Life Cycle Assessment: C4V Lithium-Ion Battery Cells for Electric Vehicles

Final Report | Report Number 19-44 | October 2019

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Life Cycle Assessment: C4V Lithium-Ion Battery Cells for Electric Vehicles

Final Report

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NYSERDA Report 19-44 NYSERDA Contract 30191 October 2019

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Abstract

This study assesses the environmental effects of Charge CCCV (C4V) LLC's lithium (Li)-ion battery production and identifies opportunities to minimize the impacts. A "cradle to gate" lifecycle assessment was performed using OpenLCA, along with the Ecoinvent 3.5 database and data provided by C4V. The results indicate that the primary energy consumption associated with the cathode active materials is a strong driver of C4V's Li-ion battery's environmental impact. Additionally, C4V's battery cell uses fewer metals and less-toxic materials than comparable lithium cell batteries. C4V's battery cell then leads to lower global warming, acidification, smog, and energy consumption when compared to other Li-ion battery production processes.

Keywords

Lithium battery, Li-ion batteries, lifecycle assessment, anode, cathode, greenhouse gas, carbon dioxide, electric vehicles, transportation, climate change

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Acronyms and Abbreviations

Abt	Abt Associates
BM-LMP	bio-mineralized lithium mixed-metal phosphate
BMS	battery management system
BOM	bill of materials
C4V	Charge CCCV LLC
CFC	chlorofluorocarbons
CFC-11	chlorofluorocarbons trichlorofluoromethane
CFC-11e	chlorofluorocarbons trichlorofluoromethane-equivalent
CO2e	carbon dioxide-equivalent
CTUe	comparative toxicity unit (ecotoxicity)
CTUh	comparative toxicity unit (health)
EOL	end of life
ETP	ecological toxicity potential
GHG	greenhouse gas
kg	kilogram
kWh	kilowatt-hour
LCA	lifecycle assessment
LCI	lifecycle inventory
LCIA	lifecycle impact assessment

LiFePO4	lithium iron phosphate
Li-ion	lithium-ion
LMO	lithium-manganese oxide
Li-NCM	lithium-nickel-cobalt-manganese oxide
LiPF6	lithium hexafluorophosphate
ME&P	Material Extraction and Processing
MJ	megajoule
Neq	nitrogen-equivalent
NMP	n-methyl-2-pyrrolidone
NO_x	nitrogen oxides
O3e	ozone equivalent
ODP	ozone-depleting potential
PAF	potentially affected fraction
PM	particulate matter
PM2.5e	particulate matter 2.5 microns equivalent
SO2e	sulfur dioxide equivalent
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
EPA	United States Environmental Protection Agency
VOC	volatile organic compound

Executive Summary

Lifecycle assessment (LCA) is a comprehensive method and technique used to evaluate the potential environmental impacts across the full lifecycle of a product, process, or activity. The need for this study stems from Charge CCCV LLC (C4V), a knowledge company specializing in lithium (Li)-ion batteries, and its desire to assess the environmental impacts of the battery production to identify opportunities for minimizing those effects. Similar LCA studies of lithium batteries did not capture the unique design or manufacturing process of C4V batteries.

The LCA of the C4V Li-ion battery production presented in this report represents a “cradle-to-gate” analysis demonstrating lifecycle inventories (LCI), starting from material extraction to when a fully manufactured Li-ion battery cell leaves the C4V facility. In this study, Abt Associates mainly used data provided by C4V to describe the material flows and processes during battery production. To fill in the data gaps, Abt Associates used the Ecoinvent 3.5 database, which provides process data for thousands of products in areas such as energy supply, agriculture, transport, biofuels and biomaterials, bulk and specialty chemicals, construction materials, wood, and waste treatment. To classify the products in the Ecoinvent data, the Allocation, Cut-Off by Classification, or Cut-Off System model was used.

C4V Li-ion batteries are composed of three layers: an anode, a cathode, and a porous separator placed in-between the anode and cathode layers. The anode is composed of graphite and other conductive additives coated on a copper current collector foil, and the cathode is composed of layered transition metal oxides together with conductive additives coated on an aluminum foil current collector. After coating the anode and cathode, the separator sheet is placed between alternate layers of the electrode sheets. C4V then winds the tri-layer sheet in an elliptical form and inserts it in a stainless-steel prismatic cell case. The cell roll in the steel case is then saturated with an electrolyte solution, consisting of a lithium salt dissolved in organic solvents. The cell case is sealed to create a battery cell.

The majority of the manufacturing and processes considered under this LCA study occur in New York State, with a variety of upstream suppliers providing the materials from unknown locations and destinations. Furthermore, the study does not account for transportation impacts at the manufacturing stage. Since C4V only manufactures Li-ion battery cells, this LCA study does not include the LCIs of battery pack manufacturing, use, or end-of-life stages.

This study found primary energy consumption to be a strong driver of C4V Li-ion battery impacts. The cathode active materials appear to require large quantities of energy to manufacture. The cathode is a dominant contributor to upstream consumption of fossil fuels from two inputs: lithium manganese oxide and N-methyl-2-pyrrolidone (NMP) production, which is responsible for about 64% of energy consumption (~ 68 megajoules surplus per kilowatt-hour). Three processes create the overall impacts: the pollution generated by the manufacture of the lithium manganese oxide, the refining of copper, and electricity generation in the northeastern United States.

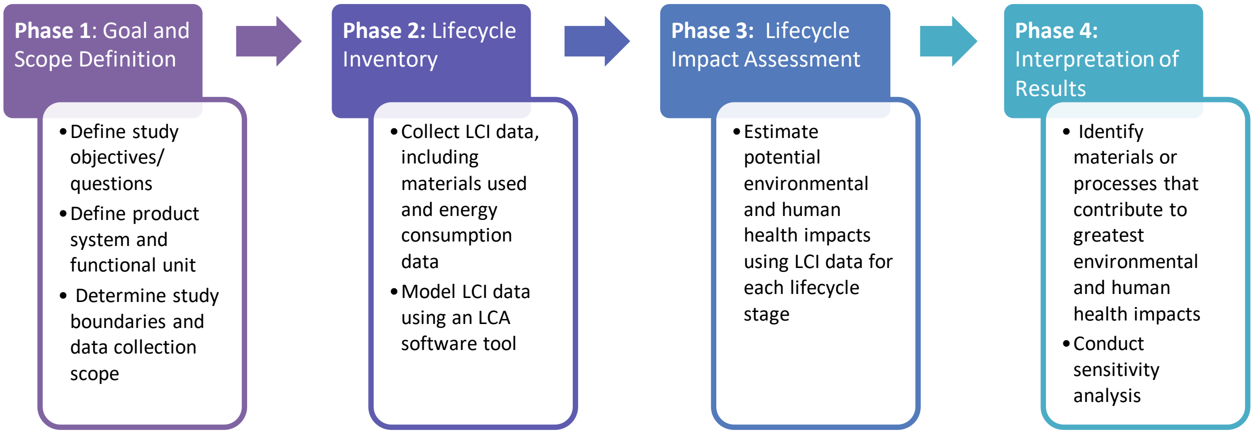
Most comparable metrics of the C4V Li-ion battery cell fall within the lower end of the expected range of LCIs generated by the manufacture of a Li-ion battery cell for several reasons. The main contributor to this result is that C4V assembles its Li-ion battery cell in the northeastern states, which generates about half of its electricity from carbon-free sources. Additionally, the C4V battery cell appears to use fewer metals and less-toxic materials than comparable modeled lithium cell batteries with higher impacts. A tertiary contributor to this result may be that this study does not include transportation emissions from the movement of downstream materials to and from the C4V factory, leading to a small underestimate of true lifecycle impacts.

1 Introduction

Lifecycle assessment (LCA) is a comprehensive method and technique used to evaluate the potential environmental impacts of a product, process, or activity, assessing impacts across the full lifecycle, starting with material acquisition to manufacturing, use, and final disposition. As outlined in the International Organization for Standardization 14040 series and illustrated in Figure 1, an LCA study has four major phases or components: (1) goal and scope definition, (2) lifecycle inventory (LCI) collection, (3) lifecycle impact assessment (LCIA), and (4) interpretation of results (ISO 2006a, 2006b).

Figure 1. LCA Phases

Sources: (ISO 2006a, 2006b).



This report presents the goals, scope, and results of an LCA of batteries manufactured by Charge CCCV LLC (C4V), located in Binghamton, NY. C4V specializes in technology development and commercialization of next-generation lithium (Li)-ion batteries for energy storage and is working on drop-in replacements for cathodes, anodes, and separators for the batteries. C4V has discovered, patented, and is now commercializing the enhanced materials, while establishing a supply chain in the Southern Tier of New York State to produce Li-ion batteries with extended life, safety, and charge performance for a variety of applications, including electric cars and battery storage (C4V 2018a). Through the company’s continued research and development of the battery technology, it has become interested in an LCA of the Li-ion battery production process to help assess, identify, and minimize environmental impacts.

Abt Associates (Abt) performed this LCA, which represents a cradle-to-gate analysis and demonstrates the full lifecycle impacts of a fully manufactured Li-ion battery cell, starting with material acquisition to when the cell leaves the C4V facility. This assessment accounts for material extraction, material processing, component manufacturing, and product manufacturing, but excludes the manufacture of the Li-ion battery pack since C4V does not assemble battery packs. This LCA analysis can be used to inform a larger "cradle-to-grave" analysis, including assembly of battery packs, use phase of the battery packs, and end-of-life phases.

1.1 Purpose and Goals

This section presents a summary of previous LCA studies of Li-ion batteries for electric vehicles, the need for this project, and target audience and goals.

1.1.1 Previous Research

Abt conducted an LCA of Li-ion batteries for electric vehicles, which was supported by the United States Environmental Protection Agency (EPA) and published in 2012 (EPA 2012). The study assessed three Li-ion battery chemistries for an electric vehicle and two chemistries for long-range, plug-in hybrid electric vehicles. The battery chemistries included lithium-manganese oxide (LMO), lithium-nickel-cobalt-manganese oxide (Li-NCM), and lithium-iron phosphate ($LiFePO_4$). In addition, a single-walled carbon nanotube anode technology for possible future use in the batteries was assessed (EPA 2012). The study relied on primary data from several battery suppliers, manufacturers, and recyclers as well as secondary data sources from published studies, including Notter (et al. 2010) and Majeau-Bettez (et al. 2011). EPA conducted the analysis consistent with the International Organization for Standardization 14040 series and identified several opportunities for improvement based on the key drivers of environmental impact, which included increasing the lifetime of the battery, reducing cobalt and nickel use, reducing the percentage of metals by mass, incorporating more recycled metals during battery manufacturing, using a solvent-less process, and reassessing the manufacturing process and upstream material selection for the cathode to reduce energy use. Although the end-of-life (EOL) stage was also examined, it was based on very preliminary data from battery recyclers and included a process that was still in the research and development phase.

LCA studies published prior to the EPA study relied primarily on secondary or modeling data to estimate impacts, while considering only a limited number of lifecycle stages, vehicle types, and/or impact categories [e.g., greenhouse gas (GHG) emissions from electric vehicles]. For example, using secondary data, Matheys (et al. 2008) conducted an environmental assessment of five types of batteries for internal combustion engine vehicles, electric vehicles, and hybrid electric vehicles, including lead-acid, nickel-cadmium, nickel-metal hydride, Li-ion, and sodium-nickel chloride. The study found higher technical and environmental performance of the Li-ion and the sodium-nickel chloride battery technologies (Matheys et al. 2008). Notter et al. (2010) published an LCA of a manganese oxide Li-ion battery. This study found that the impacts of a Li-ion battery used in electric vehicles are small relative to the whole vehicle, and the operation or use phase remains the dominant contributor to its environmental impact, assuming the electricity is not generated solely through renewable sources. Although the study used primary data from one battery cell manufacturing company (Kokam Co.), it relied largely on secondary data from Ecoinvent[1] and modeling data for the battery manufacturing, use, and EOL stages. Zackrisson (et al. 2010) also relied on modeling data for their LCA analysis, which found that it was environmentally preferable to use water as a solvent instead of N-methyl-2-pyrrolidone in the slurry for casting the cathode and anode of Li-ion batteries for hybrid electric vehicles. Majeau-Bettez (et al. 2011) conducted a "cradle-to-use"[2] analysis of three Li-ion battery chemistries for electric vehicles, including nickel metal hydride, nickel cobalt manganese Li-ion, and $LiFePO_4$. Based on average European conditions, the nickel metal hydride technology was found to have the greatest environmental impact, followed by Li-NCM and then lithium-ion iron phosphate for all LCIA categories considered, except ozone depleting potential (ODP; Majeau-Bettez et al. 2011).

Additional LCA studies have been conducted on automotive Li-ion batteries of comparable chemistries or designs to C4V batteries. For example, a study by Hawkins (et al. 2013) conducted a comparative LCA of conventional and electric vehicles, which included an analysis of Li-ion iron phosphate and Li-NCM batteries. This study found lower impacts from lithium-manganese oxide batteries compared to Li-ion iron phosphate batteries.[3] The study relied on lifecycle inventory data from Zackrisson (et al. 2010) and Majeau-Bettez (et al. 2011) and assumed a battery lifespan equal to the vehicle lifespan (Hawkins et al. 2013).

Other LCA studies on $LiFePO_4$ batteries were based on production data in China. For example, a study by Lu (et al. 2016) assessed the material production and battery production processes of $LiFePO_4$, nickel metal hydride, lithium cobalt dioxide, and nickel manganese cobalt oxide batteries in electric vehicles. The study focused on GHG emissions and other air emissions (e.g., nitrogen oxides [NO_x], sulfur oxide, and particulates). Lu (et al. 2016) found nickel metal hydride batteries to have the greatest impacts, while $LiFePO_4$ batteries had lower energy consumption and emissions, including GHG emissions. However, a cradle-to-gate LCA study on Li-ion batteries for electric vehicles manufactured in China found that $LiFePO_4$ batteries had higher GHG emissions than N-methyl-2-pyrrolidone and lithium manganese oxide (LMO) batteries (Hao et al. 2017). Key drivers of GHG emissions included anode active materials followed by wrought aluminum. Furthermore, the study found that Li-ion batteries manufactured in China emitted about three times the amount of GHG emissions compared to Li-ion batteries manufactured in the United States. This is primarily due to China's electricity grid, which generates more GHG emissions per kilowatt-hour (kWh) than the grid in the States (Hao et al. 2017).

In addition, Kim (et al. 2016) conducted a cradle-to-gate LCA analysis of the electric Ford Focus battery pack, which is a mixture of LMO and Li-NCM. The Ford Focus battery consists of 430 cells with a nominal voltage of 3.7 V and has a specific energy density of 0.08 kWh per kilogram (kg). Cradle-to-gate GHG emissions were found to be 140 kg of carbon dioxide-equivalent (CO_2e) per battery pack. The gas, electric, and water consumption accounted for 45% of the GHG emissions. Additionally, GHG emissions from cell manufacturing, cell components, and battery enclosure accounted for 82–92% of the criteria pollutant emissions (e.g., NO_x, volatile organic compounds [VOCs], carbon monoxide, particulate matter [PM], and sulfur dioxide [SO_2]).

In 2016, a study concluded that the majority of automotive Li-ion cell production was located in Asia and owned by firms with experience producing Li-ion cells for electronics. While Asian firms still dominate the market, price-competitive production may be possible from North American manufacturing locations given material pricing equivalent to that achieved by cost leaders and an 8% weighted average cost of capital (Chung et al. 2016).

1.1.2 Need for Project

Overall, the need for this study stems from C4V's desire to assess the environmental impacts of its Li-ion battery production and to identify opportunities to minimize those effects. Approximately 80% of the cost to produce Li-ion cells originates from four major components: the anode, cathode, separator, and electrolyte. The C4V battery design contains a new patented cathode crystal structure that enables high-voltage operations, corrosion resistance that enhances battery performance, and an optimized design of the components to reduce the cost of ownership. C4V has discovered, patented, and commercially developed processing technology for next generation anode and cathode materials, while working jointly to optimize the materials with current industry giants in the electrolyte and separator space (C4V 2018a). C4V's current Li-ion battery production capacity is about 1.2 gigawatt-hours (GWh) per year. The company aims to scale to 15 GWh per year in New York State (Upreti 2019).

For these reasons, similar LCA studies of lithium batteries do not capture the unique design or manufacturing process of the C4V battery, while this study considers some of the unique lifecycle considerations that have been missed by other studies. However, it is important to note that this LCA is an approximation of the impacts, since C4V's exact battery composition and manufacturing processes are proprietary. Abt worked closely with the company to select appropriate surrogates to approximate the proprietary information.

1.1.3 Target Audience and Project Goals

The target audience for the LCA study includes C4V and other Li-ion battery manufacturers and upstream suppliers. Additional stakeholders include electric vehicle manufacturers and the New York State Energy Research and Development Authority.

The study is intended to provide these stakeholders with an objective, quantitative analysis that evaluates the lifecycle environmental impacts of the C4V Li-ion battery technology to identify opportunities for potential improvement. Specifically, the results of the study will identify material and processes within the battery production lifecycle that are likely to pose the greatest impacts or potential risks to public health or the environment. Unlike prior LCA studies of Li-ion batteries for vehicles that relied mainly on secondary or modeling data to estimate impacts, this study is based on primary data provided by C4V and assesses the impacts from a United States-based standpoint.

1.2 Product System

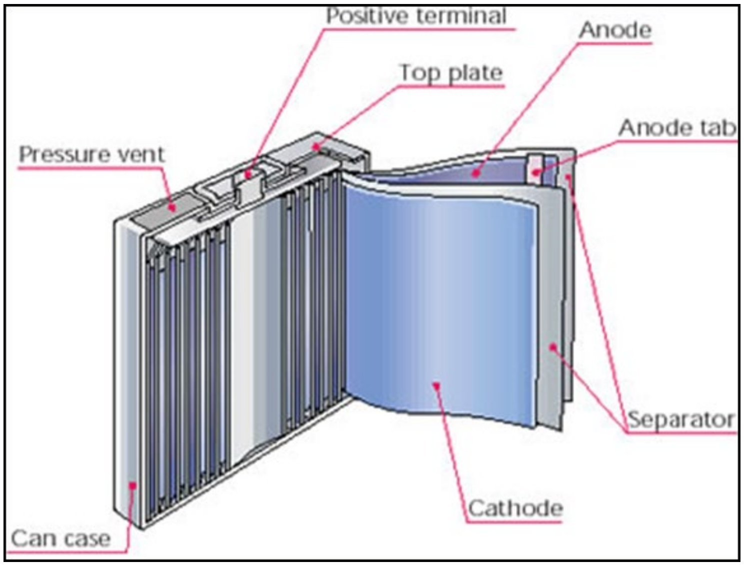
Below is a description of the Li-ion battery components (product system), and the unit by which it will be evaluated in this study (functional unit).

1.2.1 Li-ion Battery System

As illustrated in Figure 2, most Li-ion batteries are composed of three layers: an anode, a cathode, and a porous separator placed in-between the anode and cathode layers. The anode is composed of graphite and other conductive additive(s) and a binder, and the cathode is composed of layered transition metal oxides with conductive additive(s) and a binder (e.g., lithium cobaltite, $LiFePO_4$, and LMO). After coating the anode and cathode, the separator sheet is placed between the anode and cathode sheets and wrapped in an elliptical form to form a cell roll that is inserted in prismatic cell metal cases. The roll is then saturated with an electrolyte solution, composed of lithium-salt and organic solvents, and the steel case is sealed to create a battery cell.

Figure 2. Illustration of Prismatic Li-ion Battery Cell

Source: (EPA 2012)



Once the battery cell is constructed, several cells are combined in series and in parallel to form a battery pack. The battery pack manufacturer houses the battery pack with other components, including a thermal control unit, wiring, and electronic card as part of a battery management system (BMS). Once the BMS is assembled, it is ready to be placed into a vehicle. C4V only manufacturers the Li-ion cell, allowing manufacturers further downstream to assemble the cells into a battery pack that meets downstream project needs.

1.2.2 Functional Unit

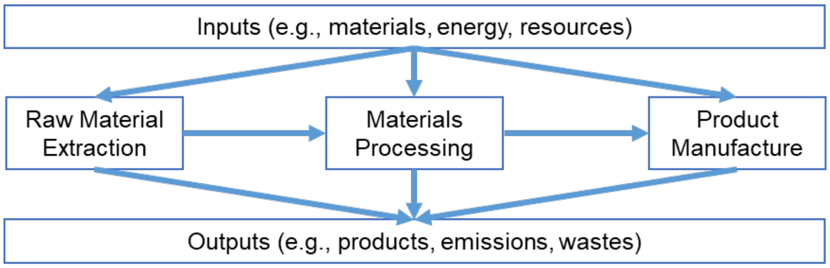
In an LCA, the functional unit normalizes data based on equivalent use (or service provided to consumers) to provide a reference for relating process inputs and outputs, and impact categories for the LCA across product systems.

As described above, the product systems evaluated in this project are Li-ion battery cells. This study is a cradle-to-gate study of the batteries from when raw materials are extracted to when they leave the C4V factory, and so the functional unit is measured by the battery's energy capacity. In other words, inventory amounts and impacts are ultimately presented on a per-kWh basis (e.g., kg of materials per kWh or ton of CO_2e emissions per kWh). This allows comparison of the battery's lifecycle impacts with that of other energy sources.

1.3 Assessment Boundaries

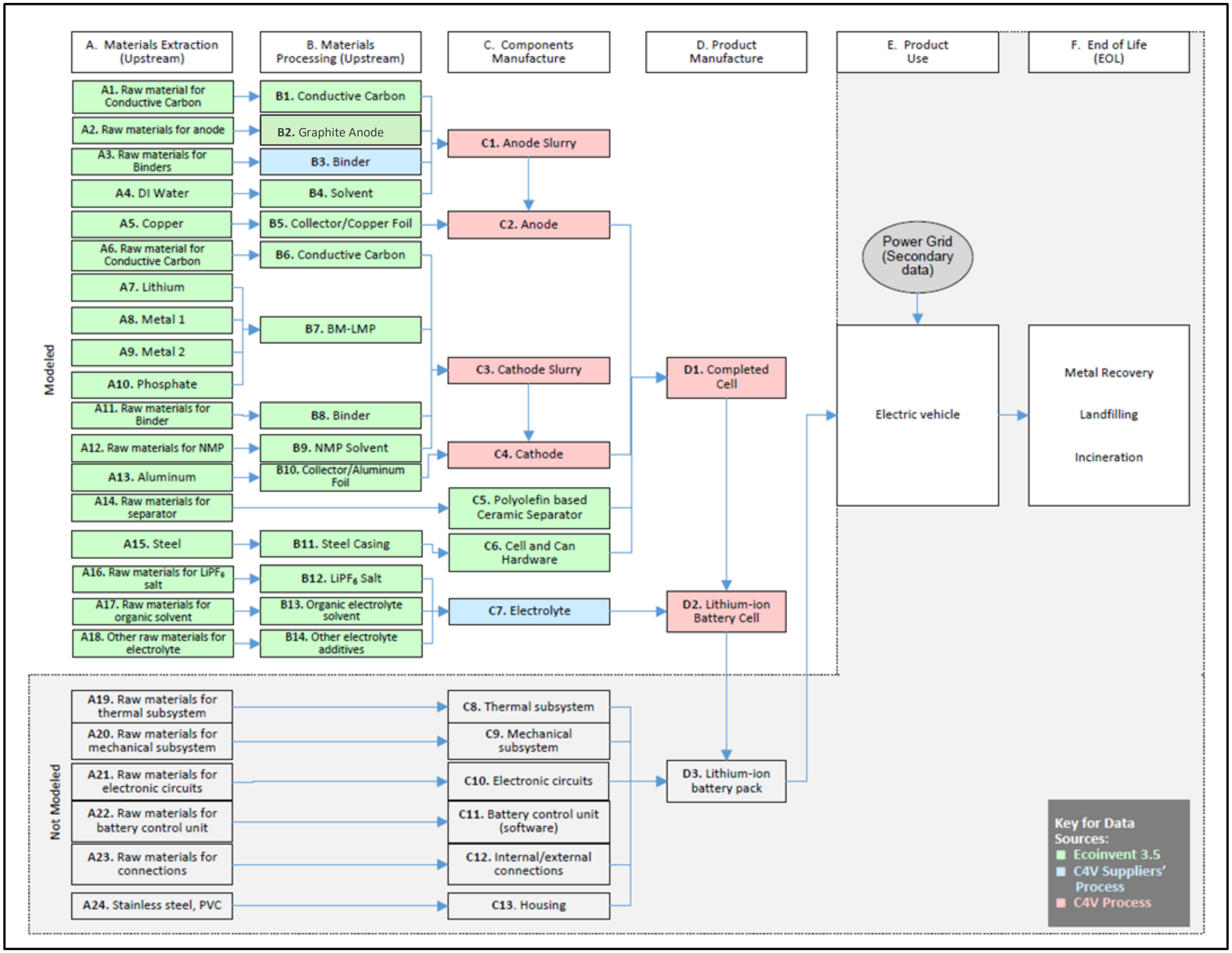
As illustrated in Figure 3, LCAs evaluate the lifecycle environmental impacts from each of the major lifecycle stages: raw material extraction, material processing, and product manufacturing. The inputs (e.g., resources and energy) and outputs (e.g., product and waste) within each lifecycle stage are evaluated to determine the environmental impacts.

Figure 3. Lifecycle Stages of the Product System



As shown in Phase 2 of Figure 1, an LCA involves quantifying raw material and fuel inputs as well as solid, liquid, and gaseous products, emissions, and effluents. The first step in this quantification involves developing a process flow diagram depicting the processes and materials that are modeled in each lifecycle stage of the study. The process flow diagram illustrating the Li-ion materials, processing, manufacture, use, and disposition activities that are modeled as part of this LCA study is presented in Figure 4. Each box in the diagram depicts a unit process, which has its own inventory of inputs and outputs. Included in the process flow diagram, developed in collaboration with C4V, are the assessment boundaries of the analysis by lifecycle stage.

Figure 4. Process Flow Diagram of C4V Lithium Battery Production



1.3.1 Spatial and Temporal Boundaries

Geographic boundaries used in LCAs show where impacts are likely to occur for each lifecycle stage. The study focuses on the manufacturing and use of Li-ion battery cells in New York State by C4V and is primarily based on recently available LCI data obtained from C4V and its consortium of manufacturers and upstream suppliers. When necessary, Ecoinvent 3.5 global defaults for material extraction and material processing are used to fill in gaps in the upstream supply chain (Ecoinvent 2018). These defaults approximate global processes but are assumed to have impacts localized to New York State.

Given the lack of temporal specificity in an LCA, impacts are assumed to be based on current technologies and conditions, despite the potential changes that might occur during the product's service life. In addition, it is assumed that parameters that may change with time (e.g., availability of landfill space, recycling rates, recycling technologies) will be similar to current conditions, and will remain constant throughout the lifetime of the product system.

1.3.2 General Exclusions

Impacts from the infrastructure needed to support the manufacturing facilities (e.g., general maintenance of manufacturing plants) are beyond the scope of this study.

Since the majority of the manufacturing and processes considered under this LCA study occur in New York State with a variety of upstream suppliers providing materials from unknown locations and destinations, this study does not account for transportation impacts. Any environmental burdens caused by the movement of goods or materials are unaccounted for in this analysis. In addition, while some of the impacts of materials sourced outside of the United States, such as China, are accounted for in the Ecoinvent 3.5 global defaults, this study does not consider the exact supply chain used by C4V.

Since C4V only manufactures the Li-ion battery cells, this LCA study does not include the lifecycle impacts of the battery pack manufacturing, use, or EOL stages. While assessing the impacts of battery pack manufacturing are outside the scope of this study, Abt recommends that the impacts of battery pack manufacturing in New York State be considered before making decisions exclusively on the results presented in this LCA.

1.3.3 Lifecycle Impact Assessment Impact Categories

The third phase of the LCA study (LCIA or LCIA phase) involves translating the environmental burdens identified in the LCA into potential environmental impacts. LCIA is typically a quantitative process involving the characterization of burdens and assessing the possible effects on human and ecological health as well as other effects, such as global warming. A number of impact categories are considered in the LCIA phase.

The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) is an EPA tool that contains characterization factors for sustainability metrics, LCIA, industrial ecology, and process design. These characterization factors allow quantification, in common equivalence units, of the potential impacts that environmental releases have on specific impact categories. TRACI 2.1 contains an expanded set of impact categories, including ozone depletion, global warming, acidification, eutrophication, photochemical smog formation, human health particulate, human health cancer and human health non-cancerous effects, and ecotoxicity. Table 1 presents the impact categories and associated media within TRACI 2.1.

Table 1. TRACI 2.1 Emissions-Related Categories

Source: (Bare et al. 2012).

Impact Category	Media
Ozone Depletion	Air
Global Warming	Air
Acidification	Air, Water
Eutrophication	Air, Water
Photochemical Smog Formation	Air
Human Health Particulate	Air
Human Health Cancer	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil
Human Health Non-cancer	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil
Ecotoxicity	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil

1.4 Data Collection Scope

This section describes the LCI data categories for which data were collected, the data sources, procedures for allocating inputs and outputs from a process to the product of interest, decision rules, and the methods for maintaining overall data quality and critical review.

1.4.1 Data Categories

Table 2 describes the data categories for which lifecycle inventory data were collected, including material inputs, energy inputs, natural resource inputs, emissions and waste outputs, and product outputs. In general, inventory data are normalized to either (1) the mass of an input or output per functional unit (in the case of material and resource inputs and emissions or material outputs) or (2) energy input (e.g., megajoules [MJ], kWh) per functional unit.

Table 2. LCI Data Categories

Data Category	Description
Inputs: Materials, Energy, Natural Resources	
Primary materials	Actual materials incorporated into the final product.
Ancillary (process) materials	Materials used during the production process that are not incorporated into the final product (e.g., solvent).
Natural resources	Materials extracted from the Earth that are non-renewable (i.e., stock resources such as coal) or renewable (i.e., flow resources such as water).
Process energy	Process energy, energy (fuel) for transportation, pre-combustion energy (i.e., energy expended to extract, process, refine, and deliver a usable fuel for combustion). Energy can be renewable or non-renewable.
Outputs: Emissions/Waste	
Air emissions	Gaseous or particulate releases to the environment from a point or diffuse source, after passing through emissions control devices, if applicable.
Water effluents	Water outputs represent actual discharges to either surface or groundwater from point or diffuse sources, after passing through any water treatment devices.
Solid wastes	Product or material that is deposited in a landfill or deep well, and can include hazardous, non-hazardous, or radioactive wastes. Represents actual disposal of either solids or liquids that are deposited either before or after treatment (e.g., incineration, composting, recovery, or recycling processes).
Outputs: Products	
Primary products	Material or component outputs from a process that are received as inputs by a subsequent unit process within the product lifecycle.
Co-products	Material outputs from a process that can be used for some other purpose, either with or without further processing, which are not used as part of the final functional unit product.

1.4.2 Data Sources

As shown in Table 3, Abt mainly used data provided by C4V to describe the material flows and processes during battery manufacturing. To fill in the data gaps, Abt used the Ecoinvent 3.5 database (Ecoinvent 2018). This database provides process data for thousands of products in areas such as energy supply, agriculture, transport, biofuels and biomaterials, bulk and specialty chemicals, construction materials, wood, and waste treatment. To classify the products in the Ecoinvent data, the Allocation, Cut-Off by Classification, or Cut-Off System Model was used.

The Cut-Off System Model assumes that the impacts of a material's production are always allocated to the primary user of the material. If the material is recycled, the initial producer does not receive any credit for recycling. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. For example, recycled paper only bears the impacts of wastepaper collection and the recycling process of turning waste paper into recycled paper. It is free of any burdens from the forestry activities and processing required for the primary production of the paper (Ecoinvent 2018).

Alternatively, waste producers are not accredited with the impacts of recycling or re-use of products. For example, heat from the incineration of municipal solid waste can be used for heating. However, the incineration is allocated completely to the treatment of the waste, and therefore, the burdens lie with the waste producer. The heat can be used burden-free (Ecoinvent 2018).

To perform the LCA, Abt used the OpenLCA platform, an open source, software program for sustainability and LCA.[4]

Table 3. Example Input/Output Data and Data Sources

Lifecycle Stage	Example Input Data	Example Output Data	Potential Data Source(s)
Upstream (material extraction and processing, ME&P)	Raw materials (e.g., iron and ore extraction for steel, copper) and energy required to process materials	Processed materials for components (e.g., copper, aluminum) and associated emissions from raw ME&P	Ecoinvent 3.5
Component manufacturing	Processed materials and energy required to manufacture components of the battery (e.g., aluminum, copper, electrolytes)	Components of the battery and emissions from manufacturing (e.g., electrolytes or sheet rolled steel)	Ecoinvent 3.5, C4V suppliers
Product manufacturing	Components and energy required to manufacture the lithium battery	Cells and associated emissions from manufacturing (e.g. Li-ion cell)	C4V

1.4.3 Data Quality

LCI data quality is often evaluated based on several data quality indicators: (1) the source type (i.e., primary or secondary data sources), (2) the method in which the data are obtained (i.e., measured, calculated, estimated), and (3) the time period for which the data are representative. For the primary data collected in this project, section 2 notes whether the data are based on C4V or its suppliers.

When specific primary data were missing or unavailable, we used secondary data; and when neither primary nor secondary data were available, we made assumptions to fill in the data gaps.

2 Lifecycle Inventory

2.1 Upstream Material Extraction and Processing Stages

The material extraction and processing (ME&P) stages, or stages A and B in Figure 4, are upstream of the Li-ion battery component and product manufacturing stages. LCI data were obtained from C4V or its suppliers (i.e., primary data) for the component and product manufacturing stages (stages C and D), and secondary data sources were used for the upstream stages. The secondary data included LCI data available in the Ecoinvent 3.5 dataset as well as published studies.

The materials included in the inventory for the ME&P stages were identified as those materials used to produce the Li-ion battery components—both primary and ancillary materials (i.e., solvents and process materials). Accordingly, the following section first describes the bill of materials (BOM) for the batteries, reflecting the key components and materials used to manufacture the batteries. Next, based on the BOM, a discussion of the upstream LCI data sources and limitations is provided.

2.1.1 Bill of Materials

The BOM for the battery cell modeling in this study is presented in Table 4. The table presents the weight for each component (kg) on a kWh of battery-capacity basis as well as corresponding percentage of total mass for the battery chemistries assessed in this study. The quantities are based on the data received from C4V and its suppliers.

Table 4. BOM for Li-ion Batteries Assessed

Total mass: ~ 7 kg per kWh

Component	Percent Mass (%)[a]
Anode	41.8%
Copper foil (collector)	11.1%
Battery grade graphite/carbon	14.6%
Polymer binder	16.2%
Auxiliary solvent[b]	n/a
Cathode	**33.0%**
Aluminum (collector)	4.3%
Li-ion cathode material	26.4%
Polymer/other binder	2.3%
Auxiliary solvent[b]	n/a
Separator	**3.2%**
Polymer	3.2%
Cell Casing	**8.7%**
Steel casing and polymer pouch	8.7%
Electrolyte	**13.3%**
Organic Carbonate solvents	11.7%
Lithium hexafluorophosphate ($LiPF_6$)	1.6%
Total	**100%**

a. The percentage mass for the components was calculated by dividing the mass of each component by the total mass of the battery cell.

b. The auxiliary solvent and cooling systems were not included in the total mass of the battery cell since they are not typically included when calculating energy density.

Note: C4V uses 1.5 kg of BM-LMP in its cathode's solid-state design. Coupled with a lithium anode, the Li-ion battery can reach energy densities around 200–280 Wh per kg.

2.1.2 Methodology and Data Sources

Based on the BOM data for each battery chemistry, and information provided by the battery manufacturers and published studies, the corresponding upstream materials required to manufacture each component were identified. The Ecoinvent 3.5 data series used as secondary data to approximate the ME&P lifecycles are described above. The manufacturing processes for the components are introduced briefly in the following section and are described in detail in section 2.2. Table 5 summarizes the upstream materials and corresponding components and data sources.

Anode: The anode consists of the negative electrode of the battery. Anodes are typically composed of a powdered graphite material, which is combined with a solvent and a binder (referred to as the anode slurry) and coated on copper foil (Gaines and Cuenca 2000). For this study, Ecoinvent 3.5 data and C4V supplier's information were used to estimate the components of the anode slurry (C1 in Figure 4). The C4V data were primarily used to estimate the lifecycle impacts of the anode assembly and manufacturing process.

The anode slurry is composed of graphite combined with a conductive carbon, binder, and some solvent(s). The C4V anode is composed of primary graphite. To estimate the upstream lifecycle impacts of the graphite material, Abt used an Ecoinvent data series titled "graphite production, battery grade" to approximate this component. This data series includes the impacts from lime mining, crushing, and milling, as well as accounts for and recognizes that grade graphite is much more energy intensive to manufacture than industrial graphite. Ecoinvent 3.5 data were also used to approximate the manufacture of the conductive additive carbon black via the furnace process.[5] For the binder, assumptions were made about mass and component inputs (e.g., carboxymethyl cellulose powder, chloroacetic acid, isopropanol, methanol, sodium hydroxide, and water), and the respective Ecoinvent 3.5 series was used to estimate lifecycle impacts. C4V uses deionized water in the anode slurry production and the processing of the anode binder. The solvent used in this LCA is deionized tap water generated by ion exchange.

Finally, the anode slurry is combined with the copper foil to produce the complete anode. The coated anode is dried, and the solvents are removed. (The used solvents are disposed of according to applicable United States and New York State regulations.) Abt used the Ecoinvent 3.5 data for copper cathode production to estimate the lifecycle impacts of the manufacture of the copper foil. Please note that the term "copper cathode" in this context is an industry term for sheets of copper, not to be confused with a battery "cathode." This material is the primary raw material input for the production of copper rods for the wire brass, copper tube, and sheet products.[6]

Cathode: The cathode is the positive electrode and is composed of metal oxides (Gaines and Cuenca, 2000). The battery chemistries used by the battery manufacturers in this partnership include an LMO-like material, whose exact chemical makeup remains confidential to protect C4V's proprietary battery design. In general, the C4V cathode is roughly 80% manganese, 20% iron with small amounts of calcium and phosphorous. There is no nickel or cobalt used in the cathode. Similar to the anode, the cathode material is combined with a binder material and mixed in a slurry paste with solvent before it is coated onto a collector composed of aluminum foil.[7]

For the cathode, Ecoinvent 3.5 data were used for assumptions about the upstream material extraction and processing stages. Ecoinvent 3.5 series were used for the conductive carbon (e.g., carbon black), the BM-LMP[8] (e.g., LMO), binder (e.g., polyvinyl fluoride), and solvent (e.g., NMP). As discussed above, the C4V cathode is mostly manganese, which is why Abt and C4V determined LMO would be the closest approximation to the C4V cathode chemistry.

Separator: The separator is another layer in the battery cell made from polyolefin. This component keeps the anode and cathode foils separated in the battery cell after they are wound together. Upstream data for the separator were obtained from Ecoinvent 3.5. Data for the manufacture of the separator itself was taken from Notter (et al. 2010).

Cell Casing: Even though aluminum is a common material for battery casings (Gaines and Cuenca 2000), the C4V casing is made from stainless steel. The casing encloses the anode, cathode, and separator. Upstream data for the steel casing came from Ecoinvent 3.5.

Electrolyte: The electrolyte solution acts as a conductor of Li-ions between the anode and cathode. The electrolyte solution is composed of lithium salt and organic solvents (Gaines and Cuenca 2000). To manufacture the electrolytes, C4V loads solvents and electrolyte additives from vendors into storage tanks. The materials in the storage tanks are then processed to remove moisture. After processing, it is loaded into mixing vessels to make customer formulas in varying quantities. Between electrolyte solvent addition and electrolyte additive addition, $LiPF_6$ solids are added. The resulting combination of electrolyte solvents, $LiPF_6$ salt, and electrolyte additives is blended and dispensed into shipping containers (C4V 2018b). For this study, C4V supplier information was used for the composition of the electrolyte solution. Ecoinvent 3.5 data were used for the upstream material extraction.

Table 5. Upstream Materials and Corresponding Components and Data Sources

Component (Stage C)	Material Name	Data Source for Extraction (Stage A)	Data Source for Processing (Stage B)
Anode	Battery grade graphite, solvents, and conductive carbons	Ecoinvent 3.5	Ecoinvent 3.5
	Anode binder	Ecoinvent 3.5	C4V Supplier
	Copper foil (collector)	Ecoinvent 3.5	Ecoinvent 3.5
Cathode	Aluminum (collector)	Ecoinvent 3.5	Ecoinvent 3.5
	BM-LMP	Ecoinvent 3.5	Ecoinvent 3.5
	Binders and solvents (e.g. NMP)	Ecoinvent 3.5	Ecoinvent 3.5
Separator	Polyolefin-based ceramic separator	Ecoinvent 3.5	Notter et al. 2010
Casing	Steel	Ecoinvent 3.5	Ecoinvent 3.5
Electrolyte	$LiPF_6$	Ecoinvent 3.5	C4V Supplier
	Ethylene carbonate / dimethyl carbonate	Ecoinvent 3.5	C4V Supplier

2.1.3 Data Limitations

Upstream data for the materials used in the Li-ion battery cell and pack were only obtained from secondary data sources. These sources mainly included LCI data available in Ecoinvent 3.5 as well as literature sources with published LCI data, including Notter (et al. 2010) and Majeau-Bettez (et al. 2011). When specific details about a chemical or material were not available or were not provided by C4V due to confidentiality issues, we applied a proxy, or modified the available LCI data. For example, for the foil material for the electrodes, we used copper and aluminum sheet LCI data, even though C4V did not specify how the products were manufactured specifically. Another example is the LMO battery chemistry. Due to confidentiality issues, C4V indicated it could not share the exact battery chemistry of the Li-ion batteries, but the chemistry is likely a modification of LMO and possibly a mixed metal oxide (C4V 2018b). As such, the production process may differ from the LMO we are using as a proxy, which is based on the Ecoinvent 3.5 default for this process.

The limitations and uncertainties associated with the ME&P stages are primarily because some of the inventories were unobtainable, and others derived only from secondary sources. Therefore, these datasets are not tailored to the specific goals and boundaries of the C4V Li-ion battery. Because the secondary data may be based on a limited number of facilities and have different geographic and temporal boundaries, they do not necessarily represent current industry practices in the geographic and temporal boundaries defined for the study (see section 1). These limitations and uncertainties are common to LCA, which strives to evaluate the lifecycle environmental impacts of entire product systems and is, therefore, limited by resource constraints that do not allow the collection of original, measured data for every unit process within a product's lifecycle.

2.2 Manufacturing Stage

The manufacture of Li-ion battery packs that are placed into vehicles generally follows four key steps:

1. Manufacture of the battery cell components (Phase C in Figure 4)
2. Manufacture of the battery cell (Phase D in Figure 4)
3. Manufacture of other battery pack components, including the BMS, passive cooling system, and housing (Phase C in Figure 4)
4. The assembly of the battery cell (Phase D in Figure 4)

The sections below describe the manufacturing process and the LCI data collection methodology, sources, and limitations for this stage.

2.2.1 Manufacturing Process

Figure 4 illustrates the manufacturing process for the anode electrode, cathode electrode, and battery cell. As shown in Figure 4, manufacture of the electrodes follows a similar process. First, C4V combines the electrode powder with a binder and mixes it into a slurry paste with solvent. Next, C4V coats the collector with the slurry paste (copper for the anode and aluminum for the cathode). This collector is dried to remove the solvent, which is recycled and reused. The aim is to have the active material maximized so as to increase the energy density of the slurry. Once dried of the solvent, the foil sheets are compressed and adjusted for thickness, and then slit and cut to the correct width to fit inside the cell (Gaines and Cuenca 2000; C4V 2018b).

The anode and cathode electrodes are then layered with a separator between them and rolled. In general, the separator is a porous polyethylene film coated with a slurry consisting of a copolymer, dibutyl phthalate, and silica dissolved in acetone (Notter et al. 2010). The slurry is then heated and dried to leave a porous film (Gaines and Cuenca 2000; Notter et al. 2010). During C4V's manufacturing process, tabs are spot welded onto the cathode and anode strips, and then the rolled layers of cathode, separator, and anode are inserted into a cell can. C4V then welds the conductive tabs to the final cell tabs. The can is sealed by laser welding or crimping the lid to the can (C4V 2018b). Generally, the Li-ion cells are placed into a thin aluminum casing or some other lightweight metal for the cell can. C4V uses a stainless-steel cell casing that is comparable to aluminum in its weight but superior in strength.

Next, the cell is evacuated and filled through a hole in the casing with a pre-mixed electrolyte solution obtained from a supplier (Gaines and Cuenca 2000; C4V 2018b). The manufacture of the electrolyte solution generally involves mixing the lithium salt, organic solvent, and other chemicals (described above). Electrolyte solutions differ based on the type of battery in which they are being used, such that a high energy-density battery will contain a different set of organic carbonates and other solvents than a high power-density battery. In the C4V process, the cell is vacuumed with non-reactive gas and then filled with a electrolyte solution. The hole used for filling the electrolyte is then sealed. Finally, the completed cell is activated through a series of charge/discharge cycles (C4V 2018b).

2.2.2 Methodology and Data Sources

LCI data for the components and product manufacturing stages are a combination of primary and secondary data. Data collection forms were distributed to partners to collect primary data for the processes associated with manufacturing the battery cell components (i.e., anode, cathode, casing, and separator). The collection form sought brief process descriptions, such as primary and ancillary material inputs; utility inputs (e.g., electricity, fuels, water); air, water, and waste outputs; and product outputs.

LCI data, including ancillary and utility data, were collected on a per energy capacity (kWh/charge cycle) basis and a per mass (kg) basis. All data were converted to a per battery basis, using information about specific energy (kWh/kg) and the mass of one battery (kg).

The primary data obtained from C4V or its suppliers were used to model the impacts of the manufacturing processes. The one exception is that the impacts of separator manufacturing were modeled based on assumptions from Notter (et al. 2010). As noted above, LCI data were obtained from C4V on a mass per kWh basis. Table 6 lists the methodology and data sources by the manufacturing stage processes.

Table 6. Manufacturing Stage Processes and Data Sources

Process	Data Source
Anode electrode	C4V
Cathode electrode	C4V
Separator	Notter et al. 2010
Casing	C4V and Ecoinvent 3.5[a]
Electrolyte	C4V Supplier
Battery cell	C4V

[a]. C4V battery casing is made from stainless steel. An Ecoinvent 3.5 process was used to approximate the impacts of the battery casing.

2.2.3 Data Limitations

The main limitation and uncertainty associated with this study resulted from C4V's need to protect proprietary and other confidential business information, which meant withholding some manufacturing process details. Alternatively, for some processes C4V relied on outside suppliers to provide a product or process input. For these products or inputs, C4V could not supply the material component or inputs. For example, the separator and casing were approximated with secondary data sources such as Ecoinvent 3.5 and Notter (et al. 2010).

Additionally, C4V did not have transportation data that estimated the distance between its suppliers and the manufacturing facility; therefore, this study does not include transportation-related impacts during the manufacturing stage.

3 Lifecycle Impact Assessment

In its simplest form, LCA is the evaluation of potential environmental, social, or economic impacts to a system as a result of some action. LCAs generally use consumption and loading data from the inventory stage to create a suite of estimates for various impact categories.

The LCA methodology used in this study began with an assessment of the overall material and primary energy input flows to the automotive Li-ion battery lifecycles (see section 1.4). Lifecycle impact category indicators were then calculated using TRACI 2.1 for a number of traditional categories, such as global warming, acidification, ozone depletion, and photochemical oxidation (smog) as well as relative category indicators for potential impacts on human health and aquatic ecotoxicity.

3.1 Overview of Material Use and Primary Energy Consumption

Drivers of the human and ecological health impacts presented in the LCIA include both upstream material and primary energy inputs. As a result, in this section, a fully aggregated input-side assessment of the materials and energy flows is presented. The context provided by the data greatly increases the ability to interpret the impact result tables (presented in section 3.2).

3.1.1 Major Material Flows

Table 4 presents a breakdown of the largest material and energy inputs to the Li-ion battery upstream and manufacturing stages by category.

Table 7. Major Material and Energy Inputs per kWh of Battery Capacity

	Li-ion battery cell	
	Input	Unit (per kWh)
Feedstock		
Calcite	2.4	kg
Manganese	1.8	kg
Fluorspar	1.3	kg
Copper ore	0.55	kg
Iron ore	0.43	kg
Lithium	0.12	kg
Lead	0.021	kg
Aluminum	0.021	kg
Other metals and ores	2.5	kg
Fuels		
Coal	13.8	kg
Crude oil	2.8	kg
Natural gas	12.7	m^3
Unconventional source (e.g., shale)	2.3	kg
Renewable energy	19.5	kWh
Ancillary inputs		
Water	342.9	m^3
Air	19.7	kg
Land	4.1	m^2
Aggregate, soil, clay	6.92	kg

As presented in Table 7, fluorspar and calcite are two of the largest feedstocks consumed in the upstream manufacturing stage for components of the Li-ion battery cell. Fluorspar and calcite are primarily an input into $LiPF_6$ production but are also feedstocks to the polyvinylflouride and LMO used to manufacture the cathode. Copper is used in the battery electronics, both in wiring and on printed wire (circuit) boards and in the anode. Most of the aluminum in the Li-ion battery is used for the manufacture of the cathode collection, N-methyl-2-pyrrolidone (NMP), and LMO.

The major fossil fuels consumed to manufacture the battery are coal, oil, and natural gas. The carbon-free sources are primarily conventional hydroelectric and nuclear. Overall, the New England and Middle Atlantic power grid is comprised of approximately 53% fossil-fuel sources and 47% carbon-free sources (EIA 2019).

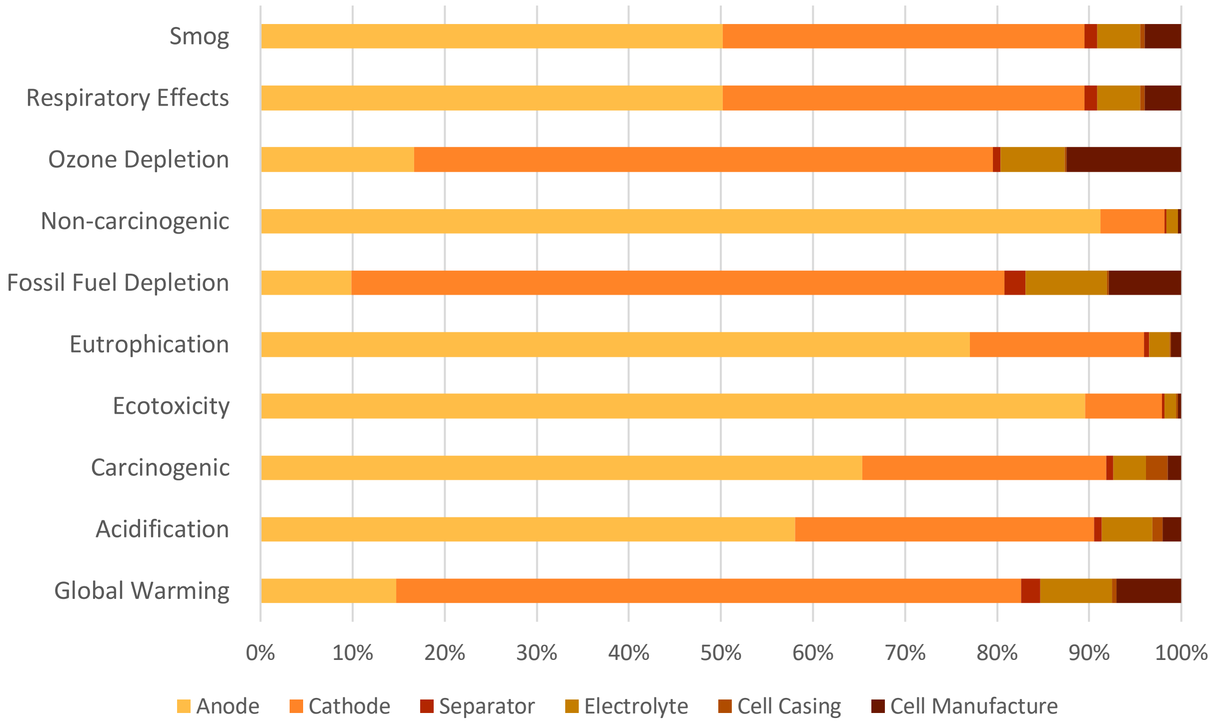
This LCA did not include any land-use assumptions for the manufacturing stages of the analysis. Therefore, the land use mainly reflects upstream impacts. The primary inputs taken from air include nitrogen, carbon dioxide, and oxygen.

3.2 Impact Category Results

In this section all impacts are reported in the functional unit of impacts per kWh of battery capacity. The functional unit represents impacts reported on a mass basis (e.g., grams, kg, milligrams) per the battery's nominal energy capacity (kWh) and is a common way of reporting the impacts associated with Li-ion battery manufacturing (Hawkins et al. 2013; Majeau-Bettez et al. 2011; Ellingsen et al. 2014; Notter et al. 2010; Kim et al. 2016; EPA 2012).

Figure 5 summarizes the overall contribution of each lifecycle stage by impact for each of the impact categories. The anode has the highest impact in seven categories and the cathode has the highest impact in the remaining three categories. This estimate is derived by summing all downstream process contributions to flows and impact categories. It displays upstream totals for each lifecycle stage of the battery manufacturing process.

Figure 5. Percent Contribution of Each Lifecycle Stage by Impact Category

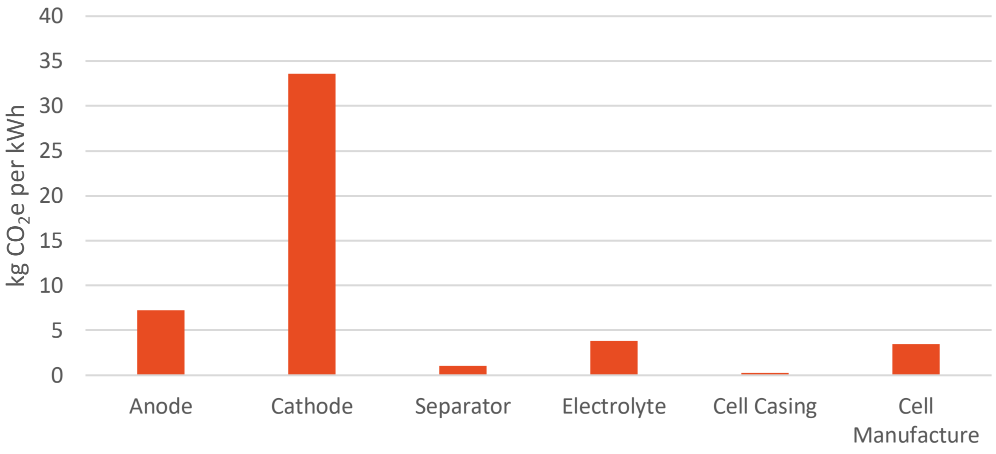


3.2.1 Global Warming Impacts

TRACI 2.1 utilizes global warming potentials to normalize the impact of GHGs relative to carbon dioxide. Consistent with the guidance of the United Nations Framework Convention on Climate Change, the methodology uses global warming potentials with 100-year time horizons. Although LCA does not necessarily include a temporal component in the calculations, impacts from releases during the lifecycle of Li-ion batteries are well within the 100-year time horizon.

Figure 6 presents the estimated lifecycle global warming impacts of the C4V Li-ion battery production. The cathode production is the largest contributor of GHGs to the manufacture of the battery, driving 52% of the emissions. Production of the lithium manganese mixture used in the cathode drives a quarter (33.6 kg CO_2e per kWh) of total impacts. Additionally, the Northeast power grid drives about 13% of the global warming impacts.

Figure 6. Global Warming Impacts by Lifecycle Stage

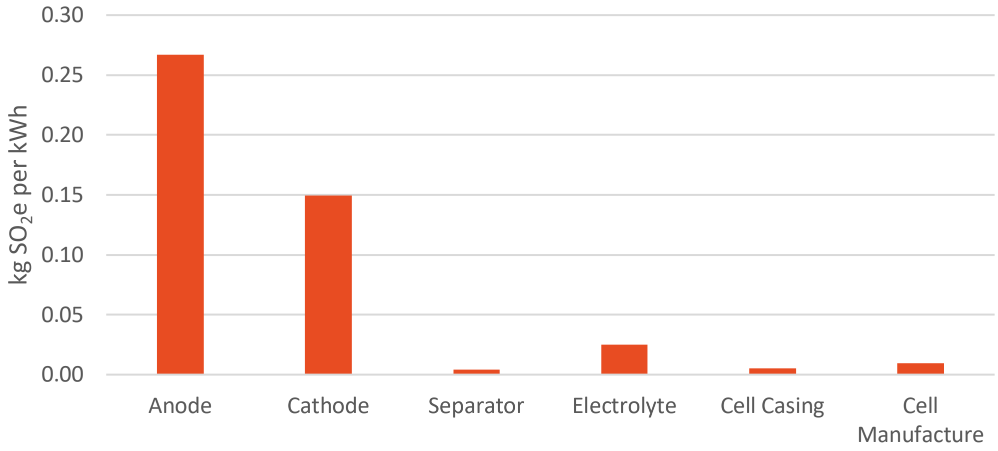


3.2.2 Acidification

Acidification is the increasing concentration of hydrogen ions within a local environment. This can be the result of the addition of acids (e.g., nitric acid and sulfuric acid) into the environment or the addition of other substances (e.g., ammonia) that increase the acidity of the environment due to various chemical reactions or biological activity.

Impact characterization is based on the inventory amount of a chemical released to the air that would cause acidification, multiplied by the acidification potential equivalency factor for that chemical. Figure 7 presents the estimated lifecycle impacts of acidification from the Li-ion battery production. TRACI 2.1 uses an acidification model that incorporates the increasing hydrogen ion potential within the environment without incorporation of site-specific characteristics such as the ability for certain environments to provide buffering capability to estimate the sulfur dioxide equivalent (SO_2e) impacts of a variety of processes (Bare et al. 2012). Most of the impacts come from the anode production, specifically from the upstream manufacturing of copper and graphite used in the manufacture of the anode.

Figure 7. Acidification Potential by Lifecycle Stage



3.2.3 Ecotoxicity

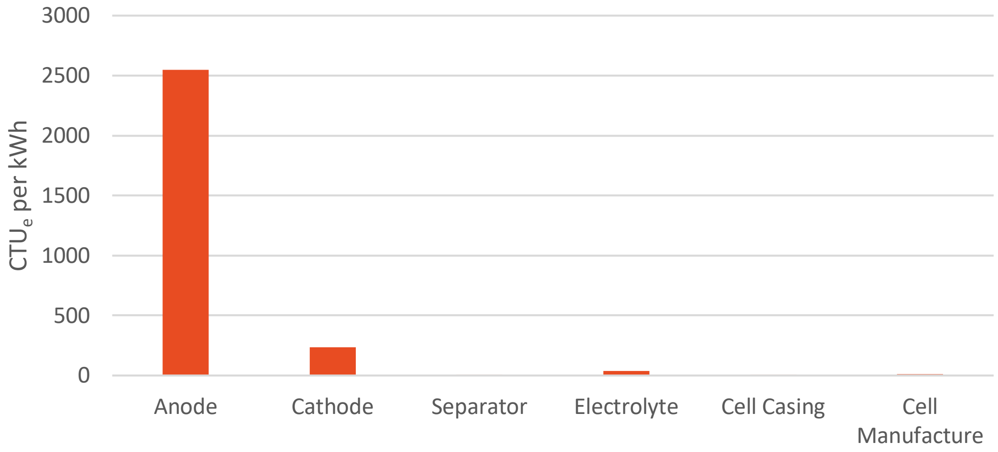
For ecological impacts, TRACI 2.1 uses a measure, known as the ecological toxicity potential (ETP), of a particular substance's toxicity to compare the relative importance of pollutants within each process. The ETP is a quantitative measure that expresses the potential ecological harm a unit quantity of a chemical released will have on the environment. The ETP is designed to capture the direct impacts of chemical emissions from industrial systems on the health of plant and animal species.

Assessing the toxicological effects of a chemical emitted into the environment implies a cause-effect-chain that links emissions to impacts through three steps: environmental fate, exposure, and ecological effects. From the three steps, a characterization factor for aquatic ETP is expressed in comparative toxic units of ecotoxicity (CTU_e) that represents an estimate of the potentially affected fraction (PAF) of species integrated over time and volume, per unit mass of a chemical emitted (e.g., CTU_e per kg emitted = PAF × m^3 × day per kg emitted). The ETPs of emitted chemicals on freshwater ecosystems are species-specific and based on the concentration at which 50% of a population displays an effect (Henderson et al. 2011).

The CTU_e is reflective of the change in the PAF of species due to the change in the concentration of a chemical. The final CTU_e impact score is derived as the sum of all incremental impacts for all substances emitted to air, water, or soils that ultimately affect water quality. The resulting score addresses the entire mixture of chemicals released throughout the Li-ion battery cell's cradle-to-gate lifecycle. It is important to note that CTU_e values do not predict impacts; they represent comparative measurements. So, for example, we can say the comparative impact of a chemical such as dibenzofuran generated by the Li-ion battery manufacturing has the greatest impact on ecotoxicity of all the chemicals involved in the Li-ion lifecycle.

Figure 8 presents the estimated lifecycle ecotoxicity effects of the C4V Li-ion battery production. Ecotoxicity impacts are primarily driven by the manufacture of copper and graphite used in anode production.

Figure 8. Ecotoxicity Potential by Lifecycle Stage



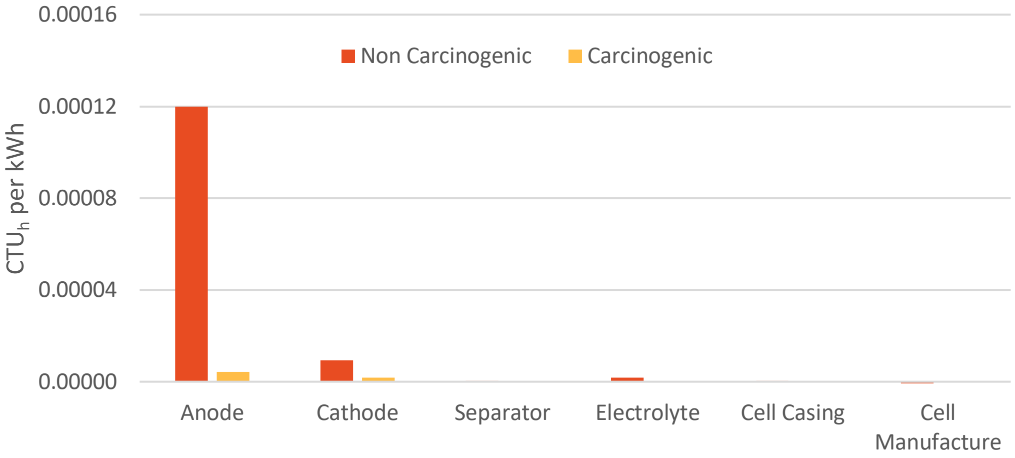
3.2.4 Cancerous and Non-Cancerous Substances

The TRACI 2.1 impact assessment method quantifies human health impacts of cancerous and non-cancerous substances. The measured effect on human populations considers ingestion and inhalation probabilities, and the potential risk that substances pose to human health. The effects are based on toxicity data for cancer and non-cancer effects derived from laboratory studies.

Similar to section 3.2.3 on ecotoxicity, human health impacts from TRACI 2.1 represent a quantitative characterization based on the integrated multimedia fate, exposure, and effect of released substances in comparative toxicity units of health (CTU_h). The units estimate an increase of morbidity due to all combined processes used to manufacture the Li-ion battery cell (i.e., human cases per kg emitted; Bare et al. 2012; Rosenbaum et al. 2008).

Figure 9 presents the estimated lifecycle cancerous and non-cancerous impacts of the C4V Li-ion battery production. Preliminary results suggest that the anode production drives the increased likelihood of human exposure to the ingestion/inhalation of toxic substances. The upstream manufacturing of the copper used in the anode is the primary driver of this impact.

Figure 9. Carcinogenic and Non-Carcinogenic Potential by Lifecycle Stage

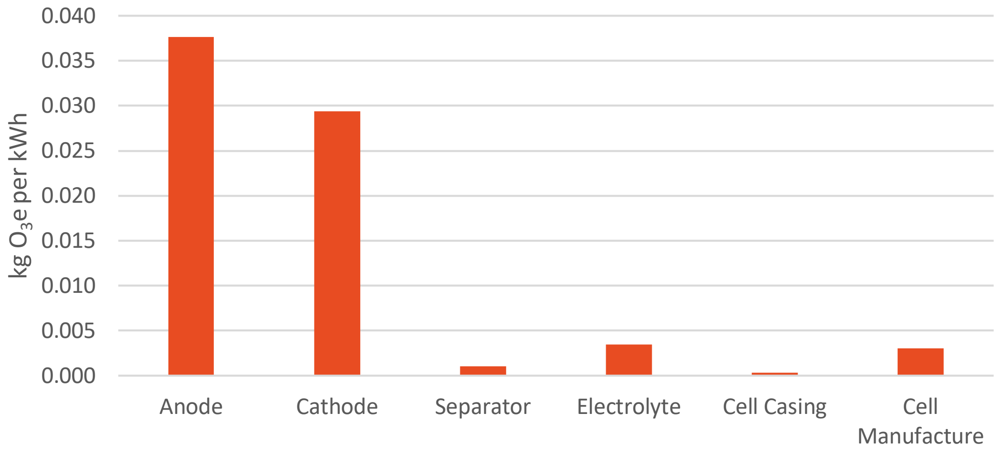


3.2.5 Smog

Various chemical reactions, which occur between nitrogen oxides (NO_x) and volatile organic compounds (VOC) in sunlight, create ground-level ozone. Human health effects can result in a variety of respiratory issues including increasing symptoms of bronchitis, asthma, and emphysema—and even permanent lung damage. Ecological impacts include damage to various ecosystems and crop damage. TRACI's approach to smog characterization analysis of VOCs and NO_x includes estimating the relative influence of individual VOCs on smog formation, the relative influence of NO_x concentrations versus average VOC mixture on smog formation, the effect of the emissions on ozone formation by release location, and methods for the aggregation of human health and ecological impacts among receiving areas.

Figure 10 presents the estimated lifecycle smog impacts of the C4V Li-ion battery production. The smog created in anode production is primarily driven by the upstream manufacturing of copper and graphite. The smog from the cathode production is primarily created by the manufacture of LMO and NMP. The aluminum collector in the cathode represents less than 1% of the smog emissions associated with Li-ion battery production.

Figure 10. Smog Potential by Lifecycle Stage



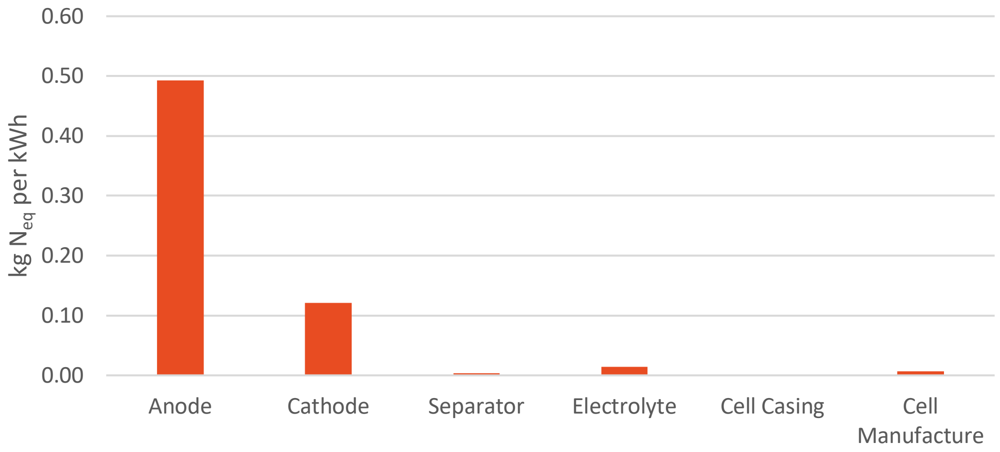
3.2.6 Eutrophication

Eutrophication is the enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerates biological productivity (growth of algae and weeds) and results in an undesirable accumulation of biomass and oxygen depletion. Although nitrogen and phosphorus play an important role in the fertilization of agricultural lands and other vegetation, excessive releases of either of the substances may provide undesired effects on the waterways they enter.

The units of the weighting values in this impact category are nitrogen equivalents (N_{eq}) per kg of emissions. Inorganic emissions that contribute to this impact category include ammonia and other water-soluble, nitrogen-containing compounds as well as phosphate and other water-soluble phosphorus-containing compounds.

Figure 11 presents the estimated lifecycle eutrophication impacts of the C4V Li-ion battery production. The upstream materials used in the anode production, more specifically the copper used to produce the anode, primarily drive the eutrophication impacts.

Figure 11. Eutrophication Potential by Lifecycle Stage



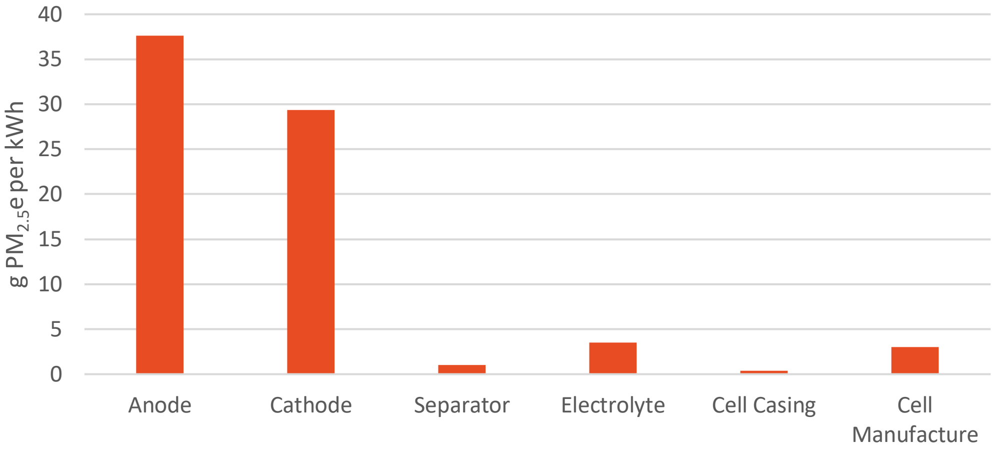
3.2.7 Respiratory Effects

This category deals with a subset of the criteria pollutants (i.e., PM and its precursors). Particulate matter (PM) is a collection of small particles in ambient air that have the ability to cause negative human health effects, including respiratory illness and death.

The method for calculating human health impacts includes modeling the fate of and exposure to PM. The term "intake fraction" refers to the portion of the PM that is expected to be inhaled by a human being. Intake fractions are calculated as a function of the amount of PM emitted into the environment, the resulting increase in ambient PM concentrations, and the breathing rate of the exposed population. The increasing ambient PM concentrations are a function of the location of the release, the accompanying meteorology, and the background PM concentrations (Bare et al. 2012).

Figure 12 presents the estimated lifecycle respiratory impacts, presented as the grams of particulate matter 2.5 microns-equivalent ($PM_{2.5}$e) emissions expected to be inhaled per kWh of battery capacity, of the C4V Li-ion battery production. The upstream manufacturing of the components used to make the battery anode, followed by the cathode, primarily drive these emissions.

Figure 12. Respiratory Effects Potential by Lifecycle Stage



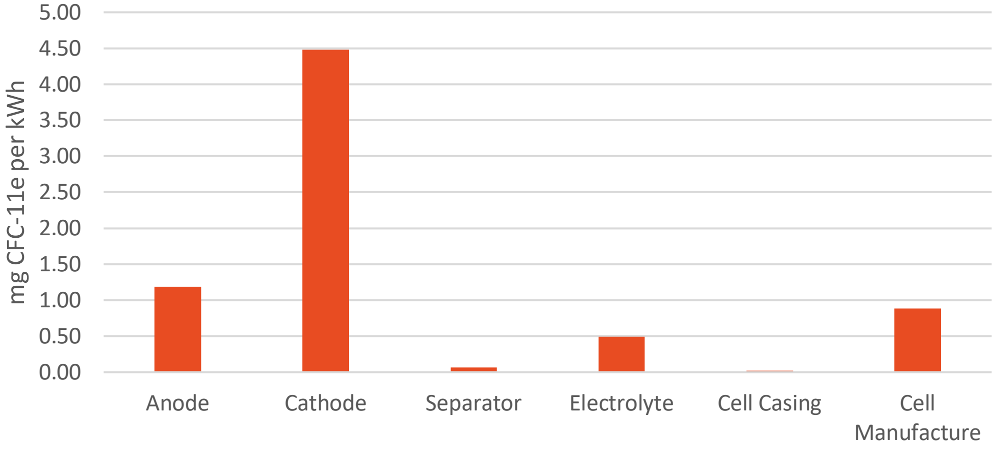
3.2.8 Ozone Depleting Potential

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons (CFCs), if released to the atmosphere, may result in ozone-destroying chemical reactions. Ozone depletion refers to the lowering of the stratospheric ozone resulting from the ozone-destroying chemical reactions.

The impacts of different processes are based on the amount of ozone-depleting chemicals released into the air and the ozone depleting potential (ODP) of each chemical. The ODP is a measure of the change in the ozone column resulting from an ozone-depleting chemical compared to CFC-11 (trichlorofluoromethane; Bare et al. 2012). TRACI 2.1 bases the individual chemical impact score for ozone depletion on the ODP and quantity of the chemical released.

Figure 13 presents the estimated lifecycle ozone depletion impacts of the C4V Li-ion battery production. The cathode slurry production primarily drives the ozone depletion impacts, which represents about 41% of the ozone depletion impacts of this lifecycle stage.

Figure 13. ODP by Lifecycle Stage



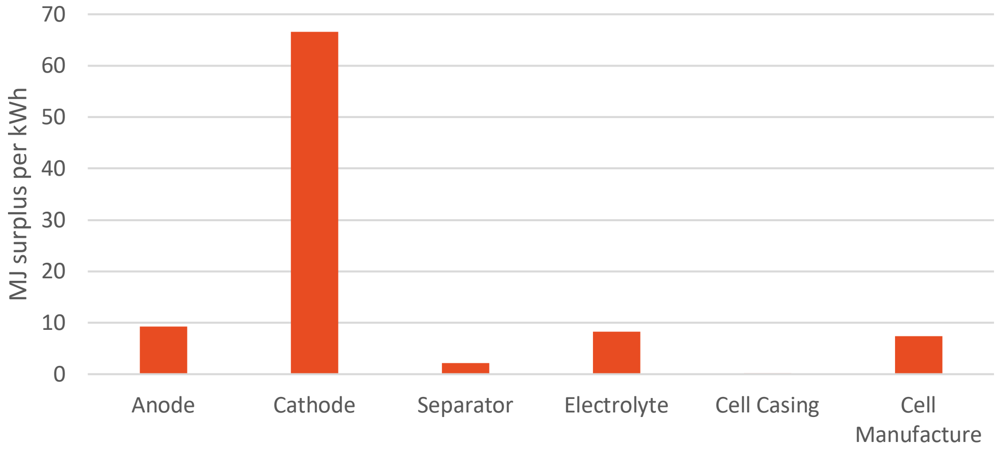
3.2.9 Primary Energy Consumption (Fossil Fuel Depletion)

This category provides information specific to the characterization of fossil fuels used for the production of the C4V Li-ion battery, and considers the extraction and processing of fossil fuels. The consideration is especially necessary once economically recoverable reserves of conventional fossil fuels are consumed, leading to the need to use unconventional resources. The analysis weighs future fuel consumption versus present cumulative consumption to estimate the incremental energy input “cost” per unit of consumption.

Energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. “Primary” describes the energetic materials or flows found in nature that have not been subjected to transformation. Thus, it represents system inputs from both raw fuels and other forms of energy. These factors then provide a basis for weighting the consumption of different fossil fuel energy resources to determine the impact of manufacturing a battery (Bare et al. 2003). Fuel inputs are converted from mass to energy units using the fuel’s heat value and density.

Figure 14 presents the estimated lifecycle fossil fuel depletion impacts of the C4V Li-ion battery production. The cathode primarily drives the impacts from the production of upstream materials such as the NMP used to manufacture the solvent and the conductive carbon used in the cathode.

Figure 14. Fossil Fuel Depletion Potential by Lifecycle Stage



3.2.10 Summary of Impact Category Results

Figure 8 summarizes the results by value and percent for all 10 impact categories assessed by TRACI 2.1. This estimate is derived by summing all downstream process contributions to flows and impact categories. It displays upstream totals of each lifecycle stage of the battery manufacturing process. All values are expressed on a unit per kWh basis. This functional unit represents impacts reported on a mass basis (e.g., grams, kg, milligrams) per the battery’s nominal energy capacity measured in kWh.

Table 815. Final Contributions of Each Impact Category by Lifecycle Stage (Impact Category Unit per kWh)

Battery Component	Global Warming	Acidification	Carcinogenic	Ecotoxicity	Eutrophication	Fossil Fuel Depletion	Non-Carcinogenic	Ozone Depletion	Respiratory Effects	Smog
By Value	kg CO$_2$e	kg SO$_2$e	CTU$_h$	CTU$_e$	kg N$_{eq}$	MJ surplus	CTU$_h$	mg CFC-11e	mg PM$_{2.5}$e	kg O$_3$e
Anode	7.27	0.27	0.000004	2,546.04	0.49	9.30	0.000120	1.19	37.61	1.61
Cathode	33.58	0.15	0.000002	237.63	0.12	66.55	0.000009	4.48	29.38	0.98
Separator	1.02	0.00	0.000000	6.83	0.00	2.20	0.000000	0.06	1.03	0.03
Electrolyte	3.83	0.02	0.000000	36.10	0.01	8.23	0.000002	0.49	3.48	0.35
Cell Casing	0.24	0.01	0.000000	6.69	0.00	0.21	0.000000	0.02	0.36	0.01
Cell Manufacture	3.50	0.01	0.000000	10.22	0.01	7.40	0.000000	0.89	3.00	0.09
Total	**49.44**	**0.46**	**0.000007**	**2,843.52**	**0.64**	**93.89**	**0.000130**	**7.13**	**74.86**	**3.09**
By Percent	**Global Warming**	**Acidification**	**Carcinogenic**	**Ecotoxicity**	**Eutrophication**	**Fossil Fuel Depletion**	**Non-Carcinogenic**	**Ozone Depletion**	**Respiratory Effects**	**Smog**
Anode	14.7%	58.1%	65.3%	89.5%	77.0%	9.9%	91.2%	16.7%	50.2%	52%
Cathode	67.9%	32.5%	26.5%	8.4%	19.0%	70.9%	7.0%	62.8%	39.3%	32%
Separator	2.1%	0.9%	0.8%	0.2%	0.5%	2.3%	0.2%	0.9%	1.4%	1%
Electrolyte	7.8%	5.4%	3.6%	1.3%	2.2%	8.8%	1.2%	6.9%	4.7%	11%
Cell Casing	0.5%	1.1%	2.4%	0.2%	0.1%	0.2%	0.0%	0.3%	0.5%	0%
Cell Manufacture	7.1%	2.1%	1.5%	0.4%	1.1%	7.9%	0.4%	12.5%	4.0%	3%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

CFC-11e = chlorofluorocarbons trichlorofluoromethane-equivalent; O$_3$e = ozone equivalent. Note: Some values may not sum due to rounding.

4 Summary of Results and Conclusions

The following sections elaborate on the results by component, place the results in context, and compare them to prior research. Due to the novel chemistry in the C4V battery cell manufacturing process, validation of the results presented in this study is challenging. However, this study uses openLCA and Ecoinvent which are widely accepted and validated. The Life Cycle Assessment Center for Excellence (LCACE) in the National Risk Management Research Laboratory of the US EPA Office of Research and Development has been both a collaborator and user of openLCA since 2012. openLCA has since been used in support of LCA studies that have been published in numerous EPA reports and top peer-reviewed journals in the field.

4.1 Battery Chemistry, Components, and Materials

Overall, as shown in section 3.2, the study found that the materials used for anode manufacturing produce many of the impacts across the 10 measured impact categories such as acidification, carcinogenic effects, ecotoxicity, eutrophication, non-carcinogenic effects, ozone depletion, respiratory effects, and smog. Specifically, the copper used in the manufacture of the anode drives many of these impacts, followed by the upstream impacts of graphite manufacturing. Other components, such as the cathode, generate a majority of the impacts for global warming, ozone depletion, and primary energy consumption of fossil fuels.

Primary energy consumption in the production of the batteries also has a significant impact on the environment. The cathode active materials appear to all require large quantities of energy to manufacture. The cathode is a dominant contributor to upstream consumption of fossil fuels from two inputs: the LMO and NMP production, which are responsible for about 64% of energy consumption (~ 68 MJ surplus per kWh).

Largely, as shown in Figure 9, the overall impacts are produced by three processes: the pollution generated by manufacture of the LMO, NMP production, the refining of copper, and electricity generation in northeastern United States. In particular, the manufacture and production of NMP is a top-two contributor in all impact categories. The refining of copper drives impacts in 7 of the 10 impact categories. LMO production and electricity generation also create impacts in several categories such as fossil fuel depletion, global warming, and/or ozone depletion.

Table 9. Top-Two Process Contributors to Each Impact Category

Impact category unit per kWh

Impact Area	Value	Percent
Global Warming (kg of CO_2e)	49.4	100%
NMP production	22.4	45%
LMO production	7.8	16%
Acidification (kg of SO_2e)	0.46	100%
Electrolytic refining of primary copper	0.25	53%
NMP production	0.10	22%
Carcinogenic (CTU_h)	6.50E-06	100%
Electrolytic refining of primary copper	3.96E-06	61%
NMP production	1.04E-06	16%
Ecotoxicity (CTU_e)	2844	100%
Electrolytic refining of primary copper	2518	89%
NMP production	160	6%
Eutrophication (kg N_{eq})	0.64	100%
Electrolytic refining of primary copper	0.47	74%
NMP production	0.08	12%
Fossil Fuel Depletion (MJ surplus)	93.9	100%
NMP production	51.8	55%
Electricity generation (northeastern United States)	15.8	17%
Non-Carcinogenic (CTU_h)	1.30E-04	100%
Electrolytic refining of primary copper	1.20E-04	92%
NMP production	6.20E-06	5%
Ozone Depletion (mg CFC-11_e)	7.13	100%
NMP production	3.06	43%
Electricity generation (northeastern United States)	1.90	27%
Respiratory Effects (mg $PM_{2.5}e$)	74.86	100%
Electrolytic refining of primary copper	29.72	40%
NMP production	19.72	26%
Smog (kg O_3e)	3.09	100%
NMP production	1.11	36%
Electrolytic refining of primary copper	0.77	25%

4.2 Comparison to Prior Research

Several comparable studies analyzed a cradle-to-gate product; however, many of those include the manufacture of the battery pack or some additional processes further downstream of the Li-ion battery cell. C4V only manufactures the battery cell, and its customers are responsible for the manufacture and assembly of the battery pack.

Two close comparisons are Kim (et al. 2016) and Ellingsen (et al. 2014). Both study cradle-to-gate impacts for a mass-produced battery in a commercial battery electric vehicle but also include the battery pack. The Kim (et al. 2016) study focused on the battery manufactured in South Korea that is used in the Ford Focus. Ellingsen (et al. 2014) modeled cradle-to-gate impacts of a Li-ion nickel-cobalt-manganese traction battery assembled in Greenland. Both studies modeled the material production, cell and component manufacturing, and battery pack assembly, including transportation. Similar to this study, Kim (et al. 2016) modeled a specific product and not a hypothetical Li-ion battery cell based on assumptions.

Figure 10 compares the results from Kim (et al. 2016) and Ellingsen (et al. 2014) for just the manufacture of the cell and its materials, excluding the component manufacturing, battery pack assembly, and transportation impacts. In general, the C4V LCA study results presented here found the impacts to be about 40% higher for cell materials but significantly less for cell manufacturing. This could reflect the fact that northeastern United States gets about half of its electricity from carbon-free sources, while Kim (et al. 2016) modeled the manufacture of the battery in South Korea where only about one-third of electricity is generated from carbon-free sources (EIA 2019). For Ellingsen (et al. 2014), the battery cell manufacturers' location was not available.

Table 10. Comparison of Global Warming Impacts to Prior Research

Kilogram CO_2e per kWh

Component	(Kim et al. 2016)	(Ellingsen et al. 2014)a	This Study
Cell Materials	27	27.52	45.94
Cell Manufacturing	63	106.64	4

Values from Ellingsen (et al. 2014) were estimated from taking the percentages from the lower bound value in Figure 2 and multiplying them by the average value in Table 2 in Ellingsen (et al. 2014).

Table 11 compares the acidification potential results for Kim (et al. 2016) and Ellingsen (et al. 2014) to this study. Again, the significantly lower results may be due to the fact that northeastern United States consumes about half of its electricity from carbon-free sources. Alternatively, since copper refining is a primary driver of particulate emissions, this could also be a reason for the large discrepancy. It appears that Ellingsen's (et al. 2014) battery cell used nearly double the copper as the C4V battery; the weight of the battery is 253 kg, and approximately 60% of the weight is from the battery cells. Additionally, the C4V battery uses less aluminum and other metals that may cause acidification during its production.

Table 11. Comparison of Acidification Impacts to Prior Research

Kilogram SO_{2e} per kWh

Component	(Kim et al. 2016)[b]	(Ellingsen et al. 2014)[a]	This Study
Cell Materials	845	1,197	0.45
Cell Manufacturing	185	418	0.01

a. Values from Ellingsen (et al. 2014) were estimated from taking the percentages from the lower bound value in Figure 2 and multiplying them by the average value in Table 2 in Ellingsen (et al. 2014).

b. Values from Kim (et al. 2016) were reported in g sulfur oxide per kWh.

Another study, conducted by EPA, also presents an LCA of Li-ion batteries used in vehicles involving single-walled carbon nanotubes for three battery chemistries. This study incorporated primary data from both battery manufacturers and recyclers and assessed the environmental and human health impacts from cradle-to-grave using TRACI 2.0's methodology (EPA 2012). Table 12 compares the lifecycle impacts for just the manufacture of the battery cell and materials for several comparable impact categories from this study. Due to changes between TRACI 2.0 and 2.1, many of the impacts are not comparable between the two studies (Bare et al. 2012). Figure 26 lists three comparable impact categories: smog, energy consumption/fossil fuel depletion, and ODP. The similarities of the smog values may stem from the fact that the proxy battery chemistry modeled in this study is similar to the LMO chemistry studied by EPA (EPA 2012). The lifecycle fossil fuel consumption impacts of the C4V battery are about an order of magnitude smaller than comparable batteries from the EPA study (EPA 2012). This may reflect the fact that the northeastern United States generates about half of its electricity from carbon-free sources compared to the more coal-centric electricity grid used in other parts of the United States that were used to assess the battery impacts in the EPA (EPA 2012) study. Lastly, the ODP of the C4V battery appears to be similar to the ODP of the battery impacts estimated in the EPA study (EPA 2012).

Table 12. Comparison of Smog and Energy Consumption Impacts to Prior Research

Smog (kg O_3e/kWh)	This Study	LMO	Li-NCM	$LiFePO_4$
Cell Materials	2.99	2.9	5.2	5.7
Cell Manufacturing	0.09	0.0	0.0	0.0
Energy Consumption/Fossil Fuel Depletion (MJ/kWh capacity)	This Study	LMO	Li-NCM	$LiFePO_4$
Cell Materials	86.5	719	1,219	1,130
Cell Manufacturing	7.4	28	0	0
ODP (mg CFC-11e/kWh)	This Study	LMO	Li-NCM	$LiFePO_4$
Cell Materials	6.24	2.0	4.8	2.1
Cell Manufacturing	0.9	0.0	0.0	0.2

The toxicity impacts (e.g., eutrophication, ecotoxicity, cancerous and non-cancerous substances) are largely driven by the manufacture and use of the copper foil used in the battery anode and NMP production. The results are consistent with similar studies such as Ellingsen (et al. 2014) and Deng (et al. 2017), which modeled a Li-ion nickel-cobalt-manganese and a lithium sulfur battery, respectively. Additionally, the small amount of aluminum contained in the battery seems to help lessen these impacts. Aluminum represents less than 1% of material inputs by mass used to assemble the Li-ion battery cell.

In conclusion, most comparable metrics of the C4V Li-ion cell fall within the lower end of the expected range of the lifecycle impacts generated by the manufacture of a Li-ion battery cell for several reasons. The main contributor to this result is that C4V assembles its Li-ion battery cell in the northeastern United States where about half the electricity is generated from carbon-free sources. Additionally, the C4V battery cell appears to use fewer metals and less-toxic materials than comparable modeled lithium cell batteries with higher impacts. A tertiary contributor to this result may be that this study does not include transportation emissions from the movement of upstream and downstream materials to and from the C4V factory. However, transportation emissions only generate a small portion of the impacts in many similar studies (Kim et al. 2016; EPA 2012).

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Endnotes

[1] Ecoinvent is a provider of an LCI database for thousands of products (Ecoinvent 2018). This data source is described further in section 2.1.2.

[2] A cradle-to-use analysis differs from a cradle-to-gate analysis since it includes some parts of the product's lifecycle use by the consumer.

[3] Note that this is opposite the conclusion of prior studies and demonstrates the uncertainty associated with lifecycle assessments of Li-ion batteries.

[4] OpenLCA is available at http://www.openlca.org/

[5] The furnace method for manufacturing carbon black uses continual thermal decomposition of feedstock using heat generated by the combustion of fuel in the presence of hot air. The fuel, when exposed to hot air, undergoes complete combustion, further elevating the temperature. Feedstock oil is then introduced downstream of the reactor and is continuously atomized by the high temperatures. Lastly, the high-temperature gas with carbon black is quenched with water downstream of the reactor to quickly lower its temperature, which stops the reaction (Asahi Carbon Co. 2010).

[6] As described by Rio Tinto (2014).

[7] Note: The C4V BM-LMP cathode uses phosphoric acid during the manufacturing process of the cathode. The LCA accounts for the phosphoric acid generically as spent and disposed solvent. However, the impacts quantified are not specific to phosphoric acid's lifecycle.

[8] BM-LMP stands for Bio-Mineralized Lithium Mixed-Metal Phosphate. C4V cannot disclose the exact metals in its battery chemistry because it would be possible to reverse engineer the design of the battery. As a proxy, this LCA study uses the process for the manufacture of $LiMnO_2$. The C4V battery chemistry is primarily manganese and iron. As such, Abt and C4V selected an LMO process that would closely match the footprint of the C4V battery chemistry.

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