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.