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).

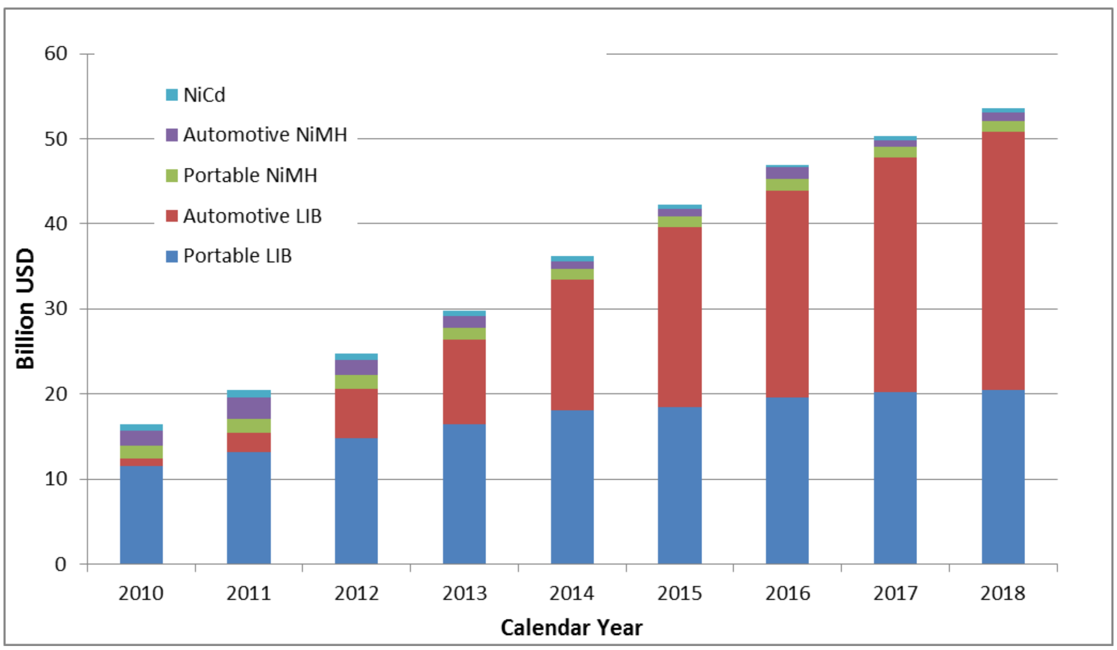

Figure 1-1. Worldwide Rechargeable Battery Demand (Billion USD/Calendar Year) (Takeshita, 2010)

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.

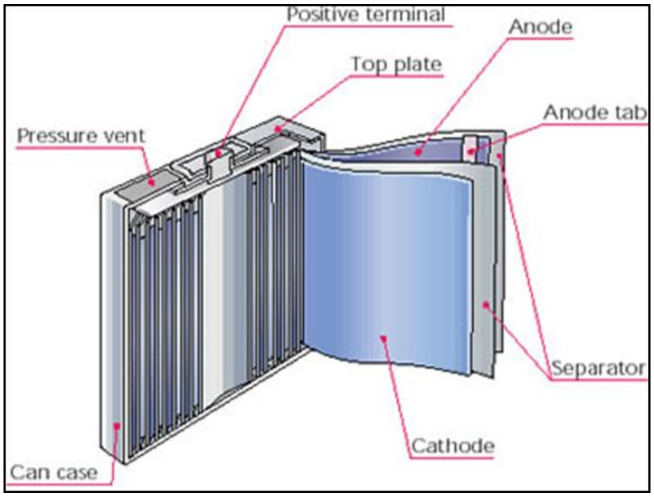

Figure 1-2. Illustration of Prismatic Li-ion Battery Cell (NEC/TOKIN, 2009)

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.

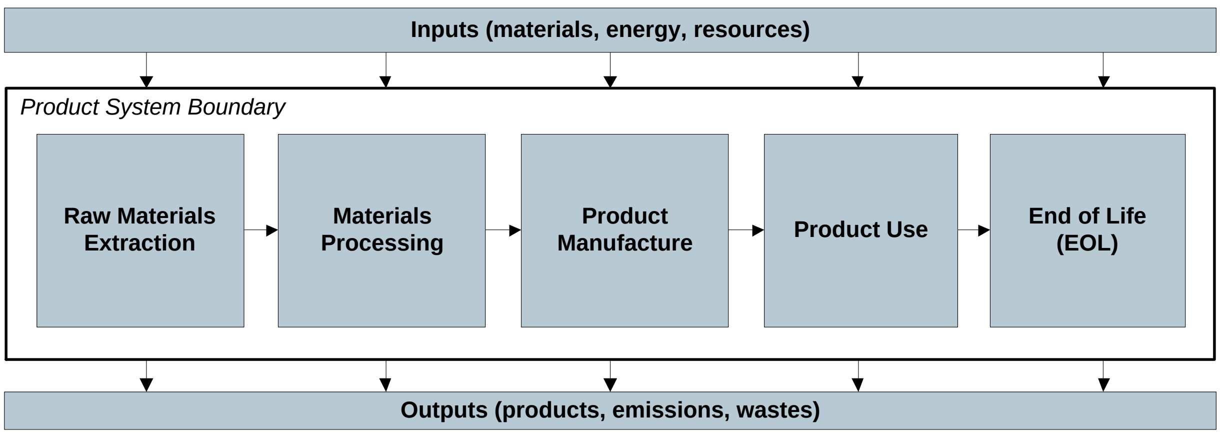

Figure 1-3. Life-Cycle Stages of the Product System

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

[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.

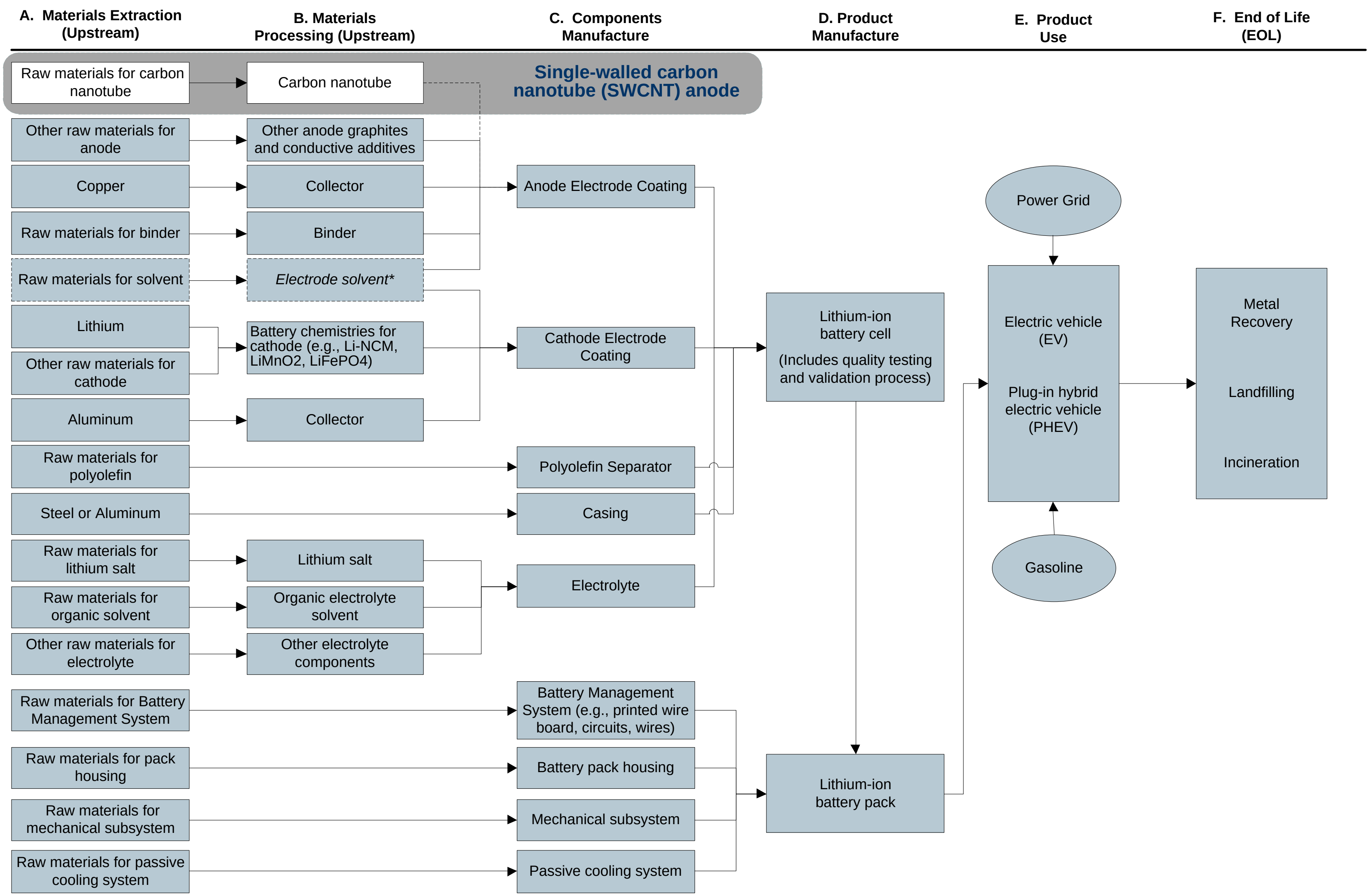

Figure 1-4. Generic Process Flow Diagram for the Manufacture of Li-ion Batteries for Vehicles

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.