly across applications.

Table 4-5 shows the overall impact scores for three scenarios of electricity generation, all reported per MWh delivered: (1) 100% renewables; (2) representation of the average California grid after 2045 [46]; and (3) 100% natural gas (the LIB ESS is assumed to support a combined cycle electric generation unit). The renewables support scenarios assumed photovoltaics are the only electricity generating technology. Renewables scenarios result in lower impacts due to the low emissions associated with generation, lower and cycle frequency, which also results in lower overall lifetime throughput. When ESSs are charged using electricity from fossil generators, the net emissions intensity of the electricity provided from storage increases according to the inverse of the round-trip efficiency. To the extent that battery systems are supporting fossil generators, they will proportionally increase the emissions intensity of electricity in proportion to the overall efficiency of battery charge cycles. Degradation of round-trip efficiency accelerates as batteries age, which is a secondary effect not reflected in the average total burdens listed in Table 4-5.

Table 4-5
Use-phase Impact of grid-connected LIB (per MWh Delivered) for different Electricity Generation Scenarios

TRACI	Renewables Support	Average CA Grid	Natural Gas Support	
Acidification	0.3	0.6	0.8	*kg SO2 eq / MWh Delivered*
Ecotoxicity	9.6	13.1	17.1	*CTUeco×10²/ MHw Delivered*
Eutrophication	0.3	1.1	1.7	*kg N eq / MWh Delivered*
GWP	37.2	125.4	208.3	*kg CO2 eq / MWh Delivered*
Humanpartic	0.1	0.4	0.7	*kg PM2.5 eq / MWh Delivered*
HumantoxCAN	0.0	0.0	0.0	*CTUcancer / MWh Delivered*
HumantoxNC	0.0	0.0	0.0	*CTUnoncancer / MWh Delivered*
ODP	0.0	0.0	0.0	*kg CFC-11 eq / MWh Delivered*
Resources	31.6	103.6	170.8	*kg fossil resource / MWh Delivered*
Smog	2.9	5.5	8.3	*kg O3 eq / MWh Delivered*

When sited for explicitly for renewables support, use-phase GWP impacts decrease to 37.2 kg CO2e/MWh compared to 125.4 kg CO2e/MWh on average for the grid tied systems. CTG burdens represent 75% of the impact score, and use phase was 20-25%, on average in the renewables scenario. In the natural gas support role, CTG phase was 10%, and use phase emissions increased to 188 kg CO2e/MWh delivered (90%).

4.5 End of Life Impacts

EOL processes include system decommissioning, transportation, battery disassembly and scrappage, smelting, and material recovery processes. The base scenario assumes that recycled and recovered materials displace virgin battery materials where appropriate, and assign a displacement credit to the battery at the EOL stage. This can result in a negative impact score for some categories, owing to the fact that recovered materials reduces the burdens caused by providing additional raw materials for replacement battery systems.

Table 4-6 shows the impact scores for EOL processes divided by the lifetime MWh delivered. Decommissioning, transportation, and disassembly (including shredding, but not smelting), have some impacts to GWP and local pollution, primarily attributable to heavy equipment use. Recovery of module and electrode materials like aluminum and copper provide significant benefits due to the large mass of these materials in battery systems, as well as the energy intensity of producing virgin materials. The displaced emissions from metals recovery are potentially much larger than emissions associated with decommissioning, resulting in a net environmental benefit due to recycling.

Table 4-6
EOL phase Impacts of grid-connected LIB (per MWh delivered from storage) for different EOL Scenarios

TRACI	Disposal	Metals Recovery	Cathode Recovery	
Acidification	0.0	-0.9	-0.4	*kg SO2 eq / MWh Delivered*
Ecotoxicity	0.8	-34.1	-30.4	*CTUeco×10²/ MHw Delivered*
Eutrophication	0.0	-1.0	-0.7	*kg N eq / MWh Delivered*
GWP	23.9	-71.9	147.6	*kg CO2 eq / MWh Delivered*
Humanpartic	0.0	-0.2	-0.1	*kg PM2.5 eq / MWh Delivered*
HumantoxCAN	0.0	0.0	0.0	*CTUcancer / MWh Delivered*
HumantoxNC	0.0	0.0	0.0	*CTUnoncancer / MWh Delivered*
ODP	0.0	0.0	0.0	*kg CFC-11 eq / MWh Delivered*
Resources	18.3	-18.9	137.3	*kg fossil resource / MWh Delivered*
Smog	1.1	-5.4	1.0	*kg O3 eq / MWh Delivered*

As described previously, recovery of the cathode materials is a more energy and reagent intensive process than production of cathode ingredients from primary materials. While the displaced materials (e.g., cobalt, nickel, lithium), are also of high value and have significant impacts associated with production, there is relatively little of these materials in a finished battery system (less than 1% lithium by mass in the LIB system) compared to the energy required to remove it. Consequently, recovery of cathode materials resulted in an increase in impact score for some categories, most notably GWP and resources. This suggests that a “full recycling” program could result in higher emissions attributable to battery system use depending on the recycling facility or technology.

5
SENSITIVITY ANALYSIS

In the previous section, we identified several key factors affecting the environmental impacts associated with the siting of stationary LIB systems. Impacts from local pollutants were driven primarily by battery and material manufacturing processes. Depending on the application and utilization, the use-phase resulted in significant impacts to GWP.

The severity of impacts was strongly affected by the choice of EOL pathway and materials crediting. As shown in the results section, material crediting resulted in a strongly negative credit for EOL for most impact categories, and significantly changed overall impacts. Cathode material recovery, while having a number of benefits, resulted in strong increases in GWP. Here we discuss a few of the key sensitivities we identified above.

The impacts of cell assembly energy are discussed extensively in academic literature; cell assembly is an energy intensive process and requires strong humidity controls which increase energy demands. Despite the emphasis on quantifying energy inputs in discussions of LCAs of LIB systems, relatively little primary data is available. Published studies also show a ride range of estimates for cell assembly energies, from 3 to 96 kWh energy input per kWh of cell capacity. The present study considers a wide range of values for energy intensity of cell manufacturing, but no emissions associated with energy for cell assembly never exceeded 5% of the total impact score. Per kW of installed capacity, 66%-75% of impact scores were attributable to emissions associated battery materials.

As an example, here we highlight two scenarios for battery assembly: one, approximately 37 kWh of assembly energy input per kWh of cell capacity; and two, 72 kWh per kWh of cell capacity. In both cases, we assume assembly energy is electricity generated by a mix of renewable and gas resources. While halving the assembly energy inputs did have impact on the overall inventory, the sensitivity of the inventory was limited as assembly energy was only a modest driver of impacts for most categories. Table 5-1 shows the share of CTG impacts attributable to cell assembly energy inputs for each scenario, as well as the total impact score. For the 37 kWh scenario, assembly energy contributes 1% - 18% of the total impact score (depending on impact category; 5-1). In the 72 kWh scenario impacts increase to 2%-36% of burdens (depending on impact category). In particular, impacts to ozone depletion and smog formation were the most sensitive to assumptions of cell assembly energy. For GWP, cell assembly contributed a maximum of 5%.

Table 5-1
Impact of Assembly Energy on Impacts

TRACI	Average CTG Impacts	Low Assembly Energy (% of CTG)	High Assembly Energy (% of CTG)
Accidification	50708.4	6%	11%
Ecotoxicity	166586336.7	1%	3%
Eutrophication	54342.5	6%	11%
GWP	4810420.4	3%	5%
Humanpartic	11836.7	3%	5%
HumantoxCAN	1.0	3%	7%
HumantoxNC	10.4	1%	2%
ODP	0.4	18%	36%
Smog	416471.7	10%	20%

There was significant variation across sites in transportation distances. Table 3-10 shows the EOL transport distances, which also reflect a portion of the installation transportation distance. While transportation of systems to and from the installation site was not a significant driver of overall impact scores, it was the main contributor to EOL disposal emissions. As our model of decommissioning activities focused on transportation and disassembly, transport was 70%-82% of impacts for disposal only, when excluding recycling.

We also explored two other potential applications for the range of LIB systems modelled: one, specifically to support renewables integration; and two, to support a combined cycle natural gas power plant (CCGT). In the renewables scenario, systems are assumed to preform daily arbitrage, cycling once per day at the respective system capacity with generation from a utility scale (>500kW) photovoltaic facility. The second (CCGT) scenario, looks at systems employed to support ramping and avoid low load level operation to support more efficient combined cycle natural gas turbine operations. [47] The CCGT scenario, assumes batteries are cycled at higher frequency (3/day) with lower depths of discharge (~60%DOD).

These scenarios resulted in significant changes to estimated impact scores, which were primarily due to differences in the emissions associated with throughput energy losses. Even considering a range of potential efficiency benefits for the CCGT operation identified in the literature, [48] GWP impacts increase by nearly a factor of 4. Alongside this, the renewables (PV) support scenario resulted in lower total throughput and lower emissions associated with throughput losses and housekeeping power. As the battery utilization is lower in PV integration, impact scores increase when measured against the total MWh delivered, instead of kW installed.

Figure 5-1 shows the variability in contribution of the use-phase (dark blue) to overall impact scores normalized to the total MWh delivered by each site/system. Variability in impacts across sites was much greater than variability across chemistries or pack designs, indicated that impacts are primarily affected by the dispatch, utilization, and types of generation technologies used to charge batteries. Impacts were generally higher for the smaller systems (S2 – S5), both when considered on the basis of installed capacity and total throughput. This could be indicative of variability in dispatch profiles across sites. Due to the limitations of the current study, it would require further research to draw these types of conclusions. Some construction commissioning activities and land transformation were not included, which could serve to increase impacts for larger installations. This study did not test the effects of system size on location, or conduct additional sensitivity analysis with respect to system design and dispatch profile. Despite the variability in specific dispatch signals between sites, the StorageVET results suggest that *on average*, systems were infrequently operated at their capacity and delivered approximately 1-3 times their maximum energy content in any given day.

Table 5-2
Storage Site Power to Energy Ratio

Site	Capacity (MW)	Energy Content (MWh)	Power/Energy Ratio	Inter-connection Level	Location (City)
S1	30	15	2	Transmission	Livermore
S2	10	40	0.25	Transmission	Sebastopol
S3	1	2	0.5	Distribution	Fresno
S4	1	2	0.5	Distribution	Mendocino
S5	0.5	2	0.25	Distribution	Browns Valley
S6	100	400	0.25	Transmission	Long Beach
S7	1.3	5.2	0.25	Distribution	Stanton
S8	2.4	3.9	0.62	Distribution	Orange
S9	30	80	0.38	Transmission	San Bernardino
S10	7.5	30	0.25	Transmission	El Cajon
S11	20	80	0.25	Transmission	Pomona

Site 1 was somewhat unique among the scenarios due to its high power to energy ratio (Table 5-2). While the dispatch model suggests the S1 had higher utilization of energy storage content than average, it had one of the lowest rates of capacity (e.g., power) utilization (Table 3-7). S1 also resulted in a higher share of CTG impacts, which both related to the high power system design, as well as the low level of throughput and capacity utilization.

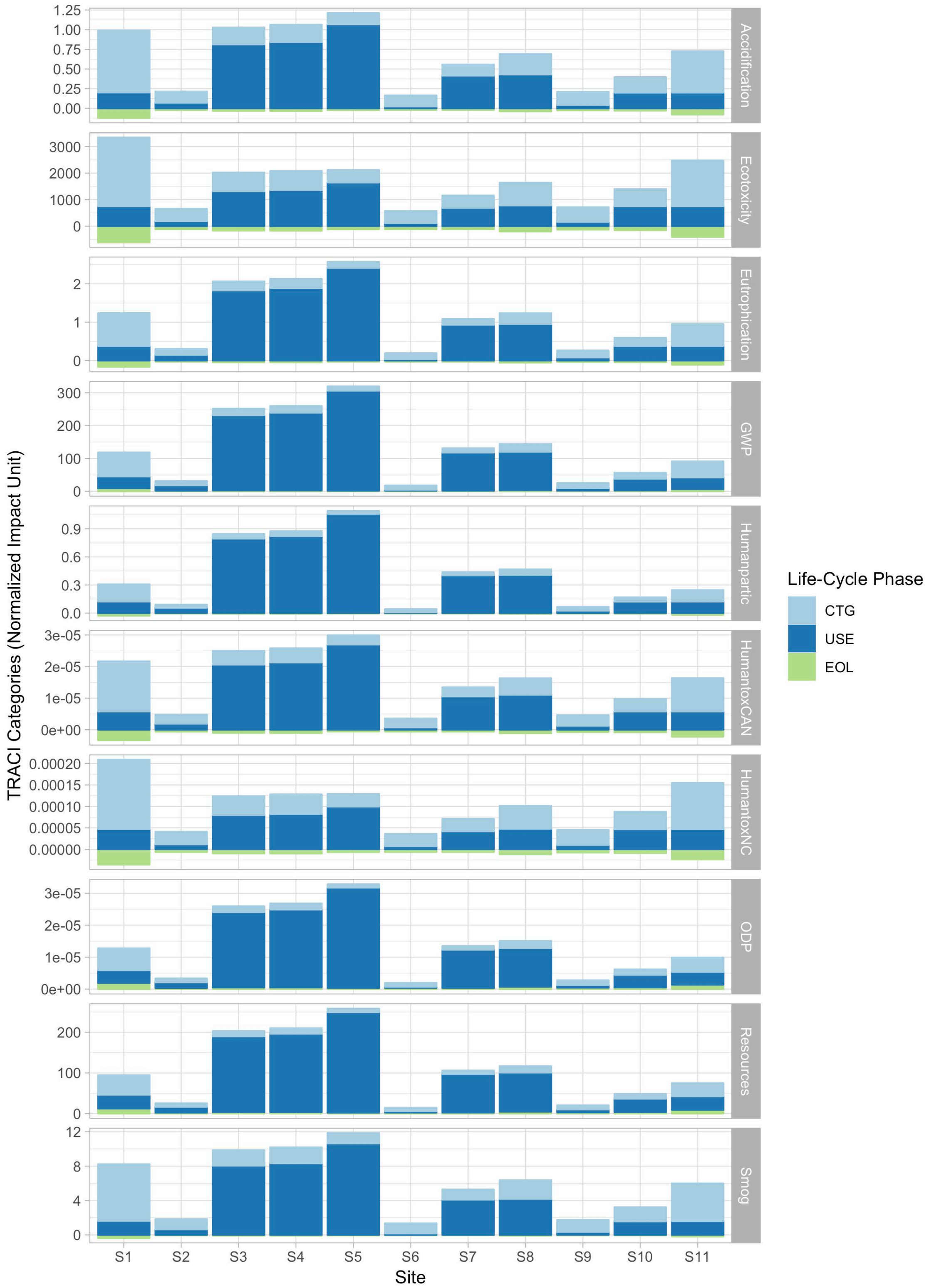


Figure 5-1
Variability in Impact score by Site per MWh Delivered

Figure 5-2 shows the distribution of average impact scores by site for all scenario runs. Figure 5-2 reflects impacts per service hour in frequency response where lifetime service hours are held constant across systems. Sites with higher capacity had with lower mean (average) impact scores and more variability in final impact estimate. Site 6, had considerably more variability per kW installed, which is likely related to the fact the system size was an order of magnitude larger than the other sites considered. These results could also be indicative of both uncertainty in methods as well as the location/design of the storage systems.

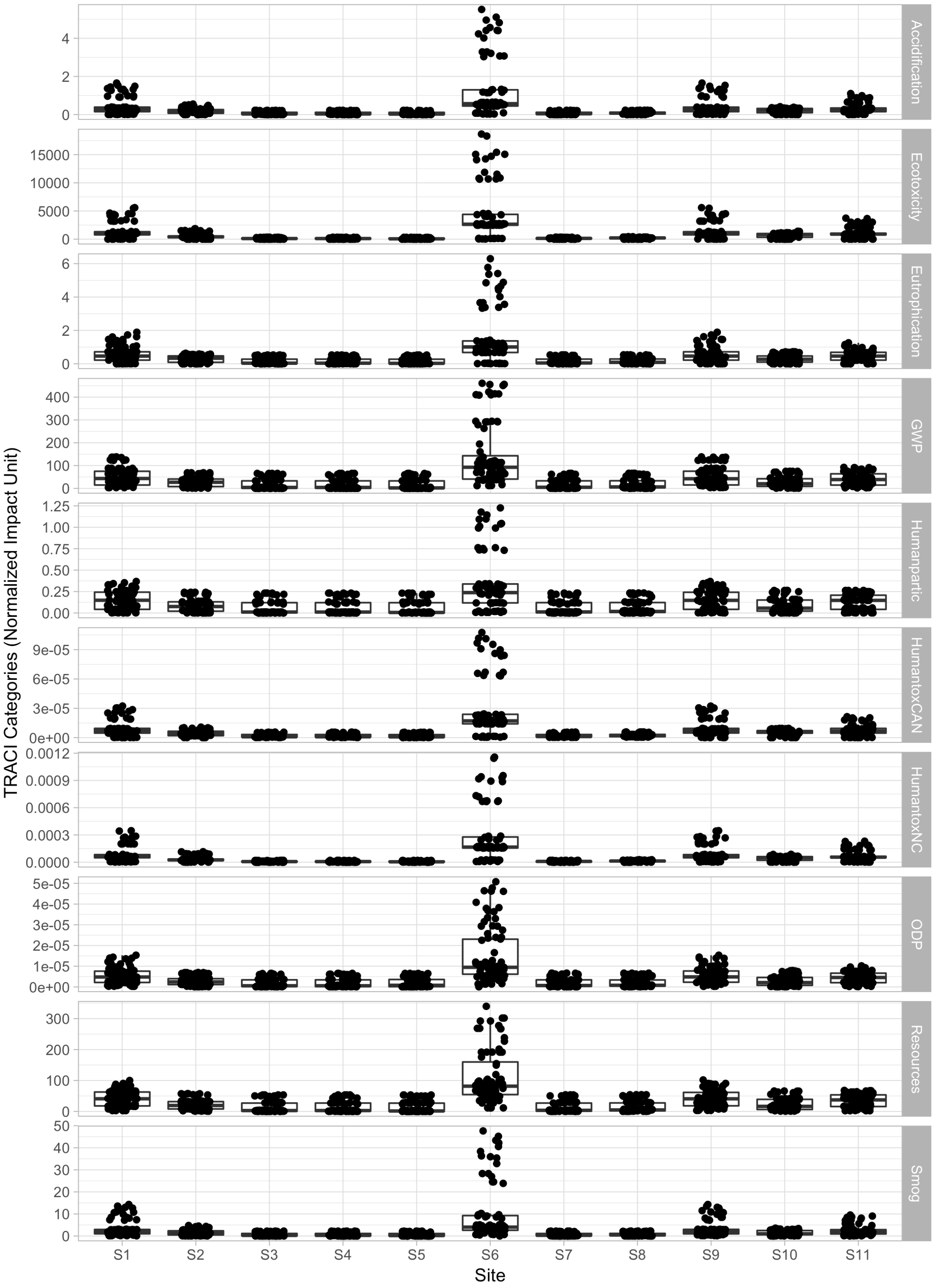


Figure 5-2
Impact score per Hour in Frequency Response by Site

6

INTERPRETATION AND DISCUSSION

This report details the drivers of emissions, effluents and subsequent environmental impacts from the use of stationary LIB systems. Results are reported for three primary functional units to reflect the range of value added services and impacts of storage systems. To consider the operational perspective of electricity delivered by a grid-tied battery system, impact scores are divided by the total energy delivered by the battery system over its service life. Impacts per MWh delivered give information about impacts for providing only one grid service (bulk energy), and not many others (ramping, frequency response, etc.). For comparison to siting other storage technologies, the impacts are divided by the installed (nameplate) capacity of the LIB. Finally, as there are many different use applications for the battery system, and the battery system can be providing value-added services when not being charged or discharged, impact scores are divided by the total service hours the system delivered.

The results of this study suggest that the operation or use-phase of LIB facilities is a significant driver of several categories environmental impact. This was primarily attributable to the throughput energy efficiency of the battery system, the types of generation technologies used to charge the battery, and the extent to which battery capacity is utilized. Emissions of GHGs in particular were strongly sensitive to use phase assumptions. How batteries are operated, as well as the types of generation and transmission assets in the grid, will affect many environmental impact categories. Since operational strategies for ESS are still in flux (even in the short-term), the results of environmental assessments for LIBs are likely to be different in the future. Over the long term (>20 years), there is also considerable uncertainty as to the development of other storage technologies and the development of LIB technologies.

This study excludes any potential consequential analysis of changes to the operation of utility generation assets. During any specific charging event, a particular generation asset with significantly different emissions than the average may be the marginal dispatch. To the extent that siting energy storage could displace fossil generators from capacity markets, these generators may re-enter the general dispatch mix increasing the GHG intensity of overall delivered electricity. Additionally, any capacity investments made to more permanently change the composition of the fleet would not be considered.

A critical objective for further research is estimating the ‘system wide’ environmental consequences of grid scenarios with and without storage, with a further goal of understanding the marginal impacts of adding storage capacity or installations. In contrast, the results of this study describe the impacts of siting specific storage projects and takes an attributional approach to quantifying environmental impacts. But these results support the notion that quantifying the value of grid storage, both economically and in reducing emissions associated with environmental impacts, will require consideration of both the design and siting of installations.

Emissions associated with battery production (CTG) were also a significant contributor to the impacts of LIB deployment on acidification, ecotoxicity impact and non-cancerous human toxicology. The vast majority of emissions from battery production were found to be associated with raw material extraction and refining. This is a consistent result among the few studies of grid-scale storage systems that have explicitly modeled different use cases and corresponding operational profiles. This theme is also echoed by LCA studies of LIBs for transportation, which consistently highlight the impact of the grid mix used to charge the vehicle battery.

Ecotoxicity impacts measure contributions of known carcinogens and toxics to air, water, and soil. Significant potential impacts to smog formation potential instead were attributable to the battery use-phase, and driven by the generators used to charge battery systems. One important observation is that the impacts of these pollutants are locally distributed, meaning that ecotoxicity impacts are likely to be concentrated up the battery supply chain, while impacts to smog will be concentrated around electricity generation facilities.

While the choice of LIB chemistry is important for performance considerations, optimization of site selection and EOL management can lead to better environmental results. Results related to the EOL phase show the potential for policy to affect the overall environmental and human health burden of these systems. Because of the limited recycling infrastructure in or near California (where the LIB systems in this study are located), batteries must travel significant distances. In addition, the recovery of metals appears to be more beneficial than the recovery of both metals and cathode materials, based on the current state of cathode recovery processes. In other words, the mean negative impacts of cathode recycling is so large that it negates the value of recovering the materials. These results point to the importance of (1) developing more efficient LIB recycling infrastructure, and (2) ensuring some is located in California, especially as currently operational LIB systems begin to approach the EOL stage.

The evolving diversity of cell chemistries, designs, and manufacturing processes complicates estimation of manufacturing energy requirements. There is a currently a lack of life cycle inventory data to reflects the wide array of LIB cathode chemistries. The wide range of potential applications, and the lack of robust information about actual use profiles, is a challenge for assessing use-phase impacts. The environmental impacts of battery degradation and of different EOL options have not been adequately addressed, yet are important to utility companies and other prospective investors in advance of acquisition.

Existing LCA studies of grid-scale LIB ESSs use materials inventories and operational profiles that do not reflect current industry practice. Existing studies therefore provide only partial insight. In order to provide accurate assessments, updated inputs are needed for materials inventories, operational profiles, and EOL practices. In particular, use phase assessments are based on ESS operational profiles that do not fully reflect the “value-stacking” operational strategy used by asset owners. Updated materials inventories should consider system components such as enclosures, cooling systems, and power conditioning systems as they are currently implemented for multi-MW scale LIB ESSs.

7

CONCLUSIONS AND FURTHER RESEARCH

This report details the drivers of emissions, effluents and subsequent environmental impacts from the use of stationary LIB systems. While the study relies heavily on literature values and other published data sources, it also offers several unique features compared with previous studies:

- A focus on LIBs installed to for utility-scale, electrical grid operations
- Inclusion of balance of system components and transportation of systems for commission and decommissioning activities
- Novel application of existing economic storage simulation tool (StorageVET) to simulate high-resolution operations of storage systems
- System designs and siting based on real-world and commissioned projects; locationally specific pricing data used to inform storage operations
- Primary data and novel approach to EOL modelling based on waste management strategy
- Extensive sensitivity and scenario analysis comparing battery system designs and performance

There are numerous qualitative considerations regarding supply chains, and EOL management options that were observed in this study. These include:

- Future supply chain risks from bottlenecks from production of cobalt, manganese, nickel, and lithium carbonate. [49]
- During the course of this research, there were several regionally-specific environmental impacts mentioned in report that were published including potential human rights and child labor issues with cobalt, from metals in supply chains. [50]
- Regulations created to address risks during transportation of EOL LIBs have resulted in increased EOL hauling costs and prohibitions on transport by train.
- A sector specializing in EOL LIB management and reverse logistics is emerging.
- No formal extended producer responsibility is required for any manufacturers. No U.S. domestic disposal sites for EOL LIBs.

8
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A

UNCERTAINTY MODELING IN LCA

Sensitivity analysis is an integral step in any life cycle assessment. Parameter assumptions and proxies can have large effects on the outcome of a study, therefore it is now standard to conduct parameter uncertainty analysis by screening or probabilistic methods in any LCA distributed to the public. Global sensitivity analysis (GSA) attributes variability in the model output (i.e. functional unit) to variability to parameter assumptions; it provides an indication of the statistical power of the experimental outcome.

If the parameters for a study are not realistically bounded, then probabilistic analysis can be of limited usefulness. In this study, public and literature data was used to estimate probability distributions (PDs) for parameter values; life cycle impacts were then estimated using a probabilistic assessment model (PAM). Monte Carlo analysis was used to explore posterior distributions of outcomes and analyze how parameter variance contributes to LC impacts. The integrated assessment model approach allows for comparison of production, use, and EOL impacts in a consolidated framework for uncertainty. The PAM allows for simultaneous sampling across several correlated and uncorrelated parameter estimates.

The environmental burdens I resulting from a series of decicions in a product system with product life cycle stages m and processes n x_{mn}=$[x_{11}, x_{12}, \cdots, x_{nm}]$, is given by:

$$\boldsymbol{I} = \begin{bmatrix} \boldsymbol{LCI_{111}} & \cdots & \boldsymbol{LCI_{1mn}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{LCI_{i11}} & \cdots & \boldsymbol{LCI_{imn}} \end{bmatrix} * \begin{bmatrix} \boldsymbol{x_{11}} \\ \vdots \\ \boldsymbol{x_{mn}} \end{bmatrix}$$

Where each decision X is multiplied by its corresponding life cycle inventory LCI_{mn}. The resulting vector I consists of the sum of the flows i from all processes and all stages.

Take a product system with a series of decisions x spanning life cycle stages m and processes n. Assume each decision results in some flow of primary materials, energy, and outputs of emissions. A life cycle inventory is compiled for each decision x, and consists of these elementary flows i. The LCI matrix consists of $flows_i$ for each $process_j$ in each $stage_i$. We can represent this more compactly as:

$$\mathbf{A} = \begin{bmatrix} \boldsymbol{a_{11}} & \boldsymbol{a_{12}} \\ \boldsymbol{a_{21}} & \boldsymbol{a_{22}} \end{bmatrix}$$

In the ideal model, we can estimate exactly the flows for each process and the quantities of each process used over the life of the product. In order to estimate to a final impact vector, the quantities X of each process j in life cycle stage i is multiplied by its corresponding LCI_j.

$$\sum^{\boldsymbol{j}} (\boldsymbol{LCI_{ij}} * \boldsymbol{X_{ij}}) \; = \; \boldsymbol{I_i}$$

Assessing and understanding uncertainty is key to modern life cycle assessment. This includes estimating the correlation of variation in mid and end point indicators and process level decisions. Simply stated, we want to know how parameter uncertainty contributes to uncertainty in impact estimates.

$$\boldsymbol{EX = f}$$

$$\boldsymbol{Gx >= h}$$

B

BATTERY DEGRADATION MODEL

This section discusses the battery degradation model and data review considered for its calibration. LIBs are known to lose capacity due to thermal degradation. [51] A two-stage capacity fade (CF) model was used in this study. Several models from the literature were reviewed, but all were found to be calibrated to designed for a specific LIB electrode chemistry. Based on work by Barre et al., a descriptive model was estimated using available battery testing data. [52] The descriptive model, as opposed to a principled or chemical model, looks at the correlation of remaining battery capacity with the observable characteristics of battery test cycles. The following model was identified using regression techniques:

$$\boldsymbol{CF_{Chem} = \beta_1 \cdot (\overline{DOD} \cdot \sqrt{x_{cycles}}) + \beta_2 \cdot \sqrt{x_{temp}}}$$

Where

- CF = Capacity Fade
- Beta1[Chem] = Effect of charge cycles by DOD and Chemistry on capacity fade
- Beta2 = Effect of temperature on capacity fade
- DOD = Average Depth of Discharge
- Xcycles = battery cycles
- Xtemp = absolute difference in operating temperature from 25ºC

The CF model describes the effect of average throughput and temperature on capacity reduction. Table B-1 displays the estimated coefficients for the model; note the range of other LIB electrode chemistries identified in the literature but not yet commercially available. While this information could inform the model, there was insufficient data to reliably estimate the effects of charge cycle for the LFP-LTO combination or the NMO-LTO combination. The full literature LIB test data used to estimate the descriptive model is provided in Table B-2.

There is a wide range of variability in estimated cycle life for batteries depending on chemistry, depth of discharge, temperature, and cycle count. The proportional increase in expected capacity fade at each cycle can be estimated from the model for a variety of DOD and temperature conditions as a function of cycle count. Figure B-1 shows the model predictions for a range of DODs. Round-trip charge-discharge losses are assumed to be a function of both power conversion equipment and increases to battery internal resistance. Internal resistance is assumed to increase linearly with capacity increase. As initial ohmic resistance is negligible, the effect of increasing ohmic losses on roundtrip losses is minor. Internal resistance is assumed to increase at a constant rate of 10.4 times the relative loss in storage capacity.

The chief limitations of this model are that it does not include consideration of power rate in charge cycles, does not separate the impacts of charging vs. discharging the battery system, or consider the potential impacts of calendar or thermal aging at static SOC. Instead, this model provides a relatively transparent view of the expected performance of different LIB chemistries, with a focus on their remaining (useful) capacity.

Table B-1
Coefficient Estimates (β1) for Cycle Life Model

	Coeffficient	Std. Error	P-value
Temperature	2.13	0.46	9.30E-05
Cycle Effect by Chemistry			
LCO-C	1.46	0.17	2.51E-07
LFP-C	0.42	0.08	0.000107
LFP-LTO	0.43	0.19	0.088281
LMO-C	1.37	0.26	0.000287
LMO-LTO	0.34	0.10	0.003157
NCA-C	0.45	0.14	0.007693
NMC-C	0.55	0.16	0.009
NMO-LTO	0.10	0.13	0.413242
Multiple R-squared	0.81		
Adjusted R-squared	0.77		
F-statistic	6.78E-11		

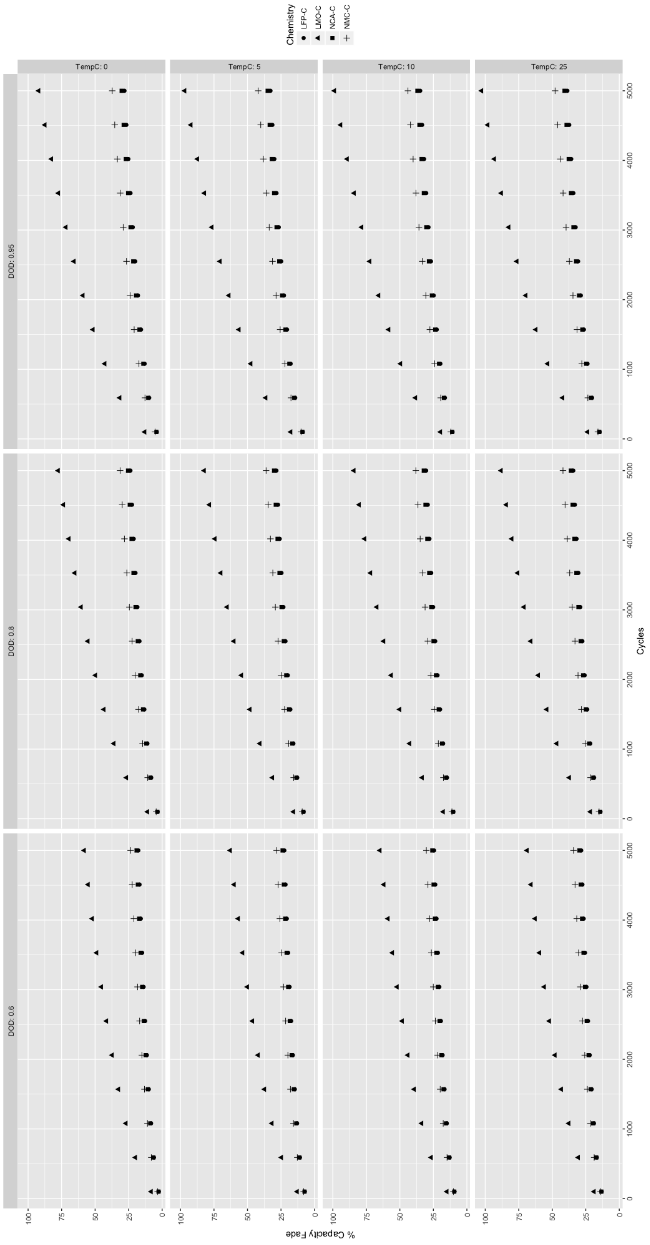

Figure B-1
Predicted Capacity Fade by Cycle Count and Temperature

Table B-2
Battery Cell Test data literature

Abbreviations: d = discharge, ch = charge, E = empirical, M = modeling, MP = manufacturer predicted, DOD = depth of discharge, RPT = reference performance test, CC-CV = constant current, constant voltage, EVPC = Electric Vehicle Power Characterization.

Lead Author and reference	Chemistry: cathode/anode	Manufacturer	Brand	Shape	C Rate	d/ch	Cycles	DOD (%)	Capacity Fade (%)	Resistance Inc. (%)	Test	Temp (C)	E/M/MP
Omar	LFP/C	-	-		1C	d	3221	80	20	126	cycle life	room	E
					1C	d	1600	80	20	127	cycle life	40	E
					10C	d	1100	80	20	156	cycle life	55	E
					15C	d	559	80	20	140	cycle life	55	E
Kim	LFP/C	-	-	Pouch	4C	d	3000	85	15	-	cycle life	room	E
Song	LFP/C	-	18650	Cylinder	3C	d	600	95	5	-	cycle life	25	E
					3C	d	600	70	30	-	cycle life	55	E
					3C	d	250	80	20	-	cycle life	55	E
Zheng [53]	LFP/C	Tianjin Lishen Battery Joint-Stock Co., Ltd.	18650	Cylinder	1C	d	600	98	2	0	cycle life	25	E
					10C	d	600	86	14	9	cycle life	25	E
					10C	d	600	73	27	13	cycle life	55	E
Ouyang [54]	LFP/C	-	-	-	1/2C	ch	50	96	4	-	cycle life, RPT	-10	E
					1/2C	ch	50	81	19	-	cycle life, RPT	-10	E
					1/2C	ch	50	73	27	-	cycle life, RPT	-10	E

Lead Author and reference	Chemistry: cathode/anode	Manufacturer	Brand	Shape	C Rate	d/ch	Cycles	DOD (%)	Capacity Fade (%)	Resistance Inc. (%)	Test	Temp (C)	E/M/MP
Zhang [55]	LCO/C	Sony US	18650S	Cylinder	1/2C	ch, d	800	68	32	747	Arbin battery	-	E
Ramadass [56]	LCO/C	Sony	18650	Cylinder	C/9-1C	d	800	69	31	58	CC-CV, discharge	room	E
					C/9-1C	d	800	64	36	83	CC-CV, discharge	45	E
Li [57]	LCO/C	Sanyo	UF653467	Prismatic	1C	ch, d	286	70	30	-37	cycle life	room	E
Ning [58]	LCO/C	Sony US	18650	Cylinder	1C	d	300	91	10	12	cycle life, Arbin battery	ambient	E
					3C	d	300	83	17	18	cycle life, Arbin battery	ambient	E
Shirk [59]	LMO/C	2012 Nissan Leaf		Prismatic	ACL2	ch	685	25	75	31	LPP, EVPC	~20-40	E
					DCFC	ch	685	30	70	33	LPP, EVPC	~20-40	E
Erdas [60]	Spinel LTO	-	CR2016	Coin	1C	d	100	59	41	-	cycle life	-	E
					1C	d	30	80	20	-	cycle life	-	E
	Spinel Ag-LTO	-	CR2016	Coin	1C	d	100	98	2	-	cycle life	-	E
Yu [61]	Spinel LTO	-	CR2025	Coin	5C	d	400	94	6	-	cycle life	25	E

Lead Author and reference	Chemistry: cathode/anode	Manufacturer	Brand	Shape	C Rate	d/ch	Cycles	DOD (%)	Capacity Fade (%)	Resistance Inc. (%)	Test	Temp (C)	E/M/MP
	Spinel V-LTO	-	CR2025	Coin	5C	d	400	88	12	-	cycle life	25	E
					2C	d	1713	98	2	-	cycle life	25	E
Yang [62]	LFMP-C/V-LTO	-	CR2032	Coin	3C	d	400	98	2	-	cycle life	room	E
Morales [63]	LFP/LTO	-	-	Coin	4C	d	2500	83	17	-	cycle life	room	E
Burke [64]	NMO/LTO	Altairnano	24V, 50Ah	Prismatic	4C&C/2	ch, d	1000	99	1	-	cycle life	40	E
					4C&C/3	ch, d	16647	80	20	-	cycle life	40	M
Yi [65]	Spinel LTO	-	CR2026	Coin	10 C	ch, d	200	87	13	-	cycle life	-	E
	LTO-LLTO	-	CR2025	Coin	10 C	ch, d	200	82	18	-	cycle life	-	E
Burke [66]	NCM/C	EIG	-	-	-	-	2000-3000	80	20	-	cycle life	-	E
	Mn Spinel/C	-	-	-	-	-	1000	80	20	-	cycle life	-	E
	NCA/C	-	-	-	-	-	2000-3000	80	20	-	cycle life	-	E
	LFP/C	EIG	-	-	-	-	>3000	80	20	-	cycle life	-	E
	Mn Spinel/LTO	Altairnano	-	-	-	-	>5000	80	20	-	cycle life	-	E
Wong [67]	NCA/C	-	-	-	1C	d	400	100	0	-	cycle life	-	E
					25C	d	400	80	20	-	pulse	50	E
					83C	d	400	94	6	-	continuous	34	E

Lead Author and reference	Chemistry: cathode/anode	Manufacturer	Brand	Shape	C Rate	d/ch	Cycles	DOD (%)	Capacity Fade (%)	Resistance Inc. (%)	Test	Temp (C)	E/M/MP
Watanabe [68]	NCA/C	-	-	Cylinder	1C	ch, d	~1000	80	20	-	cycle life	25	E
					1C	ch, d	~300	80	20	1540	cycle life	60	E
Bodenes [69]	NCM/C	-	-	Cylinder	C/5	d	26	93	8	100	cycle life	85	E
					C/5	d	29	78	22	1115	cycle life	120	E

C

LIST OF LIFE CYCLE INVENTORIES

LCIs for materials were sourced from the Ecoinvent database, Version 3.3. [70] Manufacturing energy inputs, cell performance characteristics, and material inventories were used to aggregate data into an LCI for each battery design scenario by chemistry. Mass balance information was used to scale material inventories, while process information was used to characterize energy flows. Sourcing information was used to distinguish potential geographically specific impacts, such as electricity generation mix, sourcing of reagents, or other consumable inputs.

cathode for lithium-ion battery (GLO, market)

anode, graphite, for lithium-ion battery (GLO, market)

polystyrene foam slab for perimeter insulation (CN)

market for N-methyl-2-pyrrolidone

aluminium, primary, cast alloy slab from continuous casting (GLO, market)

sheet rolling, aluminium (RER)

copper, cathode grade (GLO, market)

sheet rolling, copper (RER)

polyvinylfluoride, dispersion (for PVDF, GLO market)

average for chromium steel product manufacturing (GLO, market for metal working)

lithium hexafluorophosphate production (CN)

titanium production, primary (CN)

ethylene glycol (GLO, market)

polyethylene terephthalate, granulate, amorphous (GLO, market)

electronics for control units (GLO, market)

Inverter production, 500kW (GLO, market)

electricity, medium voltage (South Korea, market)

electricity, medium voltage (WECC, market)

electricity, from natural gas combined cycle (WECC, market)

electricity, from photovoltaic (WECC, market)

transport, freight, lorry 16-32 metric ton (RER, EURO4)

transport, freight, sea, transoceanic ship (GLO)

treatment of waste electric and electronic equipment, shredding (GLO)

treatment of electronics scrap from control units (RER)

metals recovery from electronics scrap in copper smelter (SE)

precious metal recovery from electronics scrap, in blister-copper, by electrolytic refining (SE)

D

LIB WASTE MANAGEMENT INTERVIEWS

A series of informal and unstructured interviews was conducted both by phone and email between January and August of 2017. These interviews were conducted to better understand the potential scope and structure of LIB EOL management strategies, and the roles of significant parties throughout the LIB value chain. This included battery manufacturers, Installers, haulers, recyclers, and waste management firms. The names of key contacts and dates of contact are provided below:

Tron Melzl, ABB, Inc.,
phone conversation 1/24/2017; email exchange 7/27/2017

Jasim Ahmed, LG Chem,
phone conversation, 2/24/2017

Jim McDowell, Saft Battery,
phone conversation 2/16/2017

Billy Puk, Recology,
phone conversation 8/4/2017; email exchange 8/7/2017

Jim Taggart, ECS Refining,
email exchange 5/14/2017

Mike Della Penna, PG&E,
phone conversation 2/7/2017

David Mauer, Renewance,
phone conversation 6/6/2017

Maarten Quiz, Umicore,
email exchange 5/17/2017

E

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