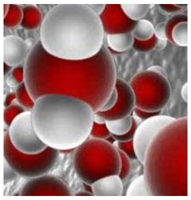
EPA United States
Environmental Protection
Agency

Design for the Environment Program
EPA's Office of Pollution Prevention and Toxics

National Risk Management Research Laboratory
EPA's Office of Research and Development

Application of Life-Cycle Assessment to Nanoscale Technology:

Lithium-ion Batteries for Electric Vehicles



April 24, 2013
EPA 744-R-12-001

For More Information

To learn more about the Design for the Environment (DfE)/Office of Research and Development (ORD) Li-ion Batteries and Nanotechnology for Electric Vehicles Partnership, or the DfE Program, please visit the DfE Program web site at: www.epa.gov/dfe.

Acknowledgements

Shanika Amarakoon, Jay Smith, and Brian Segal of Abt Associates, Inc. prepared this life-cycle assessment (LCA) under contract to the U.S. Environmental Protection Agency's (EPA) Design for the Environment (DfE) Program in the Economics, Exposure, and Technology Division (EETD) of the Office of Pollution Prevention and Toxics (OPPT). The project was also co-funded and co-led by EPA's National Risk Management Research Laboratory (NRMRL) in the Office of Research and Development (ORD).

This document was produced as part of the DfE/ORD Li-ion Batteries and Nanotechnology for Electric Vehicles Partnership, under the direction of the project's Core Group members, including: **Kathy Hart**, EPA DfE Project Co-Chair, and **Dr. Mary Ann Curran,** EPA ORD Project Co-Chair; **Clive Davies**, EPA/DfE, **Dr. David E. Meyer,** EPA/ORD; **Dr. Linda Gaines, Dr. Jennifer Dunn**, and **Dr. John Sullivan**, Argonne National Laboratory, Department of Energy (DOE); **Jack Deppe**, consultant to DOE; **Dr. Thomas Seager** and **Ben Wender**, Arizona State University; **Gitanjali Das Gupta** and **Raj Das Gupta**, Electrovaya, Inc.; **Casey Butler** and **Pam Dickerson**, EnerDel, Inc.; **Mark Caffarey**, Umicore Group; **Shane Thompson** and **Todd Coy**, Kinsbursky Brothers, Inc. (Toxco); **Steve McRae** and **Tim Ellis**, RSR Technologies, Inc.; **Barry Misquitta**, Novolyte Technologies, Inc.; **Gabrielle Gaustad**, Rochester Institute of Technology; **Roland Kibler**, NextEnergy; **George Kirchener**, Rechargeable Battery Association; and **Ralph Brodd** and **Carlos Helou**, National Alliance for Advanced Technology Batteries (NAATBatt).

The authors gratefully acknowledge the outstanding contributions of the following individuals for their assistance in providing technical support, data, and guidance that was important for the successful completion of the report:

- **Dr. Thomas Seager** of Arizona State University for the important feedback and guidance during the goal and scope definition phase of the project and assistance in developing the life-cycle inventory data methodology. Dr. Seager, with support from **Ben Wender**, provided analysis regarding the rate of SWCNT manufacturing improvements and use-phase modeling of SWCNT anode technology.
- **Dr. Brian Landi** of the Rochester Institute of Technology, for the important feedback and guidance during the goal and scope definition phase of the project.
- **Dr. Troy Hawkins** of EPA's ORD, for his important technical support and guidance, particularly in the life-cycle impact assessment phase, and in assessing impacts from varying grid mixes, as well as the overall presentation of results.
- **Maria Szilagyi** of EPA's Risk Assessment Division (OPPT), **Dr. Emma Lavoie** of the DfE Program, Economics, Exposure, and Technology Division (OPPT), **Jim Alwood** and **Kristan Markey** of the Chemical Control Division (OPPT), and **Jay Tunkel** of Syracuse Research Corporation. Their assistance in reviewing and providing health and environmental toxicity information for the project was greatly appreciated.

The authors would also like to acknowledge the contributions of the Abt Associates staff who assisted the authors, including: **Dr. Alice Tome** for her technical quality review, and **Brenden Cline** for his technical support.

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Abstract

Demand for electric vehicles is increasing, and lithium-ion (Li-ion) batteries with increased ranges will be critical to increasing electric vehicle marketability and reducing greenhouse gas emissions. While Li-ion batteries are expected to play a key role in the electric drive transportation industry, there are opportunities for improvements in the batteries' life-cycles that will reduce possible impacts to the environment and public health in a few specific areas, as their use increases.

This study, carried out through a partnership led by EPA, with the U.S. Department of Energy (DOE), the Li-ion battery industry, and academics, was the first life-cycle assessment (LCA) to bring together and use life-cycle inventory data directly provided by Li-ion battery suppliers, manufacturers, and recyclers. Its purpose was to identify the materials or processes within a Li-ion battery's life cycle (from materials extraction and processing, manufacturing, use, and end-of-life) that most contribute to impacts on public health and the environment. It also sought to evaluate the potential impacts of a nanotechnology innovation (i.e., a carbon nanotube anode) that could improve battery performance.

The study does . . .

- ✓ *Identify areas for improvement to reduce life-cycle environmental impacts for li-ion batteries used in electric vehicles*
- ✓ *Help battery manufacturers select materials and processes that result in fewer impacts*
- ✓ *Evaluate the potential impacts of a nanotechnology innovation (single-walled carbon nanotube)*
- ✓ *Use primary data from battery manufacturers, suppliers, and recyclers*
- ✓ *Follow LCA methods consistent with the EPA, SETAC, and ISO assessment guidelines*

The study does not . . .

- × *Provide a comparative assessment of the battery systems*
- × *Assess overall battery safety*
- × *Assess the manufacture of the non-battery components of the electric vehicle*
- × *Quantify actual impacts at a specific location or point in time*

Battery manufacturers and suppliers can use this information to improve the environmental profile of their products, while the technology is still emerging. This study also provides a benchmark for future research and for identifying additional opportunities for reducing environmental and human health impacts throughout the life cycles of these Li-ion battery systems.

The LCA study was conducted consistent with the International Standards Organization (ISO) 14040 series, which stipulates four phases of an LCA: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation. No comparative assertions, as defined in ISO 14040, were made about the superiority or equivalence of one type of battery system versus another in this study.

Product System

Li-ion batteries are composed of three layers: an anode, a cathode, and a porous separator, which is placed between the anode and cathode layers. The anode is composed of graphites and other conductive additives. The cathode is composed of layered transition metal oxides (e.g., lithium cobaltite ($LiCoO_2$) and lithium iron phosphates ($LiFePO_4$)). The study assessed three Li-ion battery chemistries for an electric vehicle (EV) and two chemistries for a long-range plug-in hybrid electric vehicle (PHEV) with a 40 mile all-electric range. The battery chemistries included a lithium-manganese oxide ($LiMnO_2$)-type, lithium-nickel-cobalt-manganese-oxide ($LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$), and lithium-iron phosphate ($LiFePO_4$). In addition, a single-walled carbon nanotube (SWCNT) anode technology for possible future use in these batteries was assessed.

Approach

Life-cycle inventory (LCI) data for the product systems were obtained directly from the manufacturers, suppliers, and recyclers in the partnership for the component manufacture, product manufacture, and end-of-life (EOL) stages. Data needed to supplement data gaps and protect confidential data were obtained from published studies. In addition, LCI data for SWCNT production was provided by researchers at Arizona State University. The data were then aggregated and modeling (using GaBI4 LCA software) consistent with ISO 14040 standards.

Key Results and Conclusions

The study showed that the batteries that use cathodes with nickel and cobalt, as well as solvent-based electrode processing, have the highest potential for environmental impacts. These impacts include resource depletion, global warming, ecological toxicity, and human health impacts. The largest contributing processes include those associated with the production, processing, and use of cobalt and nickel metal compounds, which may cause adverse respiratory, pulmonary, and neurological effects in those exposed. There are viable ways to reduce these impacts, including cathode material substitution, solvent-less electrode processing, and recycling of metals from the batteries.

Material and processing choices specific to producers, suppliers, and recyclers in the supply chain were not the only key contributing factors to overall environmental impacts associated with the batteries' life cycles. Among other findings, global warming potential and other environmental and health impacts were shown to be influenced by the electricity grids used to charge the batteries prior to vehicle operation. Specifically, the study results indicate that the "use stage" is an important driver of impacts for the life cycle of the battery, particularly when batteries are used with more carbon-intensive grids.

In addition, the SWCNT nanotechnology applications assessed show promise for improving the energy density and ultimate performance of the Li-ion batteries in vehicles. However, the energy needed to produce these anodes in these early stages of development is significant (i.e., may outweigh potential energy efficiency benefits in the use stage). Over time, if researchers focus on reducing the energy intensity of the manufacturing process before commercialization, the overall environmental profile of the technology has the potential to improve dramatically.

Further Research

There are many opportunities for further research on the potential impacts and benefits of Li-ion batteries for use in electric and hybrid electric vehicles, especially since it is an emerging and growing technology. Some of these opportunities are highlighted below:

- Broaden the scope to conduct a full vehicle LCA study, rather than a study of only the vehicle battery;
- Assess changes to the grid that may result from a large increase in the number of PHEVs and EVs, such as the use of more renewables, energy storage systems, and new power plants;
- Assess electricity and fuel use from battery manufacturers to address highly variable manufacturing methods, including those that use water and those that operate without solvent;

- Assess differences between battery chemistries and sizes for different vehicles, including how these differences may impact the battery lifespan;
- Assess whether the use of certain lightweight materials that generate high impacts upstream are mitigated during the use stage (e.g., aluminum);
- Assess recycling technologies as the stream of Li-ion batteries for vehicles increases and the technologies evolve; and
- Conduct additional research on SWCNTs and other nanomaterials, especially through component suppliers.

The LCA results and methodology are described in detail in the following pages. This study provides a benchmark for future research, and for identifying additional opportunities for reducing environmental and human health impacts throughout the life cycles of these Li-ion battery systems.

Summary

This report presents a life-cycle assessment (LCA) study of lithium-ion (Li-ion) batteries used in electric and plug-in hybrid electric vehicles. The study also assesses a next-generation technology involving single-walled carbon nanotubes (SWCNTs) being developed to increase the energy capacity and marketability of these battery systems. The study was undertaken through the Li-ion Batteries and Nanotechnology Partnership (hereinafter referred to as "partnership"), formed in July 2009, with EPA's Design for the Environment Program in the Office of Chemical Safety and Pollution Prevention, and EPA's National Risk Management Research Laboratory in the Office of Research and Development . Li-ion battery manufacturers, research and trade organizations, battery recycling companies, and the Department of Energy's Argonne National Laboratory also participated in the partnership.

In response to concerns about dependence on oil imports and climate change, the demand for electric vehicles, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (EVs), is increasing. Li-ion batteries will be critical to increasing electric vehicle marketability, due to their large energy storage capability. Accordingly, the demand for automotive Li-ion batteries is projected to grow significantly, from about 1 billion USD in 2010 to 30 billion USD by 2018 (Takeshita, 2010). Given the importance and projected growth of this technology, the partnership undertook this LCA study to help the Li-ion battery industry identify the materials or processes within a battery's life cycle that are likely to pose the greatest impacts to both public health and the environment, and to evaluate nanotechnology innovations in advanced Li-ion batteries for electric vehicles that may enhance battery performance. In addition, the study assessed the impacts associated with recycling the batteries after their useful life.

Prior LCA studies of Li-ion batteries for vehicles have relied primarily on secondary or modeling data to estimate impacts, while considering only a limited number of life-cycle stages, vehicle types, and/or impacts. This study is the first of its kind that brings together both battery manufacturers and battery recyclers and other stakeholders to address gaps in existing studies by: (1) incorporating primary data from both battery manufactures and recyclers, and assessing the environmental and human health impacts from cradle-to-grave; (2) assessing impacts of a next-generation technology involving carbon nanomaterials (i.e., single-walled carbon nanotubes); and (3) assessing the impacts from a U.S. standpoint.

The study was conducted consistent with the ISO 14040 series, which stipulates four phases of an LCA: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation. This study conducts the first three phases and part of the interpretation phase. Interpretation includes analyses of major contributions, sensitivity analyses, and uncertainty analyses, as necessary to determine if the goals and scope are met. Some conclusions and recommendations are presented; however, users of the study may also make their own conclusions, depending on subjective methods of interpreting the data. Further, no comparative assertions as defined in ISO 14040 are made about the superiority or equivalence of one type of battery chemistry or vehicle type versus another. Below we summarize the scope and boundaries of the study, LCI data sources, LCIA results, sensitivity analysis, and key conclusions.

Scope and Boundaries

As noted above, the product systems that are the subject of this LCA are Li-ion batteries used in electric vehicles. Based on the types of batteries and battery chemistries manufactured by members of the partnership (who provided primary data for the study), this study assessed high-energy density Li-ion battery technologies for EV and PHEV-40 (PHEVs with a 40-mile all-electric range (AER)) applications; and SWCNT anode technology for possible future use in these batteries. The battery chemistries used by the manufacturers include a lithium-manganese oxide ($LiMnO_2$)-type chemistry[1] and a lithium-nickel-cobalt-manganese-oxide ($LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$) chemistry. As part of the analysis, we also modeled lithium-iron phosphate ($LiFePO_4$) from secondary data, as a supplement to the primary data received.

In an LCA, product systems are evaluated on a functionally equivalent basis. The functional unit normalizes data based on equivalent use (or service provided to consumers) to provide a reference for relating process inputs and outputs to the inventory, and impact assessment for the LCIA, across product systems. Since the product systems evaluated in this study are Li-ion batteries used in vehicles, the service provided by these vehicles is the distance driven. Accordingly, the functional unit is based on kilometers driven. In addition, the study assumes that the anticipated lifetime of the battery is the same as the anticipated lifetime of the vehicle for which it is used (10 years). According to the partnership, this represents the anticipated lifetime the battery manufacturers seek to achieve. Therefore, our study assumes one Li-ion battery per vehicle life-time, as determined by the partnership to represent the anticipated lifetime of the batteries.

The boundaries for the study were mainly defined based on the available resources and data. Figure 1 presents a generic process flow diagram for the manufacture of Li-ion batteries within the life-cycle stages that are modeled in this study. Although the battery design and manufacturing process differ based on the cell architecture and company-specific technologies, this process flow diagram presents the key processes common to the manufacturers in the partnership. The process flow diagram also includes upstream materials processing for the SWCNT anode. Although SWCNT anodes are not currently included in commercially available Li-ion batteries, the partnership conducted a separate analysis to substitute the SWCNT anode process for the current anode technology in a Li-ion battery system. This was done in order to determine the potential impacts of that component in the cradle (extraction of raw materials) to gate (manufacture of the anode) stages of the life cycle.

Although the focus of the LCA study is on Li-ion batteries, given the fact that the purpose of the batteries is to provide energy for transportation in the use stage, the study includes an assessment of impacts resulting from the vehicles that the batteries are placed in (EVs and PHEVs), in the use stage only. It is important to note that this study does not generate and inventory or quantify impacts for the upstream, manufacturing, or end-of-life of non-battery vehicle components. The partnership selected this approach in order to focus the scope of the study on the Li-ion batteries themselves. For the end-of-life (EOL) stage, impacts are based on current EOL technologies for recycling Li-ion batteries (hydrometallurgical and pyrometallurgical), and one technology that is currently in the pilot stage (direct recovery process).

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[1] Due to confidentiality issues, the manufacturer indicated that they were producing something stoichiometrically similar to $LiMnO_2$, but provided little additional detail related to the chemical or physical state of the active material. The chemistry is likely a modification of $LiMnO_2$, and possibly a mixed metal oxide.

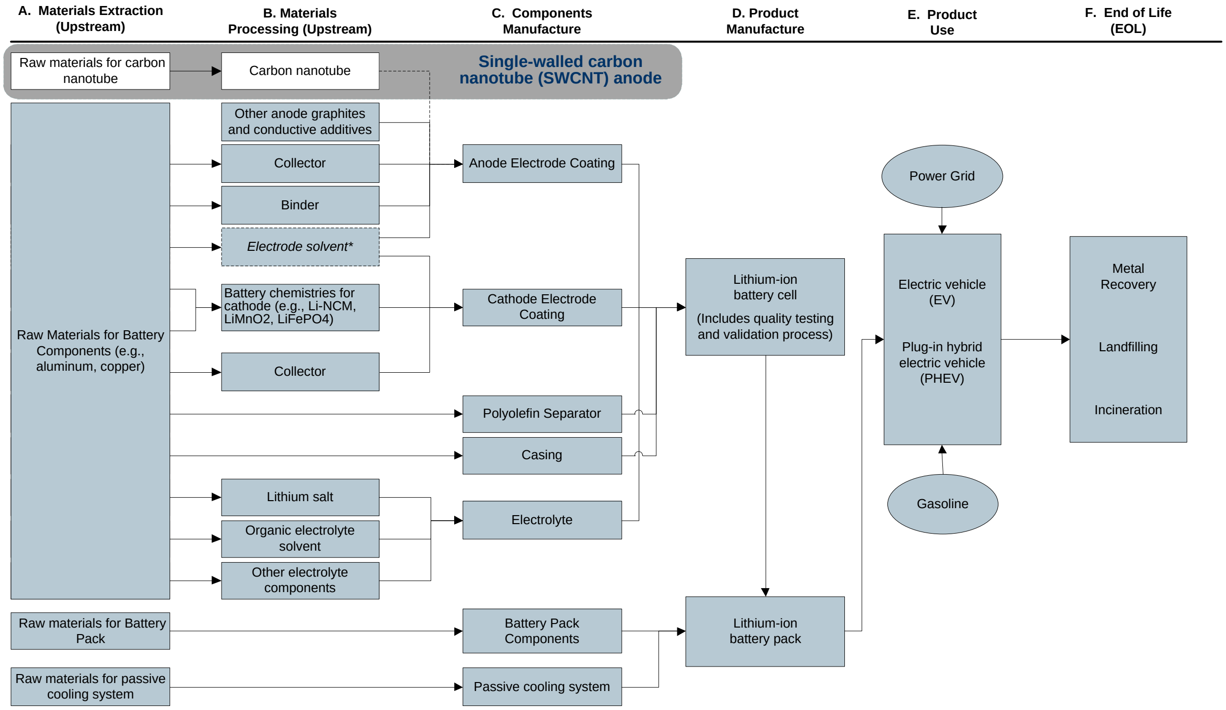

Figure 1. Generic Process Flow Diagram for Li-ion Battery for Vehicles

LCI Methodology and Sources

The LCI tallies the material and energy inputs, products generated, and environmental releases throughout the products’ life cycles. LCI data were collected for all the stages in the Li-ion battery life cycle (see Figure 1). The LCI data were compiled into the GaBi4 LCA software tool (PE & IKP, 2003) to assist with data organization and life-cycle impact analysis.

Through the manufacturers, suppliers, and recyclers in the partnership, primary data were obtained for the component manufacture, product manufacture, and EOL stages. Secondary data, needed to supplement data gaps and protect confidential data, were primarily obtained from the following studies:

- Contribution of Li-ion Batteries to the Environmental Impact of Electric Vehicles (Notter et al, 2010).
- Life-Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electric Vehicles (Majeau-Bettez et al., 2011).
- Comparative Environmental Life-Cycle Assessment of Conventional and Electric Vehicles (Hawkins et al., under review).

LCI data available within GaBi4 were also used for upstream materials and fuel inputs, as the scope of the project and resources were limited to collecting primary data from the product manufacture and recycling stages. These datasets included European Aluminum Association (EAA, 2008), the National Renewable Energy Laboratory’s (NREL’s) U.S. LCI, and proprietary GaBi4 processes developed by PE International. For the use stage, LCI data for the gasoline process were also obtained as a GaBi4 proprietary process. However, the power grid data relied on a combination of Energy Information Administration and U.S. LCI data.

LCIA Results and Sensitivity Analysis

Life-cycle impact assessments (LCIAs) generally use the consumption and loading data from the inventory stage to create a suite of estimates for various human health and ecological impact categories. Primary drivers of these impact categories for battery systems evaluated include both upstream material and primary energy inputs. With regard to upstream material use, the study found that lithium brine extracted from saline lakes in Chile is by far the largest mass input (up to 28 %) in the upstream and manufacturing stages, after water and air, and is primarily used for the cathode and electrolyte production. The major fuels, in decreasing order of mass, are hard coal, crude oil, natural gas, and lignite. Outside of the use stage, primary energy use was driven by aluminum ingot production for the passive cooling system and the extraction of materials to manufacture the cathode. Average primary energy use across the Li-ion battery chemistries totaled 1,780 MJ/kWh of battery capacity, and 2 MJ/km driven.

In addition to energy use, this LCIA presents estimated impacts of the Li-ion battery chemistries in EVs and PHEVs across 10 impact categories. One impact category is based on the direct loading measure of the inventory - abiotic resource depletion. Five impact categories use equivalency factors to translate relevant inventory flows into impacts: global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and photochemical oxidation potential. Finally, the four toxicity categories use hazard values as a relative measure of the inherent toxicity of a material, and relate the value to the amount of input or output of the material to generate a hazard score for ecological toxicity potential, human toxicity potential, occupation cancer hazard, and occupational non-cancer hazard. Final LCIA results for each impact category are the sum of all indicators for all materials in each life-cycle process that are classified into the appropriate impact category.

Figure 2 presents a summary of the LCIA results by battery chemistry and life-cycle stage for EV batteries, and Figure 3 presents a summary of results for PHEV-40 batteries.

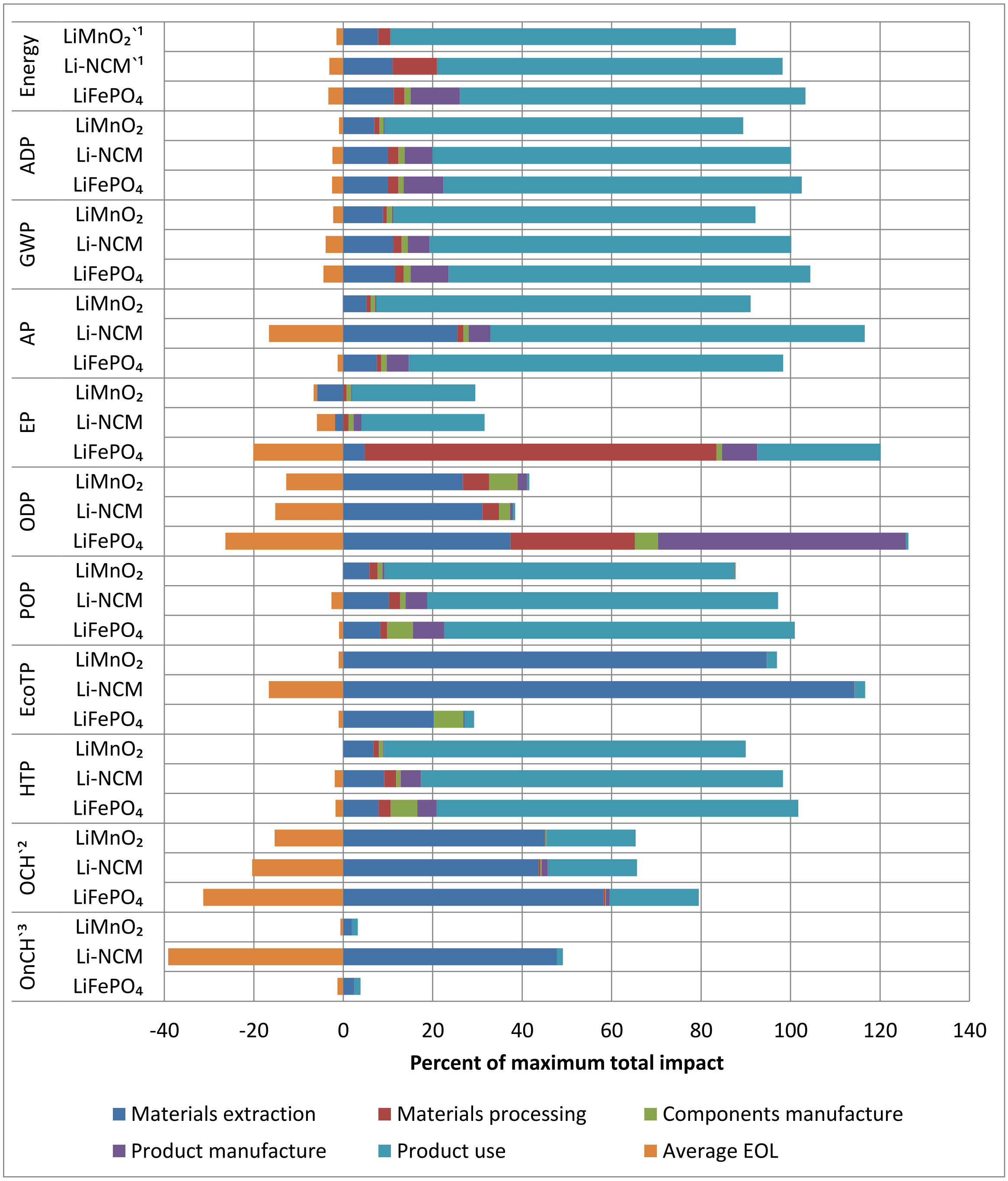

Figure 2. Life-Cycle Impact Assessment Results by Battery Chemistry and Stage for EV Batteries

Notes: ADP = abiotic depletion potential; AP = acidification potential; EcoTP = ecological toxicity potential; EP = eutrophication potential; GWP = global warming potential; HTP = human toxicity potential; OCH = occupational cancer hazard; ODP = ozone depletion potential; OnCH = occupational non-cancer hazard; POP = photochemical oxidation potential.

\1 Primary energy consumed during the materials processing, component, and product manufacture was combined to protect proprietary data submitted by manufacturer.

\2 Occupational cancer hazard impact was scaled to 50% in this figure because of the wide range across stages.

\3 Occupational non-cancer hazard impact was scaled to 10% in this figure because of the wide range across stages.

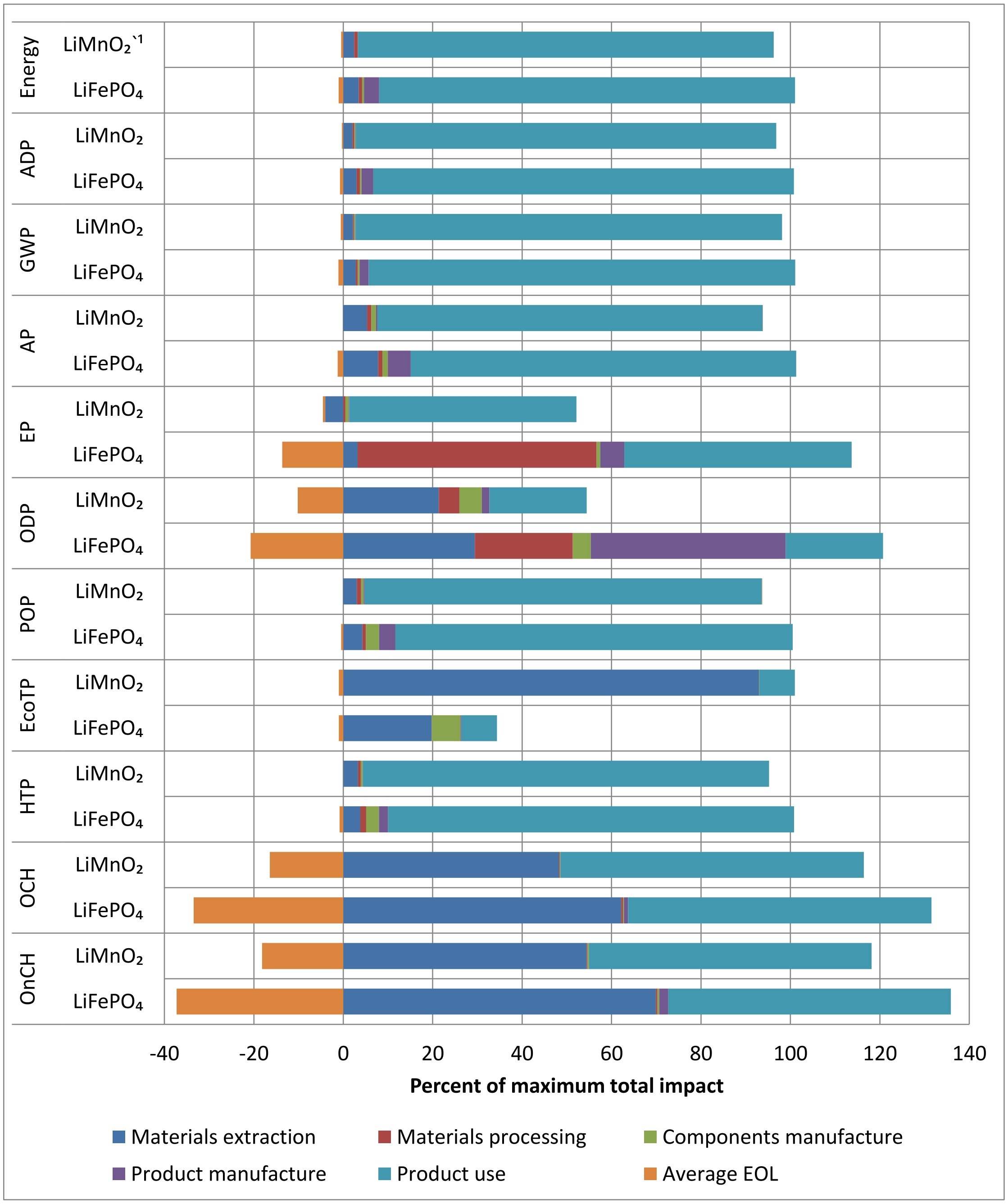

Figure 3. Life-Cycle Impact Assessment Results by Battery Chemistry and Stage for PHEV Batteries

Notes: ADP = abiotic depletion potential; AP = acidification potential; EcoTP = ecological toxicity potential; EP = eutrophication potential; GWP = global warming potential; HTP = human toxicity potential; OCH = occupational cancer hazard; ODP = ozone depletion potential; OnCH = occupational non-cancer hazard; POP = photochemical oxidation potential.

[\1] Primary energy consumed during the materials processing, component, and product manufacture was combined to protect proprietary data submitted by manufacturer.

A sensitivity analysis was also undertaken to assess the sensitivity of the LCIA results to three key variables, as follows:

- **The lifetime of the battery**. There is uncertainty with respect to the actual lifetime of batteries in automobiles. Our analysis assumes a life-time of 10 years, which we halved for the sensitivity analysis.
- **A range of recovery and reuse rates for materials in the battery pack**. LCI data were based on current recycling processes, which do not recycle large volumes of Li-ion batteries for vehicles at present. Recovery and eventual disposition of materials will be better characterized as the volume of battery waste increases and markets for recovered/recycled materials emerge. The recovery of the materials and credit for reuse was assumed using a best-case scenario. Accordingly, based on data provided by the recyclers, we used a low and high-end of the range to assess impacts under the sensitivity analysis.
- **A combination of six different charging scenarios.** With regard to use stage impacts, changes in the power grid (i.e., the types of power generation that comprise the grid) over time, from more coal-centric sources to ones using more natural gas and renewables, will influence the LCI data and overall environmental and health impacts. Accordingly, we assessed LCIA impacts based on two types of charging options (unconstrained and smart charging[2]) and three power grids from different regions (Elgowainy et al., 2009), as follows: (i) *Western Electricity Coordinating Council (WECC)* – natural gas-centric marginal[3] generation; (ii) *Independent System Operator – New England (ISO-NE)* – natural gas-centric marginal generation; and (iii) *Illinois (IL)* – coal-centric marginal generation.

Key Conclusions

The LCIA results for the three Li-ion battery chemistries and battery types (for EV and PHEV-40 vehicles) generated several interesting findings and opportunities for improvement, which we highlight below:

Battery Chemistries, Components, and Materials

- Across battery chemistries, the choice of active material for the cathode affects human health and toxicity results. For example, the nickel cobalt manganese lithium-ion (Li-NCM) chemistry relies on rare metals like cobalt and nickel, for which the data indicated significant non-cancer and cancer toxicity impact potential. The other two chemistries use the lower toxicity metals, manganese and iron.

- The cathode active materials appear to all require large quantities of energy to manufacture. However, the Li-NCM cathode active material requires 1.4 to 1.5 times as much primary energy as the other two active materials.

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[2] Unconstrained charging describes a scenario in which charging begins within the hour that the last trip ended. Smart charging describes a scenario in which charging is monitored to fill valleys in the daily utility demand profile.

[3] Marginal electricity generation considers impacts from the standpoint of the addition of marginal increments of demand, such that the applicable fuel mixture is that which provides these additional marginal increments of electricity above and beyond the fuels that would have been used in the absence of the new demand.

- The solvent-less Li-ion battery manufacturing method appeared to use very little energy compared to estimates provided in prior studies of cell and pack manufacture (e.g., Majeau-Bettez, 2011). However, we were not able to obtain primary data for electricity and fuel consumption from manufacturers using solvent, making it difficult to quantify with any certainty the difference between solvent-less and solvent-based electrode manufacturing.

- The choice of materials for cell and battery casing and housing (e.g., steel or aluminum), which are primarily chosen for weight and strength considerations, are among the top process flow contributors to impacts in the upstream and manufacturing stages.

Vehicle/Battery Types

- Global warming potential (GWP) is one of the few impact categories in which EV batteries show lower impacts than PHEV-40 batteries. However, the GWP benefit only appears when the electricity grid relies less on coal production and more on natural gas and renewables. Abiotic depletion and eutrophication potential impacts are the only other impact categories in which EV batteries show lower impacts; however, this is only the case when the grid is composed to a large extent by natural gas-based generation facilities. Accordingly, in regions where the grid is more heavily coal-centric, the study results suggest that PHEV-40 vehicles may be preferable if global warming impacts are highly valued. It is important to note, however, that this study and data contained in a previous study suggest that, in comparison to internal combustion engine vehicles, there are significant benefits in GWP for both EVs and PHEV-40s, regardless of the carbon intensity of the grid. Also note that this analysis does not consider the manufacture of the non-battery components of the vehicle itself, such as the glider and drivetrain.

Life-Cycle Stages

- Though the use stage of the battery dominates in most impact categories, upstream and production is non-negligible in all categories, and relatively important with regard to eutrophication potential, ozone depletion potential, ecological toxicity potential, and the occupational cancer and non-cancer hazard impact categories. The extraction and processing of metals, specifically aluminum used in the cathode and passive cooling system and steel used in the battery pack housing and battery management system (BMS), are key drivers of impacts.

- Recovery of materials in the EOL stage significantly reduces overall life-cycle impacts, as the extraction and processing of virgin materials is a key contributor to impacts across battery chemistries. This is particularly the case for the cathode and battery components using metals (e.g., passive cooling system, BMS, pack housing and casing). Therefore, the analysis underscores the importance of curtailing the extraction of virgin lithium to preserve valuable resources and reduce environmental impacts.

Sensitivity Analysis

- Lifetime of the battery is a significant determinant of impact results; halving the lifetime of the battery results effectively doubles the non-use stage impacts, resulting in substantial increases in global warming potential, acidification potential, ozone depletion potential, and photochemical oxidation potential (e.g., smog); this is true even for PHEV-40s batteries, which are 3.4 times smaller in terms of capacity.

- When examining the sensitivity to changes in the marginal grid mix, impacts tend to be substantially higher when based on an unconstrained charging scenario using the IL grid, which almost exclusively uses coal as a fuel. The low-end of the impact range primarily result from the ISO-NE unconstrained charging scenario, which is predominately natural gas-derived electricity. However, with ozone depletion and occupational cancer hazard, lower impacts are observed under the IL smart charging scenario, due to lower emissions of halogenated compounds and formaldehyde, respectively.

- Our analysis of the EOL impacts was based on the high-end of the ranges of recovery rates provided by the recyclers for each battery material. When conducting the sensitivity analysis and comparing the impact results between the low- and high-end of the ranges provided, we found that the impacts were not highly sensitive to the rate within these ranges, with the exception of the occupational non-cancer and, to a lesser extent, cancer categories. It is important, however, to note that the study results show that recovery of the materials in the EOL stage for use as secondary materials in the battery does significantly mitigate impacts overall, especially from the upstream processing and extraction stages, across battery chemistries.

Nanotechnology

- Nanomaterials such as SWCNTS are being researched and developed to improve the energy density and ultimate performance of the batteries. In fact, both of our battery manufacturer partners are currently researching the use of nano-based anodes for manufacture of the battery cells. SWCNT anodes made by laser vaporization result in electricity consumption that is orders of magnitude greater than that of battery-grade graphite anodes. In addition, the ratio of the SWCNT anode to the graphite anode for primary energy use is similar to the ratio for the environmental and human health impact categories, except for ozone depletion potential (where the ratio is lower) and the occupational non-cancer hazard (where the ratio is higher).

- It is expected that over time, the manufacturing process for SWCNTs will become much more energy efficient. The high pressure carbon monoxide (HiPCO) process for SWCNT production, first reported in the literature in 1999 and patented (applied) in 2004, has already seen the electrical energy required per gram of nanotube reduced by more than an order of magnitude (Gutowski et al, 2010). However, the break-even impact analysis suggests that significant additional energy efficiency gains will have to be met to be comparable to the battery grade graphite anode in terms of energy requirements per gram of material.

- No other nanomaterials were used in the batteries modeled in this study, although we are aware of much interest and research on using nano-scale cathode and anode materials (in addition to the SWCNT anode research). Both of our battery partners are researching the use of nano-based anodes within battery cells.

Opportunities for Improvement

Several opportunities for improving the environmental profile of Li-ion batteries for use in plug-in and electric vehicles were identified, based on the results of the study:

- **Increase the lifetime of the battery.** A lifetime of 10 years was assumed by the partnership, as it represents the anticipated lifetime the battery manufacturers seek to achieve. As shown in the sensitivity analysis, halving the lifetime of the battery results in notable increases across all impact categories for both PHEV-40 and EV batteries; therefore, future battery design changes should focus on increasing the battery lifetime in order to reduce overall impacts.

- **Reduce cobalt and nickel material use.** These metals showed higher toxicity impacts; specifically, non-cancer and cancer impact potential. Therefore, reducing the use of and/or exposure to these materials in the upstream, manufacturing, and EOL stages would be expected to reduce the overall potential toxicity impacts.

- **Reduce the percentage of metals by mass.** Metals were found to be a key driver of environmental and toxicity impacts–especially those found in the passive cooling system, battery management system, pack housing, and casing, which were strong contributors to impacts. Accordingly, reducing the use of metals by mass in these components, in particular, should reduce the overall life-cycle impacts of the battery systems.

- **Incorporate recovered material in the production of the battery.** Given the off-set of impacts from the use of recovered materials--as opposed to virgin materials (especially metals)--in the EOL stage, impacts can be reduced if battery manufacturers work with recyclers to maximize the use of secondary materials in the manufacture of new batteries.

- **Use a solvent-less process in battery manufacturing.** The solvent-less process was found to have lower energy use and lower potential environmental and health impacts.

- **Reassess manufacturing process and upstream materials selection to reduce primary energy use for the cathode.** The active material for the cathode, and the cathode manufacturing process itself, were significant contributors to impacts across the categories. Therefore, manufacturers can reduce impacts by carefully considering the choice of active material, and assessing their manufacturing process for energy efficiency gains.

- **Produce the SWCNT anode more efficiently for commercialization.** Given the fact that the cradle-to-gate energy use and associated impacts of the SWCNT anode, as currently manufactured, are currently orders of magnitude greater than the battery grade graphite anode, SWCNT anode laboratory research that focuses on lowering the energy intensity of manufacturing processes, in tandem with improving technology performance, will help to improve the overall environmental profile of the technology, before it is commercialized.

These opportunities for improving the environmental profile of automotive Li-ion batteries have the potential for reducing a significant amount of environmental impacts, given that advanced batteries are an emerging and growing technology. This study demonstrates how the life-cycle impacts of an emerging technology and novel application of nanomaterials (i.e., the SWCNT anode) can be assessed before the technology is mature, and provides a benchmark for future life-cycle assessments of this technology. Identifying opportunities for reducing environmental and human health impacts throughout the life cycle of the Li-ion battery should be done on a continuous basis, as the technology evolves and the market share for electric vehicles expands.

Areas for Future Research

In Section 4.8, we suggest areas for future research, including further assessing key variables in the analysis, such as: changes to the electricity grid over time (e.g., the potential for impact reductions by using more renewable sources of energy); the recovery of the battery materials (e.g., benefits associated with greater recycling); and the battery lifetime associated with different chemistries and vehicle types.

Additional areas for suggested research include:

- reducing uncertainty regarding the energy and fuel use for the processes necessary for component and battery manufacture, and differences in energy use due to battery chemistry and size;
- clarifying the actual potential for exposure, in the case of cobalt, and elements that contribute to toxicity, in the case of complex lithium chloride brines from saline lakes, to help understand their contribution to potential occupational impacts;
- research to more realistically characterize the changes in lifetime across chemistries, and differences between EV and PHEV-40 batteries;
- estimating the changes to the grid that would be expected to result from large increases in demand from the increased use of PHEVs and EVs;
- Further research on the eventual disposition of recovered and recycled materials--especially for the rare and strategically important metals used in battery production, to allow manufacturers, recyclers, and the scientific community to better understand the benefits and detriments of current recycling technologies, and to help characterize the extent to which secondary material markets might come to substitute for virgin mined material; and
- additional research on nanomaterials that may be used to increase the energy density and performance of Li-ion batteries for vehicles, to ensure that upstream impacts (e.g., energy use and toxicity) do not outweigh potential performance and environmental benefits in the use stage.

As noted above, there are many opportunities for further research on the potential impacts and benefits of Li-ion batteries for vehicles, especially given that it is an emerging and growing technology. This study provides a benchmark for future research of this technology, and for identifying additional opportunities for reducing environmental and human health impacts throughout the life cycles of these battery systems.

1. Goal and Scope Definition

Life-cycle assessment (LCA) is an environmental tool that can be used to evaluate the potential environmental impacts of a product, process, or activity. An LCA is a comprehensive method for assessing impacts across the full life cycle of a product system, from materials acquisition to manufacturing, use, and final disposition. As outlined in the International Standards Organization (ISO) 14040 series, an LCA study has four major phases or components: (i) goal and scope definition, (ii) life-cycle inventory (LCI), (iii) life-cycle impact assessment (LCIA), and (iv) interpretation of results (ISO, 2006).

This section presents the goal and scope definition, which includes the purpose and goals of the study, description of the product systems being evaluated, boundaries of the study, and data collection scope. The scoping follows the methodology recommended in the LCA process (ISO, 2006a; ISO, 2006b; Curran, 1996; Fava et al., 1991). The inventory analysis (phase 2) and impact assessment (phase 3) are included as Sections 2 and 3, respectively. Section 4 summarizes the results; however, much of the life-cycle interpretation, which is the last step of an LCA as recommended in ISO 14040, is left to the target audience.

U.S. Environmental Protection Agency's (EPA's) Office of Pollution Prevention and Toxics (OPPT) established the Design for the Environment (DfE) Program in 1992 to encourage businesses to incorporate environmental concerns into their business decisions. The DfE Program promotes risk reduction, green chemistry, pollution prevention, energy efficiency, and other resource-conserving measures through materials and process choices at a facility or industry sector level. DfE industry partnerships are cooperative, joint efforts that assist businesses in specific industries to identify and evaluate more environmentally sound materials, processes, and technologies. EPA's Office of Research and Development (ORD), the scientific research arm of EPA, conducts research on ways to prevent pollution and reduce risk, and protect human health and the environment. ORD's Nation Risk Management Research Laboratory (NRMRL) has conducted life-cycle assessment research since 1990. At NRMRL, LCA is being applied to selected nanomaterials and products to yield a comprehensive understanding of the environmental footprint associated with this fast growing family of materials.

1.1 Purpose and Goals

This section presents the background and purpose of the project, a summary of previous research related to this study, the need for the project, and target audience.

1.1.1 Background

The Lithium-ion Batteries and Nanotechnology in Electric Vehicles Partnership ("partnership") is a voluntary, cooperative partnership that includes the Design for the Environment (DfE) Program in EPA's Office of Chemical Safety and Pollution Prevention, the National Risk Management Laboratory in EPA's Office of Research and Development, the Argonne National Laboratory in the Department of Energy, individual Li-ion battery manufacturers, suppliers, and recyclers, and representatives from academia, and research and trade institutions.

The partnership conducted a screening-level LCA of Li-ion batteries used in plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs). The study also assessed a next-generation anode technology using single-walled carbon nanotubes (SWCNTs), which is being developed to increase the energy capacity and marketability of these systems.

1.1.2 Purpose

The goal of this cooperative partnership was to provide information to the advanced automotive battery industry to facilitate environmental improvements in Li-ion batteries, by identifying which materials or processes within the products' life cycles are likely to pose the greatest impacts or potential risks to public health or the environment, including greenhouse gas emissions. The partnership also aimed to evaluate a nanotechnology innovation in advanced Li-ion batteries for electric vehicles that may enhance battery performance. In addition, the study attempted to address the impacts associated with recycling the batteries after their useful life.

It is important to note that this study was not designed or intended to "select" the best battery technologies, from an environmental perspective. Rather, the information and results from the analysis should be useful to partners for further development of their individual Li-ion battery products and technologies in an environmentally responsible manner.

1.1.3 Previous Research

Previous LCA studies investigating Li-ion batteries provide key insights into the challenges associated with conducting this type of study. For example, Notter et al. (2010) published an LCA of a manganese oxide Li-ion battery. This study found that the impact of a Li-ion battery used in EVs is 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 and modeling data for the battery manufacturing, use, and end-of-life stages, which was combined with the primary data set. Zackrisson et al. (2010) also relied on modeling data for the LCA analysis, which found that it was environmentally preferable to use water as a solvent instead of N-methyl-2-pyrrolidone (NMP) in the slurry for casting the cathode and anode of lithium-ion batteries for PHEVs. In addition, using secondary data, Matheys et al. (2005) conducted an environmental assessment of five types of batteries for internal combustion engine (ICE) vehicles and EVs and HEVs, as follows: lead-acid, nickel-cadmium (Ni-Cd), nickel-metal hydride (NiMH), lithium-ion (Li-ion), and sodium-nickel chloride (Na-NiCl). The study found higher technical and environmental performance of the lithium-ion and the sodium-nickel chloride battery technologies (Matheys et al., 2005).

Other Li-ion battery studies have focused on a limited number of life-cycle stages or specific vehicle types. Focusing on the use stage, Schexnayder et al. (2001) assessed waste issues and life-cycle impacts associated with the vehicle materials and vehicle technologies being developed, including a comparison of Li-ion and NiMH used in HEVs. Between the two battery types, the study found Li-ion batteries had more favorable environmental results (Schexnayder et al., 2001). More recently, Majeau-Bettez et al. (2011) conducted a cradle-through-use analysis of three Li-ion battery chemistries for EVs, including: NiMH, nickel cobalt manganese lithium-ion (NCM), and iron phosphate lithium-ion (LFP). Based on average European conditions, the NiMH technology was found to have the highest environmental impact, followed by NCM and then LFP, for all life-cycle impact assessment categories considered, except ozone depletion potential (Majeau-Bettez et al. 2011). In addition, using a life-cycle assessment economic input-output model (LCA-EIO), Samaras et al. (2008) assessed greenhouse gas (GHG) emissions from PHEVs from cradle-to-gate. The analysis found that PHEVs reduce GHG emissions by 32% compared to conventional vehicles, but have small additional reductions over traditional HEVs. In addition, GHG emissions associated with Li-ion battery materials and production account for 2 to 5% of life-cycle emissions from PHEVs.

SWCNT paper anodes are being developed as an alternative to materials such as graphitic carbon, polymer binders, and conductive carbon additives coated on copper current collectors. This battery technology shows promise for increased current capacity, which will extend the electrical vehicle range and battery lifetime while reducing the charge times. In general, SWCNTs have been proposed for use in a variety of technologies and therefore have been the subject of numerous environmental studies. However, much of these efforts suffer from the same challenges facing the battery studies with regard to limitations on data and life-cycle stages. For example, Issacs, et al. (2006) compared the environmental impacts from three alternative processes for manufacturing SWCNTs, and found that electricity use drives environmental impacts. Due to a lack of environmental and human health data for SWCNTs, the study could only evaluate impacts due to energy and resource use during materials processing and SWCNT manufacturing, and not toxicity and ecotoxicity impacts due to the SWCNTs themselves (Issacs et al., 2006). Ganter et al. (2009) assessed the energy required to produce laser vaporization SWCNTs as compared to other processes. The study found that the energy consumption estimates fell in the middle to bottom range of previous estimates and showed promise for use in commercial applications if the energy efficiency during processing was improved (Ganter et al., 2009).

Some studies have also taken steps to assess environmental and human health impacts of nanotechnologies, and specifically carbon nanotubes (CNTs), which are used in some Li-ion batteries, addressing a key data gap noted recently by the National Research Council (NRC, 2012). Köhler et al. (2007), for example, assessed the release of CNTs in lithium-ion rechargeable batteries and synthetic textiles, and found that CNTs may be released throughout all phases of a product life cycle, depending on how they are incorporated into a particular material (Köhler et al., 2007). Mueller and Nowack (2008) modeled the expected release of CNTs into the environment, based on a substance flow analysis from products to air, soil, and water in Switzerland. This study found that 50% of CNTs from electronics and batteries are released into the environment, primarily during the end-of-life (EOL) stage (Mueller and Nowack, 2008). Based on an examination of EOL impacts from nanomaterials in Li-ion batteries, Olapiriyakul and Caudill (2008) determined that current battery recycling operations may need to be modified to accommodate new Li-ion battery technologies to prevent exposure to potentially toxic nanomaterials. In particular, nanomaterials can exhibit different melting point behavior and susceptibility to Brownian motion (i.e., random movement of particles). These two factors affect the fate of nanomaterials in high-temperature battery recycling processes and increase the likelihood of exposure if current practices are not altered (Olapiriyakul and Caudill, 2008).

Overall, the prior LCA studies of Li-ion batteries for vehicles have relied primarily on secondary or modeling data to estimate impacts, while considering only a limited number of life-cycle stages, vehicle types and/or impact categories (e.g., greenhouse gas emissions from PHEVs). While the previous studies have provided useful inventory data and impact estimates, they are nevertheless limited and would not alone satisfy the goals and objectives of our LCA study. This study addresses identified gaps in existing studies by: (1) incorporating primary data (whenever possible) from both battery manufactures and recyclers and assessing the environmental and human health impacts from cradle-to-grave; (2) assessing cradle-to-gate impacts of a next-generation anode technology using carbon nanomaterials (i.e., single-walled carbon nanotubes); and (3) assessing the impacts from a U.S. standpoint.

1.1.4 Market Trends

The Obama Administration set a near-term goal of 1 million electric vehicles on the road by 2015 (Obama, 2011). Currently, nearly all electric-powered vehicles on the market are hybrid-electric vehicles (HEVs) (Anderson, 2008). However, PHEVs are expected to gain a larger percentage of market share over the next decade, surpassing sales of HEVs around 2018 (Anderson, 2008). Toyota currently has nearly 80% of the HEV market, followed by Honda and Ford (Anderson, 2008). In the United States, half of all vehicles sold are expected to be HEVs, PHEVs, or EVs by 2020 (Anderson, 2008). The research organization IDTechEX estimates that HEV, PHEV, and EV sales will represent 35% of global car sales by 2025 (IDTechEX, 2012). Currently, the U.S. Department of Defense is looking at several strategies to increase the number of PHEVs in its large domestic fleet (DOD, 2012), and California's Air Resources Board (CARB) recently proposed regulations in February of 2012 mandating the attainment of over 15% sales penetration of zero-emission vehicles, including EVs and PHEVs, by 2025 (CARB, 2012).

Lithium-ion (Li-ion) batteries will be critical to improving the marketability of electric vehicles, due to their large energy storage capability in comparison to other types of batteries, including nickel-metal-hydride (Ni-MH) batteries primarily used in HEVs. Therefore, the share of Ni-MH batteries is anticipated to decrease in proportion to automotive Li-ion batteries as more PHEVs and EVs come on the market. In addition, the use of Li-ion batteries in HEVs is expected to grow to 30% of the HEV fleet by 2015, and 70% by 2020 (Anderson, 2008). Accordingly, as presented in Figure 1-1, the demand for automotive Li-ion batteries is projected to parallel the growth of PHEVs and EVs, growing from about 1 billion USD in 2010 to 30 billion USD by 2018 (Takeshita, 2010).

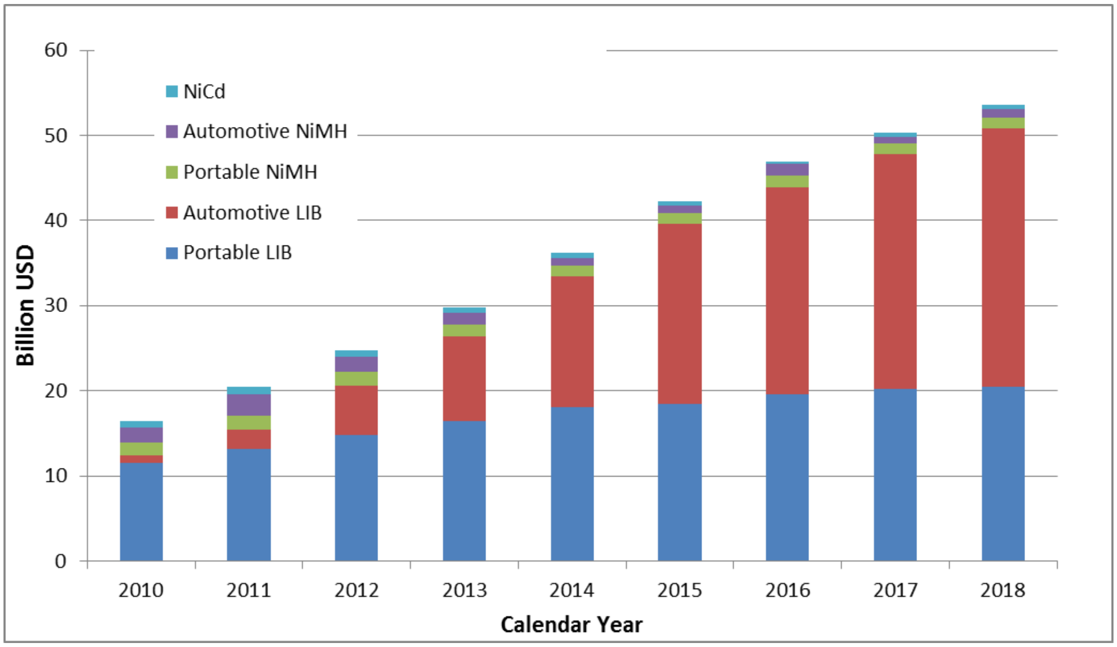

Figure 1-1. Worldwide Rechargeable Battery Demand (Billion USD/Calendar Year) (Takeshita, 2010)

Notes: \1 Figures were approximated from original graph of data by Takeshita and converted to USD using conversion rate of 0.0132 USD to 1 Japanese Yen (Bloomberg: http://www.bloomberg.com/ markets/currencies/, accessed on October 26, 2011);

\2 Abbreviations: NiMH: nickel-metal hydride; LIB: lithium battery; NiCd: nickel-cadmium

Currently, over 80% of Li-ion batteries are manufactured in Asia (Anderson, 2008). In the United States, the Department of Energy is sponsoring an initiative to increase domestic capacity to produce Li-ion batteries (DOE, 2009; NETL, 2009).

1.1.5 Need for the Project

As noted above, automotive Li-ion batteries are anticipated to be a growth market, both in the United States and abroad, given the growth of the electric vehicle market. The production and use of automotive electric vehicles will help to alleviate the United States' dependence on oil, and has the potential to mitigate future climate change.

Although the Li-ion technology has been readily used in portable electronics, its application in electric vehicles is relatively new. Given that the use of Li-ion batteries for electric vehicles is an emerging technology, and that recent government programs are encouraging the growth of the industry in the United States, this study is timely and should help battery manufacturers identify opportunities to improve the environmental footprint of their products before the industry is more mature.

The study also highlights a nanotechnology application that has the potential to improve the marketability of the batteries and vehicles, by improving its energy efficiency in the use stage. Although some nanomaterials and technologies are already being used in Li-ion batteries, further and novel uses of nanomaterials may increase the storage capacity and life of these batteries. As discussed above in Section 1.1.3, battery anodes made from single-walled carbon nanotubes (SWCNTs) are being developed for commercialization and show promise for increased current capacity, extended electric vehicle range and battery lifetime, and reduced recharge cycle time, and are included in this study.

A quantitative environmental life-cycle assessment of Li-ion batteries used in electric drive vehicles using data from battery suppliers, manufacturers, and recyclers—and a nanotechnology anode application that may be used in the future—has not been conducted, to date. This study fills this research gap, which is important to help grow the advanced vehicle battery industry in an environmentally responsible and efficient way. The results of this study present the opportunity to mitigate current and future impacts and risks, by identifying which materials and/or processes are associated with the greatest environmental impacts throughout the life cycle of the batteries. This will allow battery manufacturers, suppliers, and recyclers to make improvements in their products and processes that result in fewer environmental impacts and increased energy efficiency.

1.1.6 Target Audience and Stakeholder Objectives

This LCA provides information to the advanced automotive battery industry, and particularly to the Li-ion battery industry for electric vehicles. The study is intended to provide this industry with an objective analysis that evaluates the potential life-cycle environmental impacts of selected Li-ion battery systems, and help identify areas for environmental improvement. In addition, the study helps determine whether these systems present environmentally preferable options to existing systems, such as the use of internal combustion engine vehicles during their manufacturing and use.

Specific objectives of participation in this partnership for members of the battery industry included:

- Demonstrating a commitment to the environmentally responsible development of advanced Li-ion batteries, for use in PHEVs and EVs.

- Generating life-cycle impact assessment data that will inform environmentally responsible improvement of Li-ion batteries and their components, through the identification of material and energy-intensive processes, and identifying processes with the greatest potential for hazard related to the use of more toxic materials.
- Creating life-cycle inventory data that may be used as a benchmark for future life-cycle assessments of products and technologies, to measure environmental improvements, and to evaluate the impacts of possible design changes.
- Contributing to research that will aid current efforts to promote safety in the workplace when working with nanomaterials.

EPA objectives for the partnership included:

- Encouraging the movement toward energy independence and possible reduced greenhouse gas generation through the greater use of PHEVs and EVs in an environmentally responsible way, by evaluating the life-cycle impacts of advanced Li-ion batteries.
- Informing decisions on advanced Li-ion battery technologies, including product improvements, as the use of PHEVs and EVs increases.
- Promoting and demonstrating the importance of life-cycle thinking in developing new battery technologies and nanotechnology applications.
- Identifying key data gaps that need to be filled in order to assess the life-cycle impacts of nanomaterials and nanotechnologies.
- Providing valuable information for the Office of Pollution Prevention and Toxic's hazard, exposure, and risk experts.
- Generating information for ORD's efforts to assess and characterize the potential risks and impacts associated with nanomaterials (and SWCNTs, in particular).
- Supporting the effort by ORD's National Risk Management Research Laboratory to develop and apply a decision support framework using life-cycle assessment for the manufacture, use, and disposal of nanomaterials.
- Supporting efforts by the Organization for Economic Cooperation and Development (OECD) to identify and address the potential impacts of nanotechnology applications that may benefit the environment.

1.2 Product System

Below we describe in further detail the Li-ion battery product assessed ("product system"), and the unit by which it was evaluated in the study ("functional unit").

1.2.1 Battery System

As illustrated in Figure 1-2, the core of Li-ion batteries are composed of three layers: an anode, a cathode, and a porous separator, which is placed in between the anode and cathode layers. The anode is composed of graphites and other conductive additives. The cathode is composed of layered transition metal oxides (e.g., lithium cobaltite ($LiCoO_2$) and lithium iron phosphates ($LiFePO_4$). Once the anode and cathode are coated, they are wrapped with the separator sheet in an elliptical form for prismatic cells, and circular form for cylindrical cells. The roll is then saturated with an electrolyte solution, consisting of lithium-salt and organic solvents, and sealed in a casing usually composed of steel or aluminum material to create a battery cell.

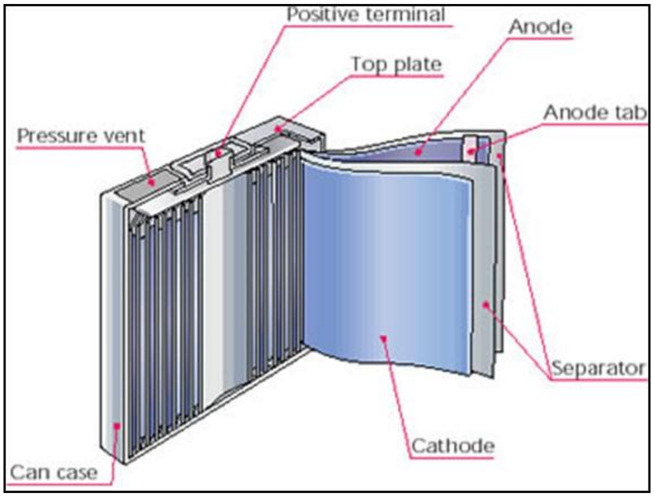

Figure 1-2. Illustration of Prismatic Li-ion Battery Cell (NEC/TOKIN, 2009)

Once the battery cell is complete, several cells are combined to form a battery pack. The battery cells are separated within the battery pack and housed with other components, including a thermal control unit, wiring, and electronic card as part of a battery management system (BMS). Once the battery pack is assembled, it is ready to be placed into a vehicle.

As discussed in Section 1.1.4, there are currently three types of electric vehicles produced:

- Hybrid electric vehicles (HEVs) use two power sources, including a gasoline combustion engine and battery system. The battery is recharged by the combustion engine.
- Plug-in hybrid electric vehicles (PHEVs) have the characteristics of an HEV, but can also charge its battery by plugging in to a grid-provided electricity system. PHEVs are typically categorized according to their all-electric range (AER), which is the maximum distance that can be travelled without using the internal combustion engine. Standard AERs include 10-mile and 40-mile PHEVs.
- Electric vehicles (EVs) are entirely powered by batteries that are recharged by plugging in to a grid-provided electricity system.

Each type of electric vehicle requires different battery performance characteristics, which are based on several factors, including energy density and power density. A higher energy density provides a higher vehicle range per charge, whereas a higher power density provides a faster acceleration rate. Accordingly, EVs require higher energy density batteries, and HEVs require higher power density batteries. Table 1-1 provides a summary of the typical battery requirements for each vehicle type.

Table 1-1. General Battery Requirements (Barnes, 2009)

Vehicle Type	Battery Size (kWh)	Power/ Energy Ratio
HEV	1-2	> 15
PHEV [\1]	5 – 15	3 - 10
EV	>40	< 3

Note: [\1] The requirements are scaled for the 10 to 40-mile range.

Based on the types of batteries and battery chemistries manufactured by members of the partnership (who provided primary data for this study), we assessed high-energy density Li-ion battery technologies for EVs and PHEV-40s (PHEVs with a 40-mile AER) applications; and a SWCNT anode technology for possible future use in these batteries. The battery chemistries used by the manufacturers include lithium-manganese oxide ($LiMnO_2$) and lithium-nickel-cobalt-manganese-oxide ($LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$ or Li-NCM). As part of the analysis, we also modeled lithium-iron phosphate ($LiFePO_4$) from secondary data, to supplement the inventories provided by our partners, to protect confidential business information, and to provide a rough indication of how closely the primary and secondary data sources correlate.

1.2.2 Functional Unit

In an LCA, product systems are evaluated on a functionally equivalent basis. The functional unit normalizes data based on equivalent use (or service provided to consumers) to provide a reference for relating process inputs and outputs to the inventory, and impact assessment for the LCA across product systems. As described above, the product systems evaluated in this project are Li-ion batteries used in PHEVs and EVs. The service provided by these vehicles is the distance driven, and so the functional unit is based on kilometers driven. In other words, inventory amounts and impacts are ultimately presented in terms of distance driven (km) (e.g., kg material/km driven, ton CO_2-equivalent emissions/km driven). Note that the functional unit is applied to total inventory amounts and impacts from all the life-cycle stages, and not just those accrued during the vehicle's use stage. For example, ton CO_2-equivalent emissions per km driven is an estimate of the CO_2-equivalent emissions from materials extraction and processing, manufacturing, use, and end-of-life, in terms of kilometers driven by the vehicle.

Most Li-ion battery systems are expected to achieve a service life of 10 years. However, the service life may vary depending on several factors, including the electrical current, temperature, and depth of discharge. These factors are affected by the vehicle type and vehicle efficiency (kWh per kilometer). The LCA assumes that the anticipated lifetime of the battery is the same as the anticipated lifetime of the vehicle for which it is used. Therefore, this study assumes one battery per vehicle.

1.3 Assessment Boundaries

Once the product system and functional unit are defined, it is important to define the scope of the study, including the life-cycle stages included as part of the analysis, and geographic and temporal boundaries. For this study, the boundaries were mainly defined based on the available resources and available data, as described below.

1.3.1 Life-Cycle Stages and Unit Processes

As illustrated in Figure 1-3, LCAs evaluate the life-cycle environmental impacts from each of the following major life-cycle stages, described below:

- **Raw materials extraction/acquisition**: Activities related to the acquisition of natural resources, including mining non-renewable material, harvesting biomass, and transporting raw materials to processing facilities.
- **Materials processing**: Processing natural resources by reaction, separation, purification, and alteration steps in preparation for the manufacturing stage; and transporting processed materials to product manufacturing facilities.
- **Product manufacture**: Manufacture of components of battery cells and battery packs.
- **Product use**: Use of batteries in vehicles (PHEVs and EVs).[4]
- **Final disposition/end-of-life (EOL)**: Recovery of the batteries at the end of their useful life.

Also included are the activities that are required to affect movement between the stages (e.g., transportation). The inputs (e.g., resources and energy) and outputs (e.g., product and waste) within each life cycle stage, as well as the interaction between each stage (e.g., transportation), are evaluated to determine the environmental impacts.

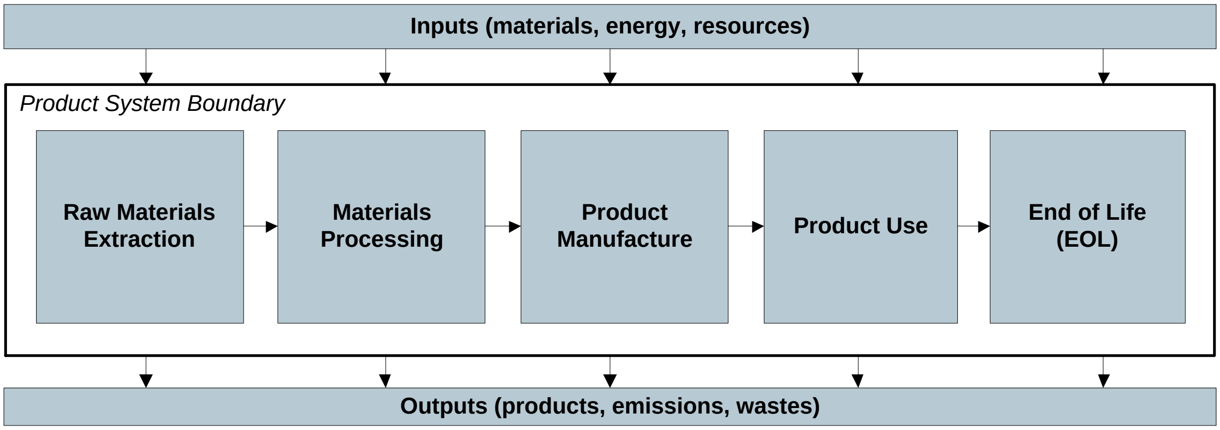

Figure 1-3. Life-Cycle Stages of the Product System

The LCI phase (phase 2) of the LCA involves quantifying raw material and fuel inputs, and solid, liquid, and gaseous products, emissions, and effluents, which are detailed in Section 2. Before LCI data were collected, the partnership generated a generic process flow diagram for the manufacture of Li-ion batteries within the life-cycle stages that are modeled in this study (see Figure 1-4). Although the battery design and manufacturing process differ based on the cell architecture and company-specific technologies, this process flow diagram presents the key processes common to the manufacturers in the partnership.

Each "box" in the process flow diagram depicts a unit process, which has its own inventory of inputs and outputs. The upstream stages include the extraction and processing of materials needed for each battery component. This includes the anode, cathode, separators, casing, and electrolyte for the battery cell. In addition, the components for the battery pack include the separator, thermal control unit, housing, wiring, electronics, and electronic card. The manufacturing stages include the processes to manufacture the components of the battery cell and the battery pack.

The process flow diagram also includes upstream materials processing for the SWCNT anode. Although SWCNT anodes are not currently included in commercially available Li-ion batteries, the partnership

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[4] It is only in the use-stage that impacts from the vehicle were included. This study did not generate and inventory or quantify impacts for the upstream, manufacturing, or end-of-life of non-battery vehicle components. The partnership selected this approach in order to focus on the Li-ion batteries themselves.

conducted a separate analysis to substitute the SWCNT anode process for the current anode technology in a Li-ion battery system, in order to determine the potential impacts of that component on the cradle (extraction of raw materials) through gate (manufacture of the anode) stages of the modeled battery system's life cycle. In addition, we included a qualitative summary of the potential benefits of this technology after efficiency gains and improved battery performance are realized.

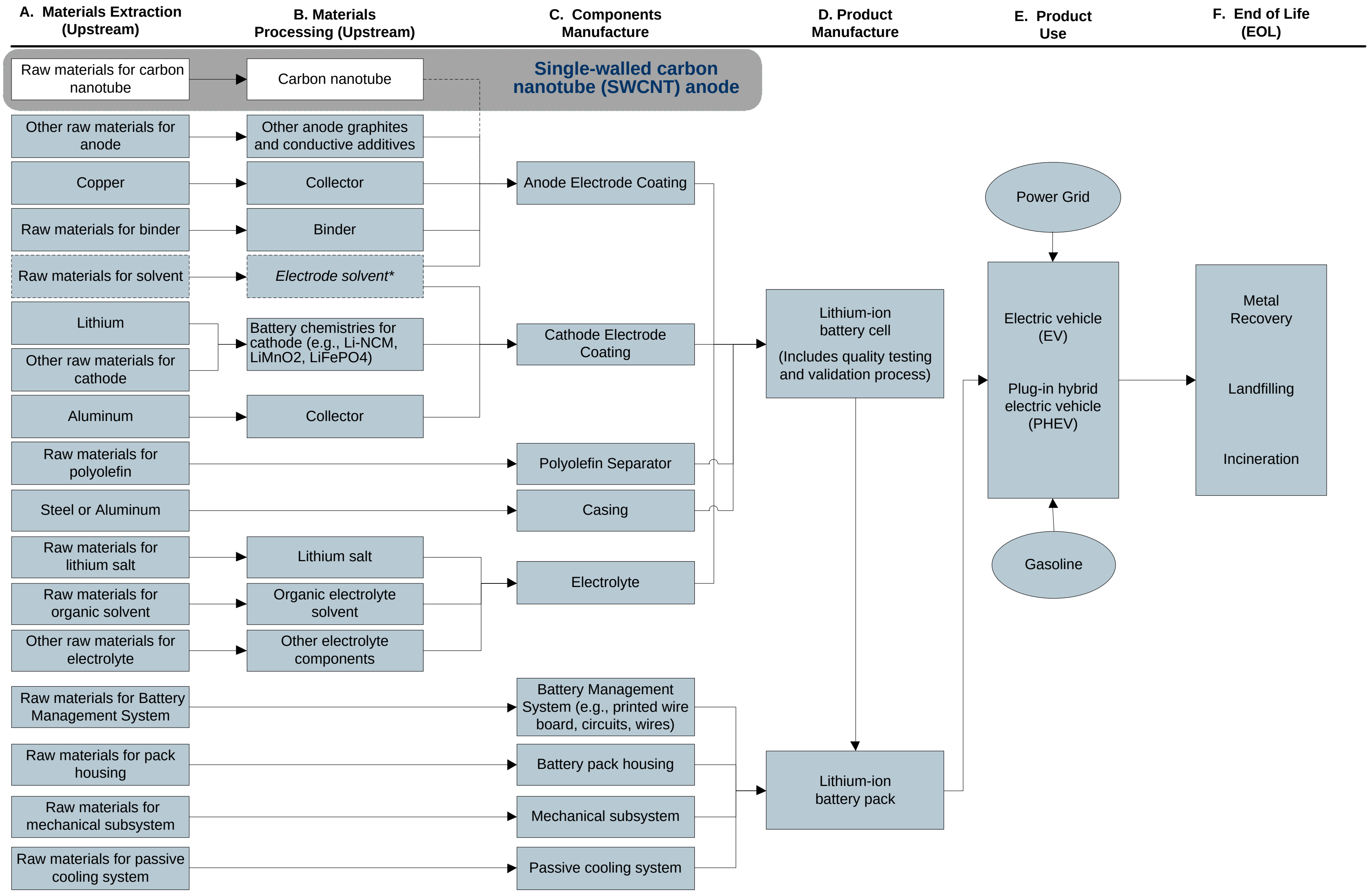

Figure 1-4. Generic Process Flow Diagram for the Manufacture of Li-ion Batteries for Vehicles

Sources: EPA, DfE/ORD, Li-ion Batteries and Nanotechnology for Electric Vehicles Partnership; NEC/TOKIN (http://www.nec-tokin.com, 2010; Olapiriyakul, 2008; Ganter et al., 2009. Notes: Electrode solvent is an ancillary material used during manufacturing, but is not incorporated into the final product.

Although the focus of the LCA study was on Li-ion batteries, given the fact that the batteries are placed into vehicles for their “use stage,” the study included an assessment of impacts resulting from the batteries’ use in vehicles (EVs and PHEVs) in that stage. The study did not generate and inventory or quantify impacts for the upstream, manufacturing, or end-of-life of vehicle components that are not related to the battery. In addition, although a traditional combustion engine vehicle, which uses a lead-acid battery, is not presented in Figure 1-4, the study included a qualitative analysis of greenhouse gas impacts associated with this vehicle, in the use stage only. To estimate impacts in the use stage, the partnership assumed that during the vehicle life-time (10 years), each vehicle travels 19,312 km per year (EPA, 2005; Rantik, 1999). As presented in Figure 1-4, for this stage, input and output data depend on the amount and type of energy (electricity or gasoline fuel) consumed to operate each vehicle.

For the end-of-life (EOL) stage, we assumed that given the value of the metals in the batteries, they will be collected and sorted for recycling (Gaines, 2009). We assessed several recycling processes: (1) a hydrometallurgical process, (2) a high-temperature or pyrometallurgical process, and (3) a direct recycling process. Although metals are recovered from Li-ion batteries, they are currently not fed back into the battery cell manufacturing process. To do so, the recovered battery materials (including lithium) would need to be processed so they are "battery grade," which means they can be used as secondary material in the battery cell manufacturing process. However, there are a few key obstacles to achieving this goal, including:

- The battery manufacturers frequently modify their battery chemistries, which makes it difficult to incorporate recovered materials. This is especially a concern for EV batteries, which may be recovered 10 to 15 years after the battery is manufactured. The battery companies continually modify their chemistries to try to obtain market distinction and to improve charge capacity and energy density, which generate benefits in the use stage of the battery.
- The battery manufacturers are hesitant to use secondary materials, as they fear it will not be of high enough quality to meet the battery specifications required by the original equipment manufacturers (OEMs) that purchase the batteries and manufacture the vehicles.

A sensitivity analysis was conducted to assess the impacts of varying the percentage of secondary material used to manufacture new battery cells (see Section 3.4).

In addition to recovering materials from batteries, the batteries themselves may eventually be refurbished for re-use. However, refurbishment of Li-ion batteries used in electric vehicles is still in the pilot stage. In addition, batteries may be capable of having a “second life” (or use as part of another product), such as to provide energy storage for an electricity grid; however, there is limited information on characterizing spent batteries in a secondary application, so the potential second life was not included in this study.

1.3.2 Spatial and Temporal Boundaries

Geographic boundaries are used in an LCA to show where impacts are likely to occur for each life-cycle stage. For this study, transportation impacts from transport of the material (e.g., shipping lithium) and batteries between life-cycle stages were to be included. In order to estimate transportation distances and impacts, assumptions were made with respect to where the raw materials will likely be obtained (e.g., Chile for lithium, Congo for cobalt) and where they will be transformed into value-added intermediates. Additionally, the location of the manufacturing facilities in relation to the vehicle manufacturers were used to model pre-use stage transportation impacts. Although battery manufacturing occurs worldwide, this study focuses on the manufacturing and use of these batteries for vehicles in the United States. However, one product partner manufactures batteries in Canada. The EOL evaluation also focuses on batteries that reach the end of their lives in the United States.

This study is based on LCI data obtained by manufacturers between the years 2010 and 2011. Installation and use of the batteries would occur shortly thereafter; however, EOL disposition would occur after the 10-year service life. Given the lack of temporal specificity in an LCA, EOL impacts are assumed to be based on current EOL technologies and conditions, despite the potential changes that might occur during the product's service life. Also, we assume that any 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.

1.3.3 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.

1.3.4 LCIA Impact Categories

The third phase of the LCA study (life-cycle impact assessment or LCIA phase) involves translating the environmental burdens identified in the LCI into environmental impacts. LCIA is typically a quantitative process involving characterizing burdens and assessing their effects on human and ecological health, as well as other effects, such as smog formation and global warming. The study followed the LCIA methodology that was used in the most recent DfE LCA, entitled Wire and Cable Insulation and Jacketing: Life-Cycle Assessment for Selected Applications (EPA, 2008), which was based on the methodology used in DfE's Lead-Free Solders: A Life-Cycle Assessment (Geibig and Socolof, 2005) and DfE's life-cycle assessment of cathode-ray tube and liquid crystal computer displays (Socolof et al., 2001). The results of the LCIA analysis are presented in Section 3.

A number of impact categories were evaluated for the product systems in the LCIA phase, including:

- Abiotic resource depletion
- Global warming potential
- Acidification potential
- Eutrophication potential
- Ozone depletion potential
- Photochemical oxidation potential
- Ecological toxicity potential
- Human toxicity potential
- Occupation cancer hazard
- Occupational non-cancer hazard

1.4 Data Collection Scope

This section describes the LCI data categories for which data were collected, as well as the key data sources and the data analysis approach. It also describes procedures for allocating inputs and outputs from a process to the product of interest, when the process is used in the manufacture, recycle, or disposal of more than one product type at the same facility. Finally, it describes the data management and analysis software used for the project, and methods for maintaining overall data quality and critical review.

1.4.1 Data Categories

Table 1-2 describes the data categories for which life-cycle inventory data were collected, including material inputs, energy inputs, natural resource inputs, emission 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 emission or material outputs), or (2) energy input (e.g., megajoules, MJ) per functional unit. As noted in Section 1.2.2, the functional unit (or service) is the distance traveled, measured in kilometers, because the services provided by the Li-ion batteries are through the vehicle systems into which they are placed. However, the inventory data for the batteries were collected on a per kilowatt-hour (kWh) basis, which reflects the batteries' energy capacity for one charge cycle. As presented in Table 1-1, because different vehicle systems require different energy capacities, this information was used to convert the inventory data from a per kWh basis to a per kilometer basis, based on the type of vehicle in which it is placed (i.e., PHEV or EV).

Data that reflect production for one year of continuous processes was scaled on a per kWh basis. Thus, excessive material or energy associated with startups, shutdowns, and changeovers were assumed to be distributed over time. Consequently, any environmental and exposure modeling associated with the impact assessment reflects continuous emissions, such that equilibrium concentrations may be assumed. Data were also collected on the final disposition of emissions outputs, such as whether outputs are recycled, treated, and/or disposed. This information helps determine which impacts should be calculated for a particular inventory item.

Table 1-2. LCI Data Categories

Data Category	Description
INPUTS: Material and Resources (kg per kWh)	
Primary materials	Actual materials that make up the final product for a particular process.
Ancillary (process) materials	Materials that are used in the processing of a product for a particular process.
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).
INPUTS: Energy (MJ per kWh)	
Process energy	Process energy, 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 (kg per kWh)	
Air emissions	Mass of a product or material that is considered a pollutant within each life-cycle stage. Air outputs represent actual gaseous or particulate releases to the environment from a point or diffuse source, after passing through emission control devices, if applicable.
Water emissions	Mass of a product or material that is considered a pollutant within each life-cycle stage. Water outputs represent actual discharges to either surface or groundwater from point or diffuse sources, after passing through any water treatment devices.
Solid wastes	Mass of a product or material that is deposited in a landfill or deep well. Could include hazardous, non-hazardous, and 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 (kg per kWh)	
Primary products	Material or component outputs from a process that are received as input by a subsequent unit process within the product life cycle.
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. [Note: Co-products for this product system have not been identified.]

1.4.2 Data Collection and Data Sources

Data from the study were obtained from both primary and secondary sources. Primary data are directly accessible, plant-specific, measured, modeled, or estimated data generated for the particular project at hand from the project partners. Secondary data are from literature sources, LCI databases, or other LCAs, but may not be specific to the product of interest. Primary data were utilized for the battery manufacturing and EOL stages through the project partners, with secondary data used to address gaps in information. Secondary data were also used for the upstream and use stages, because resource constraints prohibited the study group from acquiring primary data from all companies in the supply-chain. Table 1-3 summarizes the data types by life-cycle stage.

Table 1-3. Data Types by Life-Cycle Stage

Life-cycle stage	Data types	Scope
Upstream (materials extraction and processing)	Secondary data; possibly primary data	Greater emphasis
Product manufacturing	Primary data or secondary data for industry averages	Greater emphasis
Use	Secondary data	Greater emphasis
Final disposition (recycling and/or disposal)	Primary data or secondary data for industry averages	Less emphasis
Transportation	Secondary data	Less emphasis
Packaging	None	Less emphasis because it is assumed to be equivalent among battery systems

For the SWCNT anode modeled for use in a Li-ion battery, limited inventory data are available, or it is proprietary, or may not be descriptive of commercial scale performance (Seager et al., 2008; Ganter et al., 2009). Using lab-scale energy and material requirements data from Arizona State University, LCI data were obtained per unit weight of SWCNT anode produced (Wender et al., 2011; Ganter et al., 2009). The data were then converted to the functional unit of kWh storage capacity, to enable substitution of this material for the anode in the LCI and LCIA analysis.

Finally, although the partnership includes one partner who manufactures batteries in Canada, the LCA uses data for the U.S. power grid for both battery manufacturers that provided the LCI data, due to the similarity and integration of the U.S. and Canadian grids.

1.4.3 Allocation Procedures

Allocation procedures are typically required when multiple products or co-products are produced using the same process. For example, the battery recyclers recover multiple types of batteries with varying chemistries and for varying applications at the same facility (e.g., Li-ion batteries for electric vehicles with nickel-metal hydride batteries for portable electronics). Accordingly, allocation procedures are required to avoid overestimating the environmental burdens associated with the product under evaluation, in accordance with ISO guidelines (2006). For this study, we applied a weighted average, based on the mass of the types of batteries entering the recycling process to the inputs and outputs. In other words, if the recycling process recovered 70% Li-ion batteries by mass, we applied this factor to energy use, water and air emissions, and recovered material. Allocation procedures for the battery manufacturers were not necessary, as the data were provided for only Li-ion batteries. In the upstream stages, allocation was limited to the production of cobalt, which is a byproduct of nickel mining and beneficiation, so energy use impacts were allocated to nickel production (Majeau-Bettez et al., 2011).

1.4.4 Data Management and Analysis Software

The data collected for this study were obtained via LCI data forms developed for this project, from existing databases, or from secondary data sources (e.g., literature). The data were imported into a commercially available LCA tool: GaBi4--The Software System for Life-Cycle Engineering. The software tool stores and organizes LCI data and calculates life-cycle impacts for a product profile. It is designed to allow flexibility in conducting life-cycle design and life-cycle assessment functions, and provides the means to organize inventory data, investigate alternative scenarios, evaluate impacts, and assess data quality.

1.4.5 Data Quality

LCI data quality can be evaluated based on the following data quality indicators (DQIs): (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. LCI DQIs are discussed further in Life-Cycle Assessment Data Quality: A Conceptual Framework (Fava et al., 1994).

For the primary data collected in this project, we asked participating companies to report the method in which their data were obtained and the time period for which the data are representative, which was largely between 2010 and 2011. The time period of secondary data, and the method in which the data were originally obtained, were also recorded, where available.

When specific primary data were missing, secondary data were used. Specifically, from the Notter et al. (2010) study we sourced upstream lithium, manganese, lithium manganese oxide, organic carbonate and lithium electrolytes, graphite, and separator inventories, with slight modifications. It is important to note that proprietary information required for the assessment is subject to confidentiality agreements between Abt Associates Inc. and the participating company. Proprietary data were aggregated and presented accordingly to avoid revealing data that the submitter does not wish to be revealed, or the source of the data. For example, from the Majeau-Bettez et al. (2011) study we applied upstream cobalt, lithium nickel-cobaltite-manganese oxide, lithium iron phosphate, battery packaging, and battery management system (BMS) (or battery pack) inventories with slight modifications. These data were aggregated with the primary data from the battery manufacturers to avoid revealing confidential business information.

1.4.6 Critical Review

Critical review is a technique used to verify whether an LCA has met the requirements of the study for methodology, data, and reporting, as defined in the goal and scope definition phase. A critical review process was maintained as part of the partnership to help ensure that the following criteria were met:

- The methods used to carry out assessments are consistent with the EPA, SETAC, and ISO assessment guidelines.
- The methods used to carry out assessments are scientifically and technically valid within the LCA framework.
- The data used are appropriate and reasonable in relation to the goals of the study.

- The interpretations reflect the limitations identified and the goals of the study.
- The study results are transparent and consistent.

The partnership served as the project Steering Committee ("Core Group"), and was responsible for approving all major scoping assumptions and decisions. It also provided technical guidance and reviews of all major project deliverables, including the draft final LCA report. In addition to the Core Group review, the report also was reviewed by several EPA staff with LCA and risk assessment expertise, and by EPA management.

2. Life-Cycle Inventory

Quantification of the life-cycle inventory (LCI) is the second phase of an LCA study. A product system is made up of multiple processes needed to produce, use, and dispose, recycle, or reuse the product. As presented in Figure 2-1, each process consists of an inventory of input and output flows.

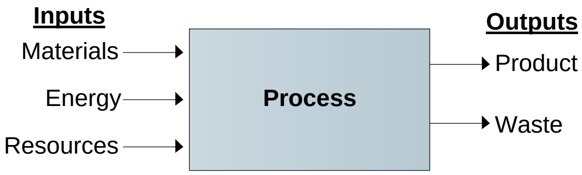

Figure 2-1. Process Input and Output Flows

Accordingly, an LCI of a product system consists of a set of inventories for processes throughout the life cycle of the product – from upstream materials extraction, to materials processing, product manufacture, product use, and then end-of-life. Figure 1-4 presents the Generic Process Flow Diagram illustrating the key processes that were modeled for this LCA study.

Section 2 presents a detailed description of the LCI data collection methodology, data sources, and limitations and uncertainties for each life-cycle stage. Detailed LCI data could not be presented due to confidentiality and data licensing restrictions.

2.1 Upstream Materials Extraction and Processing Stage

The materials extraction and materials processing (ME&P) stages, or stages A and B in Figure 1-4, are “upstream” of the Li-ion battery component and product manufacturing stages. We obtained LCI data from our project partners (i.e., primary data) for the components manufacture and product manufacture stages (stages C and D), and we relied on secondary data sources for the upstream stages. The secondary data included LCI data available in the GaBi4 LCA software tool, 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, which reflects the key components and materials used to manufacture the batteries. Next, based on the BOM, we describe the upstream LCI data sources and limitations.

2.1.1 Bill of Materials

Bills of materials for the batteries in this study are presented in Table 2-1. The table presents the range in weight for each component (kg) on a kWh of battery capacity basis, and corresponding percentage of total mass for the battery chemistries assessed in this study. The quantities are based on primary data collected from battery manufacturers under confidentiality agreements. In addition, data from two secondary sources were incorporated to mask the confidential data. However, because these sources are public, it was necessary to present a range in mass for each component to protect the confidential data.

Table 2-1. Bill of Materials for Li-ion Batteries Assessed (Total Mass: 10-12 kg)

Component	Percent Mass (%) [1]
Anode	**15 – 24**
Copper foil (collector)	1 – 12
Battery grade graphite/carbon	8 – 13
Polymer	<1 – 0
Auxiliary solvent [2]	*<1 – 6*
Cathode	**29 – 39**
Aluminum (collector)	4 – 9
Lithium-ion material	22 – 31
Polymer/other	<1 – 3
Auxiliary solvent [2]	<1 – 11
Separator	**2 – 3**
Polymer	2 – 3
Cell Casing	**3 – 20**
Aluminum casing and polymer pouch	3 – 20
Electrolyte	**8 – 15**
Carbonate solvents	7 – 13
Lithium hexafluorophosphate ($LiPF_6$)	1 – 2
BMS	**2**
Copper wiring	1
Steel	1
Printed wire board	<1
Battery Pack Casing/Housing	**17 – 23**
Polypropylene/polyethylene terephthalate/steel	17 – 23
Passive Cooling System [2]	**17 – 20**
Steel and aluminum	17 – 20
Total	**100**

Notes: [1] Percentage mass for these components was calculated by dividing the mass of each component by the total mass of the battery pack.
[2] Auxiliary solvent and cooling system were not included in total mass of battery pack since they are not typically included when calculating energy density.

In addition to the components presented above, we also assessed the single-walled carbon nanotube (SWCNT) as an anode component. As discussed in Section 1, nanomaterials such as SWCNTS are being researched and developed to improve the energy density and ultimate performance of the batteries. In fact, both of our battery partners are currently researching the use of nano-based anodes for manufacture of the battery cells. Therefore, based on laboratory data and research from Arizona State University, LCI data for SWCNT anodes were also obtained, and are described in Section 2.1.2.

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, we identified the corresponding upstream materials required to manufacture each component. The key studies we relied on for secondary data included:

- **Contribution of Li-ion Batteries to the Environmental Impact of Electric Vehicles (Notter et. al, 2010).** This study used a detailed life-cycle inventory of a Li-ion battery (manganese oxide spinel) and a rough LCA of the use stage. The LCI data used for the study were primarily ecoinvent data, modeling data, and mass data from a Kokam Co. battery cell (for the manufacturing stage).

- **Life-Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electric Vehicles (Majeau-Bettez et. al., 2011).** This study is a cradle-through-use LCA of three Li-ion battery chemistries for EVs. The batteries assessed included nickel metal hydride (NiMH), nickel cobalt manganese lithium-ion (NCM), and iron phosphate lithium-ion (LFP). The study relied primarily on ecoinvent 2.2 data and secondary data from various literature sources.
- **Comparative Environmental Life-Cycle Assessment of Conventional and Electric Vehicles (Hawkins et. al, under review).** This study, which is currently undergoing peer review before publication, provides a comparison between conventional vehicles using internal combustion engines and electric vehicles using two battery chemistries (Li-NCM and Li-$FePO_4$). The LCI data for the study relies on a combination of LCI databases (e.g., the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model), other secondary data sources, and information from vehicle manufacturers obtained through personal communication.

Data for the upstream stages were provided on a mass per kWh basis, which was then converted to a per kilometer basis (as described in Section 2.3). Below we describe the materials and data sources in detail for each component, and summarize the information in Table 2-2. The manufacturing processes for the components are described in detail in Section 2.2. Note that some materials names were left generic to protect confidential information.

- **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 binder and coated on copper foil (Gaines and Cuenca, 2000; Electropedia, 2011). For this study, we used data for a battery grade graphite material from Notter et al. (2010) and copper foil input-output data fromGaBi4. For the binder, we used data for a polymer material, which was also from GaBi4.

  During the anode manufacturing process, a solvent is also typically used to develop the slurry anode paste, which is then coated on the foil and dried. Because the solvent is an ancillary material that does not become part of the battery cell, it may be recovered and reused. The organic solvent material data were also obtained from GaBi4.

  For battery-grade graphite, we assumed production takes place in China. We also assumed a shipping distance of 7,300 mile (11,800 km) by oceangoing vessel from Shenzen to Long Beach, followed by domestic transport of 95% by mass, at an average distance of 260 miles (418 km) in a for-hire truck; and 5% by mass, at an average distance of 853 miles (1373 km) in railcars (U.S. BLS, 1997).

- **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 a lithium-manganese oxide ($LiMnO_2$)-like material, whose exact chemical makeup remains confidential, and lithium-nickel-cobalt-manganese-oxide ($LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$; Li-NCM). In order to further protect confidential information, and to have a comparison point to another frequently used cathode material, we also modeled lithium-iron phosphate ($LiFePO_4$) battery chemistry. LCI data for the for the $LiMnO_2$ were slightly modified from those of the lithium manganese oxide spinel in Notter et al. (2010), whereas the data for the other two active material chemistries were largely obtained from the Majeau-Bettez et al. (2011) study.

  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. Data for the aluminum foil came from the European Aluminum Association (EAA, 2008) via GaBi4, and data for the manufacture of the solvent were obtained from GaBi4. The same polymer material used for the binder in the anode was also used for the cathode.

For the transportation of the cathode active material, we assumed production occurs in Japan (Lowe et al., 2010), resulting in a transportation distance of 6,000 mile (9,700 km) between Tokyo, Japan, to Long Beach, CA. In addition, we assumed a domestic transport of 95% by mass, at an average distance of 260 miles (418 km) in a for-hire truck, and assumed 5% by mass, at an average distance of 853 miles (1373 km) in railcars (BLS, 1997).

- **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 GaBi4. Data for the manufacture of the separator itself were taken from Notter et al. (2010).
- **Cell Casing:** The casing encloses the anode, cathode, and separator. The casing is made from aluminum. Although older battery pack casings were made of steel, they have shifted to aluminum, due to its lighter weight and resulting energy efficiency gains (Gaines and Cuenca, 2000). A polypropylene resin pouch is also used to enclose the components before they are placed in the aluminum casing. Upstream data for the aluminum casing came from the EAA (2008) via GaBi4, and data for the resin pouch were obtained directly from GaBi4.
- **Electrolyte:** The electrolyte solution acts as a conductor of lithium-ions between the anode and cathode. Electrolyte is composed of lithium salt and organic solvents (Gaines and Cuenca, 2000). For this study we used lithium hexaflourophosphate ($LiPF_6$) as the lithium salt, and ethylene carbonate as the organic solvent. Other electrolyte materials, including alternative organic carbonates, were excluded due to a lack of data on upstream production. LCI data for the materials processing stage were obtained from Notter et al. (2010). Upstream materials extraction data were obtained from GaBi4, except for the lithium salt, which were obtained from a combination of data from GaBi4 and Notter et al. (2010).

  For the transportation of the LiPF6 and ethylene carbonate, domestic production was assumed, given the fact that the United States is the largest producer of lithium compounds and ethylene oxide (USGS, 2000; IARC 2008). Accordingly, we assumed domestic transport (i.e., 95% by mass, at an average distance of 260 miles (418 km) in a for-hire truck, and 5% by mass, at an average distance of 853 miles (1373 km) in railcars (BLS, 1997). Transport by water and other modes were excluded.
- **Battery Management System:** The battery management system (BMS) includes the electronic circuits, software, and internal/external connections and wires used to operate the battery. The BMS consists of approximately 10% printed wire (circuit) boards, 40% steel, and 50% copper by weight (Majeau-Bettez et. al., 2011). Upstream data for the BMS were obtained from GaBi4.
- **Battery Pack Casing/Housing:** The battery cells and BMS are combined into a battery pack. Due to the importance of keeping the battery pack as lightweight as possible, while maintaining a rigid structure and not being susceptible to corrosion, the pack casing is typically made of lightweight plastics. For this study, polypropylene and polyethylene terephthalate plastic materials were assumed for the pack casing, based on submitted primary data from manufacturers and the Majeau-Bettez et al. (2011) study. Steel was assumed to be a likely battery pack housing material based on input from the stakeholders, as well as submitted primary data. Upstream data

for all materials were obtained from the National Renewable Energy Laboratory's U.S. LCI database, via GaBi4.

- **Passive Cooling System:** Passive cooling systems are important to prevent overheating of the battery pack (Gaines and Cuenca, 2000). The cooling system is composed of steel and aluminum sheet metal (Hawkins et. al., in review). Upstream data for the materials were obtained from the EAA (2008) for aluminum, and the U.S. LCI for steel, via GaBi4.

Table 2-2. Upstream Materials and Corresponding Components and Data Sources

Component (Stage C)	Material Name	Data Source for Processing (Stage B)	Data Source for Extraction (Stage A)
Anode	Battery grade graphite	Notter et. al., 2010	GaBi4
	Copper foil (collector)	GaBi4	GaBi4
Cathode	Aluminum (collector)	EAA/GaBi4 \1	EAA/GaBi4 \1
	Lithium manganese oxide (LiMnO$_2$ battery)	Notter et. al., 2010 *(modified to account for a LiMnO$_2$ process from a LiMn$_2$O$_4$)*	GaBi4
	Lithium-nickel cobalt manganese oxide (Li-NCM battery)	Majeau-Bettez et. al., 2011	
	Lithium iron phosphate (LiFePO4 battery)	Majeau-Bettez et. al., 2011	
	Lithium chloride extraction	NA	Notter et. al., 2010
Anode and Cathode	Polymer (binder)	GaBi4	GaBi4
	Auxiliary solvent \2	GaBi4	GaBi4
Separator	Polyolefin	GaBi4	GaBi4
Casing	Aluminum	GaBi4	GaBi4
	Polypropylene resin (pouch material)	USLCI/GaBi4	USLCI/GaBi4
Electrolyte	Lithium hexaflourophosphate (LiPF$_6$)	Notter et. al., 2010	GaBi4
	Ethyl carbonate	Notter et. al., 2010	GaBi4
	Lithium fluoride	Notter et. al., 2010	GaBi4
	Phosphorus pentachloride	Notter et. al., 2010	GaBi4
	Lithium chloride extraction	NA	Notter et. al., 2010
BMS	Copper wiring	GaBi4	GaBi4
	Steel	USLCI/GaBi4	USLCI/GaBi4
	Printed wire board	GaBi4	GaBi4
Pack Housing	Polyethylene terephthalate	GaBi4	GaBi4
Passive Cooling System	Steel	USLCI/GaBi4	USLCI/GaBi4
	Aluminum	EAA/GaBi4	EAA/GaBi4

Notes: \1 EAA: European Aluminum Association; \2 Auxiliary solvent is only used in the manufacturing and not included in the final product.

Transportation

In order to estimate transportation distances and impacts, assumptions are made with respect to where the raw materials will likely be obtained throughout the supply chain. Overall, the LCA assumed that raw materials were obtained from where they are typically produced. For instance, we assumed that the basic lithium salts would come from Chile, cobalt and nickel would come from the Congo, battery-grade graphite would come from China, and the cathode active material would be obtained from Japan. Other, more common basic inputs were assumed to be globally sourced. Much of the transportation data were already included in GaBi4 processes.

In addition, materials and products produced or shipped domestically would be transported 95% by mass, at an average distance of 260 miles (418 km) in a for-hire truck, and 5% by mass, at an average distance of 853 miles (1373 km) in railcars) (BLS, 1997). The distance estimates are based on the U.S. Bureau of Labor Statistics "Hazmat Shipment by Mode of Transportation" (transtats.bls.gov).

Single-Walled Carbon Nanotube (SWCNT) Anodes

Engineered nanomaterials possess unique electrical and mechanical properties that make them well suited for application in electrochemical cells. Specifically, the large surface area to weight ratio, superior charge densities, and tunable surface properties exhibited by many nanomaterials are promising avenues toward improved battery performance. Recent research efforts have focused on a variety of materials including: Ge nanowires (Chan et al, 2008), Si nanowire anodes (Chan et al, 2008), and free-standing single-walled carbon nanotube (SWCNT) anodes (Landi et al, 2009). However, the life-cycle environmental profiles of nano-enabled technologies are poorly understood, and existing LCA methods are insufficient for at least two reasons:

1. Life-cycle inventory (LCI) data describing nano-manufacturing processes are lacking, proprietary, or may not be descriptive of commercial scale burdens (Theis et al. 2011; Gutowski et al, 2010; Seager 2009), and
2. The eventual use-phase performance of nano-enabled energy technologies remains unknown, and available data are obtained at laboratory-scale (Wender et al, 2011).

The inherent uncertainty in manufacturing and use phases makes comprehensive LCA (e.g., cradle-to-cradle) of nano-enabled technologies problematic. Of all of the materials that are the object of study in Li-ion battery applications, SWCNTs may have received the most attention from industrial ecologists (in terms of environmental data). Nonetheless, while previous cradle-to-gate analyses have called attention to the energy intensity of SWCNT manufacturing processes (Ganter et al, 2010; Healy et al, 2008), these studies do not reflect functional improvements in the use-phase, nor do they account for potential gains in manufacturing efficiency associated with returns to scale and experience in the future (Gutowski et al, 2010). Therefore, assessment of developing SWCNT-enabled technologies requires novel approaches to LCA that are *prospective*, rather than retrospective, such that environmentally problematic processes and technologies can be identified and mitigated early in product development cycles.

To explore potential life-cycle environmental impacts of SWCNT-enabled lithium ion batteries, this analysis combines scenario development, thermodynamic modeling, and use-phase performance bounding. Because no commercial data exist for SWCNT anode manufacturing, SWCNT anode LCI data were measured at laboratory scale per unit weight of SWCNT produced (Wender et al, 2011; Ganter et al, 2010). The energy requirements per unit mass of SWCNT produced by laser vaporization are similar to SWCNTs produced by the high pressure carbon monoxide (HiPCO) process (Healy et al, 2008). The HiPCO process, first reported in the literature in 1999 and patented (applied) in 2004, has potential for commercial-scale production because it is a continuous-flow process with recycled exhaust gasses (Smalley et al, 2004; Bronikowski et al, 1999). Over this time period, the electrical energy required per gram of SWCNT was reduced by more than an order of magnitude (Gutowski et al, 2010). Based upon idealized thermodynamic modeling of SWCNT manufacturing via the HiPCO process, this analysis projects three scenarios of improved electrical energy utilization into the near future, as shown below in Figure 2-2.

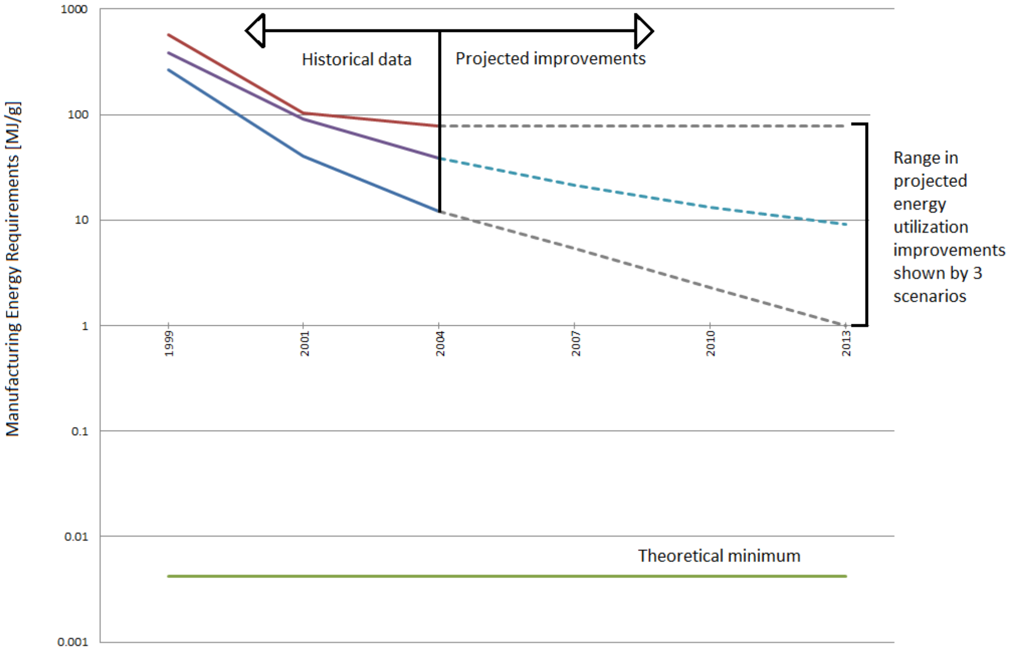

Figure 2-2. Historical Reductions in Electrical Energy Consumption of SWCNT Manufacturing via the HiPCO Process and Scenarios for Improvement (Wender, under review)

Note: The figure is on a log-scale because reductions in energy consumption may span several orders of magnitude.

Experience with other emergent technologies suggests it is reasonable to assume that the eventual energy consumption of SWCNT manufacturing will continue to fall as production volumes increase. Nonetheless, the most conservative scenario (topmost dashed line) projects 2004 SWCNT manufacturing data assuming no improvements in energy efficiency, while the lowest dashed line represents the most ambitious scenario of process improvement (a continuation of gains at approximately the current pace). Historically, improvements in energy utilization are driven by gains in the yield of SWCNT relative to the amount of carbon input. At present, the yields are small (on the order of 10^{-3} per mass), while the stoichiometric ideal is roughly 0.2 grams SWCNT per gram CO, which suggests that there remains significant potential for improvement. However, recent advances have demonstrated that SWCNT yields can be improved through novel catalysts (Schauerman et al, 2009). This rapidly changing technological backdrop demonstrates the challenge of LCA for nanotechnologies.

In addition to improvements in manufacturing, nanotechnologies are rapidly moving forward in terms of use-phase performance. This analysis provides boundaries on the performance of SWCNT in Li-ion batteries, based on their theoretical limit and existing laboratory measurements. At best, theoretical performance limit provides a lower boundary (e.g., the smallest impact per functional unit); while, at worst the upper limit (e.g., the most impact per functional unit) is set by current laboratory measurements. At present, specific capacities of SWCNT anodes under laboratory conditions are approximately 400 mAh/g (Landi et al, 2009), while the theoretical limit is roughly 1100 mAh/g (Landi et al, 2008). At a constant cell voltage of 3.6 V (corresponding to graphite-anode Li ion battery, Linden and Reddy, 2002), the energy density of SWCNT anodes will be between 1.44 Wh/g and 3.96 Wh/g (which is at least three times the 0.5 Wh/g capacity of conventional graphite anodes). Coupling these performance boundaries with the energy estimates discussed above allows manufacturing inventory data to be reported with respect to total kWh of storage capacity in the battery (Figure 2-3). The sample calculation below was used to provide a best-case scenario for the manufacturing energy use based on historical data.

$$\text{High performance scenario: } \frac{193\text{ kWh}}{1\text{g SWCNT}} \times \frac{1\text{g SWCNT}}{1100\text{ mAh}\times 3.6\text{ Volts}} = \frac{48.9\text{ MWh}}{1\text{ kWh Storage}}$$

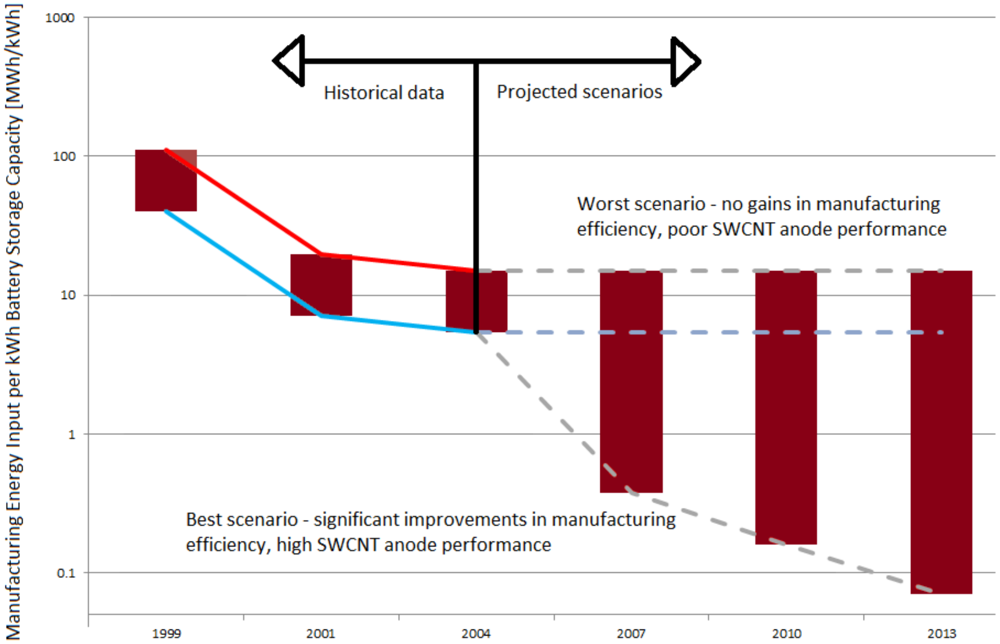

Figure 2-3. Range of Energy Requirements for SWCNT Anodes (per kWh battery storage capacity) (Wender, under review)

Note: Based on historical SWCNT manufacturing data, and two scenarios of manufacturing improvements and SWCNT anode performance.

If current laboratory data are used to model SWCNT manufacturing impacts, the extraordinary energy requirements of SWCNT manufacturing are prohibitively high, even if battery capacity is modeled at the theoretical limit (see calculation above). Gains due to energy use efficiency and lighter anode weight during the use stage are insignificant when compared to the manufacturing impacts. Conversely, if the electrical energy requirements of SWCNT manufacturing decrease as discussed above, SWCNT-anode lithium ion batteries could become competitive (e.g., the best case scenario line) on an environmental basis. This analysis reflects both the challenge and value of prospective LCA, in that it can lead to reorientation of the laboratory research agenda toward pathways with decreased environmental burden. Specifically, our analysis concludes that laboratory research of SWCNT-enabled technologies should focus on lowering the energy intensity of nano-manufacturing processes, in tandem with improving technology performance, as the significant energy consumption of SWCNT manufacturing drives the environmental profile of the technology.

2.1.3 Limitations and Uncertainties

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 GaBi4, as well as literature sources with published LCI data, including Notter et al. (2010), Majeau-Bettez et al. (2011), and Hawkins et al. (under review). When specific detail about a chemical or material was not available, or was not provided by a manufacturer 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 this was not specified by the manufacturers. Another example is the $LiMnO_2$ battery chemistry. Due to confidentiality issues, the manufacturer indicated that they were producing something stoichiometrically similar to $LiMnO_2$ but provided little additional detail related to the chemical or physical state of the active material. The chemistry is likely a modification of $LiMnO_{2,}$ and possibly a mixed metal oxide. As such, the production process may differ from the $LiMnO_2$ we are using as a proxy, which is based on a modification of the Notter et al. (2010) $LiMn_2O_4$ spinel-based process.

Battery-specific subsystem data were highly limited, and in some cases were not sufficient for inclusion. Although the cooling system was modeled as fixed across battery chemistries, the type of cooling system has an impact on cell spacing, and can also differ based on cathode chemistry. Differences in the cooling system type influence battery cell, pack, and module design, and thus have an impact on the overall bill of materials for the battery pack. The simplified modeling choice was driven by the large data gaps in these across-chemistry distinctions. The battery management system was also modeled as fixed across battery type and chemistry, despite indications that there may be substantial differences obscured by this simplification. Secondary data for the mechanical subsystem were not available, so this component was not considered in the analysis.

For the SWCNT anode, LCI data were obtained from laboratory data from Arizona State University, because commercial data for the nanotechnology are not yet available. The LCI data are based on small/laboratory-scale data. As a result, the energy efficiency should improve as the technology becomes commercialized, and the manufacturing process for the SWCNTs is improved and reaches greater economies of scale (see section 2.1.2). The eventual impact of such economies of scale is subject to substantial uncertainty. In addition, there is the possibility that laser-vaporization will not be the dominant mode for producing SWCNTs in the future. Other manufacturing processes may be less energy-intensive during production.

The limitations and uncertainties associated with the ME&P stages are primarily due to the fact that some of these inventories were unobtainable, and others were derived from secondary sources and are not tailored to the specific goals and boundaries of the study. 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 life-cycle 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 life cycle.

As noted previously, assumptions were made with respect to the distance and mode of transportation. Because many of the materials used in the production of lithium-ion batteries are globally-sourced but fairly rare, actual transportation outcomes can vary drastically depending on discovery rates, mining technology, trade agreements, and other technical or geopolitical characteristics.

Secondary data sets from EIA, U.S. LCI, and GaBi4 were also applied for all of the fuels and electricity used in the upstream extraction, manufacturing, and transportation processes. These datasets attempt to estimate national average inputs and outputs for particular processes. As a result, they do not contain information relevant to regional fuel and electricity production, which, as our grid sensitivity analysis presented in Section 3.4 shows, can vary significantly.

2.2 Manufacturing Stage

The manufacture of Li-ion battery packs that are placed into vehicles generally follows four key steps, including: (i) manufacture of the battery cell components (Stage C in Figure 1-4); (ii) manufacture of the battery cell (Stage D in Figure 1-4); (ii) manufacture of other battery pack components, including the BMS, passive cooling system, and housing (Stage C in Figure 1-4); and (iv) assembly of the battery pack (Stage D in Figure 1-4). Below we describe the manufacturing process in detail, and next describe the LCI data collection methodology, sources, and limitations for this stage.

2.2.1 Manufacturing Process

Figure 2-4 illustrates the manufacturing process for the anode electrode, cathode electrode, and battery cell. As shown in the figure, manufacture of the electrodes follows a similar process. First, the electrode powder is combined with a binder and mixed into a slurry paste with solvent. Next, the slurry paste is coated onto the collector (copper for anode and aluminum for cathode) and dried to remove the solvent, which is recycled and reused. Once dried of the solvent, the foil sheets are compressed and adjusted for thickness and then slit and cut to the correct width (Gaines and Cuenca, 2000). The anode electrode is typically 14 µm thick and the cathode 20 µm thick (Gaines and Cuenca, 2000).

The anode and cathode electrodes are then layered in between a separator and rolled. 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).

Once the three layers (anode, cathode, and separator) are wound together--either cylindrically or prismatically--they are wrapped, placed within a polypropylene resin pouch, and then placed in a thin aluminum casing. Aluminum is used as a cell casing material because of its light weight and strength.

Next, the battery cell is filled with an electrolyte solution, which is pre-mixed from a supplier (Gaines and Cuenca, 2000). The manufacture of the electrolyte solution generally involves mixing of 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.

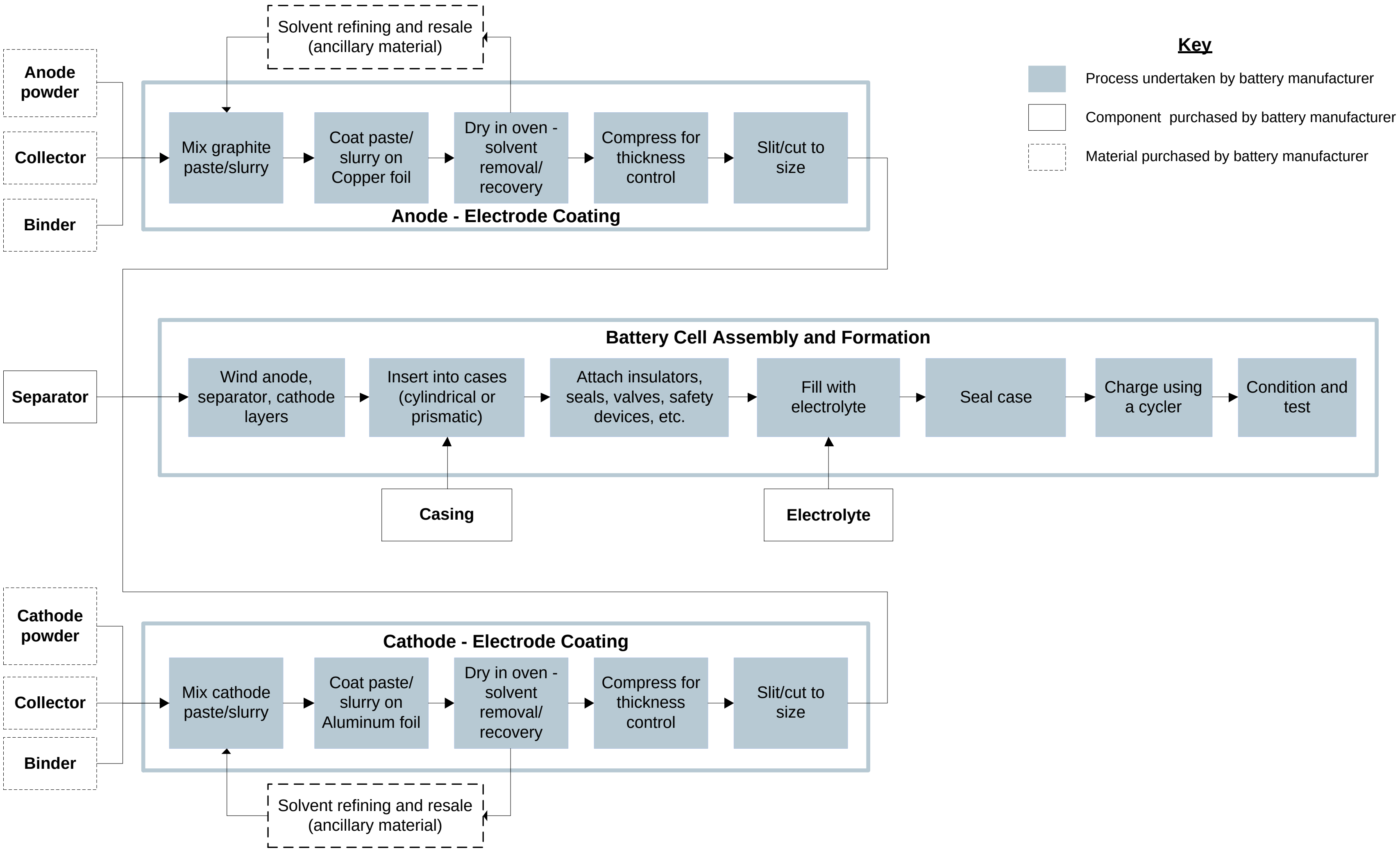

Figure 2-4. Typical Manufacturing Process for Lithium-ion Battery Cells

Sources: Gaines, L.; Cuenca, R. Cost of Li-ion Batteries for Vehicles, Argonne National Laboratory, Center for Transportation Research (CTR), May 2000. Electropedia, Battery and Energy Technologies, Lithium Ion Battery Manufacturing (http://www.mpoweruk.com/battery_manufacturing.htm accessed on June 7, 2010).

After the battery cell casing is sealed, it is charged and tested. The individual cells are then assembled with the BMS and housing to form the battery pack. The battery pack typically has a casing that contains all of the cells and BMS. The battery pack is then combined with the cooling system and placed into the vehicle in a supportive metal or plastic housing.

Solvent-less Manufacturing Process

It is important to note that one battery manufacturing partner uses a proprietary solvent-free manufacturing process. Conventional lithium-ion battery manufacturing processes typically use a significant amount of N-methyl-pyrrolidone (NMP) solvent, though some have moved to the use of water-based methods. As noted previously, Zackrisson et al. (2010) found that it was environmentally preferable to use water as a solvent, instead of NMP, in the slurry for casting the cathode and anode of lithium-ion batteries for PHEVs.

2.2.2 Methodology and Data Sources

LCI data for the components and product manufacturing stage were obtained using 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 (i.e., anode, cathode, battery cell, casing, battery pack, and housing manufacture). The data forms were developed by Abt Associates Inc. and approved by the partnership. The collection form sought brief process descriptions; 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). In addition, the partnership assumed that the anticipated lifetime of the battery is the same as the anticipated lifetime of the vehicle for which it is used (10 years).[5] Therefore, we assumed one battery per vehicle. Multiple data sets were collected for some processes. These data were aggregated to generate a composite inventory for each process that protects the confidentiality of the individual data points.

The primary data were combined with secondary data for each of the components (except the electrolyte solution) to address data gaps, and to protect the confidentiality of the primary data provided by our partners. Secondary data from two key studies were incorporated with detailed inventory data: Notter et. al (2010), and Majeau-Bettez et al. (2011). Although this study models electricity inputs from the U.S. power grid for the manufacture of the batteries produced by the partnership (i.e., Li-MnO_2 and Li-NCM), the data for the Li-$FePO_4$ battery production was based on the Canadian electricity grid, because this battery chemistry is primarily produced in Canada (Phostech Lithium, 2012). In addition, secondary data were obtained for the passive cooling system from a third study (Hawkins et al., under review). As discussed above, data for the mechanical subsystem were not available, so this component was not included and modeled in the LCA. Table 2-3 summarizes the data sources for the processes in the manufacturing stage.

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[5] Most Li-ion battery systems are expected to achieve a service life of 10 years. However, the service life may vary depending on several factors, such as temperature, charging regime, and depth and rate of discharge. These factors are affected by the demands a vehicle and driver place on the battery.

Table 2-3. Manufacturing Stage Processes and Data Sources

Process	Data source
Anode electrode	Primary; Majeau-Bettez et. al., 2011
Cathode electrode	Primary; Majeau-Bettez et. al., 2011
Separator	Notter et. al., 2010
Casing	Primary; Majeau-Bettez et. al., 2011
Electrolyte	Primary
Battery cell	Primary; Majeau-Bettez et. al., 2011
Battery management system	Majeau-Bettez et. al., 2011
Housing	Primary; Majeau-Bettez et. al., 2011
Passive cooling system	Hawkins et. al., under review
Mechanical subsystem	None

As noted above, LCI data were obtained on a mass per kWh basis. However, to model results for a battery pack placed in a PHEV-40 and EV, research was conducted on the estimated size of the battery pack for each type of vehicle (see Table 1-1). Accordingly, the data were scaled to account for a 40kWh battery pack in the EVs, and an 11.6 kWh battery pack in the PHEVs (Barnes, 2009).

We assumed a transportation distance of 444 miles by truck--the average domestic shipping distance of automobiles and components in 2002 (U.S. BTS, 2006).

2.2.3 Limitations and Uncertainties

Limitations and uncertainties related to the data collection process include the fact that companies were self-selected, which could lead to selection bias (i.e., those companies that are more advanced in terms of environmental protection might be more willing to supply data than those that are less progressive in this regard). Companies providing data also may have a vested interest in the project outcome, which could result in biased data being provided. The employment of the Core Group as reviewers in this project was intended to help identify and reduce any such bias (e.g., manufacturers or recyclers checking to ensure that other submitter data is consistent with industry norms). In addition, as noted above, to address data gaps and protect confidential information, it was necessary to combine multiple sets of secondary data with primary data for many of the components. As a result, inconsistencies between the materials linking the secondary and primary datasets introduced some uncertainty. An example of this was the matching of the modified Notter et al. (2010) lithium manganese oxide spinel process with the primary manufacturing information of the manufacturer whose manganese oxide cathode active material was incompletely characterized.

Other specific limitations and uncertainties of the study associated with the manufacturing stage LCI data include the following:

- No data were available for the actual foil fabrication process for the cathode. For this inventory, the wire drawing process was used as a proxy.
- No specific data on the battery cell container production process were available; accordingly, this process was inventoried with metal sheet rolling as a proxy.
- We assumed all components scale linearly into the battery pack to meet energy density requirements for PHEVs (11.6 kWh) and EVs (40 kWh) (see Table 1-1).
- The BMS process inventory data, obtained from Majeau-Bettez et al. (2011), was modified slightly. Specifically, the mass breakdown by Schexnayder et al., estimated that the BMS

represented about 4% of the battery mass, and circuit boards and wires each constituted about half of this mass. However, based on discussions with the partnership, this may overestimate the relative importance of the BMS. Instead, our analysis assumed the BMS is about 2% by mass relative to the whole battery pack, with integrated circuits accounting for about 10% of the BMS mass; copper wires (both for internal and external cabling) representing 50% of the BMS mass; and a stainless steel container representing 40% of the mass (Majeau-Bettez et al., 2011).

- The study did not adjust for differences in battery pack due to different chemistries (e.g., $LiFePO_4$ versus $LiMnO_2$), when in reality there are differences in the pack to account for differences in performance between the battery types (e.g., the amount of heat emitted when used).
- There were discrepancies in energy use data reported between manufacturers: one battery manufacturer reported energy and fuel use, and the other only reported material inputs. As a result, we assumed that the second manufacturer used energy at approximately the average rate of the other two processes. It is possible that this assumption is significantly different from actual energy use. Because the solvent-less and solvent-based manufacturing processes are so mechanistically different, averaging of this sort is highly uncertain.

2.3 Use Stage

Although the focus of the LCA study is on Li-ion batteries, given the fact that the purpose of the batteries is to provide energy for transportation in the use stage, the study includes an assessment of impacts resulting from the vehicles in which the batteries are placed (EVs and PHEVs), in the use phase only. As described in Section 1, as part of the use stage analysis, we assessed two types of vehicles, as follows:

- **Plug-in hybrid electric vehicles (PHEVs)** can charge its battery by plugging in to a grid-provided electricity system, as well as use gasoline to power the battery (similar to a hybrid-electric vehicle). As a result, PHEVs can consume both engine fuel and electricity from the power grid. PHEVs are typically categorized according to their all-electric range (AER), which is the maximum distance that can be travelled without using the internal combustion engine. This LCA focused on PHEVs with a 40-mile range (PHEV-40). PHEV-40s require batteries with higher energy density, similar to EVs.
- **Electric vehicles (EVs)** are entirely powered by batteries that are charged with electricity from the power grid. EVs have no internal combustion engine.

We also provide a qualitative assessment of internal combustion engine vehicles (ICEVs) in the use stage for one impact category (i.e., greenhouse gas emissions). These vehicles have a battery, but the battery is not used to increase vehicle efficiency. ICEV batteries are typically made with a lead-acid chemistry, and are only used to start the internal combustion engine. The ICEVs only consume engine fuel.

Below we provide an overview of the methodology applied to estimate LCI data for the use stage for the batteries and vehicles.

2.3.1 Energy and Consumption Estimates

As noted previously, the LCI data for the use stage are a function of the amount and type of energy consumed to operate the vehicle. Accordingly, below we describe (i) the amount of energy consumed during vehicle use, which depends on vehicle efficiency, and (ii) the types of energy consumed.

Vehicle Efficiency

The Argonne National Laboratory developed the Powertrain System Analysis Toolkit (PSAT) to model fuel economy and performance for a number of different vehicle types: “PSAT is a ‘forward-looking’ model that simulates fuel economy and performance in a realistic manner — taking into account transient behavior and control system characteristics (Argonne, 2007).” PSAT has been recognized by government, academic, and industry organizations as a reliable simulation tool. By using simulated data and keeping non-power train characteristics (e.g., drag coefficient, frontal area, wheel radius, etc.) constant across vehicle types, differences in energy efficiency can be attributed to differences in the power train, rather than other vehicle characteristics.

This LCA used PSAT simulation data to estimate vehicle efficiency. Specifically, vehicle efficiencies are based on a 2009 Argonne study that focused on the greenhouse gas emissions of PHEVs (Elgowainy, 2009). Table 2-4 shows the assumptions made in the Argonne study, which reflect a model year 2015 mid-size passenger car.

Table 2-4. Vehicle Assumptions for PSAT Model (as shown in Elgowainy, 2009)

Vehicle Type	Vehicle Mass (kg)	Engine Power (W)	Electric Motor (W)	Electric Generator (W)	Battery Power (W)	Frontal Area (m^2)	Drag Co-efficient	Wheel Radius (m)
ICEV	1,515	102,109	n/a	n/a	n/a	2.23	0.26	0.317
HEV	1,563	82,530	60,134	49,474	26,748	2.23	0.26	0.317
PHEV-10	1,592	70,373	64,461	42,186	46,610	2.23	0.26	0.317
PHEV-40	1,674	73,285	67,739	43,932	48,968	2.23	0.26	0.317
EV-100 [1]	1,896	n/a	137,000	n/a	166,000	2.23	0.26	0.317

Source: Elgowainy, 2009
Note: [1] PSAT results from Aymeric Rousseau, 6/15/2010.

The PSAT model generates results both for urban and highway driving conditions. Consistent with the Argonne study and EPA's Fuel Economy Guide, we assumed an overall mix of 55% urban driving and 45% highway driving. In addition, in keeping with Argonne's assumptions, we assumed that the battery charging efficiency is 85%; (i.e., for every 100 kWh that is drawn from the electric grid, 85 kWh is stored in the battery for discharge).

Table 2-5 presents PSAT results from the Argonne study. Vehicle efficiency for PHEVs is split into charge depleting (CD) and charge sustaining (CS) modes. During CD mode, the PHEV uses energy stored in the battery to power the vehicle. Engine fuel is also used in CD mode at times of high power demand. During CS mode, the PHEV uses engine fuel to power the vehicle and sustain battery charge.

Table 2-5. PSAT Results and Overall Vehicle Efficiency [1]

Driving conditions and vehicle efficiency	EV-100	PHEV-40	ICEV
Urban			
Charge Depleting Mode			
Electricity consumption (W-hr/km)	146.6	102.6	--
Fuel economy (km/liter)	--	65.2	--
Charge Sustaining Mode			
Fuel economy (km/liter)	--	19.6	11.7
Highway			
Charge Depleting Mode			
Electricity consumption (W-hr/km)	150.4	104.4	--
Fuel economy (km/liter)	--	64.9	--
Charge Sustaining Mode			
Fuel economy (km/liter)	--	17.1	14.5
Combined [2]			
Charge Depleting Mode			
Electricity consumption from grid [3] (W-hr/km)	174.5	121.6	
Fuel economy (km/liter)	--	65.1	--
Charge Sustaining Mode			
Fuel economy (km/liter)	--	18.5	13.0

Source: Elgowainy, 2009
Notes:
[1] PSAT results incorporated EPA mpg-based adjustment formulae to reflect the on-road fuel economy.
[2] Assumes driving mix of 55% urban and 45% highway.
[3] Assumes a charging efficiency of 85%.

In addition to the specifications listed in Table 2-5 above, the partnership assumed that each vehicle travels 19,312 km per year (EPA, 2005; Rantik, 1999). Furthermore, each vehicle was assumed to have a lifetime of 10 years, with a lifetime distance traveled of 193,120 km. The distance traveled over the lifetime of the vehicle is used to put life-cycle impacts in terms of the functional unit (km traveled).

Li-ion batteries were also assumed to have a lifetime of 10 years, resulting in one battery needed per vehicle lifetime. The number of batteries per vehicle enters into the upstream materials processing and manufacturing LCI as a scalar multiplier.

PHEV Methods

Estimating fuel and electricity consumption for PHEVs involves uncertainty regarding the amount of energy drawn from the power grid and the amount drawn from engine fuel. Unlike other vehicle types, PHEVs can draw energy from two sources: 1) engine fuel (e.g., gasoline), and 2) electricity from the power grid. The ratio of engine fuel to electricity depends both on user habits, such as how often drivers charge the battery, and vehicle performance, such as the distance that can be traveled on one charge cycle (all-electric range, or AER). More frequent charging and greater AERs lead to greater electricity consumption and less engine fuel consumption.

Utility Factor and Overall Efficiency

Vehicle miles traveled (VMT) for PHEVs are commonly split into CD and CS modes, as presented in Table 2-5 above. While the percent of VMT in CD and CS mode for a given vehicle will vary according to driver habits, standard methods have been developed to estimate the percent of VMT spent in each mode. These methods rely on utility factors (UFs), which represent the percent of VMTs likely to be driven in CD mode as a function of the AER. Commonly used UFs, as described in SAE International standards SAE J1711 and J2841, are based on the 2001 National Highway Transportation Survey (NHTS) prepared by the Bureau of Transportation Statistics.

As shown in Table 2-5, the PSAT model estimates fuel economy and electricity consumption for PHEVs in both CD and CS mode. These baseline energy efficiencies can be combined by using the UF to determine the overall electricity consumption and fuel economy, as follows:

$$\text{Overall electricity consumption (Whr/km)} = UF * (ECcd)$$

$$\text{Overall fuel economy (km/liter)} = UF/FEcd + (1 - UF) / FEcs$$

Where:

UF is the utility factor (percent of VMT in CD mode)

ECcd is the electricity consumption in charge depleting mode (Whr/km)

FEcd is the fuel economy in charge depleting mode (km/liter)

FEcs is the fuel economy in charge sustaining mode (km/liter)

Note that the PHEVs modeled during this PSAT analysis use a blended CD mode to increase overall efficiency. In a blended CD mode, the engine turns on under high power demand to preserve battery charge and increase overall efficiency. As a result, fuel consumption during CD mode is not zero. Also note that overall electricity consumption and fuel economy are only meaningful when viewed together; the implications of high fuel economy in conjunction with high electricity consumption are different than the implications of high fuel economy in conjunction with low electricity consumption.

In addition, there are some potential disadvantages to using 2001 NHTS data as a basis for the UF. In particular, the data are 10 years old, and it is likely that driving habits have changed over the last decade. There are also several assumptions inherent in the UF derivations that could impact the UF (e.g., PHEVs will be charged once per day, and will be driven the same distances as the average car). These limitations and uncertainties are addressed further in Section 2.3.3.

EV Methods

EVs only draw energy from the power grid, so unlike PHEVs, it is not necessary to combine different modes of operation to derive overall energy consumption. This is equivalent to the scenario in which the UF is equal to 1 (100% of VMT in CD mode). EV electricity consumption can be calculated directly with PSAT results.

ICEV Methods

HEVs and ICEVs only draw energy from engine fuel, and so it is not necessary to combine different modes of operation to derive overall energy consumption. This is equivalent to the scenario in which the UF is equal to zero (zero percent of VMT in CD mode). HEV and ICEV fuel consumption can also be calculated directly with PSAT results.

Energy Consumption Estimates

Table 2-6 presents electricity and engine fuel consumption estimates (items [5] and [6], respectively) in terms of the functional unit (km). These figures represent point estimates for energy consumption. It is important to note that there are uncertainties surrounding both vehicle performance (items [1] through [3]) and the utility factor (item [4]).

Table 2-6. Energy Consumption Estimates Based on PSAT Results and Overall Vehicle Efficiency[\1]

Calculation	Parameter	Vehicle/Battery Type: Li-ion EV	Vehicle/Battery Type: Li-ion PHEV-40 gasoline ICE [\2]	Vehicle/Battery Type: Gasoline ICEV
	Charge Depleting Mode			
[1]	Electricity consumption (AC W-hr/km)	174.5	121.6	n/a
[2]	Fuel economy (km/liter)	n/a	65.1	n/a
	Charge Sustaining Mode			
[3]	Fuel economy (km/liter)	n/a	18.5	13.0
	Weighted Energy Consumption Estimates			
[4]	Utility Factor	1	0.628	0
[4]*[1]=[5]	Weighted electricity consumption from grid (AC W-hr/km)	**174.5**	**76.39**[\3]	**-**
[4]/[2]+(1-[4])/[3]=[6]	Weighted fuel consumption (liter/km)	**-**	**0.030**	**0.077**

Notes:
[\1] Values have not been adjusted to represent on-road performance.
[\2] ICEV: Internal Combustion Engine Vehicle
[\3] Using EPA's New Fuel Economy MPG_e calculation methods (33.7 kWh/gallon), the electricity use of the PHEV-40 is equivalent to 0.0086 liters/km of gasoline consumption.

Energy Sources

As noted previously, LCI inputs and outputs also depend on the type of energy consumed. To this end, the following section provides an overview of factors that affect the power grid mix, and this study's approach to modeling the power grid mix and calculating LCIA impacts associated with electricity production in the use stage.

Factors that Affect the Power Grid Mix

The power grid mix varies with a number of factors, including the time of year, geographic region, and time of day. In addition, the power grid mix changes over the years, as new power-generating facilities come online and old facilities go offline (Elgowainy, 2009). As is shown in Figure 2-5, the geographic distribution of electric power plants differs by plant type (EIA, 2010a).

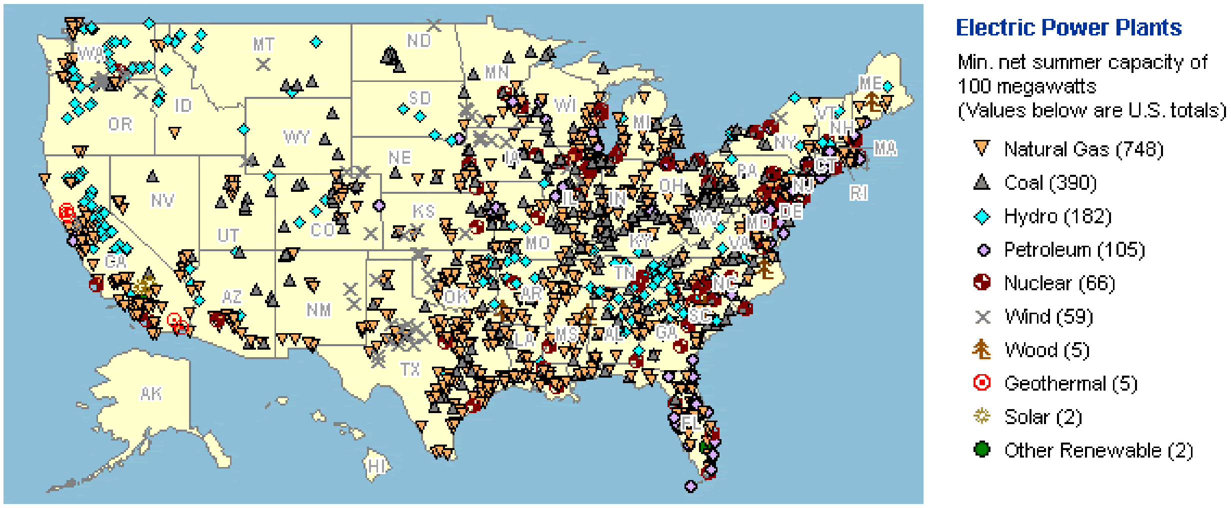

Figure 2-5. Distribution of Electric Power Plants by Type (EIA, 2010a)

North American power plants are connected together in a grid to allow for the bulk transmission of power. For oversight and practical purposes, the grid is divided into eight regions, per the North American Electric Reliability Corporation (NERC), as presented in Figure 2-6.

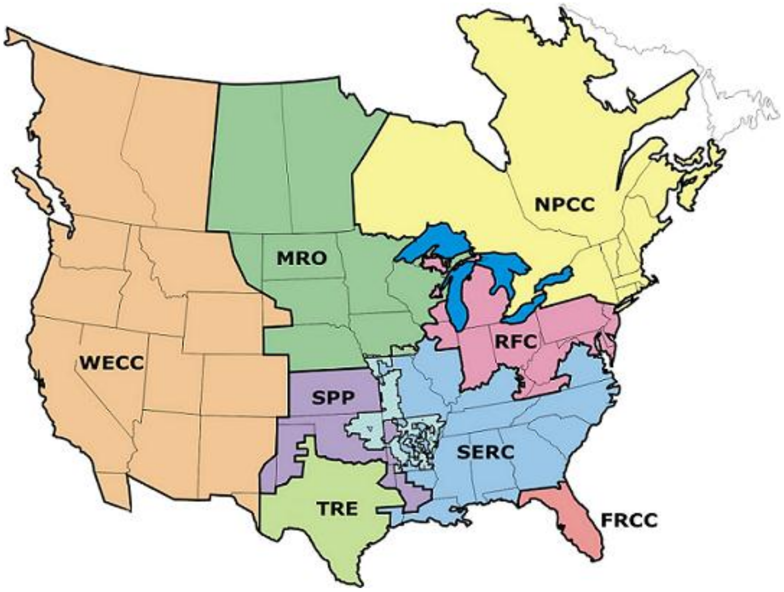

Figure 2-6. North American Electric Reliability Corporation Regions (NERC, 2011)

Key: Florida Reliability Coordinating Council (FRCC); Midwest Reliability Organization (MRO); Northeast Power Coordinating Council (NPCC); Reliability First Corporation (RFC); Southeast Electric Reliability Corporation (SERC); Southwest Power Pool Regional Entity (SPP); Texas Reliability Entity (TRE); Western Electricity Coordinating Council (WECC)

Temporal (hourly) Variation

The power grid mix also varies throughout the day, as additional generating units are dispatched to meet increased demand during peak periods. In the summer, energy demand is typically at its peak during the late afternoon and early evening as a result of air conditioning. Energy demand is typically at its lowest overnight when businesses are closed, lights are off, and air-conditioning is at its lowest (Elgowainy, 2009). The type of generating units that are dispatched vary according to the load; the most economical units are dispatched first, and the least economical are dispatched last. Furthermore, some types of generating units, such as hydroelectric and nuclear power plants, are not as responsive to short-term changes in demand, and generate a more constant output than other types of generating units. Other types of generating units, such as simple-cycle gas and oil fired turbines, can be deployed quickly to meet hourly changes in demand (Elgowainy, 2009).

Load Profile and Charging

U.S. EIA data, U.S. LCI data, and GaBi electricity datasets are all based on an average mix of electricity generation for different regions. Marginal, rather than average, electricity generation considers impacts from the standpoint of the addition of marginal increments of demand, such that the applicable fuel mixture is that which provides these additional marginal increments of electricity above and beyond the fuels that would have been used in the absence of the new demand. In such a case, the use of an average grid mix would mischaracterize the impact of the new technology on the overall environmental burden of the system. With the increase in use of electric cars, it will likely change the make-up of the grid from its current mix. So, it is important to consider the “marginal” generation, instead of solely focusing on the “average” generation.

The time of day that drivers charge their vehicles plays a large role in determining the marginal load that is placed on the power grid. Therefore, it is critical to understand when drivers will typically charge their vehicles, and to associate these charging times with the corresponding power grid mix profiles. A recent Argonne study simulated the marginal power grid mix in the year 2020 attributable to vehicle charging in four regions of the United States:

- New England Independent System Operator (NE ISO),
- New York Independent System Operator (NY ISO),
- State of Illinois, and
- Western Electric Coordinating Council (WECC) (Elgowainy, 2010):

The same study further simulated the marginal power grid mix under three charging scenarios. In each scenario it was assumed that the vehicles were charged once at the end of a day (Elgowainy, 2010):

- *Unconstrained charging*, where charging begins within the hour that the last trip ended,
- *Constrained charging*, where charging begins 3 hours after the hour in which the last trip ended, and
- *Smart charging*, where charging is monitored to fill valleys in the daily utility demand profile.

The daily charge cycles that resulted from these three scenarios is shown in Figure 2-7.

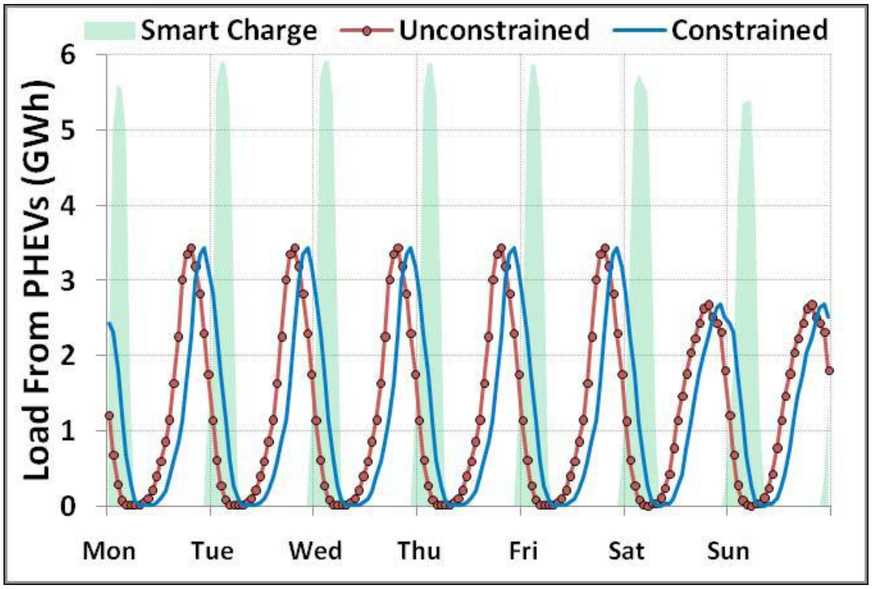

Figure 2-7. Typical Hourly Charging Pattern for All Three Charging Scenarios (week runs from Monday through Sunday) (Elgowainy, 2010)

2.3.2 Methodology and Data Sources

Below we discuss the LCI methodology and data sources for the base-case grid mix, including the average U.S. power grid mix, gasoline production, and vehicle emissions data sources. Next we discuss the data source for the grid mix sensitivity analysis and conversion of the data into the functional unit.

Average U.S. Power Grid Mix

In order to calculate the life-cycle impacts associated with a power grid mix, the mix must be connected with an inventory of inputs and outputs for each type of electricity plant. We used three data sources to construct the average grid mix:

- **The U.S. Energy Information Administration (EIA) Electric Power Annual Report:** the EIA compiles a yearly dataset that documents the domestic production, consumption, and trade of electricity broken down in a number of different categories. We used the 2010 report to determine the most recent known distribution of electricity generation by fuel type (EIA, 2010c).
- **U.S. LCI National Data:** NREL compiled inventory data for electricity generation as part of the U.S. Life-Cycle Inventory (USLCI). The data are national in scope, and mainly draw on data from the Emissions & Generation Resource Integrated Database (eGRID). This database is based on available plant-specific data for all U.S. electricity generating plants that provide power to the electric grid and report data to the U.S. government. eGRID integrates many different federal data sources on power plants and power companies, from three different federal agencies: EPA, EIA, and the Federal Energy Regulatory Commission (FERC). We used the USLCI data to model bituminous coal, natural gas, fuel oil, nuclear, and biomass-based electricity generation.
- **PE Fuel-Specific Data:** PE International derived U.S.-specific data for electricity production by fuel type. The data were compiled by PE International in 2002, are national in scope, and were last reviewed in 2006. We used these data to model lignite, hydro, and wind-derived electricity generation.

Gasoline Production

Gasoline is produced from crude oil, through a complex system of refining processes. The specific processes used at any given refinery depend on the physical-chemical characteristics of the crude oil and the desired products, both of which vary. As a result, no two refineries are exactly alike (EPA, 1995a). Furthermore, gasoline formulations vary seasonally; winter grades of gasoline have higher vapor pressure to allow the engine to start in cold weather, whereas summer grade gasoline has lower vapor pressure to reduce emissions (EIA, 2010b).

While the exact LCI associated with the production of gasoline varies due to a number of factors, it is possible to develop an average, or representative LCI. We used a process for U.S. average gasoline production and delivery at the consumer that was built by PE International. The dataset represents a mass-weighted average refinery for the United States, and covers the whole supply chain, from crude oil extraction, transportation to refineries, and processing of crude oil, to produce automobile-grade gasoline.

Vehicle Emissions

As is noted in the Argonne WTW PHEV analysis, the emission rates during the vehicle's operation will deteriorate over time. It is reasonable to assume that the rate of deterioration is constant; therefore, the data of the lifetime mileage midpoint for a typical model year (MY) vehicle should be applied for the simulation. Since, on average, the midpoint for U.S. light-duty vehicles is about five years, the fuel economy values will be based on a MY five years earlier than the calendar year targeted for simulation (Elgowainy, 2009). Two sources provide vehicle emissions data:

- **GREET:** The GREET model provides emission data for conventional gasoline ICEV, HEVs, and PHEVs. In this study, we used the GREET emissions from PHEVs as our basic model. Emissions included in GREET are shown in Table 2-7.
- **PE:** Through the GaBi professional database, PE International provides vehicle emissions for European vehicles. We use the Euro 4 vehicle model, with an engine that is smaller than 1.4 liters in displacement, to complement the GREET dataset. Emissions included in the GaBi datasets are also shown in Table 2-7.

Table 2-7. Emissions Captured by GaBi and GREET

Emission	GREET	GaBi
Carbon monoxide	✓	✓
Carbon dioxide	✓	✓
Carbon dioxide (w/C in VOC and CO)	✓	
Methane	✓	✓
Nitrous oxide	✓	✓
Nitrogen oxides	✓	✓
NMVOC		✓
VOC exhaust	✓	
VOC evaporation	✓	
Sulfur dioxide		✓[1]
Sulfur oxides	✓	
Toluene		✓
Xylene		✓
Ammonia		✓
Benzene		✓
Particulate matter 2.5 (aerodynamic diameter <= 2.5 micrometers)		✓
Particulate matter 2.5 exhaust	✓	
Particulate matter 10 exhaust	✓	
GHG	✓	

Notes: [1] SO_2 emissions depend on a free variable specifying the sulfur concentration (ppm) in the gasoline.

In situations where both GREET and GaBi characterized emissions (e.g., carbon monoxide), we used the GREET emission factor. Note that this study only considered gasoline engine fuel. Use of other engine fuels, such as ethanol, diesel, and biodiesel, were not modeled in this study.

Sensitivity Analysis Marginal Grid-Mix Data

As part of the sensitivity analysis, we built on Argonne's study by incorporating the results of the simulation described in Section 2.3.1. Accordingly, we considered changes in the grid-mix resulting from unconstrained versus smart charging scenarios for three grid types (WECC, IL, and ISO-NE), as presented in Table 2-8.

Table 2-8. Marginal Electricity Generation Mix in 2020 for Two Charging Scenarios and Three Regions (Source: Elgowainy et al. 2010) [1]

Charging scenario		Unconstrained Charging (%)			Smart Charging (%)		
Fuel	**Technology**	**WECC**	**IL**	**ISO-NE**	**WECC**	**IL**	**ISO-NE**
Coal	Utility boiler/IGCC	0.7	67.2	0	13.7	99.5	0
Natural gas	Utility boiler	7.1	0.7	-0.5	5.9	0	0.1
	Combined cycle	87.2	22.6	102	75.6	0	94.7
	Combust. turbine	5.3	8.8	23.1	4.2	0	3.7
Residual oil	Utility boiler	0	1.2	-23.9	0	0	1.3
Nuclear	n/a	-0.2	0.4	0	0.5	0	0
Biomass	Utility boiler/IGCC	-0.2	0	-0.1	0.1	0	0.2
Other	Renewable	0	-0.9	-0.6	0	0.5	0
	Total [2]	*100*	*100*	*100*	*100*	*100*	*100*

Notes:

[1] IGCC – integrated gasification combined cycle; IL – Illinois; ISO-NE – Independent System Operator - New England; WECC – Western Electricity Coordinating Council

[2] Figures may not sum to 100, due to rounding.

Functional Unit Conversion

As noted previously, although the data were collected on a mass per kWh basis, the functional unit applied for this study is on a per distance (kilometers driven) basis. Accordingly, the LCI data were multiplied by the battery capacity, and then divided by the total distance driven over the lifetime of the battery.

2.3.3 Limitations and Uncertainties

As described in Section 1.2.2, the service provided by the Li-ion batteries in the use stage is through the vehicles into which they are placed. Although the use stage analysis of this study assessed impacts from vehicles that use Li-ion batteries (PHEVs and EVs), the full life-cycle impacts of these vehicles were not assessed. Accordingly, differences between varying components used for PHEVs versus EVs were not considered (e.g., glider and drive train). Ideally, a full LCA of Li-ion batteries for electric vehicles would include an assessment of the vehicles as well, not just the batteries. However, resource limitations prevented the partnership from conducting a full LCA of the vehicles. Because of this, care must be taken not to interpret the study results as representing those for the full life-cycle of a PHEV or EV vehicle.

To address this limitation, our study relied on the PSAT to model fuel economy and performance, as it keeps the non-power train characteristics (e.g., drag coefficient, frontal area, wheel radius) constant across vehicle types (see Table 2-4). In addition, key assumptions were made with respect to the vehicle lifetime, total driving distance per year, and driving mix between highway and urban roads. The vehicle fuel/electricity estimates were based largely on the Elgowainy et al. (2009) study.

One weakness that this creates in the model is the fact that there are likely to be differences in functional battery lifetimes. The key assumption the partnership made was that the vehicle lifetime of 10 years is equal to the battery lifetime across all chemistries. However, it is anticipated that the use of certain chemistries, such as lithium iron phosphate, will result in many more battery cycles than lithium manganese oxide spinel or lithium nickel cobalt manganese. Given the uncertainty with respect to this assumption, it is addressed in the sensitivity analysis in Section 3.4.

Below we summarize additional limitations and uncertainties with the use stage LCI data:

- Differences in battery weight as a result of material choice and engineering, as well as variance in capacity, is a substantial source of uncertainty. Heavier batteries will tend to reduce the use stage efficiency of the vehicle. A number of studies have looked at material choices in automobiles and found substantial energy savings and GHG reductions possible with the use of lighter weight metals, such as aluminum and high-strength steel (Stodolsky et al., 1995; Kim et al., 2010). Findings from a study by Shiau et al. (2009) indicate that the impacts of battery weight are measurable on life-cycle GHG emissions. Although there are differences in the weight of the battery based on the chemistry (e.g., Li-FePO4 is heavier than a Li-MnO2-type battery), we did not model differences in use-stage vehicle efficiency across battery chemistries.
- The study assessed the impact of different grid mixes (i.e., ones that are more coal-centric to ones using more natural gas and renewables) on the global warming potential impact category (see Figure 3-1). However, we did not assess how changes to the grid over time would affect the other impact categories.
- Data for more recent fuel-specific electricity generation were not available (U.S. LCI data were from the early 2000s); newer facilities will have different emission profiles.
- Fully-speciated tailpipe emissions for PHEV-40 vehicles were not used; some likely VOC

components were still aggregated into the non-methane VOC block. This has the potential to affect a number of categories, including human toxicity potential.

- The study assumed linear scaling between PHEV and EV battery capacities, based on the energy capacity required. It also assumed linear scaling for battery subsystem requirements.

2.4 End-of-Life Stage

As these Li-ion batteries for electric vehicles reach the end of their useful life over the next decade, they will comprise an increasing percentage of the battery waste stream. The following section describes the key recycling processes assessed as part of this study, background on the current and future trends with respect to the generation, recovery, and disposal of Li-ion batteries, the methodology used to collect EOL LCI data, and the results and limitations of the data collected.

2.4.1 Recycling Processes Modeled

Although there are currently limited regulations related to the disposal of Li-ion batteries, there is incentive to collect the batteries for recycling, due to the value of the recovered metals. Rechargeable Li-ion batteries contain cobalt, nickel, lithium, and other organic chemicals and plastics. The composition varies, depending on the battery manufacturer (Xu et al., 2010). Historically, battery recycling focused on recovering cobalt, as its value has risen significantly in response to increased demand from the battery sector (Elliot, 2004). However, the use of cobalt in batteries is projected to decline as battery technology evolves and other metals are used instead of cobalt (Elliot, 2004; Gaines, 2009).

In addition to cobalt, battery recyclers may also recover lithium, nickel, and other materials. The use of lithium, in particular, is expected to increase, due to increased demand for Li-ion batteries in electric vehicles. As of 2007, batteries accounted for 25% of lithium resource consumption; this amount is projected to increase significantly (Gaines, 2009). Figure 2-8 presents an upper-end estimate of the potential growth of lithium demand, which underscores the importance of curtailing the extraction of virgin lithium to preserve valuable resources and reduce the environmental impact.

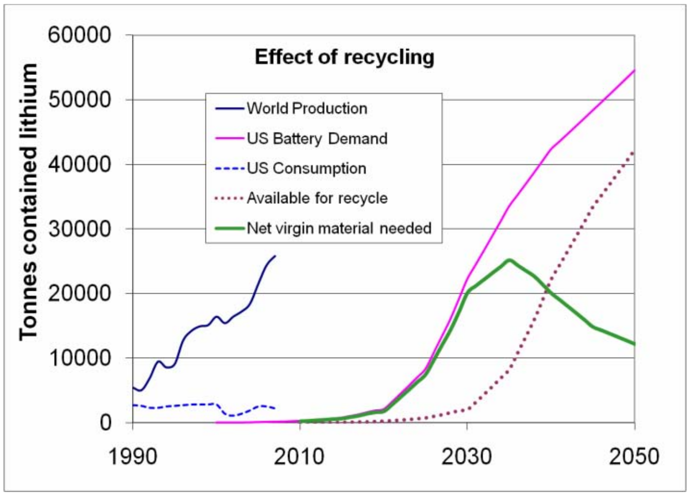

Figure 2-8. Upper-End Potential Effect of Recycling on Lithium Demand (Gaines, 2009)

Figure 2-9 shows the major EOL disposition options for Li-ion batteries used in electric vehicles. The schematic shows that consistent with current practice, pre- and post-consumer batteries will be collected for recycling. Although there are multiple recovery and recycling options, the figure illustrates those that were assessed as part of the study. As described above, some waste from the recycling process will be landfilled (estimated as <3% of the battery weight). The recovered metal will be further refined and used for steel production or other applications. In addition, non-metals (e.g., plastics) may be refined and recovered for use in new products.

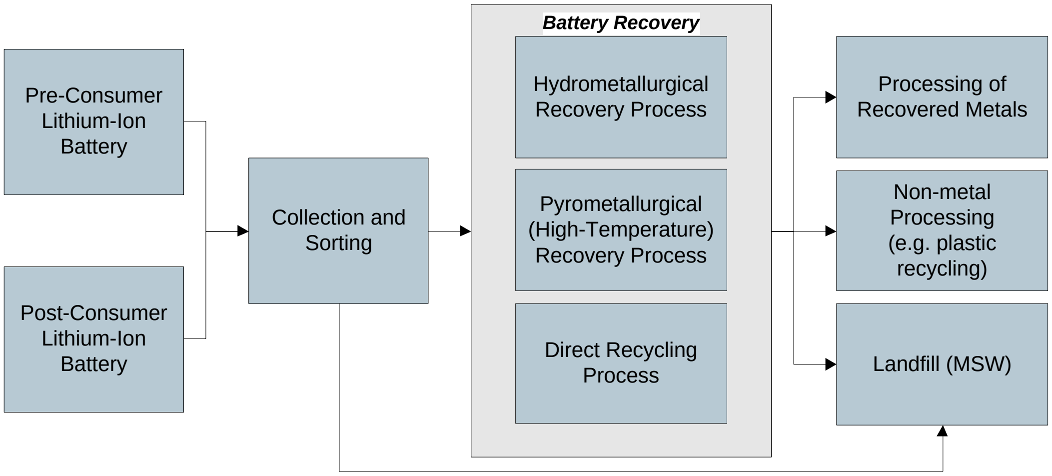

Figure 2-9. Generic Process Flow Diagram for End-of-Life (EOL) Management for Li-ion Batteries

Sources: EPA, DfE/ORD Li-ion Batteries and Nanotechnology for Electric Vehicles Partnership; Olapiriyakul, 2008.

There are several recycling processes that may be used to recover materials from the batteries. In this study, we assessed the (1) hydrometallurgical process, (2) high-temperature or pyrometallurgical process, and (3) direct recycling process; each process is described below.

- **Hydrometallurgical Recovery Process:** The hydrometallurgical recycling process can be applied to a variety of lithium battery chemistries. Under this process, the batteries are first collected, inspected, and sorted by chemistry. Next, the batteries are fed via a conveyer belt to a hammer mill to remove the paper and plastic. Once prepared, the batteries are processed in a tank, using a feed of alkali process solution (lithium brine) to further shred the cells. The materials are then separated to recover the scrap metal and remove any other non-metallic materials (Toxco, 2010). Four streams result from this process, including:

  1. Copper cobalt product: mixture of copper, aluminum, and cobalt.
  2. Cobalt filter cake: mixture of cobalt and carbon.
  3. Li-ion fluff: mixture of plastics and some steel.
  4. Lithium brine: dissolved electrolyte and lithium salts (Toxco, 2009).

  The copper cobalt product and cobalt filter cake, which comprise about 60% of the battery feed, are sold for further processing to metal refiners. The Li-ion fluff (about 30% of battery feed) is either disposed or sold to steel refiners. The fluff may contain as much as 65% steel, depending on the battery feed. Finally, the brine undergoes further processing, where it is recovered as lithium carbonate (Toxco, 2009; Toxco 2010).

- **Pyrometallurgical (High-Temperature) Recovery Process:** Pyrometallurgical recovery relies on a high-temperature smelting process to recover the metals and other materials. This process allows recycling of a variety of end-of-life (EOL) lithium-ion batteries based on different chemistries. Under this process, the unsorted and untreated EOL batteries are fed into a high temperature smelter, where the scrap is heated to temperatures of 1,250 degrees Celsius in an oxygen environment. (Depending on battery weight and size, some batteries may be dismantled by considering the process efficiency and the environmental impacts.) Through the smelter process, the metal oxides are converted to their metallic form, a molten metal alloy (e.g., containing cobalt and nickel). The metal alloy is further refined for use as new battery cathode material. The slag generated by the smelting process contains lithium. Lithium may also be valorized either by recovering when the recovery process is economically feasible and environmental friendly compared to the natural lithium extraction methods, or by its use in concrete applications (Umicore, 2009). The slag is also suitable to be used in road construction or other applications (Umicore, 2009; Olapiriyakul, 2008).

- **Direct Recycling Process:** Under the direct recycling process, the battery components are first separated using physical and chemical processes to recover the metals and other materials. Next, to generate materials suitable for reuse in battery applications, some of the recovered materials may need to undergo a purification or reactivation process. The direct recycling process, which is still in the pilot stage, may allow for a higher percentage of recovered battery materials. In addition, the process typically requires a lower temperature and energy usage (Gaines, 2010).

Once the batteries reach their end-of-life, it may be possible to refurbish them so they may be used for other applications. For example, cells from a lithium battery for vehicles could conceivably be refurbished and used for computers or other types of electronics (Partnership, 2010). Another option currently being researched and tested is to rejuvenate the battery cells with new electrolyte. As battery cells age, the electrolyte materials break down, and contaminants are deposited on the electrodes. Under a recent patent by General Motors, the company has developed a technology to treat the cells to remove the contaminants and replace the electrolyte solution. Ideally, under this method the cells could be reused in the vehicle itself (Harris, 2010). To date, however, refurbishment and rejuvenation options are not well defined, and additional research into testing and safety standards are being conducted. Once Li-ion batteries are disposed of on a large scale, the percentage of batteries that undergo refurbishment can be expected to rise (Partnership, 2010).

2.4.2 Methodology and Data Sources

LCI data for each recycling process were provided by three recyclers participating in the partnership. LCI data were provided on a mass basis. Accordingly, the data were converted to a per kilometer basis, by dividing the mass of the battery by the total distance driven over the life-time of the vehicle (193,201 kilometers), and assuming that amount as the input to the end-of-life stage.

In addition to the LCI data, the recyclers also provided a range in the recovery of the materials present in the Li-ion battery (see Table 2-9). Because some battery recycling technologies specifically designed for electric vehicles are still under development, there is uncertainty about the actual amount of material that will be recovered once the recycling processes are fully operational, and larger volumes of batteries are recycled. The recovery rates presented in Table 2-9 are based on currently achievable yields.

Recovery and reuse in this case does not specifically denote reuse in lithium-ion battery applications. Rather, it is reuse in any application as a useful input, ranging from reuse of cathode active material to use as filler in construction materials. The primary benefit modeled is the displacement of virgin material from the industrial supply chain. For example, if recycling method A produces 0.1 kg of lithium carbonate from 1 kg of battery, the impacts of the actual recycling of this kilogram are partially offset by the benefit of one less tenth of a kilogram of virgin lithium carbonate in the system. This is, by our own admission, a simplistic method of modeling the benefits of recycling and does not take into account a full counterfactual scenario. There are a number of considerations that complicate the picture, including the economics of the secondary market, acceptance of recycled material by OEMs, and uncertainty surrounding the true baseline (i.e., what is the appropriate counterfactual scenario to battery recycling?). However, we believe that this simple method gives a good first-cut approximation of the benefits of lithium-ion battery recycling.

Table 2-9. Range of Recovery and Reuse in EOL

Material	Percent Recovered
Cobalt	60–99.9%
Nickel	60–99.9%
Iron	60–90%
Copper	80–99.9%
Carbon	70–99%
Lithium	80–90%
Manganese	60–90%
Separator	75–99.9%
Aluminum	70–99%
Steel	90–99.9%
Electrolyte	70–90%
PWB \1	80–99%
Plastics	55–99.9%

Note: \1 PWB = printed wire board

2.4.3 Limitations and Uncertainties

Similar to the manufacturing stage, data for the EOL stage were primarily obtained from battery recyclers. Accordingly, limitations and uncertainties related to the data collection process include the fact that companies were self-selected, which could lead to selection bias (i.e., those companies that are more advanced in terms of environmental protection might be more willing to supply data than those that are less progressive in that regard). Companies providing data also may have a vested interest in the project outcome, which could result in biased data being provided. The employment of the Core Group as reviewers in this project was intended to help identify and reduce any such bias (e.g., manufacturers or recyclers checking to ensure that other submitter data is in line with industry norms).

Furthermore, the data provided by the recyclers were based on *current* recycling processes. However, given the fact that Li-ion batteries for vehicles are a nascent market and many batteries have not reached the end of their useful life, most of the recycling processes currently do not recycle large volumes of Li-ion batteries for vehicles. The recyclers who participated in this study all noted that they are retrofitting their current processes in anticipation of a larger volume of Li-ion batteries for vehicles. To this end, LCI data for the direct recycling process were based on pilot data provided by the recycling company.

Assumptions about the disposition percentages may not truly represent the actual dispositions. For example, our analysis currently assumes that all of the batteries will be recovered for recycling, regardless of the chemistry or vehicle type. Furthermore, there is uncertainty with respect to the percentage recovery of materials in Li-ion batteries. Our analysis assumed a best-case scenario of the recovery for the materials in the Li-ion battery, which is assessed further in the sensitivity analysis in Section 3.4. Some credit was also given to reuse of materials in batteries themselves, but in some cases the analysis also gave credit to reuse in other applications. In addition, the analysis assumed no further refinement/ purification is needed before the direct displacement of virgin materials. Such assumptions are likely to be optimistic, especially in the first years of significant EV and PHEV-40 battery recovery.

Finally, although primary data were obtained from the recyclers, secondary data from GaBi4 were used for the eventual disposition of some waste products from the recycling process into a landfill. The landfill processes used are for generic industrial waste, and do not represent the specific metal and plastic mix associated with Li-ion battery waste.

2.5 LCI Summary

The LCIs for each life-cycle stage for the Li-ion batteries in electric vehicles are the combinations of the upstream, manufacturing, and EOL data described in the preceding sections. Figure 2-10 presents a summary of the LCI data collected for each process in the Generic Process Flow Diagram for Li-ion Batteries for Electric Vehicles. As presented in the figure, primary data (obtained directly from a battery manufacturer or recycler) were obtained for the component manufacture, product manufacture, and EOL stages (Stages C, D, and F in the diagram). Secondary data were needed to supplement data gaps and protect confidential data. These data were primarily obtained from the following studies:

- Contribution of Li-ion Batteries to the Environmental Impact of Electric Vehicles (Notter et al, 2010).
- Life-Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electric Vehicles (Majeau-Bettez et al., 2011).
- Comparative Environmental Life-Cycle Assessment of Conventional and Electric Vehicles (Hawkins et al., under review).

LCI data available within GaBi4 were also used for upstream materials and fuel inputs, as the scope of the project and resources were limited to collecting primary data from the product manufacture and recycling stages. These datasets included EAA (2008), NREL’s U.S.LCI, and proprietary GaBi processes developed by PE International. For the use stage, LCI data for the gasoline process were also obtained as a GaBi proprietary process. However, the power grid data relied on a combination of EIA (Energy Information Administration) and U.S. LCI data, as follows:

- The EIA data were used to understand the make-up of the grid by fuel type (e.g., proportion of coal, natural gas, and renewables);
- The U.S. LCI provided inventory data for each of these energy sources.

Although LCI data for most of the components and processes were identified through primary or secondary sources, below we highlight key uncertainties, limitations, and assumptions with respect to the data:

- Limited primary data for battery cell and pack manufacture were available, which required reliance on additional secondary sources of data, to address data gaps and protect the confidentiality of the data.
- The same size BMS and other pack sub-systems was assumed across chemistries, when in reality there may be differences.
- It was assumed that all components scale linearly into the battery pack, to meet capacity requirements for PHEVs and EVs.
- There is uncertainty with respect to the actual lifetime of batteries in automobiles. In addition, there may be differences in lifetime across chemistries. $LiFePO_4$ batteries may have a longer useful life than other battery chemistries, due to their ability to weather a greater number of charge-discharge cycles.

- In the use stage, changes in the grid over time, from more coal-centric sources to ones using more natural gas and renewables, will influence the LCI data and impacts in this stage. Although data on current grid mixes were available, the study did not seek to obtain data on how the mix of the grid would change over time.
- LCI data were based on current recycling processes, which do not recycle large volumes of Li-ion batteries for vehicles at present. Recovery and eventual disposition of materials will be better characterized as the volume of battery waste increases and markets for recovered/recycled materials emerge.
- The recovery of the materials and credit for reuse was assumed using a best-case scenario.

To address some of these limitations, we conducted a sensitivity analyses on some of the key assumptions, including the life-time of the battery, grid and charging assumptions, and the recovery of the materials. This is discussed in detail in Section 3.4.

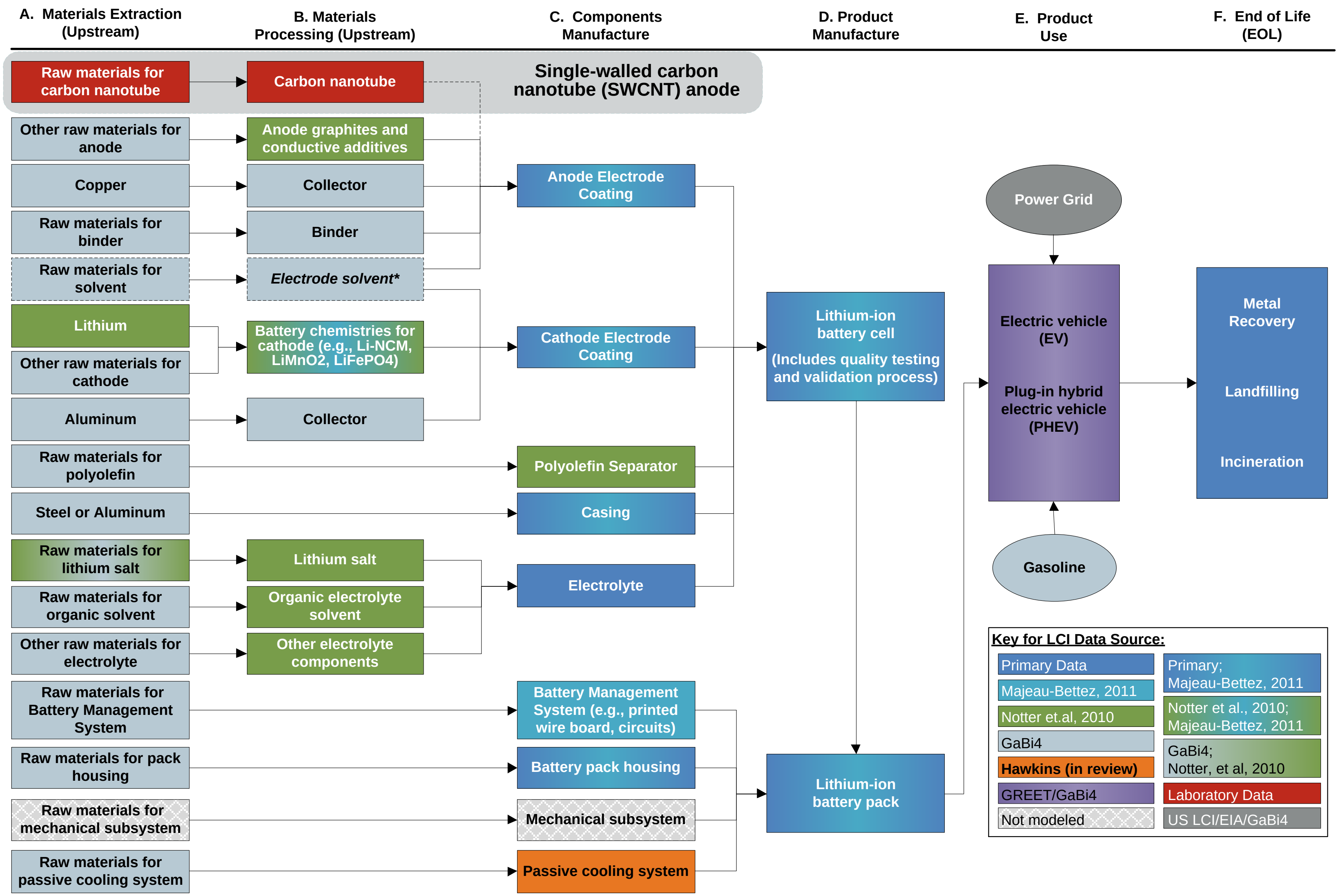

Figure 2-10. Generic Process Flow Diagram for Lithium-ion Batteries for Vehicles (color coded to present LCI data sources)

Sources: DfE/ORD Li-ion Batteries and Nanotechnology for Electric Vehicles Partnership; NEC/TOKIN (http://www.nec-tokin.com, 2010; Olapiriyakul, 2008; Ganter, 2009. Notes: Electrode solvent is an ancillary material used during manufacturing but not incorporated into batteries.

3. Life-Cycle Impact Assessment

In its simplest form, life-cycle impact assessment (LCIA) is the evaluation of potential environmental, social, or economic impacts to a system as a result of some action. LCIAs generally use the consumption and loading data from the inventory stage to create a suite of estimates for various impact categories. Characterization methods are used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava et al., 1993; Barnthouse et al., 1997). This allows for the screening and identification of impact drivers — materials, chemicals, or energetic flows that are of the highest concern due to their potential to do environmental harm.

Conceptually, there are three major phases of LCIA, as defined by the Society of Environmental Toxicology and Chemistry (SETAC) (Fava et al., 1991):

- **Classification** – The process of assignment and initial aggregation of data from the inventory to impact categories. An example would be the sorting of greenhouse gases into the global warming potential impact category for calculation.
- **Characterization** – The analyses and estimation of the magnitude of potential impacts for each impact category, derived through the application of specific impact assessment tools.
- **Valuation** – The assignment of relative values or weights to different impacts, and their integration across impact categories to allow decision makers to assimilate and consider the full range of relevant impact scores across impact categories. The international standard for life-cycle impact assessment, ISO 14042, considers valuation (“weighting”) as an optional element to be included depending on the goals and scope of the study.

Both the classification and characterization steps are completed in this lithium-ion battery study, while the valuation step is left to industry or other interested stakeholders.

The LCIA methodology used in this study began with an assessment of the overall material and primary energy input flows to the automotive lithium-ion battery life cycles (see Section 3.1). We then calculated life-cycle impact category indicators, using established quantitative methods 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 – impacts not always considered in traditional LCIA methodology (see Section 3.2).

Ecological toxicity and human health impacts have always presented a unique challenge to LCA practitioners, due to the complexity of chemical fate and transport, exposure, and dose-response relationships in the target receptors. Recent work done under the auspices of the United Nations Environment Program (UNEP) – SETAC Life-Cycle Initiative addressed these complications, and sought out a consensus on impact indicator methodologies (Rosenbaum et al., 2008). The result of this work was the consensus model – USETox – which was used in this study to characterize potential impacts to the general public and aquatic ecosystem health.

In this study, we also provide scores for the potential occupational hazards associated with lithium-ion battery life cycles. The toxicity impact method is based on work for Saturn Corporation and the EPA

Office of Research and Development originally undertaken by the University of Tennessee Center for Clean Products and Clean Technologies. This method was applied in the DfE Computer Display Partnership's LCA study (Socolof et al., 2001) and updated in two additional LCA studies, for the DfE Lead-Free Solder Partnership (Geibig and Socolof, 2005) and the DfE Wire and Cable Partnership (EPA, 2008).

For purposes of better understanding the impact of the lithium-ion battery life cycles on future environmental conditions and over a range of scenarios, we have included a pair of additional analyses. The first is an analysis to determine the sensitivity of the LCIA results to three variables: (i) the lifetime of batteries in EVs and PHEVs, (ii) the ranges of material recovery and reuse thought to bound near-future end-of-life scenarios, and (iii) the variance of electricity grids across the United States. The second analysis is an assessment of the changes in impacts—from "cradle to gate" (i.e., not counting potential benefits in the use stage)--upon switching to use of high-efficiency SWCNT anodes, from the more traditional battery-grade graphite anodes, using current SWCNT manufacturing methods.

3.1 Overview of Material Use and Primary Energy Consumption

Drivers of the environmental and human and ecological health impacts presented in the LCIA include both upstream material and primary energy inputs. As a result, in this section we present a fully aggregated input-side assessment of these material and energy flows. The context provided by these data greatly increases the ease of interpretation of the impact result tables (presented in Section 3.2).

3.1.1 Major Material Flows

Table 3-1 presents a breakdown of the largest material input flows to the lithium-ion battery upstream and manufacturing stages, by category.

Table 3-1. Major Material Input Flows and Drivers

	Li-ion battery		Primary process use
	Input (kg/kWh)	% of total	
Feedstock			
Dilute LiCl brine [\1]	540 – 750	9.2 - 28%	cathode, electrolyte
Copper ore	46 – 181	1.7 - 8.9%	anode, BMS
Calcium carbonate	10 – 17	0.2 - 0.8%	cathode
Sodium chloride	9.2 – 23	0.3 - 0.8%	cathode
Bauxite	4.1 – 13	0.1 - 0.2%	cathode
Fluorspar	0.7 - 2.2	0.02 - 0.10%	electrolyte, separator
Zinc ore	1.4 - 1.8	0.02 - 0.09%	housing
Phosphorous ore	0.3 - 6.4	0.01 - 0.08%	electrolyte, cathode
Fuels			
Hard coal	11 – 26	0.2 - 1.2%	cathode, electricity
Crude oil	4.1 – 13	0.2 - 0.4%	cathode
Natural gas	5.2 – 19	0.2 - 0.8%	combustion, cathode
Lignite	4.1 – 18	0.2 - 0.3%	electricity
Ancillary inputs			
Water	500 – 5400	24 - 67%	cathode, anode
Air	290 – 1100	13 - 17%	cathode
Inert rock	180 – 570	7.1 - 21%	cathode, BMS
Aggregate	1.2 – 98	0.02 - 4.4%	cathode
Soil	0.7 – 21	0.01 - 1.0%	cathode

Notes: [\1] The lithium brine modeled here is assumed to be 0.15% lithium chloride by mass.

As presented in the table, the lithium brine extracted from saline lakes in Chile is by far the largest mass input, after water and air. Calcium carbonate, or limestone, is associated with the brine, as it is the other major feedstock in the synthesis of lithium carbonate. Copper ore and bauxite are the sources of copper and aluminum, respectively. Copper is used in the battery electronics, both in wiring and on printed wire (circuit) board. Aluminum is the primary material in the passive cooling system, and is used in cell/pack containers. Zinc ore is associated with steel production, and phosphorus ore is associated with both electrolyte salt and $LiFePO_4$ production. The major fuels, in decreasing order of mass, are hard coal, crude oil, natural gas, and lignite. The average U.S. grid is comprised of approximately 45% coal-derived power and 25% natural gas-derived power, explaining most of the fuel use.

We attempted to model the land use impacts of batteries over their life cycles; however, data on land use impacts, even for electricity generation, domestic steel production, and some other major processes were sparse. Based on a survey of the processes used in this project, it was anticipated that only a very small proportion of the material and energy flows in the life-cycle model (likely less than 10%), would be associated with the appropriate land use impacts. As a result, we do not present land-use impacts.

3.1.2 Primary Energy Consumption

Primary energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. “Primary” is used here to describe 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. Primary energy can be thought of as differing from secondary in that it is not the measure of energy “from the plug” at a plant, but is rather the energy used originally to produce this electricity for the grid. Fuel inputs are converted from mass to energy units using the fuel’s heat value and the density as shown below:

$$\mathrm{ISE_E} = \mathrm{Amt_E} \ \text{ or } \ \mathrm{Amt_F} \cdot \frac{\mathrm{H}}{\mathrm{D}}$$

where:

$\mathrm{ISE_E}$ equals the impact score for energy use (MJ) per functional unit;

$\mathrm{Amt_E}$ equals the inventory input amount of electrical energy used (MJ) per functional unit;

$\mathrm{Amt_F}$ equals the inventory input amount of fuel used (kg) per functional unit;

H equals the heat value of fuel (MJ/L); and

D equals the density of fuel (kg/L).

Table 3-2 presents the primary energy use by battery component through the life cycle of a battery. In this table, “component” is used both to describe physical components (e.g., cathode and anode), as well as stage-based processes that could not readily be folded into one or more of the components (e.g., cell manufacture and pack manufacture).

In addition, Tables 3-3 and 3-4 present primary energy use by life-cycle stage for EV and PHEV batteries. Note that in order to protect confidential information, some values were summed across stages in Tables 3-3 and 3-4. *Note that the impacts by component are presented on a kWh battery capacity basis, whereas the impacts by stage are presented on a functional unit basis (per km).*

Table 3-2. Primary Energy Use by Battery Component (MJ/kWh Capacity) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	1.86E+02	21.4%	1.68E+02	8.6%	1.52E+02	6.1%	1.69E+02	9.5%
Cathode	4.26E+02	49.0%	6.45E+02	32.9%	4.62E+02	18.5%	5.11E+02	28.8%
Separator	1.69E+01	1.9%	0.00E+00	0.0%	3.76E+01	1.5%	1.81E+01	1.0%
Electrolyte	6.31E+01	7.3%	2.48E+02	12.6%	1.40E+02	5.6%	1.50E+02	8.5%
Cell casing	2.68E+01	3.1%	1.58E+02	8.1%	3.39E+02	13.6%	1.75E+02	9.8%
Cell manufacture	2.83E+01	3.3%	0.00E+00	0.0%	0.00E+00	0.0%	9.42E+00	0.5%
Cell subtotal	*7.47E+02*	*86.0%*	*1.22E+03*	*62.1%*	*1.13E+03*	*45.2%*	*1.03E+03*	*58.1%*
BMS	4.37E+01	5.0%	4.37E+01	2.2%	4.37E+01	1.7%	4.37E+01	2.5%
Pack case/housing	6.89E+01	7.9%	6.89E+01	3.5%	1.65E+02	6.6%	1.01E+02	5.7%
Pack manufacture	8.95E-01	0.1%	6.21E+02	31.6%	1.15E+03	46.0%	5.91E+02	33.2%
Transportation	8.46E+00	1.0%	1.02E+01	0.5%	9.63E+00	0.4%	9.45E+00	0.5%
Total	***8.69E+02***	***100%***	***1.96E+03***	***100%***	***2.50E+03***	***100%***	***1.78E+03***	***100%***

Notes: \1 kWh = kilowatt-hour battery capacity; MJ = megajoules of primary energy

Table 3-3. Primary Energy Use by Life-Cycle Stage for EV Batteries (MJ/km) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	1.69E-01	8.9%	2.40E-01	11.2%	2.44E-01	10.9%	2.18E-01	10.4%
Materials processing	5.91E-02	3.1%	2.15E-01	10.1%	5.31E-02	2.4%	1.99E-01	9.5%
Component manuf.					2.87E-02	1.3%		
Product manuf.					2.40E-01	10.7%		
Product use	1.68E+00	88.0%	1.68E+00	78.7%	1.68E+00	74.7%	1.68E+00	80.1%
Subtotal	*1.91E+00*	*100%*	*2.13E+00*	*100%*	*2.24E+00*	*100%*	*2.09E+00*	*100%*
Average EOL	-3.25E-02	-1.7%	-6.74E-02	-3.2%	-7.27E-02	-3.2%	-5.75E-02	-2.7%
Total	***1.87E+00***	***98.3%***	***2.06E+00***	***96.8%***	***2.17E+00***	***96.8%***	***2.04E+00***	***97.3%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); MJ = megajoules of primary energy

Table 3-4. Primary Energy Use by Life-Cycle Stage for PHEV Batteries (MJ/km) \1

Chemistry	$LiMnO_2$		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	4.96E-02	2.5%	7.08E-02	3.4%	6.02E-02	3.0%
Materials processing	1.72E-02	0.9%	1.54E-02	0.7%	5.53E-02	2.7%
Components manuf.			8.34E-03	0.4%		
Product manuf.			6.97E-02	3.4%		
Product use	1.90E+00	96.6%	1.90E+00	92.1%	1.90E+00	94.3%
Subtotal	*1.97E+00*	*100%*	*2.07E+00*	*100%*	*2.02E+00*	*100%*
Average EOL	-9.74E-03	-0.5%	-2.11E-02	-1.0%	-1.54E-02	-0.8%
Total	***1.96E+00***	***99.5%***	***2.05E+00***	***99.0%***	***2.00E+00***	***99.2%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); MJ = megajoules

Outside of the use stage, it is clear that energy use is primarily incurred during the materials extraction stage. This is mostly due to aluminum ingot production for the passive cooling system and cathode. In addition, the production of soda (Na_2CO_3), and the synthesis of lithium carbonate for the cathode and electrolyte, are also substantial contributors. In the case of the Li-NCM and $LiFePO_4$ chemistries, plastic resin production results in a fairly large amount of primary energy use (about 10% of the total stage-specific value).

Higher energy use is also seen in the product manufacture of the Li-NCM and $LiFePO_4$ chemistries. In the case of both batteries, this is attributable to the fuels that generate the electricity required to manufacture the battery pack, as well as the fuels used directly during pack production. For the $LiFePO_4$ battery, the purification of process water used during battery production is also a substantial contributor.

The LCIA methodology for the energy use category is a direct measure of the net calorific value of energy inputs, and is not associated with great uncertainty. The LCI, however, generates greater uncertainty, since energy use during upstream materials extraction is highly dependent on the accuracy of the inventory for upstream materials, such as aluminum.

3.2 Impact Category Results

The complete list of impact categories examined in this study includes:

- Abiotic resource depletion
- Global warming potential
- Acidification potential
- Eutrophication potential
- Ozone depletion potential
- Photochemical oxidation potential
- Ecological toxicity potential
- Human toxicity potential
- Occupation cancer hazard
- Occupational non-cancer hazard

Each impact category sub-section discusses data sources, data quality, and the limitations and uncertainties, in addition to the category-specific LCIA results. *As noted above, impacts by component and stage are presented in different units. The impacts by component are presented on a kWh battery capacity basis, whereas the impacts by stage are presented on a functional unit basis (per km).*

3.2.1 Abiotic Resource Depletion

Abiotic resource depletion potential (ADP) is a measure of the potential for non-renewable resource depletion during the production of a material or energy flow. This measure is calculated using the ratio of the extraction rate to the squared global reserves of the material, divided by this same ratio for the valuable heavy metal antimony (Sb). The per-unit mass impact is directly related to the rate of resource depletion, and indirectly related to the abundance of the material. The ADP is calculated as shown below (Guinée et al., 2002):

$$\mathrm{EF}_{\mathrm{ADP}}=\frac{\mathrm{DR}/\mathrm{R}^2}{\mathrm{DR}_{\mathrm{Sb}}/\mathrm{R}_{\mathrm{Sb}}^2}$$

where:

$\mathrm{EF}_{\mathrm{ADP}}$ equals the abiotic depletion potential of material (unitless);

DR equals the global extraction rate of the material (kg/yr);

R equals the ultimate global reserve of the material (kg);

$\mathrm{DR}_{\mathrm{Sb}}$ equals the global extraction rate of the reference material, antimony (kg/yr); and

R_{Sb} equals the ultimate global reserve of the reference material, antimony (kg).

The abiotic depletion impact score can then be calculated as follows:

$$\mathrm{IS}_{\mathrm{AD}} = \mathrm{EF}_{\mathrm{ADP}} \cdot \mathrm{Amt}$$

where:

$\mathrm{IS}_{\mathrm{AD}}$ equals the abiotic depletion impact score for the material (kg antimony-equivalents) per functional unit; and

Amt equals the amount of material extracted (kg) per functional unit.

Table 3-5 presents the abiotic resource depletion by battery component through the life cycle of a battery. In addition, Tables 3-6 and 3-7 present the abiotic resource depletion by life-cycle stage for EV and PHEV batteries.

Table 3-5. Abiotic Resource Depletion Potential by Battery Component (kg Sb-Eq./kWh Capacity)[\1]

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	8.79E-02	23.9%	8.01E-02	9.0%	7.35E-02	7.3%	8.05E-02	10.7%
Cathode	1.65E-01	44.9%	2.64E-01	29.8%	2.04E-01	20.4%	2.11E-01	28.1%
Separator	7.38E-03	2.0%	0.00E+00	0.0%	1.64E-02	1.6%	7.94E-03	1.1%
Electrolyte	2.76E-02	7.5%	1.10E-01	12.4%	6.06E-02	6.0%	6.61E-02	8.8%
Cell casing	1.29E-02	3.5%	7.61E-02	8.6%	1.17E-01	11.7%	6.88E-02	9.1%
Cell manufacture	8.87E-03	2.4%	0.00E+00	0.0%	0.00E+00	0.0%	2.96E-03	0.4%
Cell subtotal	*3.10E-01*	*84.3%*	*5.31E-01*	*59.9%*	*4.72E-01*	*47.1%*	*4.37E-01*	*58.2%*
BMS	2.01E-02	5.5%	2.01E-02	2.3%	2.01E-02	2.0%	2.01E-02	2.7%
Pack case/housing	3.31E-02	9.0%	3.31E-02	3.7%	7.94E-02	7.9%	4.85E-02	6.5%
Pack manufacture	2.81E-04	0.1%	2.97E-01	33.5%	4.26E-01	42.5%	2.41E-01	32.1%
Transportation	4.07E-03	1.1%	4.93E-03	0.6%	4.63E-03	0.5%	4.54E-03	0.6%
Total	***3.67E-01***	***100%***	***8.86E-01***	***100%***	***1.00E+00***	***100%***	***7.52E-01***	***100%***

Notes: [\1] kWh = kilowatt-hour battery capacity; kg SB-Eq. = kilograms of antimony equivalent abiotic resource depletion through extraction

Overall, the $LiFePO_4$ battery shows the greatest abiotic resource depletion impacts, compared to the other battery chemistries, mainly due to higher impacts for the cell casing and pack housing and manufacture. For the other chemistries, the impacts seem to be primarily attributable to the cathode in the $LiMnO_2$ battery, or battery pack manufacture in the Li-NCM batteries. Extraction of the raw materials for the cathode (e.g., aluminum and lithium) contributes to the greatest abiotic resource depletion impacts for $LiMnO_2$ batteries. For the Li-NCM and $LiFePO_4$, the pack manufacture contributes to resource depletion mainly due to electricity and fuel consumption.

The difference between the battery chemistries is partly due to inconsistent data between the chemistries. In the case of the $LiMnO_2$ battery chemistry, detailed information on the energy consumption during the manufacture of the battery pack was made available. This same information was not available for the Li-NCM battery pack manufacture; therefore, we averaged the fuel and electricity use of the $LiMnO_2$ with that of the $LiFePO_4$ battery pack, which was reported in Majeau-Bettez et al. (2011).

Table 3-6. Abiotic Resource Depletion Potential by Life-Cycle Stage for EV Batteries (kg Sb-Eq./km) \1

Chemistry	LiMnO$_2$		Li-NCM		LiFePO$_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	6.97E-05	7.7%	1.00E-04	9.9%	1.00E-04	9.7%	9.01E-05	9.2%
Materials processing	1.18E-05	1.3%	2.38E-05	2.4%	2.38E-05	2.3%	1.98E-05	2.0%
Component manuf.	8.98E-06	1.0%	1.41E-05	1.4%	1.15E-05	1.1%	1.15E-05	1.2%
Product manuf.	2.74E-06	0.3%	6.25E-05	6.2%	8.92E-05	8.7%	5.15E-05	5.3%
Product use	8.06E-04	89.6%	8.06E-04	80.1%	8.06E-04	78.2%	8.06E-04	82.3%
Subtotal	*9.00E-04*	*100%*	*1.01E-03*	*100%*	*1.03E-03*	*100%*	*9.79E-04*	*100%*
Average EOL	-9.58E-06	-1.1%	-2.45E-05	-2.4%	-2.53E-05	-2.5%	-1.98E-05	-2.0%
Total	***8.90E-04***	***98.9%***	***9.82E-04***	***97.6%***	***1.01E-03***	***97.5%***	***9.59E-04***	***98.0%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg SB-Eq. = kilograms of antimony equivalent abiotic resource depletion through extraction

Table 3-7. Abiotic Resource Depletion Potential by Life-Cycle Stage for PHEV Batteries (kg Sb-Eq./km) \1

Chemistry	LiMnO$_2$		LiFePO$_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	2.04E-05	2.2%	2.91E-05	3.0%	2.47E-05	2.6%
Materials processing	3.43E-06	0.4%	6.89E-06	0.7%	5.16E-06	0.5%
Components manuf.	2.62E-06	0.3%	3.34E-06	0.3%	2.98E-06	0.3%
Product manuf.	7.94E-07	0.1%	2.59E-05	2.6%	1.33E-05	1.4%
Product use	9.12E-04	97.1%	9.12E-04	93.3%	9.12E-04	95.2%
Subtotal	*9.39E-04*	*100%*	*9.77E-04*	*100%*	*9.58E-04*	*100%*
Average EOL	-2.90E-06	-0.3%	-7.33E-06	-0.7%	-5.11E-06	-0.5%
Total	***9.36E-04***	***99.7%***	***9.70E-04***	***99.3%***	***9.53E-04***	***99.5%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg SB-Eq. = kilograms of antimony equivalent abiotic resource depletion through extraction

As shown in Tables 3-6 and 3-7, in the use stage, ADP is driven by consumption of electricity for the EV batteries, and gasoline for the PHEV batteries. As discussed above, materials extraction is driving the non-use-stage impacts. Top contributing processes across the three battery chemistries include aluminum production for the passive cooling system and cathode, extraction of soda (Na_2CO_3) used in the production of lithium carbonate for the cathode and lithium electrolyte salt, and resins used in the cell and battery pack casing.

It is important to note that this method of calculating abiotic resource depletion is limited, and subject to uncertainty. The mathematical relationship that yields the ADP for each material flow relies on variables that are highly uncertain. This is especially true for global reserves, the estimates of which change quite frequently, based on new geological resource surveys and technological advances in the extractive industries. In addition, it is subject to the uncertainty of the underlying LCI. One of the supply chains where the data are very sparse is that of the lithium compounds. Though Notter et al. (2010) do manage to compile data from Chile on lithium production, it is unclear if this is at all representative of the lithium extraction and processing in the rest of the world. Any deviation in processing yields could potentially change the ADP impact estimate.

3.2.2 Global Warming Impacts

The build-up of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere may generate a "greenhouse effect" of rising temperature and climate change. Global warming potential (GWP) refers to the warming, relative to CO_2, that chemicals contribute to this effect by trapping the Earth's heat. The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change, compared to the reference chemical CO_2; therefore, GWPs are in units of CO_2 equivalents. GWPs have been published for known global warming chemicals within differing time horizons. The LCIA methodology employed here used GWPs from the EPA's TRACI 2.0 model. Although LCA does not necessarily include a temporal component of the inventory, impacts from releases during the life cycle of lithium-ion automotive batteries are expected to be well within the 100 year time frame.

The equation to calculate the impact score for an individual chemical is as follows:

$$\mathrm{IS_{GW}} = \mathrm{EF_{GWP}} \cdot \mathrm{Amt_{GG}}$$

where:

$\mathrm{IS_{GW}}$ equals the global warming impact score for the greenhouse gas (kg CO_2-equivalents) per functional unit;

$\mathrm{EF_{GWP}}$ equals the GWP equivalency factor for the greenhouse gas (CO_2-equivalents, 100-year time horizon); and

$\mathrm{Amt_{GG}}$ equals the inventory amount of the greenhouse gas (GG) released to air (kg) per functional unit.

Table 3-8 presents the GWP by battery component through the life cycle of a battery. In addition, Tables 3-9 and 3-10 presents the GWP by life-cycle stage for EV and PHEV batteries.

Table 3-8. Global Warming Potential by Battery Component (kg CO_2-Eq./kWh Capacity) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	1.23E+01	19.5%	7.81E+00	6.5%	9.61E+00	6.4%	9.92E+00	8.9%
Cathode	3.29E+01	51.9%	4.86E+01	40.3%	3.27E+01	21.6%	3.81E+01	34.1%
Separator	7.62E-01	1.2%	0.00E+00	0.0%	1.70E+00	1.1%	8.19E-01	0.7%
Electrolyte	3.73E+00	5.9%	1.46E+01	12.1%	9.69E+00	6.4%	9.35E+00	8.4%
Cell casing	7.68E-01	1.2%	4.53E+00	3.8%	2.50E+01	16.5%	1.01E+01	9.0%
Cell manufacture	1.77E+00	2.8%	0.00E+00	0.0%	0.00E+00	0.0%	5.91E-01	0.5%
Cell subtotal	*5.23E+01*	*82.4%*	*7.56E+01*	*62.7%*	*7.87E+01*	*52.0%*	*6.89E+01*	*61.6%*
BMS	4.14E+00	6.5%	4.14E+00	3.4%	4.14E+00	2.7%	4.14E+00	3.7%
Pack case/housing	6.26E+00	9.9%	6.26E+00	5.2%	7.43E+00	4.9%	6.65E+00	6.0%
Pack manufacture	5.61E-02	0.1%	3.38E+01	28.0%	6.02E+01	39.8%	3.14E+01	28.1%
Transportation	6.62E-01	1.0%	8.02E-01	0.7%	7.54E-01	0.5%	7.40E-01	0.7%
Total	***6.34E+01***	***100%***	***1.21E+02***	***100%***	***1.51E+02***	***100%***	***1.12E+02***	***100%***

Notes: \1 kWh = kilowatt-hour battery capacity; kg CO_2-Eq. = kilograms of carbon dioxide equivalent greenhouse gas emissions

Across the battery chemistries, the GWP impacts attributable to the cathode are substantial, ranging from approximately 21.6 to 51.9%. In the case of the Li-NCM and $LiFePO_4$ chemistries, the battery pack is also a substantial contributor. The absolute impact values are significantly higher for the Li-NCM and $LiFePO_4$ batteries, due to higher energy use in the production of the cathode, electrolyte, and battery pack. In addition, the use of a solvent-less process by the manufacturer may contribute to the fact that the $LiMnO_2$ battery chemistry uses less energy and has smaller global warming impacts.

Table 3-9. Global Warming Potential by Life-Cycle Stage for EV Batteries (kg CO_2-Eq./km) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	1.32E-02	9.7%	1.66E-02	11.1%	1.73E-02	11.1%	1.57E-02	10.7%
Materials processing	1.27E-03	0.9%	2.83E-03	1.9%	2.85E-03	1.8%	2.32E-03	1.6%
Component manuf.	1.76E-03	1.3%	2.06E-03	1.4%	2.23E-03	1.4%	2.02E-03	1.4%
Product manuf.	5.16E-04	0.4%	7.17E-03	4.8%	1.26E-02	8.1%	6.77E-03	4.6%
Product use	1.20E-01	87.8%	1.20E-01	80.8%	1.20E-01	77.4%	1.20E-01	81.8%
Subtotal	*1.37E-01*	*100%*	*1.49E-01*	*100%*	*1.55E-01*	*100%*	*1.47E-01*	*100%*
Average EOL	-3.35E-03	-2.4%	-5.82E-03	-3.9%	-6.57E-03	-4.2%	-5.25E-03	-3.6%
Total	***1.34E-01***	***97.6%***	***1.43E-01***	***96.1%***	***1.49E-01***	***95.8%***	***1.42E-01***	***96.4%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg CO_2-Eq. = kilograms of carbon dioxide equivalent greenhouse gas emissions

Table 3-10. Global Warming Potential by Life-Cycle Stage for PHEV Batteries (kg CO_2-Eq./km) \1

Chemistry	$LiMnO_2$		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	3.87E-03	2.2%	5.01E-03	2.8%	4.44E-03	2.5%
Materials processing	3.68E-04	0.2%	8.25E-04	0.5%	5.97E-04	0.3%
Components manuf.	5.13E-04	0.3%	6.47E-04	0.4%	5.80E-04	0.3%
Product manuf.	1.50E-04	0.1%	3.66E-03	2.0%	1.91E-03	1.1%
Product use	1.70E-01	97.2%	1.70E-01	94.4%	1.70E-01	95.8%
Subtotal	*1.75E-01*	*100%*	*1.80E-01*	*100%*	*1.77E-01*	*100%*
Average EOL	-1.00E-03	-0.6%	-1.91E-03	-1.1%	-1.45E-03	-0.8%
Total	***1.74E-01***	***99.4%***	***1.78E-01***	***98.9%***	***1.76E-01***	***99.2%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg CO_2-Eq. = kilograms of carbon dioxide equivalent greenhouse gas emissions

GWP impacts are dominated by the use stage for EV and PHEV batteries. Outside of the use stage, some key contributors from the materials extraction and product manufacture stage include, in decreasing order of magnitude, aluminum production for the passive cooling system and cathode, soda production (Na_2CO_3) for use in lithium salt synthesis, as well as steel production for the battery housing.

Key contributors during the component and product manufacture stages include electricity and fuel consumption during battery pack manufacture. The transportation of the battery pack appears to contribute little to the overall global warming impacts.

Figure 3-1, below, shows the relationship between the carbon intensity of the grid and the global warming potential of the overall battery life cycle for the battery types and vehicles. We present the carbon intensity of the grid-mix resulting from (i) unconstrained charging in the ISO-NE grid, and (ii) smart charging in the IL grid, as presented in the Elgowainy et al. (2010) study (see Table 2-8). As noted in Table 2-8, the ISO-NE grid relies primarily on natural gas in an unconstrained charging scenario (see “natural gas centric” grid line) and the IL grid relies primarily on coal in a smart charging scenario (see “coal centric” grid line). We also plot the carbon intensity of the U.S. average grid mix.

As presented in the figure, while CO_2-equivalent emission differences between PHEV-40 and EV batteries are slight at the coal-heavy end of the scale (Illinois smart charging grid scenario), there is a substantial gap at the U.S. average grid and the natural-gas centric ISO-NE unconstrained marginal grid. At all points along the carbon intensity scale, PHEVs and EVs are estimated to generate lower total GHG emissions over the life cycle of the battery (and vehicle during the use stage) than the ICEV batteries (and vehicles), from Samaras and Meisterling (2008). It should be noted that their estimate does include car production, which adds on the order of 25 g CO_2-equivalent/km to the GWP impacts.

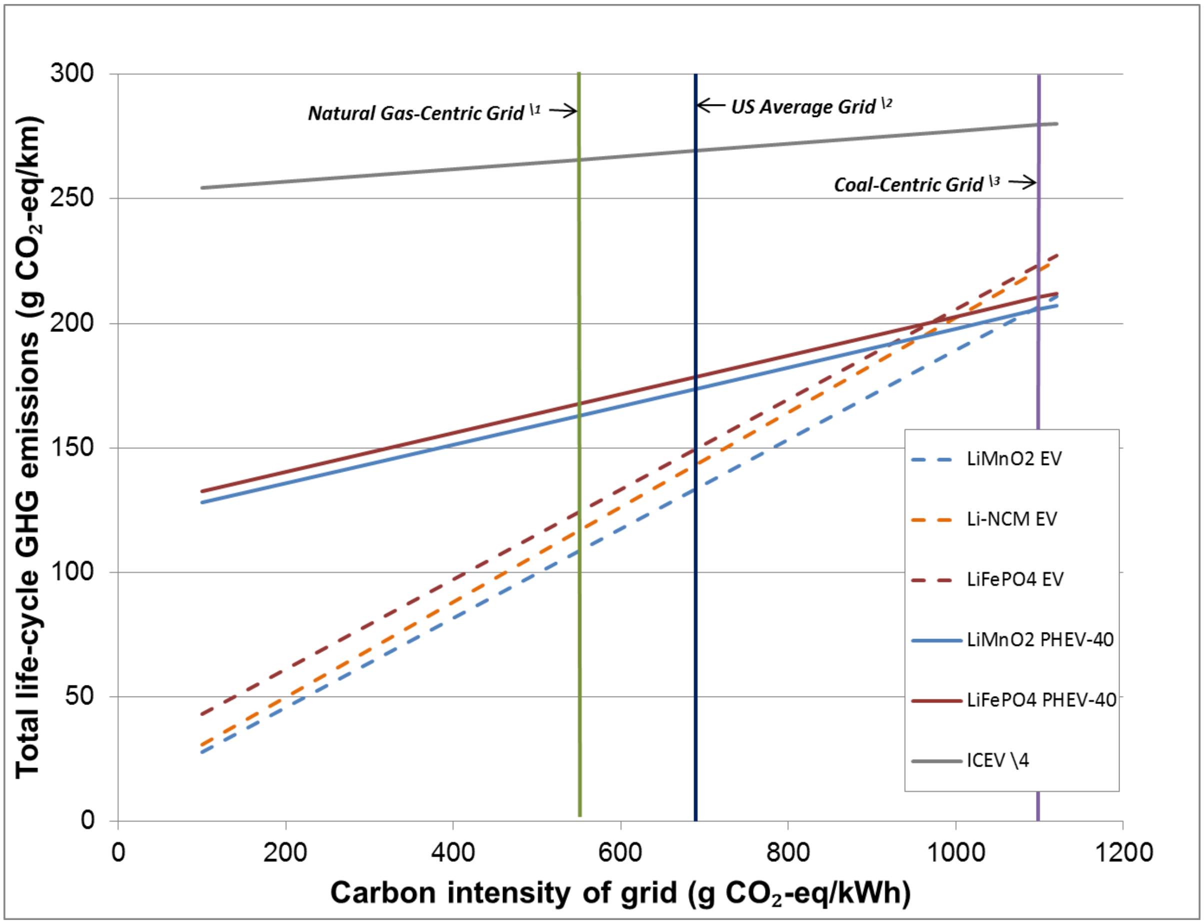

Figure 3-1. GHG Emissions by Carbon Intensity of Electricity Grid

Notes:

\1 Based on ISO-NE grid unconstrained charging grid from the Elgowainy et al., 2010 study.

\2 U.S. Average Grid based on EIA, 2010c.

\3 Based on the IL smart charging grid from the Elgowainy et al., 2010 study, which relies primarily on coal (over 99 percent).

\4 Internal Combustion Engine Vehicle (ICEV) emisssions based on Samaras and Meisterling (2008).

The LCIA methodology for the global warming category is based on equivalency factors for chemicals with global warming potentials, which are commonly used in LCA and are considered reliable data, to the extent that science is able to predict the radiative forcing of chemicals. The LCI-based uncertainty is similar to that discussed in the energy use section, as similar processes drive the global warming impact. As a result, the limitations and uncertainties of this impact category are modest.

3.2.3 Acidification Potential

In this study, we used EPA's Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2.0 to determine the potential acidification impacts from inorganic air emissions across the life cycle. Air acidification causes increases in the acidity of soil and water, with the most visible manifestation being acid rain. The units of this impact are hydrogen ion molar equivalents produced per kilogram of emission. Inorganic emissions that contribute to this impact category include ammonia, strong inorganic acids (e.g., HCl), and nitrogen and sulfur oxides.

Impact characterization is based on the inventory amount of a chemical released to air that would cause acidification, multiplied by the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of moles of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released.

The impact score is calculated by:

$$\mathrm{IS_{AP}} = \mathrm{EF_{AP}} \cdot \mathrm{Amt_{AC}}$$

where:

$\mathrm{IS_{AP}}$ equals the impact score for acidification for the chemical (kg H+ mole-equivalents) per functional unit;

$\mathrm{EF_{AP}}$ equals the AP equivalency factor for the chemical (kg H+ mole-equivalents); and

$\mathrm{Amt_{AC}}$ equals the amount of the acidic chemical (AC) released to the air (kg) per functional unit.

Table 3-11 presents the acidification potential by battery component through the life cycle of a battery. In addition, Tables 3-12 and 3-13 present the acidification potential by life-cycle stage for EV and PHEV batteries.

Table 3-11. Acidification Potential by Battery Component (kg H+ Mol-Eq./kWh) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	6.24E+00	34.2%	2.84E+00	3.0%	4.51E+00	11.2%	4.53E+00	8.9%
Cathode	6.43E+00	35.3%	6.73E+01	70.7%	6.97E+00	17.4%	2.69E+01	52.6%
Separator	1.61E-01	0.9%	0.00E+00	0.0%	3.58E-01	0.9%	1.73E-01	0.3%
Electrolyte	8.91E-01	4.9%	3.61E+00	3.8%	2.19E+00	5.5%	2.23E+00	4.4%
Cell casing	6.27E-01	3.4%	3.70E+00	3.9%	5.82E+00	14.5%	3.38E+00	6.6%
Cell manufacture	5.68E-01	3.1%	0.00E+00	0.0%	0.00E+00	0.0%	1.89E-01	0.4%
Cell subtotal	*1.49E+01*	*81.8%*	*7.74E+01*	*81.4%*	*1.98E+01*	*49.5%*	*3.74E+01*	*73.1%*
BMS	1.79E+00	9.8%	1.79E+00	1.9%	1.79E+00	4.5%	1.79E+00	3.5%
Pack case/housing	1.28E+00	7.0%	1.28E+00	1.3%	3.56E+00	8.9%	2.04E+00	4.0%
Pack manufacture	1.80E-02	0.1%	1.44E+01	15.1%	1.47E+01	36.6%	9.68E+00	18.9%
Transportation	2.21E-01	1.2%	2.67E-01	0.3%	2.51E-01	0.6%	2.46E-01	0.5%
Total	***1.82E+01***	***100%***	***9.51E+01***	***100%***	***4.01E+01***	***100%***	***5.11E+01***	***100%***

Notes: \1 kWh = kilowatt-hour battery capacity; kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

The cathode is a significant contributor to acidification impacts for all battery chemistries. Here, acidification impacts are linked to raw materials needed for the battery chemistries. However, across battery chemistries, the impact of Li-NCM cathode production is significantly higher. This is due to the upstream production of nickel sulfate, which generates substantial emissions of sulfur dioxide as a reaction byproduct (Majeau-Bettez et al., 2010). In the case of the Li-NCM and the LiFePO4 batteries, the manufacture of the battery pack is estimated to cause substantial impacts as a result of electricity consumption. As was the case with primary energy use, differences across chemistries for the battery pack are partly due to inconsistencies in submitted inventory data.

Table 3-12. Acidification Potential by Life-Cycle Stage for EV Batteries (kg H+ Mol-Eq./km) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	3.23E-03	5.7%	1.60E-02	21.9%	4.72E-03	7.7%	7.97E-03	12.5%
Materials processing	5.87E-04	1.0%	8.39E-04	1.2%	5.91E-04	1.0%	6.72E-04	1.1%
Component manuf.	6.32E-04	1.1%	7.18E-04	1.0%	7.47E-04	1.2%	6.99E-04	1.1%
Product manuf.	1.67E-04	0.3%	3.03E-03	4.2%	3.09E-03	5.0%	2.10E-03	3.3%
Product use	5.23E-02	91.9%	5.23E-02	71.8%	5.23E-02	85.1%	5.23E-02	82.0%
Subtotal	*5.69E-02*	*100%*	*7.28E-02*	*100%*	*6.14E-02*	*100%*	*6.37E-02*	*100%*
Average EOL	6.27E-06	0.0%	-1.04E-02	-14.2%	-7.72E-04	-1.3%	-3.71E-03	-5.8%
Total	***5.69E-02***	***100%***	***6.24E-02***	***85.8%***	***6.06E-02***	***98.7%***	***6.00E-02***	***94.2%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

Table 3-13. Acidification Potential by Life-Cycle Stage for PHEV Batteries (kg H+ Mol-Eq./km) \1

Chemistry	LiMnO2		LiFePO4		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	9.44E-04	3.1%	1.37E-03	4.3%	1.16E-03	3.8%
Materials processing	1.70E-04	0.6%	1.71E-04	0.5%	1.71E-04	0.6%
Components manuf.	1.84E-04	0.6%	2.17E-04	0.7%	2.00E-04	0.7%
Product manuf.	4.85E-05	0.2%	8.95E-04	2.8%	4.72E-04	1.5%
Product use	2.88E-02	95.5%	2.88E-02	91.6%	2.88E-02	93.5%
Subtotal	*3.02E-02*	*100%*	*3.15E-02*	*100%*	*3.08E-02*	*100%*
Average EOL	-5.52E-06	0.0%	-2.24E-04	-0.7%	-1.15E-04	-0.4%
Total	***3.01E-02***	***100%***	***3.12E-02***	***99.3%***	***3.07E-02***	***99.6%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

Outside of the use stage, the materials extraction stage contributes to acidification impacts, especially for the Li-NCM battery. Within the materials extraction stage, nickel sulfate dominates in the Li-NCM battery, while aluminum ingot production for the passive cooling system and cathode are significant contributors to impacts for the other chemistries. However, it appears that electricity consumption during the use stage is the major driver of overall acidification impacts.

As mentioned above, the reported acidification impact is a function of the mass of an acid-forming chemical emitted to air and the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of moles of hydrogen ions that can theoretically be formed per unit mass of the pollutant being released. This is a full equivalency approach to impact characterization, where all substances are addressed in a unified, technical model that lends more certainty to the characterization results than partial equivalency factors discussed with regard to other impacts. AP equivalency factors are commonly used in LCA and are considered reliable data.

3.2.4 Eutrophication Potential

TRACI 2.0 was also used to determine the potential for eutrophication, or fertilization of surface waters by previously scarce nutrients like nitrogen and phosphorus, from life-cycle emissions. The units of the weighting values in this impact category are nitrogen equivalents per kilogram of emission. Inorganic emissions that contribute to this impact category include ammonia and other water-soluble nitrogen-containing compounds, phosphate and other water-soluble phosphorus-containing compounds, and biological and chemical oxygen demand.

The impact score is calculated by:

$$\mathrm{IS}_{\mathrm{EP}} = \mathrm{EF}_{\mathrm{EP}} \cdot \mathrm{Amt}_{\mathrm{EC}}$$

where:

$\mathrm{IS}_{\mathrm{EP}}$	equals the impact score for regional water quality impacts from the chemical (kg nitrogen-equivalents) per functional unit;
$\mathrm{EF}_{\mathrm{EP}}$	equals the EP equivalency factor for the chemical (kg nitrogen-equivalents); and
$\mathrm{Amt}_{\mathrm{EC}}$	equals the inventory mass (kg) of the eutrophication-inducing chemical (EC) per functional unit in a wastewater stream released to surface water after treatment, if applicable.

It should be noted that the results indicate negative net impacts. This is because the cold-rolled steel process inventory, which was taken from NREL's U.S. LCI database, documents net negative emissions of phosphate, ammonia, and other water-soluble nutrient-rich inorganics. The dataset appears to be accounting for the observation that input process water shows higher levels of these contaminants than the ultimate effluent water. This characteristic is not shared by all cold-rolled steel production processes that were available for use in modeling.

Table 3-14 presents the eutrophication potential by battery component through the life cycle of a battery. In addition, Tables 3-15 and 3-16 present the eutrophication potential by life-cycle stage for EV and PHEV batteries.

Table 3-14. Eutrophication Potential by Battery Component (kg N-Eq./kWh) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	1.96E-03	31.2%	1.52E-03	17.8%	1.50E-03	0.7%	1.66E-03	2.2%
Cathode	8.83E-03	140.6%	1.77E-02	206.6%	1.99E-01	87.7%	7.51E-02	98.4%
Separator	1.26E-04	2.0%	0.00E+00	0.0%	2.81E-04	0.1%	1.36E-04	0.2%
Electrolyte	9.66E-04	15.4%	3.07E-03	35.9%	2.15E-03	0.9%	2.06E-03	2.7%
Cell casing	1.42E-04	2.3%	8.35E-04	9.8%	2.00E-03	0.9%	9.92E-04	1.3%
Cell manufacture	2.07E-04	3.3%	0.00E+00	0.0%	0.00E+00	0.0%	6.91E-05	0.1%
Cell subtotal	*1.22E-02*	*194.7%*	*2.31E-02*	*270.0%*	*2.05E-01*	*90.3%*	*8.00E-02*	*104.8%*
BMS	1.22E-03	19.4%	1.22E-03	14.2%	1.22E-03	0.5%	1.22E-03	1.6%
Pack case/housing	-2.00E-02	-317.7%	-2.00E-02	-233.4%	1.61E-03	0.7%	-1.28E-02	-16.7%
Pack manufacture	6.56E-06	0.1%	3.94E-03	46.0%	1.89E-02	8.4%	7.63E-03	10.0%
Transportation	2.21E-04	3.5%	2.67E-04	3.1%	2.51E-04	0.1%	2.46E-04	0.3%
Total	***-6.29E-03***	***100%***	***8.56E-03***	***100%***	***2.27E-01***	***100%***	***7.64E-02***	***100%***

Notes: \1 kWh = kilowatt-hour battery capacity; kg N-Eq. = kilograms of nitrogen equivalents

As discussed above, the most significant and unusual component-based impact is the large negative eutrophication potential from the pack housing production for the LiMnO2 and Li-NCM chemistries. The cold-rolled steel production process from the U.S. LCI (National Renewable Energy Laboratory) indicates that the effluent water from plants is cleaner in terms of multiple nutrient-rich inorganic compounds (e.g., phosphate and ammonia) than when it enters the plant.

Table 3-15. Eutrophication Potential by Life-Cycle Stage for EV Batteries (kg N-Eq./km) [\1]

Chemistry	LiMnO$_2$		Li-NCM		LiFePO$_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	-2.93E-06	-24.8%	-9.10E-07	-6.1%	2.38E-06	4.0%	-4.88E-07	-1.7%
Materials processing	3.57E-07	3.0%	5.91E-07	4.0%	3.94E-05	65.5%	1.34E-05	46.4%
Component manuf.	5.35E-07	4.5%	5.73E-07	3.8%	6.05E-07	1.0%	5.71E-07	2.0%
Product manuf.	9.00E-08	0.8%	8.71E-07	5.8%	3.98E-06	6.6%	1.65E-06	5.7%
Product use	1.38E-05	116.5%	1.38E-05	92.5%	1.38E-05	22.9%	1.38E-05	47.6%
Subtotal	*1.18E-05*	*100%*	*1.49E-05*	*100%*	*6.01E-05*	*100%*	*2.89E-05*	*100%*
Average EOL	-3.89E-07	-3.3%	-2.03E-06	-13.6%	-1.01E-05	-16.8%	-4.16E-06	-14.4%
Total	***1.14E-05***	***96.7%***	***1.29E-05***	***86.4%***	***5.00E-05***	***83.2%***	***2.48E-05***	***85.6%***

Notes: [\1] km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg N-Eq. = kilograms of nitrogen equivalents

Table 3-16. Eutrophication Potential by Life-Cycle Stage for PHEV Batteries (kg N-Eq./km) [\1]

Chemistry	LiMnO$_2$		LiFePO$_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	-8.57E-07	-8.3%	6.90E-07	2.8%	-8.34E-08	-0.5%
Materials processing	1.04E-07	1.0%	1.14E-05	47.0%	5.76E-06	33.3%
Components manuf.	1.55E-07	1.5%	1.75E-07	0.7%	1.65E-07	1.0%
Product manuf.	2.61E-08	0.3%	1.15E-06	4.7%	5.90E-07	3.4%
Product use	1.09E-05	105.6%	1.09E-05	44.7%	1.09E-05	62.8%
Subtotal	*1.03E-05*	*100%*	*2.43E-05*	*100%*	*1.73E-05*	*100%*
Average EOL	-1.15E-07	-1.1%	-2.92E-06	-12.0%	-1.52E-06	-8.8%
Total	***1.02E-05***	***98.9%***	***2.14E-05***	***88.0%***	***1.58E-05***	***91.2%***

Notes: [\1] km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

In the case of the LiMnO$_2$ battery, the large negative eutrophication potential from the pack housing production displaces a substantial proportion of the nutrient emissions due to electricity consumption in the use stage. The Li-NCM battery is assumed to use more energy during the upstream stages and battery manufacturing and, as a result, does not displace much of the use stage impact. The LiFePO$_4$ battery shows net positive eutrophication potential during material extraction. It should be noted that due to an inability to disaggregate the material extraction and process of cold-rolled steel, it was included in the material extraction stage.

The LCIA methodology calculates impacts from the mass of a chemical released directly to surface water, and the chemical's eutrophication potential (EP) equivalency factor. The EP is a partial equivalency factor derived from the relationship between the chemical and nitrogen. As a partial equivalency approach, only a subset of substances can be converted into equivalency factors, which is a limitation of this LCIA methodology. The methodology, however, does take into account nitrogen and phosphorus, which are two major limiting nutrients of importance to eutrophication, and the EPs are commonly used in LCA and are considered reliable data.

3.2.5 Ozone Depletion

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons, if released to the atmosphere, may result in ozone-destroying chemical reactions. Stratospheric ozone depletion refers to the release of chemicals that may contribute to this effect. Impact scores are based on the identity and amount of ozone-depleting chemicals released to air. Currently identified ozone-depleting chemicals are those with an ozone depletion potential (ODP), which is a measure of the change in the ozone column in the equilibrium state of a substance compared to the reference chemical chlorofluorocarbon (CFC), CFC 11 (trichlorofluoromethane) (Heijungs et al., 1992; EPA, 1990). The ODPs of chemicals in the battery inventories come from the EPA's TRACI 2.0 model. The individual chemical impact score for ozone depletion is based on the ODP and inventory amount of the chemical:

$$\mathrm{IS_{ODP}} = \mathrm{EF_{ODP}} \cdot \mathrm{Amt_{ODC}}$$

where:

$\mathrm{IS_{ODP}}$ equals the impact score for ozone depletion for the chemical (kg CFC 11-equivalents) per functional unit;

$\mathrm{EF_{ODP}}$ equals the ODP equivalency factor for the chemical (kg CFC 11-equivalents); and

$\mathrm{Amt_{ODC}}$ equals the amount of the ozone depleting chemical (ODC) released to the air (kg) per functional unit.

Table 3-17 presents the ozone depletion potential by battery component through the life cycle of a battery. In addition, Tables 3-18 and 3-19 present the ozone depletion potential by life-cycle stage for EV and PHEV batteries.

Table 3-17. Ozone Depletion Potential by Li-ion Battery Component (kg CFC 11-Eq./kWh) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	2.77E-07	11.5%	5.50E-08	2.6%	3.68E-07	3.8%	2.33E-07	4.9%
Cathode	1.54E-06	64.1%	1.59E-06	74.4%	2.02E-06	21.0%	1.72E-06	36.3%
Separator	2.16E-07	9.0%	0.00E+00	0.0%	4.82E-07	5.0%	2.33E-07	4.9%
Electrolyte	1.01E-07	4.2%	3.48E-07	16.3%	2.53E-07	2.6%	2.34E-07	4.9%
Cell casing	5.05E-11	0.0%	2.98E-10	0.0%	1.70E-06	17.6%	5.67E-07	12.0%
Cell manufacture	1.75E-07	7.3%	0.00E+00	0.0%	0.00E+00	0.0%	5.85E-08	1.2%
Cell subtotal	*2.31E-06*	*96.1%*	*1.99E-06*	*93.3%*	*4.83E-06*	*50.1%*	*3.04E-06*	*64.4%*
BMS	7.08E-08	2.9%	7.08E-08	3.3%	7.08E-08	0.7%	7.08E-08	1.5%
Pack case/housing	1.77E-08	0.7%	1.77E-08	0.8%	7.15E-09	0.1%	1.42E-08	0.3%
Pack manufacture	5.55E-09	0.2%	5.37E-08	2.5%	4.74E-06	49.1%	1.60E-06	33.8%
Transportation	2.55E-11	0.0%	3.09E-11	0.0%	2.90E-11	0.0%	2.85E-11	0.0%
Total	***2.40E-06***	***100%***	***2.13E-06***	***100%***	***9.64E-06***	***100%***	***4.73E-06***	***100%***

Notes: \1 kWh = kilowatt-hour battery capacity; kg CFC 11-Eq. = kilograms of trichlorofluoromethane (CFC 11) equivalents

The production of aluminum for the cathode is a key contributor to ozone depletion. This impact of aluminum use in the cathode is smaller in relative, but not absolute, terms in the $LiFePO_4$ battery. Interestingly, the Canadian power grid, which was used to model pack manufacturing for the $LiFePO_4$ battery, generates much more sizeable emissions of trichlorofluoromethane (CFC 11) than the U.S. grid. This particular flow dominates the $LiFePO_4$ impacts. As a result, care should be taken in interpretation, as the impact is highly sensitive to the make-up of the grid. Overall, the $LiFePO_4$ chemistry has substantially higher impacts, due to higher impacts from materials and electricity consumption for the cathode, cell casing, and battery pack.

Table 3-18. Ozone Depletion Potential by Life-Cycle Stage for EV Batteries (kg CFC 11-Eq./km) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	4.74E-10	64.3%	5.51E-10	80.9%	6.62E-10	29.6%	5.62E-10	46.2%
Materials processing	1.03E-10	14.0%	6.60E-11	9.7%	4.92E-10	22.0%	2.20E-10	18.1%
Component manuf.	1.13E-10	15.3%	4.28E-11	6.3%	9.10E-11	4.1%	8.21E-11	6.7%
Product manuf.	3.75E-11	5.1%	1.11E-11	1.6%	9.81E-10	43.9%	3.43E-10	28.2%
Product use	9.80E-12	1.3%	9.80E-12	1.4%	9.80E-12	0.4%	9.80E-12	0.8%
Subtotal	*7.37E-10*	*100%*	*6.81E-10*	*100%*	*2.24E-09*	*100%*	*1.22E-09*	*100%*
Average EOL	-2.25E-10	-30.6%	-2.69E-10	-39.6%	-4.66E-10	-20.8%	-3.20E-10	-26.3%
Total	***5.12E-10***	***69.4%***	***4.12E-10***	***60.4%***	***1.77E-09***	***79.2%***	***8.98E-10***	***73.7%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg CFC 11-Eq. = kilograms of trichlorofluoromethane (CFC 11) equivalents

Table 3-19. Ozone Depletion Potential by Life-Cycle Stage for PHEV Batteries (kg CFC 11-Eq./km)\1

Chemistry	$LiMnO_2$		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	1.39E-10	39.3%	1.92E-10	24.4%	1.66E-10	29.0%
Materials processing	3.00E-11	8.4%	1.43E-10	18.1%	8.63E-11	15.1%
Components manuf.	3.29E-11	9.3%	2.64E-11	3.3%	2.96E-11	5.2%
Product manuf.	1.09E-11	3.1%	2.85E-10	36.1%	1.48E-10	25.9%
Product use	1.42E-10	40.0%	1.42E-10	18.0%	1.42E-10	24.8%
Subtotal	*3.55E-10*	*100%*	*7.88E-10*	*100%*	*5.71E-10*	*100%*
Average EOL	-6.64E-11	-18.7%	-1.35E-10	-17.2%	-1.01E-10	-17.6%
Total	***2.89E-10***	***81.3%***	***6.52E-10***	***82.8%***	***4.71E-10***	***82.4%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km);
kg CFC 11-Eq. = kilograms of trichlorofluoromethane (CFC 11) equivalents

For PHEV and EV batteries, the material extraction phase contributes substantially to ozone depletion. Top contributing processes include aluminum production for the passive cooling system, cathode, and, in the case of the $LiFePO_4$ battery chemistry, the cell containers. As discussed above, this impact category is highly sensitive to the make-up of the grid (see the impact of the product manufacturing stage in the case of the $LiFePO_4$ battery).

The LCIA methodology is based on ozone depletion potential equivalency factors, which are commonly used in LCA and are considered reliable data. However, the variance of CFC-11 emissions from electrical grids is a substantial source of uncertainty.

3.2.6 Photochemical Oxidation Potential

Photochemical oxidants are produced in the atmosphere from sunlight reacting with hydrocarbons and nitrogen oxides. At higher concentrations they may cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Photochemical oxidation potential (POP) refers to the release of chemicals that contribute to this effect. TRACI 2.0 was used to determine the potential for photochemical oxidation, or the production of photochemical smog through the reaction of volatile organic compounds (VOCs) and inorganic oxides of sulfur and nitrogen, from life-cycle air emissions. The values taken from TRACI 2.0 come from the chemical-specific maximum incremental reactivity for ozone production (MIR) for the U.S. average urban atmosphere, originally developed by California EPA. The units of the weighting values in this impact category are kilogram ozone equivalents per kilogram of emission. Inorganic emissions that contribute to this impact category include all non-methane VOCs, nitrogen and sulfur oxides, and a handful of other compounds. The impact score can be calculated as follows:

$$\mathrm{IS}_{\mathrm{POP}} = \mathrm{EF}_{\mathrm{POP}} \cdot \mathrm{Amt}_{\mathrm{POC}}$$

where:

$\mathrm{IS}_{\mathrm{POP}}$ equals the impact score for photochemical oxidation for the chemical (kg ozone-equivalents) per functional unit;

$\mathrm{EF}_{\mathrm{POP}}$ equals the POP equivalency factor for the chemical (kg ozone-equivalents); and

$\mathrm{Amt}_{\mathrm{POC}}$ equals the amount of the photochemically oxidizing chemical (POC) released to the air (kg) per functional unit.

Table 3-20 presents the photochemical oxidation potential by battery component through the life cycle of a battery. In addition, Tables 3-21 and 3-22 present the photochemical oxidation potential by life-cycle stage for EV and PHEV batteries.

Table 3-20. Photochemical Oxidation Potential by Battery Component (kg O_3-Eq./kWh) [\1]

Chemistry	LiMnO$_2$		Li-NCM		LiFePO$_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	8.19E-01	23.3%	6.13E-01	7.8%	6.61E-01	6.9%	6.98E-01	10.0%
Cathode	1.77E+00	50.2%	3.54E+00	45.2%	3.51E+00	36.9%	2.94E+00	42.3%
Separator	4.55E-02	1.3%	0.00E+00	0.0%	1.01E-01	1.1%	4.89E-02	0.7%
Electrolyte	2.02E-01	5.7%	7.95E-01	10.1%	5.17E-01	5.4%	5.05E-01	7.3%
Cell casing	4.36E-02	1.2%	2.57E-01	3.3%	8.95E-01	9.4%	3.99E-01	5.7%
Cell manufacture	9.49E-02	2.7%	0.00E+00	0.0%	0.00E+00	0.0%	3.16E-02	0.5%
Cell subtotal	*2.97E+00*	*84.4%*	*5.20E+00*	*66.5%*	*5.69E+00*	*59.7%*	*4.62E+00*	*66.4%*
BMS	2.21E-01	6.3%	2.21E-01	2.8%	2.21E-01	2.3%	2.21E-01	3.2%
Pack case/housing	2.14E-01	6.1%	2.14E-01	2.7%	4.66E-01	4.9%	2.98E-01	4.3%
Pack manufacture	3.01E-03	0.1%	2.06E+00	26.3%	3.03E+00	31.8%	1.70E+00	24.4%
Transportation	1.08E-01	3.1%	1.31E-01	1.7%	1.23E-01	1.3%	1.21E-01	1.7%
Total	***3.52E+00***	***100%***	***7.83E+00***	***100%***	***9.52E+00***	***100%***	***6.96E+00***	***100%***

Notes: [\1] kWh = kilowatt-hour battery capacity; kg O_3-Eq. = kilograms of ozone equivalents

The photochemical oxidation impacts are primarily attributable to production of the cathode and anode for the LiMnO$_2$ battery, and cathode and pack manufacture for the other two battery chemistries. Pack manufacture impacts are attributable to electricity consumption across all battery chemistries. In addition, the purification and pumping of process water during LiFePO$_4$ production contributes substantially to this impact category. As noted above, limited primary data for pack manufacture were provided for the LiMnO$_2$ battery.

Table 3-21. Photochemical Oxidation Potential by Life-Cycle Stage for EV Batteries (kg O_3-Eq./km) [\1]

Chemistry	LiMnO$_2$		Li-NCM		LiFePO$_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	5.45E-04	6.7%	9.51E-04	10.5%	7.76E-04	8.2%	7.57E-04	8.5%
Materials processing	1.73E-04	2.1%	2.40E-04	2.6%	1.39E-04	1.5%	1.84E-04	2.1%
Component manuf.	9.92E-05	1.2%	1.08E-04	1.2%	5.37E-04	5.7%	2.48E-04	2.8%
Product manuf.	4.27E-05	0.5%	4.53E-04	5.0%	6.52E-04	6.9%	3.83E-04	4.3%
Product use	7.32E-03	89.5%	7.32E-03	80.7%	7.32E-03	77.7%	7.32E-03	82.3%
Subtotal	*8.18E-03*	*100%*	*9.08E-03*	*100%*	*9.43E-03*	*100%*	*8.90E-03*	*100%*
Average EOL	1.39E-05	0.2%	-2.47E-04	-2.7%	-8.90E-05	-0.9%	-1.07E-04	-1.2%
Total	***8.20E-03***	***100.2%***	***8.83E-03***	***97.3%***	***9.34E-03***	***99.1%***	***8.79E-03***	***98.8%***

Notes: [\1] km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg O_3-Eq. = kilograms of ozone equivalents

Table 3-22. Photochemical Oxidation Potential by Life-Cycle Stage for PHEV Batteries ($kg\ O_3$-Eq./km) \1

Chemistry	LiMnO$_2$		LiFePO$_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	1.59E-04	3.2%	2.25E-04	4.3%	1.92E-04	3.8%
Materials processing	5.00E-05	1.0%	4.02E-05	0.8%	4.51E-05	0.9%
Components manuf.	2.89E-05	0.6%	1.56E-04	3.0%	9.23E-05	1.8%
Product manuf.	1.24E-05	0.3%	1.89E-04	3.6%	1.01E-04	2.0%
Product use	4.65E-03	94.9%	4.65E-03	88.4%	4.65E-03	91.5%
Subtotal	*4.90E-03*	*100%*	*5.26E-03*	*100%*	*5.08E-03*	*100%*
Average EOL	3.14E-06	0.1%	-2.58E-05	-0.5%	-1.13E-05	-0.2%
Total	***4.91E-03***	***100.1%***	***5.24E-03***	***99.5%***	***5.07E-03***	***99.8%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km);
$kg\ O_3$-Eq. = kilograms of ozone equivalents

Outside of the use stage, the materials extraction stage contributes most significantly to photochemical oxidation potential for EV and PHEV batteries. This is mainly due to the production of soda (Na_2CO_3), which is used in the synthesis of downstream lithium salts, and of aluminum that ultimately goes into the passive cooling system and cathode.

The LCIA methodology is based on ozone-equivalent photochemical oxidation potential equivalency factors, which are commonly used in LCA, come from a full equivalence mode, and are considered reliable data. As a result, uncertainty associated with these results is assumed to be modest, with the exception of the energy use during pack manufacture.

3.2.7 Ecological Toxicity Potential

The USETox freshwater characterization factors are a chemical-specific aggregation of chemical fate, ecological exposure, and effect (i.e., toxicity) factors that seek to systematically characterize the ecological impact of emissions on freshwater organisms. The USETox model provides an estimate of the potentially affected fraction of species (PAF), integrated over time and volume per unit mass of a chemical emitted, PAF m^3 day kg^{-1} (Rosenbaum et al., 2008).

$$\mathrm{IS}_{\mathrm{ETP}} = \mathrm{CF}_{\mathrm{ETP}} \cdot \mathrm{Amt}_{\mathrm{ETC}}$$

where:

$\mathrm{IS}_{\mathrm{ETP}}$ equals the impact score for ecological toxicity of the chemical (PAF m^3 day) per functional unit;

$\mathrm{CF}_{\mathrm{ETP}}$ equals the ecological toxicity potential (ETP) characterization factor for the chemical (PAF m^3 day); and

$\mathrm{Amt}_{\mathrm{ETC}}$ equals the amount of the ecologically toxic chemical (ETC) released to the air, soil, or water (kg) per functional unit.

Table 3-23 presents the ecological toxicity potential impact scores by battery component through the life cycle of a battery. In addition, Tables 3-24 and 3-25 present the ecological toxicity potential impact scores by life-cycle stage for EV and PHEV batteries.

Table 3-23. Ecological Toxicity Potential Impact Score by Battery Component (PAF m^3 day/kWh) [\1]

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	9.12E-03	0.1%	4.64E-03	0.0%	2.82E-02	2.6%	1.40E-02	0.2%
Cathode	1.54E-02	0.2%	2.03E+00	20.1%	6.64E-01	62.2%	9.03E-01	14.1%
Separator	4.84E-04	0.0%	0.00E+00	0.0%	1.08E-03	0.1%	5.21E-04	~0%
Electrolyte	4.80E-03	0.1%	1.43E-02	0.1%	1.03E-02	1.0%	9.78E-03	0.2%
Cell casing	9.54E-04	0.0%	5.63E-03	0.1%	2.08E-02	1.9%	9.11E-03	0.1%
Cell manufacture	4.99E-04	0.0%	0.00E+00	0.0%	0.00E+00	0.0%	1.66E-04	~0%
Cell subtotal	*3.13E-02*	*0.4%*	*2.05E+00*	*20.4%*	*7.24E-01*	*67.9%*	*9.36E-01*	*14.6%*
BMS	3.14E-01	3.9%	3.14E-01	3.1%	3.14E-01	29.4%	3.14E-01	4.9%
Pack case/housing	7.70E+00	95.7%	7.70E+00	76.4%	6.34E-03	0.6%	5.14E+00	80.3%
Pack manufacture	1.58E-05	0.0%	1.35E-02	0.1%	2.17E-02	2.0%	1.17E-02	0.2%
Transportation	6.34E-04	0.0%	7.68E-04	0.0%	7.22E-04	0.1%	7.08E-04	~0%
Total	***8.05E+00***	***100%***	***1.01E+01***	***100%***	***1.07E+00***	***100%***	***6.40E+00***	***100%***

Notes: [\1] kWh = kilowatt-hour battery capacity; PAF m^3 day = potentially affected fraction of species integrated over one day and one square meter

Impacts are primarily attributable to the steel used for the pack housing and battery management system in the $LiMnO_2$ and Li-NCM batteries. The use of steel in this housing is associated with significant freshwater cyanide emissions, which drive the ecotoxicity impacts. For the $LiFePO_4$ chemistry, impacts primarily result from production of the cathode and the battery management system. Impacts for the $LiFePO_4$ battery are an order of magnitude smaller, because of the substantial reduction in steel use in the inventory.

Table 3-24. Ecological Toxicity Potential Impact Score by Life-Cycle Stage for EV Batteries (PAF m^3 day/km) [\1]

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	2.02E-03	97.7%	2.44E-03	97.9%	4.32E-04	69.2%	1.63E-03	94.3%
Materials processing	1.01E-06	0.0%	2.04E-06	0.1%	1.56E-06	0.2%	1.54E-06	0.1%
Component manuf.	7.33E-07	0.0%	8.15E-07	0.0%	1.40E-04	22.4%	4.71E-05	2.7%
Product manuf.	2.38E-07	0.0%	2.95E-06	0.1%	4.64E-06	0.7%	2.61E-06	0.2%
Product use	4.66E-05	2.3%	4.66E-05	1.9%	4.66E-05	7.5%	4.66E-05	2.7%
Subtotal	*2.07E-03*	*100%*	*2.49E-03*	*100%*	*6.25E-04*	*100%*	*1.73E-03*	*100%*
Average EOL	-2.18E-05	-1.1%	-3.56E-04	-14.3%	-2.17E-05	-3.5%	-1.33E-04	-7.7%
Total	***2.05E-03***	***98.9%***	***2.14E-03***	***85.7%***	***6.03E-04***	***96.5%***	***1.60E-03***	***92.3%***

Notes: [\1] km = kilometer driven over base-case battery lifetime (10 year/193,120 km); PAF m^3 day = potentially affected fraction of species integrated over one day and one square meter.

Table 3-25. Ecological Toxicity Potential Impact Score by Life-Cycle Stage for PHEV Batteries (PAF m^3 day/km) \1

Chemistry	$LiMnO_2$		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	5.90E-04	92.1%	1.25E-04	57.5%	3.58E-04	83.3%
Materials processing	2.94E-07	0.0%	4.52E-07	0.2%	3.73E-07	0.1%
Components manuf.	2.13E-07	0.0%	4.06E-05	18.6%	2.04E-05	4.7%
Product manuf.	6.90E-08	0.0%	1.35E-06	0.6%	7.08E-07	0.2%
Product use	5.03E-05	7.8%	5.03E-05	23.1%	5.03E-05	11.7%
Subtotal	*6.41E-04*	*100%*	*2.18E-04*	*100%*	*4.30E-04*	*100%*
Average EOL	-6.34E-06	-1.0%	-6.30E-06	-2.9%	-6.32E-06	-1.5%
Total	***6.35E-04***	***99.0%***	***2.12E-04***	***97.1%***	***4.23E-04***	***98.5%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); PAF m^3 day = potentially affected fraction of species integrated over one day and one square meter.

Metal ore extraction and raw processing in the materials extraction stage is driving ecological toxicity potential impacts. This is largely due to the use of steel for all battery chemistries. Cold-rolled steel is primarily used in the passive cooling system, the battery housing, and the battery management system. $LiFePO_4$ shows higher impacts in the component manufacture stage, as opposed to the other battery chemistries, due to the materials used for the manufacture of the cathode (e.g., iron).

Because the calculation of an ecological toxicity potential must by its nature take into account the chemical fate and transport, exposure, and receptor organism-specific dose-response relationship, the inherent model-based uncertainties are substantial. Actual ecological impacts are highly sensitive to the temporal and spatial characteristics of emissions. As a result, this category can give some screening-level indications of impact, but should be treated carefully during the interpretation of results. The use of steel in the battery housing is a substantial source of uncertainty, as this is something that can change rapidly depending on relative material cost, vehicle model, and other factors.

3.2.8 Human Toxicity Potential (General Public)

The USETox characterization factors are a chemical-specific aggregation of chemical fate, exposure, and effect (i.e., toxicity) factors that seek to systematically characterize the human health impact of emissions (i.e., potential toxicity impacts to the general public). The characterization factor provides the estimated increase in morbidity in the total human population per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer (Rosenbaum et al., 2008).

$$\mathrm{IS}_{\mathrm{HTP}} = \mathrm{CF}_{\mathrm{HTP}} \cdot \mathrm{Amt}_{\mathrm{HTC}}$$

where:

IS_{HTP} equals the impact score for human toxicity potential (HTP) of the chemical (cases) per functional unit;

CF_{HTP} equals the HTP characterization factor for the chemical (cases); and

Amt_{HTC} equals the amount of the human toxic chemical (HTC) released to the air, soil, or water (kg) per functional unit.

Table 3-26 presents the human toxicity potential impact scores for the general public (i.e., based on emissions from processes) by battery component through the life cycle of a battery. In addition, Tables 3-27 and 3-28 present the human toxicity potential impact scores by life-cycle stage for EV and PHEV batteries.

Table 3-26. Human Toxicity Potential Impact Score by Battery Component (Cases/kWh) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	2.41E-10	22.7%	1.08E-10	4.6%	2.04E-10	7.0%	1.38E-10	8.7%
Cathode	2.66E-10	25.1%	6.69E-10	28.3%	1.01E-09	34.9%	4.87E-10	30.8%
Separator	1.59E-11	1.5%	0.00E+00	0.0%	3.53E-11	1.2%	1.28E-11	0.8%
Electrolyte	1.55E-10	14.6%	4.17E-10	17.6%	2.91E-10	10.0%	2.15E-10	13.6%
Cell casing	2.12E-11	2.0%	1.25E-10	5.3%	4.58E-10	15.8%	1.51E-10	9.5%
Cell manufacture	2.42E-11	2.3%	0.00E+00	0.0%	0.00E+00	0.0%	6.05E-12	0.4%
Cell subtotal	*7.23E-10*	*68.1%*	*1.32E-09*	*55.7%*	*2.00E-09*	*68.9%*	*1.01E-09*	*63.8%*
BMS	7.33E-11	6.9%	7.33E-11	3.1%	7.33E-11	2.5%	5.50E-11	3.5%
Pack case/housing	2.64E-10	24.8%	2.64E-10	11.2%	1.62E-10	5.6%	1.72E-10	10.9%
Pack manufacture	7.66E-13	0.1%	7.09E-10	30.0%	6.68E-10	23.0%	3.44E-10	21.7%
Transportation	1.11E-12	0.1%	1.35E-12	0.1%	1.27E-12	0.0%	9.34E-13	0.1%
Total	***1.06E-09***	***100%***	***2.37E-09***	***100%***	***2.91E-09***	***100%***	***1.58E-09***	***100%***

Notes: \1 kWh = kilowatt-hour battery capacity; Cases = unit increase in morbidity in the total human population

Human toxicity impacts during upstream and manufacturing stages primarily result from the materials used to manufacture the cathode, battery pack, and housing. Processes that represent the extraction of ore and initial processing of aluminum, steel, and copper account for the majority of the component-based impacts, across all battery chemistries.

Table 3-27. Human Toxicity Potential Impact Score by Life-Cycle Stage for EV Batteries (Cases/km) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	2.19E-13	7.5%	2.96E-13	9.3%	2.58E-13	7.8%	2.58E-13	8.2%
Materials processing	3.99E-14	1.4%	8.79E-14	2.8%	8.71E-14	2.6%	7.16E-14	2.3%
Component manuf.	2.90E-14	1.0%	3.26E-14	1.0%	1.92E-13	5.8%	8.45E-14	2.7%
Product manuf.	5.40E-15	0.2%	1.47E-13	4.6%	1.39E-13	4.2%	9.70E-14	3.1%
Product use	2.63E-12	89.9%	2.63E-12	82.3%	2.63E-12	79.5%	2.63E-12	83.7%
Subtotal	*2.92E-12*	*100%*	*3.19E-12*	*100%*	*3.30E-12*	*100%*	*3.14E-12*	*100%*
Average EOL	-2.34E-15	-0.1%	-6.23E-14	-2.0%	-5.61E-14	-1.7%	-4.03E-14	-1.3%
Total	***2.92E-12***	***99.9%***	***3.13E-12***	***98.0%***	***3.25E-12***	***98.3%***	***3.10E-12***	***98.7%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); Cases = unit increase in morbidity in the total human population

Table 3-28. Human Toxicity Potential Impact Score by Life-Cycle Stage for PHEV Batteries (Cases/km) \1

Chemistry	$LiMnO_2$		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	6.43E-14	3.5%	7.48E-14	3.8%	6.96E-14	3.6%
Materials processing	1.16E-14	0.6%	2.53E-14	1.3%	1.84E-14	1.0%
Components manuf.	8.46E-15	0.5%	5.56E-14	2.8%	3.21E-14	1.7%
Product manuf.	1.57E-15	0.1%	4.02E-14	2.0%	2.09E-14	1.1%
Product use	1.77E-12	95.4%	1.77E-12	90.1%	1.77E-12	92.6%
Subtotal	*1.86E-12*	*100%*	*1.97E-12*	*100%*	*1.91E-12*	*100%*
Average EOL	-1.06E-15	-0.1%	-1.63E-14	-0.8%	-8.67E-15	-0.5%
Total	***1.86E-12***	***99.9%***	***1.95E-12***	***99.2%***	***1.91E-12***	***99.5%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km); Cases = unit increase in morbidity in the total human population

The use stage human toxicity impacts primarily result from air emissions due to the combustion of fuels to supply electricity. Combustion of bituminous coal is the major driver (~60% of stage total), followed by biomass (~25%), and natural gas (~15%). The top three air emissions in order of impact are the organic compounds acrolein (~50%), isoprene (~25%), and benzene (~10%). In terms of non-use-stage impacts, materials extraction, followed by product and component manufacture, are the key stages driving impacts in this category. In the materials extraction stage, aluminum production for the cooling system and cathode is a key contributor, due to air emissions of formaldehyde, benzo[a]pyrene, and dioxins. In addition, the manufacture of the cathode and printed wiring (circuit) board for the battery management system contribute substantially in the components manufacture stage, due to air emissions of formaldehyde and, in the case of the cathode active material, emissions of dioxins to surface water.

Similar to ecological toxicity potential, quantifying human toxicity potential to the general public requires aggregation of chemical fate and transport, exposure, and receptor-specific dose-response relationship data. As a result, the inherent model-based uncertainties are substantial. Actual risk to the general public from chemical emissions is highly sensitive to the temporal and spatial characteristics of these emissions, along with weather, population distribution, and a host of other characteristics. As a result, this category can give some screening-level indications of impact, but should be treated carefully during the interpretation of results. The use of steel in the battery housing and aluminum in the passive cooling system is a substantial source of uncertainty, as this is something that can change rapidly depending on relative material cost, vehicle model, and other factors.

3.2.9 Occupational Cancer Hazard

Occupational hazard impacts are defined in the context of life-cycle assessment as relative measures of potential chemical hazard to workers. The chemical characteristic that classifies inventory items within the occupational hazard categories is toxicity. Assessments of potential occupational cancer hazard impacts in this LCA rely on measures of chronic cancer toxicity, which are manifestations of carcinogenicity that occur as a result of repeated exposure to toxic agents over a relatively long period of time (i.e., years). Carcinogens were identified by searching lists of toxic chemicals (e.g., Toxic Release Inventory), toxicity databases (e.g., International Agency for Research on Cancer Classification Database, Hazardous Substances Data Bank, Registry of Toxic Effects of Chemical Substances), and other literature. Materials in the battery inventories that had not been reviewed in previous DfE partnership

LCAs were excluded from review for carcinogenicity if they were “generally regarded as safe” (e.g., nitrogen, calcium).

Occupational cancer hazard impact scores are calculated based on a chemical scoring method modified from the CHEMS-1 method found in Swanson et al. (1997). Any chemical that is assumed to be potentially toxic is assigned a toxicity hazard value (HV). This involves collecting cancer slope factors, or raw epidemiological or animal toxicity data, from the resources mentioned above. If toxicity data are unavailable for a chemical, a mean default HV is assigned, the derivation of which is described below. The distinction between pure chemicals and mixtures is made, if possible, by specifying component ingredients of mixtures in the inventory. Calculation of the occupational cancer HVs are described below, and the occupational non-cancer calculations are described in the following section.

The cancer HV uses cancer slope factors or cancer weight of evidence (WOE) classifications assigned by EPA or the International Agency for Research on Cancer (IARC). If both an oral and inhalation slope factor exist, the slope factor representing the larger hazard is chosen:

$$\text{oral :} \qquad HV_{\text{CA oral}} = \frac{\text{Oral}_{\text{SF}}}{\text{Oral}_{\text{SF, GM}}}$$

$$\text{inhalation :} \qquad HV_{\text{CA inhalation}} = \frac{\text{Inhalation}_{\text{SF}}}{\text{Inhalation}_{\text{SF, GM}}}$$

where:

$HV_{\text{CA oral}}$	equals the cancer oral hazard value for the chemical (unitless);
oral_{SF}	equals the cancer oral slope factor for the chemical $(\text{mg/kg-day})^{-1}$;
$\text{oral}_{\text{SF, GM}}$	equals the geometric mean cancer slope factor of all available slope factors $(\text{mg/kg-day})^{-1}$
$HV_{\text{CA inhalation}}$	equals the cancer inhalation hazard value for the chemical (unitless);
$\text{inhalation}_{\text{SF}}$	equals the cancer inhalation slope factor for the chemical $(\text{mg/kg-day})^{-1}$; and
$\text{inhalation}_{\text{SF, GM}}$	equals the geometric mean cancer inhalation slope factor of all available inhalation slope factors $(\text{mg/kg-day})^{-1}$

Where no slope factor is available for a chemical, but there is a WOE classification, the WOE is used to designate default hazard values as follows: EPA WOE Groups D (not classifiable) and E (non-carcinogen) under the 1986 cancer hazard identification guidelines, EPA WOE descriptions “inadequate information to assess carcinogenic potential” and “not likely to be carcinogenic to humans” under the 2005 cancer hazard identification guidelines, and IARC Groups 3 (not classifiable) and 4 (probably not carcinogenic) are given a hazard value of zero. All other WOE classifications (known, probable, and possible human carcinogen) are given a default HV of 1 (representative of a geometric mean slope factor). Similarly, materials for which no cancer data exist, but are designated as potentially toxic, are also given a default value of 1.

The cancer HV for a particular chemical, whether it is from a slope factor or WOE, is then multiplied by the applicable inventory amount to calculate the impact score for potential cancer effects:

$$IS_{\text{CHO-CA}} = HV_{\text{CA}} \cdot \text{Amt}_{\text{TC, input}}$$

where:

$IS_{CHO\text{-}CA}$ equals the impact score for chronic occupational cancer health effects for the chemical (kg cancertox-equivalents) per functional unit;

HV_{CA} equals the hazard value for carcinogenicity for the chemical; and

$Amt_{TC\ input}$ equals the amount of toxic chemical input (kg) per functional unit for the chemical.

Table 3-29 presents the occupational cancer hazard impact scores by battery component through the life cycle of a battery. In addition, Tables 3-30 and 3-31 present the occupational cancer hazard impact scores by life-cycle stage for EV and PHEV batteries.

Table 3-29. Occupational Cancer Hazard Impact Score by Battery Component (Unitless) [\1]

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	5.10E+00	0.8%	5.12E+00	0.8%	4.22E+00	0.5%	4.81E+00	0.7%
Cathode	5.87E+02	96.3%	5.37E+02	87.6%	7.40E+02	92.5%	6.21E+02	92.2%
Separator	3.51E-01	0.1%	0.00E+00	0.0%	7.80E-01	0.1%	3.77E-01	0.1%
Electrolyte	1.23E+01	2.0%	4.40E+01	7.2%	3.21E+01	4.0%	2.95E+01	4.4%
Cell casing	7.31E-01	0.1%	4.31E+00	0.7%	5.13E+00	0.6%	3.39E+00	0.5%
Cell manufacture	2.78E-01	0.0%	0.00E+00	0.0%	0.00E+00	0.0%	9.27E-02	0.0%
Cell subtotal	*6.05E+02*	*99.3%*	*5.91E+02*	*96.3%*	*7.83E+02*	*97.8%*	*6.60E+02*	*97.8%*
BMS	1.15E+00	0.2%	1.15E+00	0.2%	1.15E+00	0.1%	1.15E+00	0.2%
Pack case/housing	2.68E+00	0.4%	2.68E+00	0.4%	4.59E+00	0.6%	3.31E+00	0.5%
Pack manufacture	8.81E-03	0.0%	1.86E+01	3.0%	1.15E+01	1.4%	1.01E+01	1.5%
Transportation	2.04E-01	0.0%	2.47E-01	0.0%	2.33E-01	0.0%	2.28E-01	0.0%
Total	***6.09E+02***	***100%***	***6.14E+02***	***100%***	***8.00E+02***	***100%***	***6.74E+02***	***100%***

Notes: [\1] kWh = kilowatt-hour battery capacity

Cancer impacts are primarily attributable to the materials and extraction needed for the cathode, especially the lithium brine. Impacts from the $LiFePO_4$ battery are significantly larger, due to the increase in the quantity of lithium brine consumed upstream of the production of the cathode active material. Little is known about the full chemical makeup and toxicity of this saline brine. EPA's Structure Activity Team estimated that soluble lithium salts like lithium chloride and lithium carbonate would not be absorbed through the skin, but would have good absorption from the lung and GI tract. However, they were not aware of any evidence of mutagenicity or carcinogenicity. It is likely that there are an abundance of other mineral salts in the brine; however, a full characterization was beyond the scope of this study. Given such uncertainty, this chemical was represented by a default hazard value of 1.

Given the likely possibility that the brine is actually of low carcinogenic concern, we also note the influence of the aluminum and steel mining and preliminary processing on this impact category.

Table 3-30. Occupational Cancer Hazard Impact Score by Life-Cycle Stage for EV Batteries (Unitless) [\1]

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	1.26E-01	69.1%	1.22E-01	66.5%	1.63E-01	73.2%	1.37E-01	69.8%
Materials processing	3.77E-04	0.2%	1.20E-03	0.7%	9.73E-04	0.4%	8.48E-04	0.4%
Component manuf.	3.75E-04	0.2%	7.69E-04	0.4%	5.52E-04	0.2%	5.65E-04	0.3%
Product manuf.	1.02E-04	0.1%	3.91E-03	2.1%	2.44E-03	1.1%	2.15E-03	1.1%
Product use	5.57E-02	30.5%	5.57E-02	30.3%	5.57E-02	25.1%	5.57E-02	28.4%
Subtotal	*1.83E-01*	*100%*	*1.84E-01*	*100%*	*2.22E-01*	*100%*	*1.96E-01*	*100%*
Average EOL	-4.29E-02	-23.5%	-5.69E-02	-31.0%	-8.75E-02	-39.4%	-6.25E-02	-31.8%
Total	***1.40E-01***	***76.5%***	***1.27E-01***	***69.0%***	***1.35E-01***	***60.6%***	***1.34E-01***	***68.2%***

Notes:[\1] km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

Table 3-31. Occupational Cancer Hazard Impact Score by Life-Cycle Stage for PHEV Batteries (Unitless) [\1]

Chemistry	$LiMnO_2$		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	3.66E-02	41.5%	4.72E-02	47.3%	4.19E-02	44.5%
Materials processing	1.09E-04	0.1%	2.82E-04	0.3%	1.96E-04	0.2%
Components manuf.	1.09E-04	0.1%	1.60E-04	0.2%	1.35E-04	0.1%
Product manuf.	2.95E-05	0.0%	7.07E-04	0.7%	3.68E-04	0.4%
Product use	5.14E-02	58.3%	5.14E-02	51.6%	5.14E-02	54.7%
Subtotal	*8.83E-02*	*100%*	*9.97E-02*	*100%*	*9.40E-02*	*100%*
Average EOL	-1.25E-02	-14.1%	-2.54E-02	-25.5%	-1.89E-02	-20.1%
Total	***7.58E-02***	***85.9%***	***7.44E-02***	***74.5%***	***7.51E-02***	***79.9%***

Notes: [\1] km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

Materials extraction and use stages are the key life-cycle stage drivers of impacts in this category. The use stage impacts are primarily due to coal fired electricity generation (about 75%) and natural gas fired electricity generation (about 20%). Fuel inputs including coal and crude oil are the implicated material flows for these impacts, respectively. These fuels have default hazard values due to the lack of information on cancer slope factors, and show up mainly as a result of the significant mass used per kilometer.

This occupational cancer hazard category has a number of limitations. The impact category represents a ranking of the potential of a chemical to cause chronic effects, rather than a prediction of actual effects. Also, the fact that the inputs of the model are dependent on the boundaries of the various datasets, and that chemical intermediates that might be synthesized at a plant and consumed in subsequent reactions were unavailable from secondary data sets, limit the robustness of this category. In addition, chemicals that are used in large quantities and that cannot strictly be ruled as "generally regarded as safe" have the potential to overwhelm the effect from known toxicants.

3.2.10 Occupational Non-Cancer Hazard

Non-cancer hazard impact scores are also calculated based on the chemical scoring method modified from the CHEMS-1 method found in Swanson et al. (1997). Any chemical that is assumed to be potentially toxic is assigned a toxicity hazard value (HV). This involves collecting epidemiological or animal toxicity data from the resources mentioned in the previous section (e.g., IRIS or HSDB). If toxicity data are unavailable for a chemical, a mean default HV is assigned, the derivation of which is described below. The distinction between pure chemicals and mixtures is made, if possible, by specifying component ingredients of mixtures in the inventory.

The non-carcinogen HV is based on no-observed-adverse-effect levels (NOAELs) or lowest-observed-adverse-effect levels (LOAELs) derived from laboratory animal toxicity experiments. Priority is given to the NOAELs or LOAELs used to calculate reference doses or concentrations (RfD/RfCs). The non-carcinogen HV is the greater of the oral and inhalation HV:

$$\text{oral :} \qquad HV_{\text{NC oral}} = \frac{1/\text{Oral NOAEL}}{1/\text{Oral NOAEL}_{\text{GM}}}$$

$$\text{inhalation :} \qquad HV_{\text{NC inhal}} = \frac{1/\text{Inhal NOAEL}}{1/\text{Inhal NOAEL}_{\text{GM}}}$$

where:

$HV_{\text{NC oral}}$	equals the non-carcinogen oral hazard value for the chemical (unitless);
oral NOAEL	equals the oral NOAEL for the chemical (mg/kg-day);
oral NOAEL_{GM}	equals the geometric mean oral NOAEL of all available oral NOAELs (mg/kg-day);
$HV_{\text{NC inhalation}}$	equals the non-carcinogen inhalation hazard value for the chemical (unitless);
inhal NOAEL	equals the inhalation NOAEL for the chemical (mg/m^3); and
inhal NOAEL_{GM}	equals the geometric mean inhalation NOAEL of all available inhalation NOAELs (mg/m^3).

If LOAEL data are available, instead of NOAEL data, the LOAEL, divided by 10, is used to substitute for the NOAEL. The most sensitive endpoint is used if there are multiple data points for one chemical.

The non-carcinogen HVs for a particular chemical are multiplied by the applicable inventory input to calculate the impact score for non-cancer effects:

$$IS_{\text{CHO-NC}} = HV_{\text{NC}} \text{ x } \text{Amt}_{\text{TC, input}}$$

where:

$IS_{\text{CHO-NC}}$	equals the impact score for chronic occupational non-cancer health effects for the chemical (kg noncancertox-equivalent) per functional unit;
HV_{NC}	equals the hazard value for chronic non-cancer effects for the chemical; and

$Amt_{TC\ input}$ equals the amount of toxic chemical input (kg) per functional unit for the chemical.

Table 3-32 presents the occupational non-cancer hazard impact scores by battery component through the life cycle of a battery. In addition, Tables 3-33 and 3-34 present the occupational non-cancer hazard impact scores by life-cycle stage for EV and PHEV batteries.

Table 3-32. Occupational Non-Cancer Hazard Impact Score by Battery Component (Unitless) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Component	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Anode	4.83E+00	0.8%	4.48E+00	0.0%	3.58E+00	0.4%	4.30E+00	0.1%
Cathode	5.90E+02	96.4%	1.53E+04	99.5%	7.39E+02	91.2%	5.54E+03	99.0%
Separator	2.64E-01	~0%	0.00E+00	0.0%	5.88E-01	0.1%	2.84E-01	0.0%
Electrolyte	1.17E+01	1.9%	4.26E+01	0.3%	3.08E+01	3.8%	2.84E+01	0.5%
Cell casing	7.42E-01	0.1%	4.38E+00	0.0%	8.42E+00	1.0%	4.51E+00	0.1%
Cell manufacture	7.68E-01	0.1%	0.00E+00	0.0%	0.00E+00	0.0%	2.56E-01	0.0%
Cell subtotal	*6.08E+02*	*99.4%*	*1.54E+04*	*99.8%*	*7.83E+02*	*96.5%*	*5.58E+03*	*99.6%*
BMS	1.10E+00	0.2%	1.10E+00	0.0%	1.10E+00	0.1%	1.10E+00	0.0%
Pack case/housing	2.54E+00	0.4%	2.54E+00	0.0%	4.24E+00	0.5%	3.11E+00	0.1%
Pack manufacture	2.43E-02	~0%	2.73E+01	0.2%	2.29E+01	2.8%	1.67E+01	0.3%
Transportation	2.97E-02	~0%	3.60E-02	0.0%	3.38E-02	0.0%	3.32E-02	0.0%
Total	***6.12E+02***	***100%***	***1.54E+04***	***100%***	***8.11E+02***	***100%***	***5.60E+03***	***100%***

Notes: \1 kWh = kilowatt-hour battery capacity

Similar to the occupational cancer impact results presented in the previous section, the potential occupational non-cancer impacts are primarily attributable to the materials and extraction needed to produce the cathode, especially the lithium brine, about which little is known. EPA's Structure Activity Team described the potential for non-cancer toxicity from soluble lithium salts, in a technical memorandum to the authors as follows:

> *"There is concern for neurotoxicity and developmental toxicity and uncertain concern for immunotoxicity for lithium. Lithium carbonate was tested in an oral 28-day repeated dose and 2-generation reproduction study in rats with doses of 30, 60, 100, and 150 mg/kg (8e-18246). The effects that were identified are deaths of animals or sacrifice of animals due to poor condition at 150 mg/kg; hypoactivity and lower hind limb grip strength in males at 100 mg/kg; increase in liver weights in females at 100 mg/kg; increase in adrenal weights at 60 and 100 mg/kg; and histopatholgical effects on kidneys and adrenals at 60 mg/kg."*

The data given above are indicative of potential for non-cancer hazard; however, they are not sufficient to derive a non-default hazard value, because a chronic data point is lacking. Therefore, this chemical is represented by a default hazard value of one.

Impacts from the Li-NCM battery are significantly larger than the other battery chemistries, due to the upstream extraction of cobalt for the production of the cathode active material. The potential occupational non-cancer hazard impact from cobalt is nearly two orders of magnitude greater, on a per kWh basis, than any other contributor in any of the battery chemistries.

The impact of N-methylpyrrolidone (NMP), the solvent typically used to manufacture lithium-ion electrodes, represented a small fraction of the overall occupational non-cancer impact in the solvent-based chemistries. This is because NMP has low volumetric use versus the lithium brine and fuel inputs.

Table 3-33. Occupational Non-Cancer Hazard Impact Score by Life-Cycle Stage for EV Batteries (Unitless) \1

Chemistry	$LiMnO_2$		Li-NCM		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	1.27E-01	58.2%	3.18E+00	97.0%	1.63E-01	62.9%	1.16E+00	92.4%
Materials processing	4.07E-04	0.2%	9.42E-04	~0%	8.19E-04	0.3%	7.23E-04	0.1%
Component manuf.	6.78E-04	0.3%	1.07E-03	~0%	8.87E-04	0.3%	8.77E-04	0.1%
Product manuf.	1.70E-04	0.1%	5.65E-03	0.2%	4.76E-03	1.8%	3.53E-03	0.3%
Product use	8.96E-02	41.2%	8.96E-02	2.7%	8.96E-02	34.6%	8.96E-02	7.2%
Subtotal	*2.18E-01*	*100%*	*3.28E+00*	*100%*	*2.59E-01*	*100%*	*1.25E+00*	*100%*
Average EOL	-4.22E-02	-19.4%	-2.61E+00	-79.6%	-8.68E-02	-33.5%	-9.13E-01	-73.0%
Total	***1.75E-01***	***80.6%***	***6.67E-01***	***20.4%***	***1.72E-01***	***66.5%***	***3.38E-01***	***27.0%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

Table 3-34. Occupational Non-Cancer Hazard Impact Score by Life-Cycle Stage for PHEV Batteries (Unitless) \1

Chemistry	$LiMnO_2$		$LiFePO_4$		Average	
Life-Cycle Stage	**Value**	**Pct.**	**Value**	**Pct.**	**Value**	**Pct.**
Materials extraction	3.67E-02	46.1%	4.72E-02	51.5%	4.20E-02	49.0%
Materials processing	1.18E-04	0.1%	2.37E-04	0.3%	1.78E-04	0.2%
Components manuf.	1.98E-04	0.2%	2.57E-04	0.3%	2.27E-04	0.3%
Product manuf.	4.94E-05	0.1%	1.38E-03	1.5%	7.15E-04	0.8%
Product use	4.26E-02	53.5%	4.26E-02	46.5%	4.26E-02	49.7%
Subtotal	7.98E-02	100%	9.17E-02	100%	8.57E-02	100%
Average EOL	-1.23E-02	-15.4%	-2.52E-02	-27.4%	-1.87E-02	-21.8%
Total	***6.75E-02***	***84.6%***	***6.66E-02***	***72.6%***	***6.70E-02***	***78.2%***

Notes: \1 km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

As was the case with the occupational cancer hazard category, the occupational non-cancer hazard category shows significant impacts emanating from the use stage. This is primarily due to fuel inputs during power production, and in particular bituminous coal, which is used in relatively large quantities to generate electricity for the average U.S. grid. Coal is given a default hazard value of 1 because of the lack of non-cancer toxicity data for this resource.

After the use stage, most potential occupational non-cancer impacts are attributed to the materials extraction stage. This is mainly attributable to lithium brine used in cathode manufacturing for the $LiMnO_2$ and $LiFePO_4$ batteries. In addition, the cobalt sulfate produced upstream for use in the synthesis of the Li-NCM cathode active material overwhelms the contribution from the use stage to the overall occupational non-cancer hazard impacts for this battery chemistry.

3.3 SWCNT Anode Analysis

The potential commercial use of SWCNT anodes in lithium-ion batteries has become a topic of great interest for battery manufacturers looking for a way to increase power and energy density, as well as for regulators, interested in the impact of the use of these materials on the environment, and human and ecological health. As a result, we undertook a screening-level analysis of the comparative impacts of the production of two different anodes: the SWCNT anode, and the traditional, battery-grade graphite anode.

As presented in Table 3-35, based on the laboratory modeling data, the energy required for the production of the SWCNT anode is significantly greater than the energy required for the production of battery-grade graphite anodes, and as currently produced in the lab, would certainly outweigh any potential benefits in the use stage. The results indicate that if electricity consumption during SWCNT manufacture were reduced to 11 kWh per kWh capacity, all but the occupational non-cancer hazard impacts would be comparable to the graphite anode. This would be slightly under, though roughly comparable to, the 42 – 52 kWh/kWh capacity of primary energy needed to make current, battery-grade graphite-based anodes, if one assumes an electricity conversion efficiency of one-third. This primary energy use corresponds to a fairly small proportion of the overall primary energy required for battery production: 6.1 – 21.4% for the batteries examined in this study. When compared to the primary energy use during the full life cycle of the battery, the impact of anode production is even smaller, representing 1.4-2.1% of the total.

The occupational non-cancer hazard impact estimate is especially sensitive to the SWCNT-based anode because SWCNTs have a hazard value that is 120,000-times higher than the geometric mean hazard of all chemical feedstocks in the impact category. Due to the dearth of SWCNT-specific data in the toxicology literature, the hazard value was based on an extrapolation from multi-walled carbon nanotube toxicity in rodents, and is subject to a high degree of uncertainty. The value was derived using standard health-protective assumptions, and is in line with other peer reviewed nanotube hazard characterizations (NIOSH 2010) (See Appendix A for a memorandum on the determination of the toxicity value for this material). The occupational cancer impact is less sensitive to SWCNTs, given their default hazard value of 1 (assigned due to the absence of carcinogenicity data for SWCNTs). In contrast, ozone depletion is especially insensitive to the electricity required to manufacture the SWCNT-based anode, because the generation of domestic electricity does not emit a large quantity of ozone depletors.

Table 3-35. Comparison of SWCNT and Battery Grade Graphite Anode Manufacturing Impacts

Impact Category	Impact ratio (-) \1	Break-even (kWh) \2
Primary Energy	*1559*	*11.5*
Abiotic Depletion Potential	1589	11.4
Global Warming Potential	1684	10.6
Acidification Potential	1450	14.6
Eutrophication Potential	1217	13.0
Ozone Depletion Potential	6	3838.0
Photochemical Oxidation Potential	1549	11.6
Ecological Toxicity Potential	886	24.9
Human Toxicity Potential	1887	12.3
Occupational Cancer Hazard	1892	15.2
Occupational Non-Cancer Hazard	3210	4.1

Notes:

\1 Impact ratio is the ratio of the SWCNT anode manufacturing impacts to those of the battery grade graphite anode. For example, the energy impacts of manufacturing the SWCNT is 1,599 times greater than the graphite anode.

\2 The break-even metric represents the at-plug electricity consumption during production of 1 kWh capacity of SWCNT anode, below which the impacts would be less than that of the corresponding conventional graphite-based anode. (Note: Current electricity consumption during the production of a 1 kWh capacity SWCNT anode is approximately 28,000 kWh.) For instance, in order to register the same global warming impact as the graphite anode, the SWCNT-based anode would have to be produced using less than 11 kWh of electricity drawn from the average U.S. grid.

3.4 Sensitivity Analysis

Based on key assumptions made in our analysis, we undertook a sensitivity analysis to assess the sensitivity of all impact category results to the following variables:

- **The lifetime of the battery**, which we halved from the base-case of 10 years, to 5 years; and
- **A range of recovery and reuse rates for materials in the battery pack**, as provided in primary data submissions by recyclers; and
- **A combination of six different charging scenarios** based on two types of charging options (unconstrained and smart charging) and three grids from different regions (Elgowainy et al., 2009), as follows:

In addition, we built on Argonne's study by incorporating the results of the simulation described in Section 2.3.1 into the sensitivity analysis. Accordingly, we considered changes in the grid-mix resulting from unconstrained versus smart charging scenarios for three grid types (WECC, IL, and ISO-NE), as follows and presented in Table 2-8.

- *Western Electricity Coordinating Council (WECC)* – Natural gas-centric marginal generation
- *Independent System Operator – New England (ISO-NE)* – Natural gas-centric marginal generation
- *Illinois (IL)* – Coal-centric marginal generation

The results of the sensitivity analysis from reducing the lifetime from 10 to 5 years are presented in Tables 3-36 and 3-37 below.

Table 3-36. Sensitivity to Halving Battery Lifetime for EV Batteries

Battery Chemistry	$LiMnO_2$	LiNCM	$LiFePO_4$
Impact Category	**Pct. deviation**	**Pct. deviation**	**Pct. deviation**
Primary Energy	9.9%	18.8%	23.8%
Abiotic Depletion Potential	8.9%	17.9%	20.9%
Global Warming Potential	9.2%	16.0%	20.9%
Acidification Potential	7.8%	16.3%	14.6%
Eutrophication Potential	-28.2%	-7.1%	73.4%
Ozone Depletion Potential	98.1%	97.6%	99.5%
Photochemical Oxidation Potential	9.8%	17.0%	23.2%
Ecological Toxicity Potential	97.7%	97.8%	92.3%
Human Toxicity Potential	9.9%	16.0%	19.2%
Occupational Cancer Hazard	29.9%	55.0%	80.6%
Occupational Non-Cancer Hazard	22.1%	86.6%	72.4%

Table 3-37. Sensitivity to Halving Battery Lifetime for PHEV Batteries

Battery Chemistry	$LiMnO_2$	$LiFePO_4$
Impact Category	**Pct. deviation**	**Pct. deviation**
Primary Energy	2.8%	7.4%
Abiotic Depletion Potential	2.4%	6.3%
Global Warming Potential	2.0%	5.1%
Acidification Potential	4.2%	8.3%
Eutrophication Potential	-8.9%	50.4%
Ozone Depletion Potential	50.5%	78.4%
Photochemical Oxidation Potential	4.7%	12.1%
Ecological Toxicity Potential	92.1%	76.3%
Human Toxicity Potential	4.5%	9.3%
Occupational Cancer Hazard	11.8%	56.6%
Occupational Non-Cancer Hazard	14.7%	61.5%

Halving the lifetime of the battery has a significant adverse effect on impact categories, including occupational cancer and non-cancer, ecotoxicity, and ozone depletion. These adverse effects are more evident for EV batteries versus PHEV batteries, because the replacement of a full EV battery entails substantially more battery produced than is the case in a PHEV. As expected, impact categories that are driven by energy, and particularly electricity consumption, are less sensitive to the halving of the battery lifetime, due to the overwhelming influence of the use stage. This list includes abiotic depletion potential, photochemical oxidation potential, global warming potential, acidification potential, and human toxicity potential.

Eutrophication impacts are negative in value and vary significantly between battery chemistries. This has to do with the production of steel being a net sink for phosphate and other nutrients. Increased steel production appears "beneficial" from a nutrient reduction standpoint, so halving the lifetime of the battery actually improves the outcome.

Tables 3-38 and 3-39 give the sensitivity results for the material recovery and reuse ranges provided by recyclers.

Table 3-38. Sensitivity to Ranges of Material Recovery and Reuse Estimates for EV Batteries

Battery Chemistry	$LiMnO_2$		LiNCM		$LiFePO_4$	
Impact Category	**Low**	**High**	**Low**	**High**	**Low**	**High**
Primary Energy	0.2%	-0.2%	0.4%	-0.4%	0.4%	-0.4%
Abiotic Depletion Potential	0.2%	-0.2%	0.4%	-0.4%	0.4%	-0.4%
Global Warming Potential	0.2%	-0.2%	0.4%	-0.4%	0.5%	-0.5%
Acidification Potential	0.1%	-0.1%	1.3%	-1.3%	0.3%	-0.3%
Eutrophication Potential	0.7%	-0.7%	1.7%	-1.7%	2.9%	-2.8%
Ozone Depletion Potential	2.6%	-2.5%	3.4%	-3.4%	2.7%	-2.6%
Photochemical Oxidation Potential	0.2%	-0.2%	0.5%	-0.5%	0.4%	-0.4%
Ecological Toxicity Potential	~0.0%	~0.0%	1.1%	-1.1%	0.2%	-0.2%
Human Toxicity Potential	0.1%	-0.1%	0.3%	-0.3%	0.3%	-0.3%
Occupational Cancer Hazard	4.8%	-4.8%	4.8%	-4.8%	3.9%	-3.9%
Occupational Non-Cancer Hazard	3.3%	-3.3%	27.4%	-27.3%	3.5%	-3.5%

Table 3-39. Sensitivity to Ranges of Material Recovery and Reuse Estimates for PHEV Batteries

Battery Chemistry	$LiMnO_2$		$LiFePO_4$	
Impact Category	**Low**	**High**	**Low**	**High**
Primary Energy	0.1%	-0.1%	0.1%	-0.1%
Abiotic Depletion Potential	0.1%	-0.1%	0.1%	-0.1%
Global Warming Potential	0.1%	-0.1%	0.1%	-0.1%
Acidification Potential	0.1%	-0.1%	0.2%	-0.2%
Eutrophication Potential	0.2%	-0.2%	2.0%	-2.0%
Ozone Depletion Potential	1.3%	-1.3%	2.1%	-2.1%
Photochemical Oxidation Potential	0.1%	-0.1%	0.2%	-0.2%
Ecological Toxicity Potential	0.0%	0.0%	0.1%	-0.1%
Human Toxicity Potential	0.1%	-0.1%	0.1%	-0.1%
Occupational Cancer Hazard	1.9%	-1.9%	2.8%	-2.8%
Occupational Non-Cancer Hazard	2.2%	-2.2%	3.0%	-3.0%

Our primary analysis of the EOL impacts was based on the high-end of the ranges of recovery rates provided by the recyclers for each battery material. When conducting the sensitivity analysis and comparing the impact results between the low- and high-end of the ranges provided, we found that the impacts were not highly sensitive to the rate (within these ranges), with the exception of the occupational non-cancer and, to a lesser extent, cancer categories. It is important, however, to remember that the study results show that recovery of the materials in the EOL stage for use as secondary materials in the battery does significantly mitigate impacts overall, especially from the upstream processing and extraction stages, across battery chemistries.

As noted above, within the range of recovery estimate provided by the recyclers, impacts do not appear to be highly sensitive, with the exception of the occupational non-cancer and, to a lesser extent, cancer categories. The sensitivity of the occupational non-cancer hazard impacts has to do with the recovery and reuse of metals used in the battery, especially cobalt, a metal that has elevated potential for human toxicity impacts. Ozone depletion potential also appears somewhat sensitive to recycling assumptions. This is predominately due to the emission of CFC 11 upstream during the aluminum production process.

Tables 3-40 and 3-41 give the results of the marginal grid comparisons, expressing the low and high impact values.

Table 3-40. Low and High Impacts from Grid and Charging Scenarios for EV Batteries [\1]

Battery Chemistry	**$LiMnO_2$**				**LiNCM**			
Impact Category	**Low**	**Scenario**	**High**	**Scenario**	**Low**	**Scenario**	**High**	**Scenario**
Primary Energy (MJ)	*1.80E+00*	*ISO-NE Un*	*2.20E+00*	*IL Sm*	*2.00E+00*	*ISO-NE Un*	*2.40E+00*	*IL Sm*
ADP (kg Sb-Eq.)	8.36E-04	ISO-NE Un	1.05E-03	IL Sm	9.34E-04	ISO-NE Un	1.14E-03	IL Sm
GWP (kg CO_2-Eq.)	1.08E-01	ISO-NE Un	2.04E-01	IL Sm	1.19E-01	ISO-NE Un	2.14E-01	IL Sm
AP (kg H+ Mol-Eq.)	9.70E-03	ISO-NE Un	8.72E-02	IL Sm	1.55E-02	ISO-NE Un	9.30E-02	IL Sm
EP (kg N-Eq.)	6.55E-06	WECC Un	3.08E-05	IL Sm	8.67E-06	WECC Un	3.29E-05	IL Sm
ODP (kg CFC 11-Eq.)	5.38E-10	IL Sm	1.13E-09	ISO-NE Un	4.44E-10	IL Sm	1.04E-09	ISO-NE Un
POP (kg O_3-Eq.)	5.56E-03	WECC Un	1.66E-02	IL Sm	6.27E-03	WECC Un	1.73E-02	IL Sm
EcoTP (PAF m^3 day)	2.01E-03	ISO-NE Un	2.06E-03	IL Sm	2.10E-03	ISO-NE Un	2.14E-03	IL Sm
HTP (Cases)	2.16E-12	IL Sm	2.78E-12	WECC Sm	2.37E-12	IL Sm	2.99E-12	WECC Sm
OCH (Unitless)	5.78E-02	ISO-NE Un	9.82E-02	IL Sm	1.02E-01	ISO-NE Un	1.42E-01	IL Sm
OnCH (Unitless)	6.38E-02	ISO-NE Sm	9.92E-02	IL Sm	6.17E-01	ISO-NE Sm	6.52E-01	IL Sm

Battery Chemistry	**$LiFePO_4$**			
Impact Category	**Low**	**Scenario**	**High**	**Scenario**
Primary Energy (MJ)	*2.13E+00*	*ISO-NE Un*	*2.54E+00*	*IL Sm*
ADP (kg Sb-Eq.)	9.71E-04	ISO-NE Un	1.18E-03	IL Sm
GWP (kg CO2-Eq.)	1.28E-01	ISO-NE Un	2.23E-01	IL Sm
AP (kg H+ Mol-Eq.)	1.42E-02	ISO-NE Un	9.17E-02	IL Sm
EP (kg N-Eq.)	4.76E-05	WECC Un	7.19E-05	IL Sm
ODP (kg CFC 11-Eq.)	2.93E-09	IL Sm	3.94E-09	ISO-NE Un
POP (kg O3-Eq.)	6.98E-03	WECC Un	1.80E-02	IL Sm
EcoTP (PAF m3 day)	5.68E-04	ISO-NE Un	6.12E-04	IL Sm
HTP (Cases)	2.50E-12	IL Sm	3.12E-12	WECC Sm
OCH (Unitless)	2.65E-01	ISO-NE Un	3.06E-01	IL Sm
OnCH (Unitless)	2.73E-01	ISO-NE Sm	3.09E-01	IL Sm

Notes: [\1] ADP = abiotic depletion potential; AP = acidification potential; EcoTP = ecological toxicity potential; EP = eutrophication potential; HTP = human toxicity potential; IL = Illinois electricity grid; ISO-NE = Independent System Operators – New England grid; OCH = occupational cancer hazard; ODP = ozone depletion potential; OnCH = occupational non-cancer hazard; POP = photochemical oxidation potential; Sm = smart charging scenario; Un = unconstrained charging scenario; WECC = Western Electricity Coordinating Council

Table 3-41. Low and High Impacts from Grid and Charging Scenarios for PHEV Batteries[\1]

Battery Chemistry	$LiMnO_2$				$LiFePO_4$			
Impact Category	**Low**	**Scenario**	**High**	**Scenario**	**Low**	**Scenario**	**High**	**Scenario**
Primary Energy (MJ)	1.93E+00	ISO-NE Un	2.11E+00	IL Sm	2.03E+00	ISO-NE Un	2.20E+00	IL Sm
ADP (kg Sb-Eq.)	9.13E-04	ISO-NE Un	1.01E-03	IL Sm	9.52E-04	ISO-NE Un	1.04E-03	IL Sm
GWP (kg CO2-Eq.)	1.63E-01	ISO-NE Un	2.05E-01	IL Sm	1.68E-01	ISO-NE Un	2.10E-01	IL Sm
AP (kg H+ Mol-Eq.)	9.53E-03	ISO-NE Un	4.34E-02	IL Sm	1.08E-02	ISO-NE Un	4.48E-02	IL Sm
EP (kg N-Eq.)	8.13E-06	WECC Un	1.88E-05	IL Sm	2.00E-05	WECC Un	3.07E-05	IL Sm
ODP (kg CFC 11-Eq.)	3.01E-10	IL Sm	5.61E-10	ISO-NE Un	6.71E-10	IL Sm	9.31E-10	ISO-NE Un
POP (kg O3-Eq.)	3.76E-03	WECC Un	8.59E-03	IL Sm	4.18E-03	WECC Un	9.00E-03	IL Sm
EcoTP (PAF m3 day)	6.19E-04	ISO-NE Un	6.38E-04	IL Sm	1.96E-04	ISO-NE Un	2.16E-04	IL Sm
HTP (Cases)	1.53E-12	IL Sm	1.80E-12	WECC Sm	1.62E-12	IL Sm	1.90E-12	WECC Sm
OCH (Unitless)	4.89E-02	ISO-NE Un	6.66E-02	IL Sm	1.09E-01	ISO-NE Un	1.27E-01	IL Sm
OnCH (Unitless)	2.76E-02	ISO-NE Sm	4.31E-02	IL Sm	8.83E-02	ISO-NE Sm	1.04E-01	IL Sm

Notes: [\1] ADP = abiotic depletion potential; AP = acidification potential; EcoTP = ecological toxicity potential; EP = eutrophication potential; HTP = human toxicity potential; IL = Illinois electricity grid; ISO-NE = Independent System Operators – New England grid; OCH = occupational cancer hazard; ODP = ozone depletion potential; OnCH = occupational non-cancer hazard; POP = photochemical oxidation potential; Sm = smart charging scenario; Un = unconstrained charging scenario; WECC = Western Electricity Coordinating Council

Based on the results shown in the tables above, impacts tend to be substantially higher when based on an unconstrained charging scenario using the IL grid, which almost exclusively uses coal as a fuel. The low-end of the impacts primarily result from the ISO-NE unconstrained charging scenario, which is predominately natural gas-derived electricity. However, for ozone depletion and human toxicity, lower impacts are observed under the IL – smart charging scenario. The reduction in ozone depletion potential in the coal-centric grid is due to lower emission of halogenated compounds like R11 and R12 (dichlorodifluoromethane), in comparison to grids dependent on natural gas. The lower human health impacts of the IL smart-charging scenario appear to be due to the fact that formaldehyde emission during coal combustion is lower than that occurring with natural gas combustion.

4. Summary of Results and Conclusions

In the following section, we summarize the results and key conclusions from the LCA study. In addition, we present additional research ideas based on the study, for future researchers to consider.

4.1 Battery Chemistry, Components, and Materials

Battery chemistry appears to influence the results in a number of impact categories, due to impacts associated with upstream materials extraction and processing, and energy use. Overall, the study found that the choice of active material for the cathode influences the results across most of the impact categories. For example, the Li-NCM chemistry relies on rare metals, such as cobalt and nickel, for which the data indicate significant non-cancer and cancer toxicity impact potential; this is reflected in the occupational hazard categories. The other two battery chemistries use the relatively lower toxicity metals, manganese and iron.

Other material choices also produce differences in impact results. One choice that stands out in particular is the use of aluminum in various battery components, from the cathode substrate to the cell casing. Battery chemistries that use larger quantities of aluminum, such as $LiMnO_2$ and $LiFePO_4$, show distinctly higher potential for ozone depletion impacts than the battery chemistry that does not, Li-NCM. As discussed before, this is a direct outcome of the CFC 11 releases during the upstream processes that lead to aluminum end-products.

Energy use is another chemistry-specific driver. Across battery chemistries, the cathode is a dominant contributor to upstream and component manufacturing impacts. The cathode active materials appear to all require large quantities of energy to manufacture. However, the data indicate that the Li-NCM cathode active material requires approximately 50% more primary energy than the other two active materials.

Energy use also differed among battery manufacturing methods, and those that did and did not use solvent for electrode production. The solvent-less method appeared to use much less energy compared to estimates provided in prior studies of cell and pack manufacture (e.g., Majeau-Bettez, 2011). This translated into low manufacturing-stage impacts in categories driven by energy consumption, such as global warming potential, acidification potential, and human toxicity potential. However, we were not able to obtain primary data for electricity and fuel consumption from our other manufacturing partner, making it difficult to quantify with any certainty the difference between solvent-less and solvent-based electrode manufacturing.

Impact differences across battery chemistries are mitigated by high rates of recovery and reuse in the end-of-life (EOL) stage. This is particularly the case with cathode active materials and bulk metals like aluminum. The low-temperature recycling technologies are especially beneficial, because of lower energy use, less material transformation, and more direct reuse/recycling of materials used in batteries.

4.2 Vehicle/Battery Type

The EV and PHEV-40 battery results from this study suggest a number of interesting findings. Although greenhouse gas emissions during the production and use of lithium-ion batteries in these vehicles has been a significant focus in the scientific literature, an assessment of the other impact categories, including potential human and ecological impacts, has not been as readily considered in past studies as it has in this LCA study.

In looking at the impacts for PHEV and EV Li-ion batteries, this study found that, in general, global warming potential is one of the few categories in which EV batteries show lower impacts than PHEV batteries; however, this is not unequivocal. A true net benefit in global warming potential for EV batteries only appears when the grid is not coal-centric, and battery production does not represent a substantial proportion of primary energy consumption (e.g., $LiMnO_2$). Drawing on the average U.S. grid, EV batteries show a small average net benefit over PHEV batteries across all battery chemistries (about 25 g CO_2-eq./km). However, the electricity grid in Illinois, which is more representative of the Southeast, Appalachia, and Midwest, shows PHEV-40 batteries more favorable than EV batteries, on a GWP-basis. In other words, given present grid conditions, it might be preferable for people living in these regions to buy PHEV-40s if mitigation of global warming impacts are highly valued (based on assessment of the battery life cycle, including its use—not the entire vehicle).

Abiotic depletion and eutrophication potential impacts are the only other impact categories in which EV batteries show lower impacts; however, there are some caveats. Specifically, lower impacts for EV batteries are only evident in these categories when the grid is comprised to a large extent of natural gas-based generation facilities, and battery production does not represent a substantial proportion of the overall primary energy use (e.g., for $LiMnO_2$ batteries). It is likely that most of the impacts across categories would be lower for EV batteries if the average electricity grid were less dependent on fossil fuels, and relied more on renewable sources of energy.

4.3 Life-Cycle Stages

Impacts vary significantly across life-cycle stages for all battery chemistries and vehicle battery types. Though the use stage of the battery dominates in nearly all impact categories, upstream materials extraction and processing and battery production are non-negligible in all categories, and are significant contributors to eutrophication potential, ozone depletion potential, ecological toxicity potential, and the occupational cancer and non-cancer hazard impact categories.

The dominant influence of the use stage makes clear the importance of baseline assumptions and sensitivity of LCA models when examining the grid. Both coal and natural gas-based electricity are associated with significant air emissions of toxics, global warming chemicals, and ozone depletors; however, the relative impacts of the two fuels are often distinct, as can be seen in the grid sensitivity analysis of Section 3.4. We further discuss the implications of sensitivity to the grid in Section 4.5, below. Furthermore, use stage results are highly dependent on assumptions surrounding fuel efficiency and driving style. We made few modifications to the effective energy efficiency reported by researchers from Argonne, but this is an area of uncertainty.

During the upstream materials extraction and processing stages, which are implicated in a number of impact categories, common metals drive stage-specific impacts. Aluminum used in manufacture of the cathode and passive cooling system comes up as a driver in a number of impact categories, especially in ozone depletion potential. Steel, which is used in the battery pack housing and BMS, is another metal that shows up in a number of different impact categories as a driver, including global warming potential and ecological toxicity potential, due to cyanide emissions. In addition, the results suggest that the use of steel may work to reduce the eutrophication potential of waters used during its processing, by reducing nutrient levels, thereby resulting in overall net negative eutrophication potential. In contrast to the metals, plastic resins show up in fewer categories as drivers, due both to the lower mass used in the batteries, and to lower energy consumption during part manufacture.

Lifetime of the battery is a significant determinant of impact results, as it directly modifies the proportion of the impact attributable to all non-use stages. Halving the lifetime of the battery results in sizeable changes in global warming potential, acidification potential, ozone depletion potential, and photochemical oxidation potential (e.g., smog); this is true even for PHEV-40 batteries that are 3.4 times smaller in terms of capacity. Longevity by battery chemistry should be assessed in future research, because of the correlation of greater battery lifetimes with reduced environmental impacts.

4.4 SWCNT Anodes and Other Nano-Scale Materials

According to the results of the analysis of SWCNT anodes made by laser vaporization, massive electricity consumption in this manufacturing method results in impacts that are orders of magnitude greater than those of battery-grade graphite. Given the vast array of lab- and pilot-scale methods of manufacturing carbon nanomaterials, it is likely that over time, manufacturing will become much more energy efficient; however, it is difficult to say if or when they will be comparable, or result in net environmental benefits versus the conventional technology. This rapidly changing technological backdrop demonstrates the challenge of LCA for nanotechnologies. The data presented in Section 2.1.2 of this report suggest that in a best-case scenario, within the decade we could see reductions from the baseline of approximately two orders of magnitude, due to increases in yield and more efficient processes. The results presented in Section 3.3 indicate that a greater than 3 orders of magnitude reduction in energy use during anode manufacturing is needed to get to a break-even impact in most categories. This suggests that laboratory research of SWCNT-enabled technologies should focus on lowering the energy intensity of nano-manufacturing processes, in tandem with improving technology performance, as the significant energy consumption of SWCNT manufacturing drives the environmental profile of the technology.

Our analysis also suggests that the use of SWCNTs presents potential hazards to workers at the anode production and EOL stages. The hazard impact results from this LCA are a first step in assessing the potential environmental and health impacts (and potential benefits) of nanomaterials in this specialized application. Unless future risk assessments specific to SWCNTs-- which take into account not only the toxicity of the material but also the potential for exposure--suggest otherwise, occupational handling of these materials should be treated with a degree of caution. No other nanomaterials were used in the batteries modeled in this study, although there is much interest and research on using nano-scale cathode and anode materials (in addition to the SWCNT anode research).

4.5 Implications for the Electricity Grid

One factor that has the potential to significantly change the outcome of an electric vehicle battery LCA is the choice of average versus marginal electricity generation to generate impact estimates. U.S. LCI data and GaBi data currently apply an average mix of electricity generation for different regions. Though average electricity provisions may make more sense when thinking about the impact of battery product systems in static, long-run analyses, the electricity grid is subject to cyclical as well as structural changes in the distribution of underlying energy generation processes. Marginal generation considers the deployment of new technology that may draw a lot more electricity at different times from the electric grid. With the increase in use of electric cars, it will likely change the make-up of the grid from its current mix. So, it may be important to consider the “marginal” generation, instead of focusing only on the "average" generation. Accordingly, attribution of the average grid mix to battery charging may not accurately reflect the impact of the batteries on overall electricity production.

Marginal electricity generation is not the only issue to consider when modeling the electrical grid. Over the long-run, the economic and regulatory environment might change in such a way as to incentivize producers and consumers to shift over to smart charge strategies, or may cause drastic changes to the underlying fuel mix (e.g., the mothballing of old coal plants). Accordingly, it may be necessary to look at the dynamics of the system over time, and try to tease out how changes in the underlying grid will be associated with the increase in electricity demand of lithium-ion batteries, through both policy changes and private-sector changes. This study is by its fundamental nature a forward looking and long-term analysis. As such, the baseline that we present is subject to significant limitations on its applicability to future scenarios. However, the carbon intensity analysis presented in Section 3.2.2, and the grid sensitivity analysis presented in Section 3.4, should provide a reasonable foundation on which future analyses can be assessed.

4.6 Comparison to Prior Research

As discussed in Section 1.1.3, a number of groups have quantified the life-cycle impacts of lithium-ion batteries for use in vehicle applications, based primarily on secondary data sources. In general, the results of this study are fairly similar to and bound these prior LCA studies. Specifically, in terms of upstream materials extraction and battery manufacture stages, our estimates of primary energy use and greenhouse gas emissions, which range from 870-2500 MJ/kWh and 60-150 kg CO2-eq./kWh, respectively, are similar to results reported by Samaras and Meisterling (2008): 1700 MJ/kWh and 120 kg CO2-eq./kWh. Our global warming potential (GWP) results are lower than those of Majeau-Bettez et al. (2011), which estimated upstream and manufacturing impacts for Li-NCM and LiFePO4 of 200 and 250 kg CO2-eq./kWh, respectively. Given that our LiFePO4 battery assumed the same elevated energy use during production as their study, and our component and battery manufacturing GWP impacts are in line with their result (7-10 kg CO2-eq./km versus 7-15 kg CO2-eq./km, respectively), we attribute this difference primarily to the difference in the energy needed during upstream production of the anode and cathode materials, as well as the lithium salts. Our eutrophication results were similarly lower, versus those of Majeau-Bettez et al. (2011). In addition, our ozone depletion potential results were approximately two orders of magnitude lower. This is likely due to the use of a polytetrafluoroethylene production process in the Majeau-Bettez et al. (2011) study, which accounted for essentially all of the ozone depletion potential impacts.

The proportional breakdown of energy demand, abiotic resource depletion potential, and global warming potential impacts from the various battery components presented in Notter et al. (2010) is similar to our results, although we found the anode to be a slightly less significant contributor overall. For instance, our two primary datasets generated anode GWP impacts at approximately 6.5% of the overall battery impacts, while their estimate appears to lie between 15% and 20% (Notter et al., 2010). In addition, based on a percentage breakdown between the GWP and eutrophication impacts in the Majeau-Bettez et al. (2011) study, our results are similar, but with a larger emphasis on battery production impacts.

Notter et al. (2010) reports use stage consumption of roughly 162 g CO2-eq./km for an EV battery that requires a total of 170 Wh/km for operation. This larger impact compared to our modeling result (120 g CO2-eq./km) is primarily due to their assumption of a lower charging efficiency (80% versus 85%), as well as a lower assumed battery-to-wheel efficiency. Thus, even despite the lower carbon-intensity of the modeled European grid, our use stage results indicated lower impacts. The Majeau-Bettez et al. (2011)

study, on the other hand, showed distinctly lower GWP impacts over the use stage, when normalized to 1 km driving (14-19 g CO2-eq./km). This is mostly attributable to the difference in two modeling parameters: (1) the functional unit of 50 MJ delivered to the drive train, which does not take drive train-to-wheel energy loss into account; and (2) the lifetime of the battery, as defined by the number of charge-discharge cycles, rather than time. Other contributing factors are their assumed 90% charging efficiency (versus our 85%), as well as the lower carbon-intensity of the European grid.

Our results, along with other recent literature, suggest that there is good consensus on the importance of the cathode materials, in particular, as being a driver of impacts upstream. However, with respect to the use stage impacts, variations result from different assumptions about the vehicle efficiency and other modeling parameters.

4.7 Opportunities for Improvement

A number of opportunities for improving the environmental profile of Li-ion batteries for use in plug-in hybrid and electric vehicles were identified, based on the results of this LCA study. These opportunities are listed below and do not reflect order of importance:

- **Increase the lifetime of the battery.** A lifetime of 10 years was assumed by the partnership, as it represents the anticipated lifetime the battery manufacturers seek to achieve. As shown in the sensitivity analysis, halving the lifetime of the battery results in notable increases across all impact categories for both PHEV-40 and EV batteries; therefore, future battery designs should focus on increasing the battery lifetime, in order to reduce overall impacts.

- **Reduce cobalt and nickel material use.** These metals showed higher toxicity impacts; specifically, non-cancer and cancer impact potential. Therefore, reducing the use of and/or exposure to these materials in the upstream, manufacturing, and EOL stages would be expected to reduce the overall potential toxicity impacts.

- **Reduce the percentage of metals by mass.** Metals were found to be a key driver of environmental and toxicity impacts--especially those found in the passive cooling system, battery management system, pack housing, and casing, which were strong contributors to impacts. Accordingly, reducing the use of metals by mass, in these components, in particular, should reduce the overall life-cycle impacts of the battery systems.

- **Incorporate recovered material in the production of the battery.** Given the off-set of impacts from the use of recovered materials--as opposed to virgin materials (especially metals)--in the EOL stage, impacts can be reduced if battery manufacturers work with recyclers to maximize the use of secondary materials in the manufacture of new batteries.

- **Use a solvent-less process in battery manufacturing.** The solvent-less process was found to have lower energy use and lower potential environmental and health impacts.

- **Reassess manufacturing process and upstream materials selection to reduce primary energy use for the cathode.** The choice of the active material for the cathode, and the cathode manufacturing process itself, contributed to higher impacts across the categories. Therefore, manufacturers can reduce impacts by carefully considering the choice of active material, and assessing their manufacturing process for energy efficiency gains.

- **Produce the SWCNT anode more efficiently for commercialization.** Given the fact that the cradle-to-gate energy use and associated impacts of the SWCNT anode, as currently manufactured, are orders of magnitude greater than the battery grade graphite anode, SWCNT anode laboratory research that focuses on lowering the energy intensity of manufacturing processes, in tandem with improving technology performance, will help to improve the overall environmental profile of the technology before it is commercialized.

These opportunities for improving the environmental profile of automotive Li-ion batteries have the potential for reducing a significant amount of environmental impacts, given that advanced batteries are an emerging and growing technology. This study demonstrates how the life-cycle impacts of an emerging technology and novel application of nanomaterials (i.e., the SWCNT anode) can be assessed before the technology is mature, and provides a benchmark for future life-cycle assessments of this technology. Identifying opportunities for reducing environmental and human health impacts throughout the life cycle of the Li-ion battery should be done on a continuous basis, as the technology evolves and the market share for electric vehicles expands.

4.8 Ideas for Further Research

This study strives to provide battery manufacturers, suppliers, recyclers, the broader scientific community, policymakers, and the general public with a scientifically sound and accurate assessment of the likely life-cycle impacts of high energy density lithium-ion batteries used in vehicle applications and next-generation nanomaterials for use in anodes (i.e., SWCNTs). The data gaps and uncertainties described throughout the report yield a roadmap for future areas of research that will further strengthen the advanced battery industry and public's ability to assess the strengths and weaknesses of these technologies, as well as where they stand vis a vis alternative modes of transportation. Below, we describe seven areas that we believe would greatly enhance the body of knowledge surrounding the life-cycle impacts of these batteries, as follows:

- We found that energy use for the processes necessary for component and battery manufacture was highly uncertain, and possibly a substantial contributor to pre-use stage life-cycle impacts. Part of the uncertainty was due to the fact that we were only able to obtain one set of primary energy data for component and battery production. Future research into electricity and fuel use should take into account the highly variable manufacturing methods, including those that use water and those that operate without solvent.

- In addition to energy, the study found that upstream materials have the potential for substantial occupational impacts. Cobalt, in particular, was flagged as a toxic upstream material that presents potential occupational non-cancer hazards, due to its demonstrated toxicity in mammalian toxicological studies. The lithium chloride brine also showed up as a driver of occupational impacts, due to the considerable input quantities. Research that clarifies the actual potential for exposure, in the case of cobalt, and elements that contribute to toxicity, in the case of complex lithium chloride brines from saline lakes, would be helpful in understanding these potential impacts.

- Research into energy use should also strive to capture differences in energy use during manufacturing across battery chemistries and sizes, so that it is possible to make reasonable estimates of the changes over time, as a larger market share is established for various battery and vehicle types. This study was not able to examine many differences specifically associated with battery chemistry and battery size, and many of our assumptions were predicated on there being little to no difference across these variables:

  - All batteries were assumed to yield the same electricity and fuel efficiency during the use stage, despite differences in mass;
  - Within the battery size, all were assumed to use sub-systems of the same type and mass (e.g., passive cooling system, battery management system); and
  - PHEV batteries were assumed to be a linearly scaled-down version of the EV batteries, including the sub-systems.

  Future research could help correct and ground assumptions realistically, based on actual manufacturing and use stage data.

- One of the most important of the chemistry and size-specific assumptions involves the battery lifetime. This study found a number of impact categories to be highly sensitive to changes in battery lifetime, which was held constant across chemistry and battery type. We believe this assumption may not hold, given documented differences in the number of cycles that the various chemistries can tolerate. Future research might strive to more realistically characterize the changes in lifetime across chemistries, and differences between EV and PHEV-40 batteries.
- The biggest contributor to most impact categories—larger in most cases than the upstream, and component and battery manufacturing stages combined—was the electricity grid. The sensitivity analysis conducted in the study showed that distinctive patterns emerged when electricity was derived primarily from coal (Illinois smart charging scenario), versus when it was derived primarily from natural gas (WECC and ISO-NE unconstrained charging). However, we did not attempt to estimate the changes to the grid that would be expected to result from large increases in demand from the increased use of PHEVs and EVs. These changes might include the building of new electricity storage systems to smooth consumption, use of a larger proportion of renewable sources of energy, such as wind and solar, and economic and policy-associated changes to the trajectory of traditional electricity generation facilities (e.g., mothballing of older coal plants and development of new control technologies).
- Because the market for recovered and recycled material from lithium-ion batteries is not well developed for large battery packs, we assumed an optimistic scenario for the reuse and recycling of materials, essentially modeling all recovered materials as being directly reinserted into the applicable commodity market and displacing virgin materials. Further research on the eventual disposition of recovered and recycled materials would allow manufacturers, recyclers, and the scientific community to better understand the benefits and detriments of current recycling technologies. Such research would also help characterize the extent to which secondary material markets might come to substitute for virgin mined material. This would be especially valuable for the rare and strategically important metals used in battery production.
- Finally, given the emerging nanotechnology applications for Li-ion batteries, and the fact that these technologies are currently undergoing commercialization, additional research on the materials should continue to be conducted to ensure that upstream impacts (e.g., energy use and toxicity) do not outweigh benefits gained in the use stage (e.g., increased energy density).

As noted above, there are many opportunities for further research on the potential impacts and benefits of Li-ion batteries for vehicles, especially given that it is an emerging and growing technology. This study provides a benchmark for future research of this technology, and for identifying additional opportunities for reducing environmental and human health impacts throughout the life cycles of these battery systems.

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Appendix A – Single-Walled Carbon Nanotube Toxicity Memorandum

Date	February 24, 2011
To	Kathy Hart, EPA/OPPT, Mary Ann Curran, EPA/ORD
From	Jay Smith and Shanika Amarakoon, Abt Associates Inc.
Subject	Determination of a toxicity value for single-walled carbon nanotubes (SWCNTs)

Due to their unique electrical, thermal, and mechanical properties, single-walled carbon nanotubes (SWCNTs) are being embedded in an increasing number of consumer and manufactured products. These properties are the reason that an anode containing SWCNTs is being developed for possible future use in Li-ion batteries, and will be evaluated in the Lithium-ion Batteries and Nanotechnology for Electric Vehicles Partnership Life-Cycle Assessment (LCA) study. The following memorandum presents Abt's progress to date in determining an appropriate toxicity value for SWCNTs, and asks for inputs from EPA technical staff so that the process can move forward. Below we provide: (1) a summary of available literature related to carbon nanotube (CNT) toxicity and exposure potential, (2) our process and rationale for toxicity value selection, and (3) proposed next steps in the review and finalization of an appropriate toxicity value.

A.1 Literature Review of CNT Toxicity

There are two main limitations affecting the choice of appropriate occupational and public hazard values for SWCNTs: (1) the dearth of vetted toxicity values available from reputable institutions whose recommendations are preceded by a rigorous peer review process, and (2) the heavy focus in the literature on the toxicity of multi-walled carbon nanotubes (MWCNTs), which differ in macromolecular structure from SWCNTs. Despite these limitations, there is an abundance of literature addressing *in vivo* and *in vitro* carbon nanotube (CNT) toxicity, from 2004 onwards. This literature is described in detail below.

A.1.1 *In vitro* impacts

Reported *in vitro* impacts have by and large involved some form of cytotoxicity, or toxicity to cells. In mouse lung macrophage tissue, the adverse cell response to SWCNTs and MWCNTs was observed to be similar to that seen with exposure to chrysotile asbestos (Murr et al., 2005). The cytotoxic effects of rope-like aggregations of SWCNTs on human mesothelioma tumor cells were demonstrated to be greater in magnitude than those of asbestos (Wick et al., 2007). In alveolar macrophage cells, SWCNTs were found to be more cytotoxic than MWCNTs by mass (Jia et al., 2005). MWCNTs were observed to be more cytotoxic than metal oxide nanoparticles, such as titanium and aluminum oxide (Simon-Deckers et al., 2008). Different properties of the CNTs, such as their structure, length, level of aggregation, chemical modification of sidewalls, surface area, level of oxidation, and manufacturing method all influence the degree of cytotoxicity demonstrated by the material (Magrez et al., 2006; Sayes et al., 2006; Kayat et al., 2011). Taken together, the *in vitro* findings emphasize the potential for a high degree of chemical hazard.

A.1.2 *In vivo* impacts

Tests conducted on test animals have shown mixed results, but have also demonstrated that serious adverse pulmonary effects are a potential outcome of exposure to these materials. Acute intratracheal and intrapharyngeal instillation of SWCNTs has been shown to cause pulmonary granulomas, or microscopic nodules, along with inflammation, fibrosis, and other toxicological changes in the lungs of mice and rats (Warheit et al., 2004; Muller et al., 2005; Lam et al., 2006). The association with asbestos and fibrotic toxicological endpoints has been explored using *in vivo* animal models. Injection of MWCNTs into the abdominal cavities of mice has been shown to result "in asbestos-like, length-dependent, pathogenic behaviour" (Poland et al., 2008). In addition to pulmonary impacts, some evidence of cardiovascular effects due to SWCNT exposure has been observed in mice (Li et al., 2006). Evidence of the potential for harm is not always clear cut. Other *in vivo* studies have shown no association between exposure to CNTs and adverse health endpoints, including asbestos-like endpoints. In one study, no acute or chronic toxicity was seen after 4 months of direct bloodstream injection of SWCNTs in mice (Schipper et al., 2008). In another study assessing the carcinogenicity of MWCNTs, no increase in mesothelioma (i.e., a disease typically associated with chronic exposure to asbestos) was seen over 2 years in rats that were injected in the body cavity (Muller et al., 2009).

Of the existing *in vivo* studies, some have yielded results that could be used to derive an effect threshold for MWCNTs, though none for SWCNTs. In a subchronic MWCNT inhalation study in rats, the no adverse effect level (NOAEL) for multiple pulmonary endpoints was 0.1 mg/m^3, and the lowest adverse effect level (LOAEL) was 0.4 mg/m^3, at which exposure-related lesions were observed (Pauluhn, 2010). A slightly earlier study in the same animal model resulted in observations of minor lung inflammation, even at 0.1 mg/m^3 (Ma-Hock et al., 2009). In mice, MWCNT exposures at particle concentrations of 0.3 mg/m^3 and higher caused immunosuppression after 14 days, as shown by elevated spleen enzyme levels (Mitchell et al., 2007). These three studies are important in that they demonstrate dose-related injury via the existing physiological mechanism of inhalation, as opposed to intra-cavity injections or instillations (Warheit, 2009). The National Institute for Occupational Safety and Health used the animal studies reported here to derive a suggested occupational recommended exposure limit (REL) of 0.007 mg CNT/m^3 (NIOSH, 2010). This limit was an 8-hour time-weighted average based on the upper limit of quantitation of current CNT analytical methods, and therefore, would have been lower in the presence of more sensitive analytical methods.

A.2 Selection of Toxicity Value

In choosing a toxicity value suitable for use in the calculation of an occupational hazard value, a number of factors need to be taken into account:

- First, the similarity of the material analyzed to the form it will be used in the production of lithium-ion batteries for electric vehicles should be considered. In this case, the toxicity values all correspond to MWCNTs, rather than SWCNTs. There are likely differences in toxicity between the two nanotube types; however, the exact magnitude or direction of the difference is unknown. Although this is a substantial source of uncertainty, the importance of placing the hazard of these novel materials into the context of occupational hazard over the overall battery supply chain outweighs the potential lack of quantitative accuracy at the screening level.
- In addition, the reproducibility of the toxicity value results should be factored into the level of confidence in the selection. Two studies using rats generated results that were similar in magnitude (Ma-Hock et al., 2009; Pauluhn, 2010). One found no adverse effect to MWCNT exposure at 0.1 mg/m^3, while the other found minor lung tissue inflammation at this concentration. The study in mice did not find a NOAEL, and the LOAEL was similar to that seen in rats. Thus, even with the small sample size, the degree of reproducibility in animal models is relatively good.
- Finally, the length of exposure in the toxicological studies should map as closely as possible with chronic (>1 year) exposure to the material that the hazard values are supposed to represent. The rodent studies mentioned above are subchronic, and therefore, represent shorter periods of exposure than is typically used to inform the derivation of chronic toxicity values (e.g., two-year

> studies in rats). The standard EPA risk policy in such a case is to apply a factor to make up for the uncertainty in extrapolating from sub-chronic to chronic exposures. It is generally assumed that chronic non-cancer toxicity thresholds will be lower than subchronic thresholds, due to the increased length of exposure.

Taking the rat NOAEL of 0.1 mg MWCNT/m^3 from the 2010 Pauluhn study, we divide by an uncertainty factor of 100 to address the MWCNT to SWCNT extrapolation, the subchronic to chronic extrapolation, and the uncertainty surrounding the minor lung inflammation seen at the same concentration in the 2009 Ma-Hock study (factors of $10^{1/2} \times 10 \times 10^{1/2}$, respectively). **Accordingly, our selected non-cancer toxicity value—which is a synthetic (non-observed) chronic NOAEL in the most sensitive species, rats—is 0.001 mg SWCNT/m^3.** This is in the range of NIOSH's recommended occupational REL value (0.007 mg CNT/m^3), which has been adjusted to compensate for 40-hour weekly exposure duration rather than constant exposure, and insensitive analytical methods of detection. We apply a generic cancer value of 1 to SWCNTs, due to the sparseness of data on carcinogenic potential.

In terms of the actual potential for CNT exposure in the workplace or environment, little quantitative information is available, though there is no reason to assume that exposure cannot take place during the production or end-of-life stages of the lithium-ion battery life cycle. Release and exposure during the use phase is unlikely given the batteries are encapsulated within a sealed case (Köhler et al., 2007). A laboratory and field study of occupational SWCNT release showed that the agitation of the material would cause suspended concentrations of less than 0.53 mg SWCNT/m^3, and glove loadings of 0.2 to 6 mg/hand (Maynard et al., 2004; Helland et al., 2007). This study also demonstrated variable behavior in nanotubes produced using different manufacturing methods. Those produced using laser ablation resulted in a more aggregated material and lower air concentrations. However, those produced using high-pressure carbon monoxide resulted in a material that was more conducive to suspension in air.

With regard to transport in the environment, biomagnification up the food chain and atmospheric transport are possible components of complete human and ecological exposure pathways. CNTs are very persistent, insoluble in water in pure form, and lipophilic. As a result, these chemicals have significant potential to increase in tissue concentration as one moves up the food chain through biomagnification, eventually resulting in dietary exposure in humans (Lam et al., 2004; Helland et al., 2007). A risk assessment based on emissions during the CNT life cycle in Switzerland assumed that CNTs were likely to enter the environment via air emissions and landfilling (Mueller and Nowack, 2008). This study also found that even using conservative assumptions for fate, transport, and exposure, the expected concentration of the CNTs in air, water, and soil was many orders of magnitude lower than concentrations of toxicological concern. No other studies were found that estimated concentrations in environmental media or quantified human and ecological exposure. As a result, there is little background information on the potential for the general public to be exposed to emitted CNTs.

A.3 EPA Response

Based on EPA's review of the memorandum above, EPA indicated that the toxicity value selected by Abt Associates was within the range of acceptable values, and likely on the more conservative end of that range (Partnership, 2011).

A.4 Appendix A References

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