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.

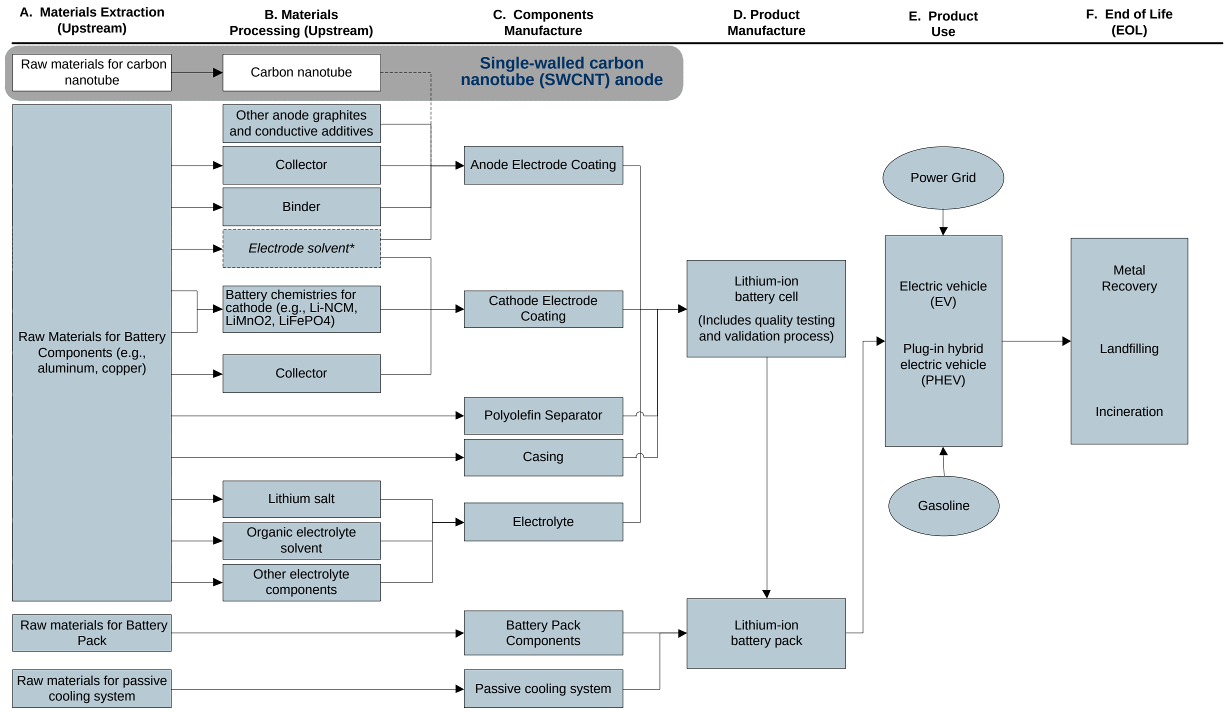

Figure 1. Generic Process Flow Diagram for Li-ion Battery for Vehicles

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.

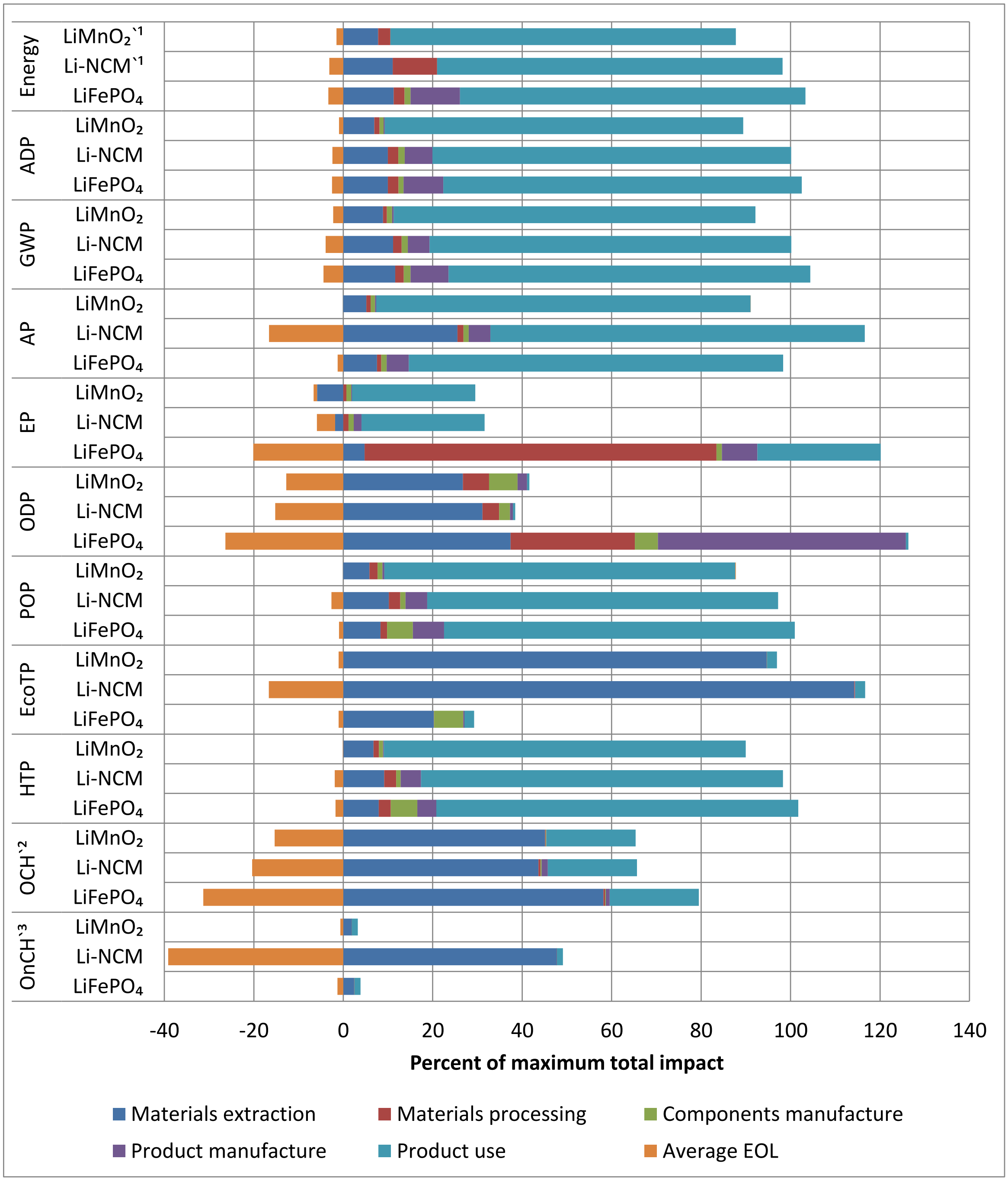

Figure 2. Life-Cycle Impact Assessment Results by Battery Chemistry and Stage for EV Batteries

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.

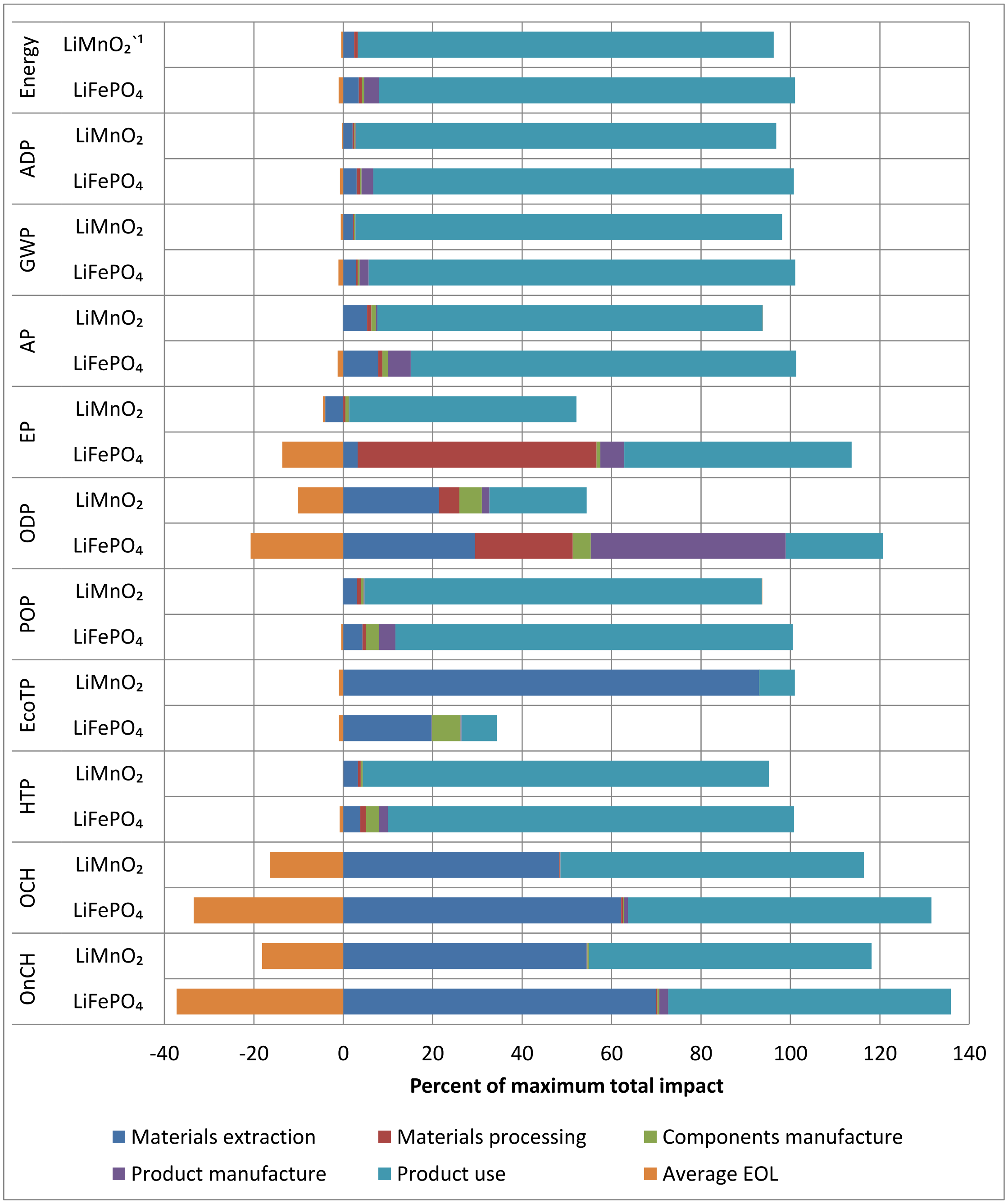

Figure 3. Life-Cycle Impact Assessment Results by Battery Chemistry and Stage for PHEV Batteries

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.