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.