

3. Life-Cycle Impact Assessment

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

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

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

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

The LCIA methodology used in this study began with an assessment of the overall material and primary energy input flows to the automotive lithium-ion battery life cycles (see Section 3.1). We then calculated life-cycle impact category indicators, using established quantitative methods for a number of traditional categories, such as global warming, acidification, ozone depletion, and photochemical oxidation (smog), as well as relative category indicators for potential impacts on human health and aquatic ecotoxicity – impacts not always considered in traditional LCIA methodology (see Section 3.2).

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

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

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

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

3.1 Overview of Material Use and Primary Energy Consumption

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

3.1.1 Major Material Flows

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

Table 3-1. Major Material Input Flows and Drivers

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

Notes: ¹¹ The lithium brine modeled here is assumed to be 0.15% lithium chloride by mass.

As presented in the table, the lithium brine extracted from saline lakes in Chile is by far the largest mass input, after water and air. Calcium carbonate, or limestone, is associated with the brine, as it is the other major feedstock in the synthesis of lithium carbonate. Copper ore and bauxite are the sources of copper and aluminum, respectively. Copper is used in the battery electronics, both in wiring and on printed wire (circuit) board. Aluminum is the primary material in the passive cooling system, and is used in cell/pack containers. Zinc ore is associated with steel production, and phosphorus ore is associated with both electrolyte salt and LiFePO₄ production. The major fuels, in decreasing order of mass, are hard coal, crude oil, natural gas, and lignite. The average U.S. grid is comprised of approximately 45% coal-derived power and 25% natural gas-derived power, explaining most of the fuel use.

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

3.1.2 Primary Energy Consumption

Primary energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. “Primary” is used here to describe energetic materials or flows found in nature that have not been subjected to transformation. Thus, it represents system inputs from both raw fuels and other forms of energy. Primary energy can be thought of as differing from secondary in that it is not the measure of energy “from the plug” at a plant, but is rather the energy used originally to produce this electricity for the grid. Fuel inputs are converted from mass to energy units using the fuel’s heat value and the density as shown below:

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

where:

- ISE_E equals the impact score for energy use (MJ) per functional unit;
- Amt_E equals the inventory input amount of electrical energy used (MJ) per functional unit;
- Amt_F equals the inventory input amount of fuel used (kg) per functional unit;
- H equals the heat value of fuel (MJ/L); and
- D equals the density of fuel (kg/L).

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

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

Table 3-2. Primary Energy Use by Battery Component (MJ/kWh Capacity)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	1.86E+02	21.4%	1.68E+02	8.6%	1.52E+02	6.1%	1.69E+02	9.5%
Cathode	4.26E+02	49.0%	6.45E+02	32.9%	4.62E+02	18.5%	5.11E+02	28.8%
Separator	1.69E+01	1.9%	0.00E+00	0.0%	3.76E+01	1.5%	1.81E+01	1.0%
Electrolyte	6.31E+01	7.3%	2.48E+02	12.6%	1.40E+02	5.6%	1.50E+02	8.5%
Cell casing	2.68E+01	3.1%	1.58E+02	8.1%	3.39E+02	13.6%	1.75E+02	9.8%
Cell manufacture	2.83E+01	3.3%	0.00E+00	0.0%	0.00E+00	0.0%	9.42E+00	0.5%
<i>Cell subtotal</i>	<i>7.47E+02</i>	<i>86.0%</i>	<i>1.22E+03</i>	<i>62.1%</i>	<i>1.13E+03</i>	<i>45.2%</i>	<i>1.03E+03</i>	<i>58.1%</i>
BMS	4.37E+01	5.0%	4.37E+01	2.2%	4.37E+01	1.7%	4.37E+01	2.5%
Pack case/housing	6.89E+01	7.9%	6.89E+01	3.5%	1.65E+02	6.6%	1.01E+02	5.7%
Pack manufacture	8.95E-01	0.1%	6.21E+02	31.6%	1.15E+03	46.0%	5.91E+02	33.2%
Transportation	8.46E+00	1.0%	1.02E+01	0.5%	9.63E+00	0.4%	9.45E+00	0.5%
Total	8.69E+02	100%	1.96E+03	100%	2.50E+03	100%	1.78E+03	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity; MJ = megajoules of primary energy

Table 3-3. Primary Energy Use by Life-Cycle Stage for EV Batteries (MJ/km)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	1.69E-01	8.9%	2.40E-01	11.2%	2.44E-01	10.9%	2.18E-01	10.4%
Materials processing	5.91E-02	3.1%	2.15E-01	10.1%	5.31E-02	2.4%	1.99E-01	9.5%
Component manuf.					2.87E-02	1.3%		
Product manuf.					2.40E-01	10.7%		
Product use	1.68E+00	88.0%	1.68E+00	78.7%	1.68E+00	74.7%	1.68E+00	80.1%
<i>Subtotal</i>	<i>1.91E+00</i>	<i>100%</i>	<i>2.13E+00</i>	<i>100%</i>	<i>2.24E+00</i>	<i>100%</i>	<i>2.09E+00</i>	<i>100%</i>
Average EOL	-3.25E-02	-1.7%	-6.74E-02	-3.2%	-7.27E-02	-3.2%	-5.75E-02	-2.7%
Total	1.87E+00	98.3%	2.06E+00	96.8%	2.17E+00	96.8%	2.04E+00	97.3%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); MJ = megajoules of primary energy

Table 3-4. Primary Energy Use by Life-Cycle Stage for PHEV Batteries (MJ/km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	4.96E-02	2.5%	7.08E-02	3.4%	6.02E-02	3.0%
Materials processing	1.72E-02	0.9%	1.54E-02	0.7%	5.53E-02	2.7%
Components manuf.			8.34E-03	0.4%		
Product manuf.			6.97E-02	3.4%		
Product use	1.90E+00	96.6%	1.90E+00	92.1%	1.90E+00	94.3%
<i>Subtotal</i>	<i>1.97E+00</i>	<i>100%</i>	<i>2.07E+00</i>	<i>100%</i>	<i>2.02E+00</i>	<i>100%</i>
Average EOL	-9.74E-03	-0.5%	-2.11E-02	-1.0%	-1.54E-02	-0.8%
Total	1.96E+00	99.5%	2.05E+00	99.0%	2.00E+00	99.2%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); MJ = megajoules

Outside of the use stage, it is clear that energy use is primarily incurred during the materials extraction stage. This is mostly due to aluminum ingot production for the passive cooling system and cathode. In addition, the production of soda (Na₂CO₃), and the synthesis of lithium carbonate for the cathode and electrolyte, are also substantial contributors. In the case of the Li-NCM and LiFePO₄ chemistries, plastic resin production results in a fairly large amount of primary energy use (about 10% of the total stage-specific value).

Higher energy use is also seen in the product manufacture of the Li-NCM and LiFePO₄ chemistries. In the case of both batteries, this is attributable to the fuels that generate the electricity required to manufacture the battery pack, as well as the fuels used directly during pack production. For the LiFePO₄ battery, the purification of process water used during battery production is also a substantial contributor.

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

3.2 Impact Category Results

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

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

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

3.2.1 Abiotic Resource Depletion

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

$$EF_{ADP} = \frac{DR/R^2}{DR_{Sb}/R_{Sb}^2}$$

where:

EF_{ADP} equals the abiotic depletion potential of material (unitless);

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

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

DR_{Sb} equals the global extraction rate of the reference material, antimony (kg/yr); and

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

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

$$IS_{AD} = EF_{ADP} \cdot Amt$$

where:

IS_{AD} equals the abiotic depletion impact score for the material (kg antimony-equivalents) per functional unit; and

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

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

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

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
Component	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	8.79E-02	23.9%	8.01E-02	9.0%	7.35E-02	7.3%	8.05E-02	10.7%
Cathode	1.65E-01	44.9%	2.64E-01	29.8%	2.04E-01	20.4%	2.11E-01	28.1%
Separator	7.38E-03	2.0%	0.00E+00	0.0%	1.64E-02	1.6%	7.94E-03	1.1%
Electrolyte	2.76E-02	7.5%	1.10E-01	12.4%	6.06E-02	6.0%	6.61E-02	8.8%
Cell casing	1.29E-02	3.5%	7.61E-02	8.6%	1.17E-01	11.7%	6.88E-02	9.1%
Cell manufacture	8.87E-03	2.4%	0.00E+00	0.0%	0.00E+00	0.0%	2.96E-03	0.4%
<i>Cell subtotal</i>	<i>3.10E-01</i>	<i>84.3%</i>	<i>5.31E-01</i>	<i>59.9%</i>	<i>4.72E-01</i>	<i>47.1%</i>	<i>4.37E-01</i>	<i>58.2%</i>
BMS	2.01E-02	5.5%	2.01E-02	2.3%	2.01E-02	2.0%	2.01E-02	2.7%
Pack case/housing	3.31E-02	9.0%	3.31E-02	3.7%	7.94E-02	7.9%	4.85E-02	6.5%
Pack manufacture	2.81E-04	0.1%	2.97E-01	33.5%	4.26E-01	42.5%	2.41E-01	32.1%
Transportation	4.07E-03	1.1%	4.93E-03	0.6%	4.63E-03	0.5%	4.54E-03	0.6%
Total	3.67E-01	100%	8.86E-01	100%	1.00E+00	100%	7.52E-01	100%

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

Overall, the LiFePO₄ battery shows the greatest abiotic resource depletion impacts, compared to the other battery chemistries, mainly due to higher impacts for the cell casing and pack housing and manufacture. For the other chemistries, the impacts seem to be primarily attributable to the cathode in the LiMnO₂ battery, or battery pack manufacture in the Li-NCM batteries. Extraction of the raw materials for the cathode (e.g., aluminum and lithium) contributes to the greatest abiotic resource depletion impacts for LiMnO₂ batteries. For the Li-NCM and LiFePO₄, the pack manufacture contributes to resource depletion mainly due to electricity and fuel consumption.

The difference between the battery chemistries is partly due to inconsistent data between the chemistries. In the case of the LiMnO₂ battery chemistry, detailed information on the energy consumption during the manufacture of the battery pack was made available. This same information was not available for the Li-NCM battery pack manufacture; therefore, we averaged the fuel and electricity use of the LiMnO₂ with that of the LiFePO₄ battery pack, which was reported in Majeau-Bettez et al. (2011).

Table 3-6. Abiotic Resource Depletion Potential by Life-Cycle Stage for EV Batteries (kg Sb-Eq./km)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	6.97E-05	7.7%	1.00E-04	9.9%	1.00E-04	9.7%	9.01E-05	9.2%
Materials processing	1.18E-05	1.3%	2.38E-05	2.4%	2.38E-05	2.3%	1.98E-05	2.0%
Component manuf.	8.98E-06	1.0%	1.41E-05	1.4%	1.15E-05	1.1%	1.15E-05	1.2%
Product manuf.	2.74E-06	0.3%	6.25E-05	6.2%	8.92E-05	8.7%	5.15E-05	5.3%
Product use	8.06E-04	89.6%	8.06E-04	80.1%	8.06E-04	78.2%	8.06E-04	82.3%
<i>Subtotal</i>	<i>9.00E-04</i>	<i>100%</i>	<i>1.01E-03</i>	<i>100%</i>	<i>1.03E-03</i>	<i>100%</i>	<i>9.79E-04</i>	<i>100%</i>
Average EOL	-9.58E-06	-1.1%	-2.45E-05	-2.4%	-2.53E-05	-2.5%	-1.98E-05	-2.0%
Total	8.90E-04	98.9%	9.82E-04	97.6%	1.01E-03	97.5%	9.59E-04	98.0%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg Sb-Eq. = kilograms of antimony equivalent abiotic resource depletion through extraction

Table 3-7. Abiotic Resource Depletion Potential by Life-Cycle Stage for PHEV Batteries (kg Sb-Eq./km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	2.04E-05	2.2%	2.91E-05	3.0%	2.47E-05	2.6%
Materials processing	3.43E-06	0.4%	6.89E-06	0.7%	5.16E-06	0.5%
Components manuf.	2.62E-06	0.3%	3.34E-06	0.3%	2.98E-06	0.3%
Product manuf.	7.94E-07	0.1%	2.59E-05	2.6%	1.33E-05	1.4%
Product use	9.12E-04	97.1%	9.12E-04	93.3%	9.12E-04	95.2%
<i>Subtotal</i>	<i>9.39E-04</i>	<i>100%</i>	<i>9.77E-04</i>	<i>100%</i>	<i>9.58E-04</i>	<i>100%</i>
Average EOL	-2.90E-06	-0.3%	-7.33E-06	-0.7%	-5.11E-06	-0.5%
Total	9.36E-04	99.7%	9.70E-04	99.3%	9.53E-04	99.5%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg Sb-Eq. = kilograms of antimony equivalent abiotic resource depletion through extraction

As shown in Tables 3-6 and 3-7, in the use stage, ADP is driven by consumption of electricity for the EV batteries, and gasoline for the PHEV batteries. As discussed above, materials extraction is driving the non-use-stage impacts. Top contributing processes across the three battery chemistries include aluminum production for the passive cooling system and cathode, extraction of soda (Na₂CO₃) used in the production of lithium carbonate for the cathode and lithium electrolyte salt, and resins used in the cell and battery pack casing.

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

3.2.2 Global Warming Impacts

The build-up of carbon dioxide (CO₂) and other greenhouse gases in the atmosphere may generate a “greenhouse effect” of rising temperature and climate change. Global warming potential (GWP) refers to the warming, relative to CO₂, that chemicals contribute to this effect by trapping the Earth's heat. The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change, compared to the reference chemical CO₂; therefore, GWPs are in units of CO₂ equivalents. GWPs have been published for known global warming chemicals within differing time horizons. The LCIA methodology employed here used GWPs from the EPA's TRACI 2.0 model. Although LCA does not necessarily include a temporal component of the inventory, impacts from releases during the life cycle of lithium-ion automotive batteries are expected to be well within the 100 year time frame.

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

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

where:

IS_{GW} equals the global warming impact score for the greenhouse gas (kg CO₂-equivalents) per functional unit;

EF_{GWP} equals the GWP equivalency factor for the greenhouse gas (CO₂-equivalents, 100-year time horizon); and

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

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

Table 3-8. Global Warming Potential by Battery Component (kg CO₂-Eq./kWh Capacity)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
Component	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	1.23E+01	19.5%	7.81E+00	6.5%	9.61E+00	6.4%	9.92E+00	8.9%
Cathode	3.29E+01	51.9%	4.86E+01	40.3%	3.27E+01	21.6%	3.81E+01	34.1%
Separator	7.62E-01	1.2%	0.00E+00	0.0%	1.70E+00	1.1%	8.19E-01	0.7%
Electrolyte	3.73E+00	5.9%	1.46E+01	12.1%	9.69E+00	6.4%	9.35E+00	8.4%
Cell casing	7.68E-01	1.2%	4.53E+00	3.8%	2.50E+01	16.5%	1.01E+01	9.0%
Cell manufacture	1.77E+00	2.8%	0.00E+00	0.0%	0.00E+00	0.0%	5.91E-01	0.5%
<i>Cell subtotal</i>	<i>5.23E+01</i>	<i>82.4%</i>	<i>7.56E+01</i>	<i>62.7%</i>	<i>7.87E+01</i>	<i>52.0%</i>	<i>6.89E+01</i>	<i>61.6%</i>
BMS	4.14E+00	6.5%	4.14E+00	3.4%	4.14E+00	2.7%	4.14E+00	3.7%
Pack case/housing	6.26E+00	9.9%	6.26E+00	5.2%	7.43E+00	4.9%	6.65E+00	6.0%
Pack manufacture	5.61E-02	0.1%	3.38E+01	28.0%	6.02E+01	39.8%	3.14E+01	28.1%
Transportation	6.62E-01	1.0%	8.02E-01	0.7%	7.54E-01	0.5%	7.40E-01	0.7%
Total	6.34E+01	100%	1.21E+02	100%	1.51E+02	100%	1.12E+02	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity; kg CO₂-Eq. = kilograms of carbon dioxide equivalent greenhouse gas emissions

Across the battery chemistries, the GWP impacts attributable to the cathode are substantial, ranging from approximately 21.6 to 51.9%. In the case of the Li-NCM and LiFePO₄ chemistries, the battery pack is also a substantial contributor. The absolute impact values are significantly higher for the Li-NCM and LiFePO₄ batteries, due to higher energy use in the production of the cathode, electrolyte, and battery pack. In addition, the use of a solvent-less process by the manufacturer may contribute to the fact that the LiMnO₂ battery chemistry uses less energy and has smaller global warming impacts.

Table 3-9. Global Warming Potential by Life-Cycle Stage for EV Batteries (kg CO₂-Eq./km)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
Life-Cycle Stage	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	1.32E-02	9.7%	1.66E-02	11.1%	1.73E-02	11.1%	1.57E-02	10.7%
Materials processing	1.27E-03	0.9%	2.83E-03	1.9%	2.85E-03	1.8%	2.32E-03	1.6%
Component manuf.	1.76E-03	1.3%	2.06E-03	1.4%	2.23E-03	1.4%	2.02E-03	1.4%
Product manuf.	5.16E-04	0.4%	7.17E-03	4.8%	1.26E-02	8.1%	6.77E-03	4.6%
Product use	1.20E-01	87.8%	1.20E-01	80.8%	1.20E-01	77.4%	1.20E-01	81.8%
<i>Subtotal</i>	<i>1.37E-01</i>	<i>100%</i>	<i>1.49E-01</i>	<i>100%</i>	<i>1.55E-01</i>	<i>100%</i>	<i>1.47E-01</i>	<i>100%</i>
Average EOL	-3.35E-03	-2.4%	-5.82E-03	-3.9%	-6.57E-03	-4.2%	-5.25E-03	-3.6%
Total	1.34E-01	97.6%	1.43E-01	96.1%	1.49E-01	95.8%	1.42E-01	96.4%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg CO₂-Eq. = kilograms of carbon dioxide equivalent greenhouse gas emissions

Table 3-10. Global Warming Potential by Life-Cycle Stage for PHEV Batteries (kg CO₂-Eq./km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	3.87E-03	2.2%	5.01E-03	2.8%	4.44E-03	2.5%
Materials processing	3.68E-04	0.2%	8.25E-04	0.5%	5.97E-04	0.3%
Components manuf.	5.13E-04	0.3%	6.47E-04	0.4%	5.80E-04	0.3%
Product manuf.	1.50E-04	0.1%	3.66E-03	2.0%	1.91E-03	1.1%
Product use	1.70E-01	97.2%	1.70E-01	94.4%	1.70E-01	95.8%
<i>Subtotal</i>	<i>1.75E-01</i>	<i>100%</i>	<i>1.80E-01</i>	<i>100%</i>	<i>1.77E-01</i>	<i>100%</i>
Average EOL	-1.00E-03	-0.6%	-1.91E-03	-1.1%	-1.45E-03	-0.8%
Total	1.74E-01	99.4%	1.78E-01	98.9%	1.76E-01	99.2%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg CO₂-Eq. = kilograms of carbon dioxide equivalent greenhouse gas emissions

GWP impacts are dominated by the use stage for EV and PHEV batteries. Outside of the use stage, some key contributors from the materials extraction and product manufacture stage include, in decreasing order of magnitude, aluminum production for the passive cooling system and cathode, soda production (Na₂CO₃) for use in lithium salt synthesis, as well as steel production for the battery housing.

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

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

As presented in the figure, while CO₂-equivalent emission differences between PHEV-40 and EV batteries are slight at the coal-heavy end of the scale (Illinois smart charging grid scenario), there is a substantial gap at the U.S. average grid and the natural-gas centric ISO-NE unconstrained marginal grid. At all points along the carbon intensity scale, PHEVs and EVs are estimated to generate lower total GHG emissions over the life cycle of the battery (and vehicle during the use stage) than the ICEV batteries (and vehicles), from Samaras and Meisterling (2008). It should be noted that their estimate does include car production, which adds on the order of 25 g CO₂-equivalent/km to the GWP impacts.

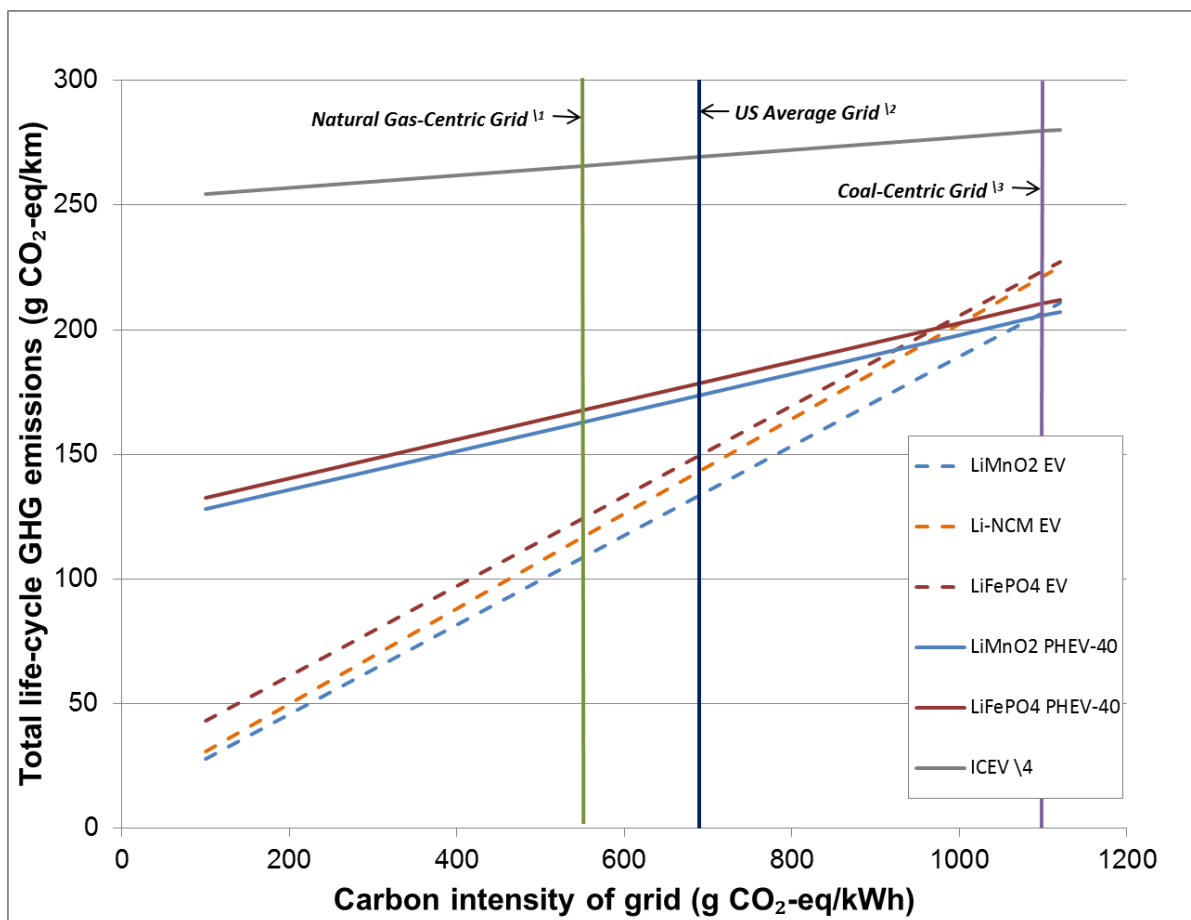


Figure 3-1. GHG Emissions by Carbon Intensity of Electricity Grid

Notes:

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

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

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

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

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

3.2.3 Acidification Potential

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

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

The impact score is calculated by:

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

where:

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

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

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

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

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

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	6.24E+00	34.2%	2.84E+00	3.0%	4.51E+00	11.2%	4.53E+00	8.9%
Cathode	6.43E+00	35.3%	6.73E+01	70.7%	6.97E+00	17.4%	2.69E+01	52.6%
Separator	1.61E-01	0.9%	0.00E+00	0.0%	3.58E-01	0.9%	1.73E-01	0.3%
Electrolyte	8.91E-01	4.9%	3.61E+00	3.8%	2.19E+00	5.5%	2.23E+00	4.4%
Cell casing	6.27E-01	3.4%	3.70E+00	3.9%	5.82E+00	14.5%	3.38E+00	6.6%
Cell manufacture	5.68E-01	3.1%	0.00E+00	0.0%	0.00E+00	0.0%	1.89E-01	0.4%
<i>Cell subtotal</i>	<i>1.49E+01</i>	<i>81.8%</i>	<i>7.74E+01</i>	<i>81.4%</i>	<i>1.98E+01</i>	<i>49.5%</i>	<i>3.74E+01</i>	<i>73.1%</i>
BMS	1.79E+00	9.8%	1.79E+00	1.9%	1.79E+00	4.5%	1.79E+00	3.5%
Pack case/housing	1.28E+00	7.0%	1.28E+00	1.3%	3.56E+00	8.9%	2.04E+00	4.0%
Pack manufacture	1.80E-02	0.1%	1.44E+01	15.1%	1.47E+01	36.6%	9.68E+00	18.9%
Transportation	2.21E-01	1.2%	2.67E-01	0.3%	2.51E-01	0.6%	2.46E-01	0.5%
Total	1.82E+01	100%	9.51E+01	100%	4.01E+01	100%	5.11E+01	100%

Notes: ¹¹ kWh = kilowatt-hour battery capacity; kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

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

Table 3-12. Acidification Potential by Life-Cycle Stage for EV Batteries (kg H+ Mol-Eq./km)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	3.23E-03	5.7%	1.60E-02	21.9%	4.72E-03	7.7%	7.97E-03	12.5%
Materials processing	5.87E-04	1.0%	8.39E-04	1.2%	5.91E-04	1.0%	6.72E-04	1.1%
Component manuf.	6.32E-04	1.1%	7.18E-04	1.0%	7.47E-04	1.2%	6.99E-04	1.1%
Product manuf.	1.67E-04	0.3%	3.03E-03	4.2%	3.09E-03	5.0%	2.10E-03	3.3%
Product use	5.23E-02	91.9%	5.23E-02	71.8%	5.23E-02	85.1%	5.23E-02	82.0%
<i>Subtotal</i>	<i>5.69E-02</i>	<i>100%</i>	<i>7.28E-02</i>	<i>100%</i>	<i>6.14E-02</i>	<i>100%</i>	<i>6.37E-02</i>	<i>100%</i>
Average EOL	6.27E-06	0.0%	-1.04E-02	-14.2%	-7.72E-04	-1.3%	-3.71E-03	-5.8%
Total	5.69E-02	100%	6.24E-02	85.8%	6.06E-02	98.7%	6.00E-02	94.2%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

Table 3-13. Acidification Potential by Life-Cycle Stage for PHEV Batteries (kg H+ Mol-Eq./km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	9.44E-04	3.1%	1.37E-03	4.3%	1.16E-03	3.8%
Materials processing	1.70E-04	0.6%	1.71E-04	0.5%	1.71E-04	0.6%
Components manuf.	1.84E-04	0.6%	2.17E-04	0.7%	2.00E-04	0.7%
Product manuf.	4.85E-05	0.2%	8.95E-04	2.8%	4.72E-04	1.5%
Product use	2.88E-02	95.5%	2.88E-02	91.6%	2.88E-02	93.5%
<i>Subtotal</i>	<i>3.02E-02</i>	<i>100%</i>	<i>3.15E-02</i>	<i>100%</i>	<i>3.08E-02</i>	<i>100%</i>
Average EOL	-5.52E-06	0.0%	-2.24E-04	-0.7%	-1.15E-04	-0.4%
Total	3.01E-02	100%	3.12E-02	99.3%	3.07E-02	99.6%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

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

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

3.2.4 Eutrophication Potential

TRACI 2.0 was also used to determine the potential for eutrophication, or fertilization of surface waters by previously scarce nutrients like nitrogen and phosphorus, from life-cycle emissions. The units of the weighting values in this impact category are nitrogen equivalents per kilogram of emission. Inorganic

emissions that contribute to this impact category include ammonia and other water-soluble nitrogen-containing compounds, phosphate and other water-soluble phosphorus-containing compounds, and biological and chemical oxygen demand.

The impact score is calculated by:

$$IS_{EP} = EF_{EP} \cdot Amt_{EC}$$

where:

IS_{EP} equals the impact score for regional water quality impacts from the chemical (kg nitrogen-equivalents) per functional unit;

EF_{EP} equals the EP equivalency factor for the chemical (kg nitrogen-equivalents); and

Amt_{EC} equals the inventory mass (kg) of the eutrophication-inducing chemical (EC) per functional unit in a wastewater stream released to surface water after treatment, if applicable.

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

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

Table 3-14. Eutrophication Potential by Battery Component (kg N-Eq./kWh)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	1.96E-03	31.2%	1.52E-03	17.8%	1.50E-03	0.7%	1.66E-03	2.2%
Cathode	8.83E-03	140.6%	1.77E-02	206.6%	1.99E-01	87.7%	7.51E-02	98.4%
Separator	1.26E-04	2.0%	0.00E+00	0.0%	2.81E-04	0.1%	1.36E-04	0.2%
Electrolyte	9.66E-04	15.4%	3.07E-03	35.9%	2.15E-03	0.9%	2.06E-03	2.7%
Cell casing	1.42E-04	2.3%	8.35E-04	9.8%	2.00E-03	0.9%	9.92E-04	1.3%
Cell manufacture	2.07E-04	3.3%	0.00E+00	0.0%	0.00E+00	0.0%	6.91E-05	0.1%
<i>Cell subtotal</i>	<i>1.22E-02</i>	<i>194.7%</i>	<i>2.31E-02</i>	<i>270.0%</i>	<i>2.05E-01</i>	<i>90.3%</i>	<i>8.00E-02</i>	<i>104.8%</i>
BMS	1.22E-03	19.4%	1.22E-03	14.2%	1.22E-03	0.5%	1.22E-03	1.6%
Pack case/housing	-2.00E-02	-317.7%	-2.00E-02	-233.4%	1.61E-03	0.7%	-1.28E-02	-16.7%
Pack manufacture	6.56E-06	0.1%	3.94E-03	46.0%	1.89E-02	8.4%	7.63E-03	10.0%
Transportation	2.21E-04	3.5%	2.67E-04	3.1%	2.51E-04	0.1%	2.46E-04	0.3%
Total	-6.29E-03	100%	8.56E-03	100%	2.27E-01	100%	7.64E-02	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity; kg N-Eq. = kilograms of nitrogen equivalents

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

Table 3-15. Eutrophication Potential by Life-Cycle Stage for EV Batteries (kg N-Eq./km)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	-2.93E-06	-24.8%	-9.10E-07	-6.1%	2.38E-06	4.0%	-4.88E-07	-1.7%
Materials processing	3.57E-07	3.0%	5.91E-07	4.0%	3.94E-05	65.5%	1.34E-05	46.4%
Component manuf.	5.35E-07	4.5%	5.73E-07	3.8%	6.05E-07	1.0%	5.71E-07	2.0%
Product manuf.	9.00E-08	0.8%	8.71E-07	5.8%	3.98E-06	6.6%	1.65E-06	5.7%
Product use	1.38E-05	116.5%	1.38E-05	92.5%	1.38E-05	22.9%	1.38E-05	47.6%
<i>Subtotal</i>	<i>1.18E-05</i>	<i>100%</i>	<i>1.49E-05</i>	<i>100%</i>	<i>6.01E-05</i>	<i>100%</i>	<i>2.89E-05</i>	<i>100%</i>
Average EOL	-3.89E-07	-3.3%	-2.03E-06	-13.6%	-1.01E-05	-16.8%	-4.16E-06	-14.4%
Total	1.14E-05	96.7%	1.29E-05	86.4%	5.00E-05	83.2%	2.48E-05	85.6%

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

Table 3-16. Eutrophication Potential by Life-Cycle Stage for PHEV Batteries (kg N-Eq./km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	-8.57E-07	-8.3%	6.90E-07	2.8%	-8.34E-08	-0.5%
Materials processing	1.04E-07	1.0%	1.14E-05	47.0%	5.76E-06	33.3%
Components manuf.	1.55E-07	1.5%	1.75E-07	0.7%	1.65E-07	1.0%
Product manuf.	2.61E-08	0.3%	1.15E-06	4.7%	5.90E-07	3.4%
Product use	1.09E-05	105.6%	1.09E-05	44.7%	1.09E-05	62.8%
<i>Subtotal</i>	<i>1.03E-05</i>	<i>100%</i>	<i>2.43E-05</i>	<i>100%</i>	<i>1.73E-05</i>	<i>100%</i>
Average EOL	-1.15E-07	-1.1%	-2.92E-06	-12.0%	-1.52E-06	-8.8%
Total	1.02E-05	98.9%	2.14E-05	88.0%	1.58E-05	91.2%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg H+ Mol-Eq. = kilograms of hydrogen ion molar equivalents

In the case of the LiMnO₂ battery, the large negative eutrophication potential from the pack housing production displaces a substantial proportion of the nutrient emissions due to electricity consumption in the use stage. The Li-NCM battery is assumed to use more energy during the upstream stages and battery manufacturing and, as a result, does not displace much of the use stage impact. The LiFePO₄ battery shows net positive eutrophication potential during material extraction. It should be noted that due to an inability to disaggregate the material extraction and process of cold-rolled steel, it was included in the material extraction stage.

The LCIA methodology calculates impacts from the mass of a chemical released directly to surface water, and the chemical's eutrophication potential (EP) equivalency factor. The EP is a partial equivalency

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

3.2.5 Ozone Depletion

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

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

where:

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

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

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

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

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

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	2.77E-07	11.5%	5.50E-08	2.6%	3.68E-07	3.8%	2.33E-07	4.9%
Cathode	1.54E-06	64.1%	1.59E-06	74.4%	2.02E-06	21.0%	1.72E-06	36.3%
Separator	2.16E-07	9.0%	0.00E+00	0.0%	4.82E-07	5.0%	2.33E-07	4.9%
Electrolyte	1.01E-07	4.2%	3.48E-07	16.3%	2.53E-07	2.6%	2.34E-07	4.9%
Cell casing	5.05E-11	0.0%	2.98E-10	0.0%	1.70E-06	17.6%	5.67E-07	12.0%
Cell manufacture	1.75E-07	7.3%	0.00E+00	0.0%	0.00E+00	0.0%	5.85E-08	1.2%
<i>Cell subtotal</i>	<i>2.31E-06</i>	<i>96.1%</i>	<i>1.99E-06</i>	<i>93.3%</i>	<i>4.83E-06</i>	<i>50.1%</i>	<i>3.04E-06</i>	<i>64.4%</i>
BMS	7.08E-08	2.9%	7.08E-08	3.3%	7.08E-08	0.7%	7.08E-08	1.5%
Pack case/housing	1.77E-08	0.7%	1.77E-08	0.8%	7.15E-09	0.1%	1.42E-08	0.3%
Pack manufacture	5.55E-09	0.2%	5.37E-08	2.5%	4.74E-06	49.1%	1.60E-06	33.8%
Transportation	2.55E-11	0.0%	3.09E-11	0.0%	2.90E-11	0.0%	2.85E-11	0.0%
Total	2.40E-06	100%	2.13E-06	100%	9.64E-06	100%	4.73E-06	100%

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

The production of aluminum for the cathode is a key contributor to ozone depletion. This impact of aluminum use in the cathode is smaller in relative, but not absolute, terms in the LiFePO₄ battery. Interestingly, the Canadian power grid, which was used to model pack manufacturing for the LiFePO₄ battery, generates much more sizeable emissions of trichlorofluoromethane (CFC 11) than the U.S. grid. This particular flow dominates the LiFePO₄ impacts. As a result, care should be taken in interpretation, as the impact is highly sensitive to the make-up of the grid. Overall, the LiFePO₄ chemistry has substantially higher impacts, due to higher impacts from materials and electricity consumption for the cathode, cell casing, and battery pack.

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

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	4.74E-10	64.3%	5.51E-10	80.9%	6.62E-10	29.6%	5.62E-10	46.2%
Materials processing	1.03E-10	14.0%	6.60E-11	9.7%	4.92E-10	22.0%	2.20E-10	18.1%
Component manuf.	1.13E-10	15.3%	4.28E-11	6.3%	9.10E-11	4.1%	8.21E-11	6.7%
Product manuf.	3.75E-11	5.1%	1.11E-11	1.6%	9.81E-10	43.9%	3.43E-10	28.2%
Product use	9.80E-12	1.3%	9.80E-12	1.4%	9.80E-12	0.4%	9.80E-12	0.8%
<i>Subtotal</i>	<i>7.37E-10</i>	<i>100%</i>	<i>6.81E-10</i>	<i>100%</i>	<i>2.24E-09</i>	<i>100%</i>	<i>1.22E-09</i>	<i>100%</i>
Average EOL	-2.25E-10	-30.6%	-2.69E-10	-39.6%	-4.66E-10	-20.8%	-3.20E-10	-26.3%
Total	5.12E-10	69.4%	4.12E-10	60.4%	1.77E-09	79.2%	8.98E-10	73.7%

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

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

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	1.39E-10	39.3%	1.92E-10	24.4%	1.66E-10	29.0%
Materials processing	3.00E-11	8.4%	1.43E-10	18.1%	8.63E-11	15.1%
Components manuf.	3.29E-11	9.3%	2.64E-11	3.3%	2.96E-11	5.2%
Product manuf.	1.09E-11	3.1%	2.85E-10	36.1%	1.48E-10	25.9%
Product use	1.42E-10	40.0%	1.42E-10	18.0%	1.42E-10	24.8%
<i>Subtotal</i>	<i>3.55E-10</i>	<i>100%</i>	<i>7.88E-10</i>	<i>100%</i>	<i>5.71E-10</i>	<i>100%</i>
Average EOL	-6.64E-11	-18.7%	-1.35E-10	-17.2%	-1.01E-10	-17.6%
Total	2.89E-10	81.3%	6.52E-10	82.8%	4.71E-10	82.4%

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

For PHEV and EV batteries, the material extraction phase contributes substantially to ozone depletion. Top contributing processes include aluminum production for the passive cooling system, cathode, and, in the case of the LiFePO₄ battery chemistry, the cell containers. As discussed above, this impact category is highly sensitive to the make-up of the grid (see the impact of the product manufacturing stage in the case of the LiFePO₄ battery).

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

3.2.6 Photochemical Oxidation Potential

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

$$IS_{POP} = EF_{POP} \cdot Amt_{POC}$$

where:

IS_{POP} equals the impact score for photochemical oxidation for the chemical (kg ozone-equivalents) per functional unit;

EF_{POP} equals the POP equivalency factor for the chemical (kg ozone-equivalents); and

Amt_{POC} equals the amount of the photochemically oxidizing chemical (POC) released to the air (kg) per functional unit.

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

Table 3-20. Photochemical Oxidation Potential by Battery Component (kg O₃-Eq./kWh)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	8.19E-01	23.3%	6.13E-01	7.8%	6.61E-01	6.9%	6.98E-01	10.0%
Cathode	1.77E+00	50.2%	3.54E+00	45.2%	3.51E+00	36.9%	2.94E+00	42.3%
Separator	4.55E-02	1.3%	0.00E+00	0.0%	1.01E-01	1.1%	4.89E-02	0.7%
Electrolyte	2.02E-01	5.7%	7.95E-01	10.1%	5.17E-01	5.4%	5.05E-01	7.3%
Cell casing	4.36E-02	1.2%	2.57E-01	3.3%	8.95E-01	9.4%	3.99E-01	5.7%
Cell manufacture	9.49E-02	2.7%	0.00E+00	0.0%	0.00E+00	0.0%	3.16E-02	0.5%
<i>Cell subtotal</i>	<i>2.97E+00</i>	<i>84.4%</i>	<i>5.20E+00</i>	<i>66.5%</i>	<i>5.69E+00</i>	<i>59.7%</i>	<i>4.62E+00</i>	<i>66.4%</i>
BMS	2.21E-01	6.3%	2.21E-01	2.8%	2.21E-01	2.3%	2.21E-01	3.2%
Pack case/housing	2.14E-01	6.1%	2.14E-01	2.7%	4.66E-01	4.9%	2.98E-01	4.3%
Pack manufacture	3.01E-03	0.1%	2.06E+00	26.3%	3.03E+00	31.8%	1.70E+00	24.4%
Transportation	1.08E-01	3.1%	1.31E-01	1.7%	1.23E-01	1.3%	1.21E-01	1.7%
Total	3.52E+00	100%	7.83E+00	100%	9.52E+00	100%	6.96E+00	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity; kg O₃-Eq. = kilograms of ozone equivalents

The photochemical oxidation impacts are primarily attributable to production of the cathode and anode for the LiMnO₂ battery, and cathode and pack manufacture for the other two battery chemistries. Pack manufacture impacts are attributable to electricity consumption across all battery chemistries. In addition, the purification and pumping of process water during LiFePO₄ production contributes substantially to this impact category. As noted above, limited primary data for pack manufacture were provided for the LiMnO₂ battery.

Table 3-21. Photochemical Oxidation Potential by Life-Cycle Stage for EV Batteries (kg O₃-Eq./km)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	5.45E-04	6.7%	9.51E-04	10.5%	7.76E-04	8.2%	7.57E-04	8.5%
Materials processing	1.73E-04	2.1%	2.40E-04	2.6%	1.39E-04	1.5%	1.84E-04	2.1%
Component manuf.	9.92E-05	1.2%	1.08E-04	1.2%	5.37E-04	5.7%	2.48E-04	2.8%
Product manuf.	4.27E-05	0.5%	4.53E-04	5.0%	6.52E-04	6.9%	3.83E-04	4.3%
Product use	7.32E-03	89.5%	7.32E-03	80.7%	7.32E-03	77.7%	7.32E-03	82.3%
<i>Subtotal</i>	<i>8.18E-03</i>	<i>100%</i>	<i>9.08E-03</i>	<i>100%</i>	<i>9.43E-03</i>	<i>100%</i>	<i>8.90E-03</i>	<i>100%</i>
Average EOL	1.39E-05	0.2%	-2.47E-04	-2.7%	-8.90E-05	-0.9%	-1.07E-04	-1.2%
Total	8.20E-03	100.2%	8.83E-03	97.3%	9.34E-03	99.1%	8.79E-03	98.8%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); kg O₃-Eq. = kilograms of ozone equivalents

Table 3-22. Photochemical Oxidation Potential by Life-Cycle Stage for PHEV Batteries (kg O₃-Eq./km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	1.59E-04	3.2%	2.25E-04	4.3%	1.92E-04	3.8%
Materials processing	5.00E-05	1.0%	4.02E-05	0.8%	4.51E-05	0.9%
Components manuf.	2.89E-05	0.6%	1.56E-04	3.0%	9.23E-05	1.8%
Product manuf.	1.24E-05	0.3%	1.89E-04	3.6%	1.01E-04	2.0%
Product use	4.65E-03	94.9%	4.65E-03	88.4%	4.65E-03	91.5%
<i>Subtotal</i>	<i>4.90E-03</i>	<i>100%</i>	<i>5.26E-03</i>	<i>100%</i>	<i>5.08E-03</i>	<i>100%</i>
Average EOL	3.14E-06	0.1%	-2.58E-05	-0.5%	-1.13E-05	-0.2%
Total	4.91E-03	100.1%	5.24E-03	99.5%	5.07E-03	99.8%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km);
kg O₃-Eq. = kilograms of ozone equivalents

Outside of the use stage, the materials extraction stage contributes most significantly to photochemical oxidation potential for EV and PHEV batteries. This is mainly due to the production of soda (Na₂CO₃), which is used in the synthesis of downstream lithium salts, and of aluminum that ultimately goes into the passive cooling system and cathode.

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

3.2.7 Ecological Toxicity Potential

The USETox freshwater characterization factors are a chemical-specific aggregation of chemical fate, ecological exposure, and effect (i.e., toxicity) factors that seek to systematically characterize the ecological impact of emissions on freshwater organisms. The USETox model provides an estimate of the potentially affected fraction of species (PAF), integrated over time and volume per unit mass of a chemical emitted, PAF m³ day kg⁻¹ (Rosenbaum et al., 2008).

$$IS_{ETP} = CF_{ETP} \cdot Amt_{ETC}$$

where:

IS_{ETP} equals the impact score for ecological toxicity of the chemical (PAF m³ day) per functional unit;

CF_{ETP} equals the ecological toxicity potential (ETP) characterization factor for the chemical (PAF m³ day); and

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

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

Table 3-23. Ecological Toxicity Potential Impact Score by Battery Component (PAF m³ day/kWh)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
Component	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	9.12E-03	0.1%	4.64E-03	0.0%	2.82E-02	2.6%	1.40E-02	0.2%
Cathode	1.54E-02	0.2%	2.03E+00	20.1%	6.64E-01	62.2%	9.03E-01	14.1%
Separator	4.84E-04	0.0%	0.00E+00	0.0%	1.08E-03	0.1%	5.21E-04	~0%
Electrolyte	4.80E-03	0.1%	1.43E-02	0.1%	1.03E-02	1.0%	9.78E-03	0.2%
Cell casing	9.54E-04	0.0%	5.63E-03	0.1%	2.08E-02	1.9%	9.11E-03	0.1%
Cell manufacture	4.99E-04	0.0%	0.00E+00	0.0%	0.00E+00	0.0%	1.66E-04	~0%
<i>Cell subtotal</i>	<i>3.13E-02</i>	<i>0.4%</i>	<i>2.05E+00</i>	<i>20.4%</i>	<i>7.24E-01</i>	<i>67.9%</i>	<i>9.36E-01</i>	<i>14.6%</i>
BMS	3.14E-01	3.9%	3.14E-01	3.1%	3.14E-01	29.4%	3.14E-01	4.9%
Pack case/housing	7.70E+00	95.7%	7.70E+00	76.4%	6.34E-03	0.6%	5.14E+00	80.3%
Pack manufacture	1.58E-05	0.0%	1.35E-02	0.1%	2.17E-02	2.0%	1.17E-02	0.2%
Transportation	6.34E-04	0.0%	7.68E-04	0.0%	7.22E-04	0.1%	7.08E-04	~0%
Total	8.05E+00	100%	1.01E+01	100%	1.07E+00	100%	6.40E+00	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity; PAF m³ day = potentially affected fraction of species integrated over one day and one square meter

Impacts are primarily attributable to the steel used for the pack housing and battery management system in the LiMnO₂ and Li-NCM batteries. The use of steel in this housing is associated with significant freshwater cyanide emissions, which drive the ecotoxicity impacts. For the LiFePO₄ chemistry, impacts primarily result from production of the cathode and the battery management system. Impacts for the LiFePO₄ battery are an order of magnitude smaller, because of the substantial reduction in steel use in the inventory.

Table 3-24. Ecological Toxicity Potential Impact Score by Life-Cycle Stage for EV Batteries (PAF m³ day/km)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
Life-Cycle Stage	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	2.02E-03	97.7%	2.44E-03	97.9%	4.32E-04	69.2%	1.63E-03	94.3%
Materials processing	1.01E-06	0.0%	2.04E-06	0.1%	1.56E-06	0.2%	1.54E-06	0.1%
Component manuf.	7.33E-07	0.0%	8.15E-07	0.0%	1.40E-04	22.4%	4.71E-05	2.7%
Product manuf.	2.38E-07	0.0%	2.95E-06	0.1%	4.64E-06	0.7%	2.61E-06	0.2%
Product use	4.66E-05	2.3%	4.66E-05	1.9%	4.66E-05	7.5%	4.66E-05	2.7%
<i>Subtotal</i>	<i>2.07E-03</i>	<i>100%</i>	<i>2.49E-03</i>	<i>100%</i>	<i>6.25E-04</i>	<i>100%</i>	<i>1.73E-03</i>	<i>100%</i>
Average EOL	-2.18E-05	-1.1%	-3.56E-04	-14.3%	-2.17E-05	-3.5%	-1.33E-04	-7.7%
Total	2.05E-03	98.9%	2.14E-03	85.7%	6.03E-04	96.5%	1.60E-03	92.3%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); PAF m³ day = potentially affected fraction of species integrated over one day and one square meter.

Table 3-25. Ecological Toxicity Potential Impact Score by Life-Cycle Stage for PHEV Batteries (PAF m³ day/km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	5.90E-04	92.1%	1.25E-04	57.5%	3.58E-04	83.3%
Materials processing	2.94E-07	0.0%	4.52E-07	0.2%	3.73E-07	0.1%
Components manuf.	2.13E-07	0.0%	4.06E-05	18.6%	2.04E-05	4.7%
Product manuf.	6.90E-08	0.0%	1.35E-06	0.6%	7.08E-07	0.2%
Product use	5.03E-05	7.8%	5.03E-05	23.1%	5.03E-05	11.7%
<i>Subtotal</i>	<i>6.41E-04</i>	<i>100%</i>	<i>2.18E-04</i>	<i>100%</i>	<i>4.30E-04</i>	<i>100%</i>
Average EOL	-6.34E-06	-1.0%	-6.30E-06	-2.9%	-6.32E-06	-1.5%
Total	6.35E-04	99.0%	2.12E-04	97.1%	4.23E-04	98.5%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); PAF m³ day = potentially affected fraction of species integrated over one day and one square meter.

Metal ore extraction and raw processing in the materials extraction stage is driving ecological toxicity potential impacts. This is largely due to the use of steel for all battery chemistries. Cold-rolled steel is primarily used in the passive cooling system, the battery housing, and the battery management system. LiFePO₄ shows higher impacts in the component manufacture stage, as opposed to the other battery chemistries, due to the materials used for the manufacture of the cathode (e.g., iron).

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

3.2.8 Human Toxicity Potential (General Public)

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

$$IS_{HTP} = CF_{HTP} \cdot Amt_{HTC}$$

where:

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

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

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

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

Table 3-26. Human Toxicity Potential Impact Score by Battery Component (Cases/kWh)¹¹

Chemistry Component	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	2.41E-10	22.7%	1.08E-10	4.6%	2.04E-10	7.0%	1.38E-10	8.7%
Cathode	2.66E-10	25.1%	6.69E-10	28.3%	1.01E-09	34.9%	4.87E-10	30.8%
Separator	1.59E-11	1.5%	0.00E+00	0.0%	3.53E-11	1.2%	1.28E-11	0.8%
Electrolyte	1.55E-10	14.6%	4.17E-10	17.6%	2.91E-10	10.0%	2.15E-10	13.6%
Cell casing	2.12E-11	2.0%	1.25E-10	5.3%	4.58E-10	15.8%	1.51E-10	9.5%
Cell manufacture	2.42E-11	2.3%	0.00E+00	0.0%	0.00E+00	0.0%	6.05E-12	0.4%
<i>Cell subtotal</i>	<i>7.23E-10</i>	<i>68.1%</i>	<i>1.32E-09</i>	<i>55.7%</i>	<i>2.00E-09</i>	<i>68.9%</i>	<i>1.01E-09</i>	<i>63.8%</i>
BMS	7.33E-11	6.9%	7.33E-11	3.1%	7.33E-11	2.5%	5.50E-11	3.5%
Pack case/housing	2.64E-10	24.8%	2.64E-10	11.2%	1.62E-10	5.6%	1.72E-10	10.9%
Pack manufacture	7.66E-13	0.1%	7.09E-10	30.0%	6.68E-10	23.0%	3.44E-10	21.7%
Transportation	1.11E-12	0.1%	1.35E-12	0.1%	1.27E-12	0.0%	9.34E-13	0.1%
Total	1.06E-09	100%	2.37E-09	100%	2.91E-09	100%	1.58E-09	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity; Cases = unit increase in morbidity in the total human population

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

Table 3-27. Human Toxicity Potential Impact Score by Life-Cycle Stage for EV Batteries (Cases/km)¹¹

Chemistry Life-Cycle Stage	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	2.19E-13	7.5%	2.96E-13	9.3%	2.58E-13	7.8%	2.58E-13	8.2%
Materials processing	3.99E-14	1.4%	8.79E-14	2.8%	8.71E-14	2.6%	7.16E-14	2.3%
Component manuf.	2.90E-14	1.0%	3.26E-14	1.0%	1.92E-13	5.8%	8.45E-14	2.7%
Product manuf.	5.40E-15	0.2%	1.47E-13	4.6%	1.39E-13	4.2%	9.70E-14	3.1%
Product use	2.63E-12	89.9%	2.63E-12	82.3%	2.63E-12	79.5%	2.63E-12	83.7%
<i>Subtotal</i>	<i>2.92E-12</i>	<i>100%</i>	<i>3.19E-12</i>	<i>100%</i>	<i>3.30E-12</i>	<i>100%</i>	<i>3.14E-12</i>	<i>100%</i>
Average EOL	-2.34E-15	-0.1%	-6.23E-14	-2.0%	-5.61E-14	-1.7%	-4.03E-14	-1.3%
Total	2.92E-12	99.9%	3.13E-12	98.0%	3.25E-12	98.3%	3.10E-12	98.7%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); Cases = unit increase in morbidity in the total human population

Table 3-28. Human Toxicity Potential Impact Score by Life-Cycle Stage for PHEV Batteries (Cases/km)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
Life-Cycle Stage	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	6.43E-14	3.5%	7.48E-14	3.8%	6.96E-14	3.6%
Materials processing	1.16E-14	0.6%	2.53E-14	1.3%	1.84E-14	1.0%
Components manuf.	8.46E-15	0.5%	5.56E-14	2.8%	3.21E-14	1.7%
Product manuf.	1.57E-15	0.1%	4.02E-14	2.0%	2.09E-14	1.1%
Product use	1.77E-12	95.4%	1.77E-12	90.1%	1.77E-12	92.6%
<i>Subtotal</i>	<i>1.86E-12</i>	<i>100%</i>	<i>1.97E-12</i>	<i>100%</i>	<i>1.91E-12</i>	<i>100%</i>
Average EOL	-1.06E-15	-0.1%	-1.63E-14	-0.8%	-8.67E-15	-0.5%
Total	1.86E-12	99.9%	1.95E-12	99.2%	1.91E-12	99.5%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km); Cases = unit increase in morbidity in the total human population

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

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

3.2.9 Occupational Cancer Hazard

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

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

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

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

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

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

where:

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

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

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

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

where:

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

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

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

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

Table 3-29. Occupational Cancer Hazard Impact Score by Battery Component (Unitless)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	5.10E+00	0.8%	5.12E+00	0.8%	4.22E+00	0.5%	4.81E+00	0.7%
Cathode	5.87E+02	96.3%	5.37E+02	87.6%	7.40E+02	92.5%	6.21E+02	92.2%
Separator	3.51E-01	0.1%	0.00E+00	0.0%	7.80E-01	0.1%	3.77E-01	0.1%
Electrolyte	1.23E+01	2.0%	4.40E+01	7.2%	3.21E+01	4.0%	2.95E+01	4.4%
Cell casing	7.31E-01	0.1%	4.31E+00	0.7%	5.13E+00	0.6%	3.39E+00	0.5%
Cell manufacture	2.78E-01	0.0%	0.00E+00	0.0%	0.00E+00	0.0%	9.27E-02	0.0%
<i>Cell subtotal</i>	<i>6.05E+02</i>	<i>99.3%</i>	<i>5.91E+02</i>	<i>96.3%</i>	<i>7.83E+02</i>	<i>97.8%</i>	<i>6.60E+02</i>	<i>97.8%</i>
BMS	1.15E+00	0.2%	1.15E+00	0.2%	1.15E+00	0.1%	1.15E+00	0.2%
Pack case/housing	2.68E+00	0.4%	2.68E+00	0.4%	4.59E+00	0.6%	3.31E+00	0.5%
Pack manufacture	8.81E-03	0.0%	1.86E+01	3.0%	1.15E+01	1.4%	1.01E+01	1.5%
Transportation	2.04E-01	0.0%	2.47E-01	0.0%	2.33E-01	0.0%	2.28E-01	0.0%
Total	6.09E+02	100%	6.14E+02	100%	8.00E+02	100%	6.74E+02	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity

Cancer impacts are primarily attributable to the materials and extraction needed for the cathode, especially the lithium brine. Impacts from the LiFePO₄ battery are significantly larger, due to the increase in the quantity of lithium brine consumed upstream of the production of the cathode active material. Little is known about the full chemical makeup and toxicity of this saline brine. EPA’s Structure Activity Team estimated that soluble lithium salts like lithium chloride and lithium carbonate would not be absorbed through the skin, but would have good absorption from the lung and GI tract. However, they were not aware of any evidence of mutagenicity or carcinogenicity. It is likely that there are an abundance of other mineral salts in the brine; however, a full characterization was beyond the scope of this study. Given such uncertainty, this chemical was represented by a default hazard value of 1.

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

Table 3-30. Occupational Cancer Hazard Impact Score by Life-Cycle Stage for EV Batteries (Unitless)^{vi}

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	1.26E-01	69.1%	1.22E-01	66.5%	1.63E-01	73.2%	1.37E-01	69.8%
Materials processing	3.77E-04	0.2%	1.20E-03	0.7%	9.73E-04	0.4%	8.48E-04	0.4%
Component manuf.	3.75E-04	0.2%	7.69E-04	0.4%	5.52E-04	0.2%	5.65E-04	0.3%
Product manuf.	1.02E-04	0.1%	3.91E-03	2.1%	2.44E-03	1.1%	2.15E-03	1.1%
Product use	5.57E-02	30.5%	5.57E-02	30.3%	5.57E-02	25.1%	5.57E-02	28.4%
<i>Subtotal</i>	<i>1.83E-01</i>	<i>100%</i>	<i>1.84E-01</i>	<i>100%</i>	<i>2.22E-01</i>	<i>100%</i>	<i>1.96E-01</i>	<i>100%</i>
Average EOL	-4.29E-02	-23.5%	-5.69E-02	-31.0%	-8.75E-02	-39.4%	-6.25E-02	-31.8%
Total	1.40E-01	76.5%	1.27E-01	69.0%	1.35E-01	60.6%	1.34E-01	68.2%

Notes:^{vi} km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

Table 3-31. Occupational Cancer Hazard Impact Score by Life-Cycle Stage for PHEV Batteries (Unitless)^{vi}

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	3.66E-02	41.5%	4.72E-02	47.3%	4.19E-02	44.5%
Materials processing	1.09E-04	0.1%	2.82E-04	0.3%	1.96E-04	0.2%
Components manuf.	1.09E-04	0.1%	1.60E-04	0.2%	1.35E-04	0.1%
Product manuf.	2.95E-05	0.0%	7.07E-04	0.7%	3.68E-04	0.4%
Product use	5.14E-02	58.3%	5.14E-02	51.6%	5.14E-02	54.7%
<i>Subtotal</i>	<i>8.83E-02</i>	<i>100%</i>	<i>9.97E-02</i>	<i>100%</i>	<i>9.40E-02</i>	<i>100%</i>
Average EOL	-1.25E-02	-14.1%	-2.54E-02	-25.5%	-1.89E-02	-20.1%
Total	7.58E-02	85.9%	7.44E-02	74.5%	7.51E-02	79.9%

Notes:^{vi} km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

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

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

3.2.10 Occupational Non-Cancer Hazard

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

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

$$\begin{aligned} \text{oral :} & & HV_{\text{NC oral}} &= \frac{1/\text{Oral NOAEL}}{1/\text{Oral NOAEL}_{\text{GM}}} \\ \text{inhalation :} & & HV_{\text{NC inhal}} &= \frac{1/\text{Inhal NOAEL}}{1/\text{Inhal NOAEL}_{\text{GM}}} \end{aligned}$$

where:

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

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

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

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

where:

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

Amt_{TC input}

equals the amount of toxic chemical input (kg) per functional unit for the chemical.

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

Table 3-32. Occupational Non-Cancer Hazard Impact Score by Battery Component (Unitless)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
Component	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Anode	4.83E+00	0.8%	4.48E+00	0.0%	3.58E+00	0.4%	4.30E+00	0.1%
Cathode	5.90E+02	96.4%	1.53E+04	99.5%	7.39E+02	91.2%	5.54E+03	99.0%
Separator	2.64E-01	~0%	0.00E+00	0.0%	5.88E-01	0.1%	2.84E-01	0.0%
Electrolyte	1.17E+01	1.9%	4.26E+01	0.3%	3.08E+01	3.8%	2.84E+01	0.5%
Cell casing	7.42E-01	0.1%	4.38E+00	0.0%	8.42E+00	1.0%	4.51E+00	0.1%
Cell manufacture	7.68E-01	0.1%	0.00E+00	0.0%	0.00E+00	0.0%	2.56E-01	0.0%
<i>Cell subtotal</i>	<i>6.08E+02</i>	<i>99.4%</i>	<i>1.54E+04</i>	<i>99.8%</i>	<i>7.83E+02</i>	<i>96.5%</i>	<i>5.58E+03</i>	<i>99.6%</i>
BMS	1.10E+00	0.2%	1.10E+00	0.0%	1.10E+00	0.1%	1.10E+00	0.0%
Pack case/housing	2.54E+00	0.4%	2.54E+00	0.0%	4.24E+00	0.5%	3.11E+00	0.1%
Pack manufacture	2.43E-02	~0%	2.73E+01	0.2%	2.29E+01	2.8%	1.67E+01	0.3%
Transportation	2.97E-02	~0%	3.60E-02	0.0%	3.38E-02	0.0%	3.32E-02	0.0%
Total	6.12E+02	100%	1.54E+04	100%	8.11E+02	100%	5.60E+03	100%

Notes:¹¹ kWh = kilowatt-hour battery capacity

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

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

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

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

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

Table 3-33. Occupational Non-Cancer Hazard Impact Score by Life-Cycle Stage for EV Batteries (Unitless)¹¹

Chemistry	LiMnO ₂		Li-NCM		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	1.27E-01	58.2%	3.18E+00	97.0%	1.63E-01	62.9%	1.16E+00	92.4%
Materials processing	4.07E-04	0.2%	9.42E-04	~0%	8.19E-04	0.3%	7.23E-04	0.1%
Component manuf.	6.78E-04	0.3%	1.07E-03	~0%	8.87E-04	0.3%	8.77E-04	0.1%
Product manuf.	1.70E-04	0.1%	5.65E-03	0.2%	4.76E-03	1.8%	3.53E-03	0.3%
Product use	8.96E-02	41.2%	8.96E-02	2.7%	8.96E-02	34.6%	8.96E-02	7.2%
<i>Subtotal</i>	<i>2.18E-01</i>	<i>100%</i>	<i>3.28E+00</i>	<i>100%</i>	<i>2.59E-01</i>	<i>100%</i>	<i>1.25E+00</i>	<i>100%</i>
Average EOL	-4.22E-02	-19.4%	-2.61E+00	-79.6%	-8.68E-02	-33.5%	-9.13E-01	-73.0%
Total	1.75E-01	80.6%	6.67E-01	20.4%	1.72E-01	66.5%	3.38E-01	27.0%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

Table 3-34. Occupational Non-Cancer Hazard Impact Score by Life-Cycle Stage for PHEV Batteries (Unitless)¹¹

Chemistry	LiMnO ₂		LiFePO ₄		Average	
	Value	Pct.	Value	Pct.	Value	Pct.
Materials extraction	3.67E-02	46.1%	4.72E-02	51.5%	4.20E-02	49.0%
Materials processing	1.18E-04	0.1%	2.37E-04	0.3%	1.78E-04	0.2%
Components manuf.	1.98E-04	0.2%	2.57E-04	0.3%	2.27E-04	0.3%
Product manuf.	4.94E-05	0.1%	1.38E-03	1.5%	7.15E-04	0.8%
Product use	4.26E-02	53.5%	4.26E-02	46.5%	4.26E-02	49.7%
<i>Subtotal</i>	<i>7.98E-02</i>	<i>100%</i>	<i>9.17E-02</i>	<i>100%</i>	<i>8.57E-02</i>	<i>100%</i>
Average EOL	-1.23E-02	-15.4%	-2.52E-02	-27.4%	-1.87E-02	-21.8%
Total	6.75E-02	84.6%	6.66E-02	72.6%	6.70E-02	78.2%

Notes:¹¹ km = kilometer driven over base-case battery lifetime (10 year/193,120 km)

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

After the use stage, most potential occupational non-cancer impacts are attributed to the materials extraction stage. This is mainly attributable to lithium brine used in cathode manufacturing for the LiMnO₂ and LiFePO₄ batteries. In addition, the cobalt sulfate produced upstream for use in the synthesis of the Li-NCM cathode active material overwhelms the contribution from the use stage to the overall occupational non-cancer hazard impacts for this battery chemistry.

3.3 SWCNT Anode Analysis

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

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

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

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

Impact Category	Impact ratio (-) ¹¹	Break-even (kWh) ¹²
Primary Energy	1559	11.5
Abiotic Depletion Potential	1589	11.4
Global Warming Potential	1684	10.6
Acidification Potential	1450	14.6
Eutrophication Potential	1217	13.0
Ozone Depletion Potential	6	3838.0
Photochemical Oxidation Potential	1549	11.6
Ecological Toxicity Potential	886	24.9
Human Toxicity Potential	1887	12.3
Occupational Cancer Hazard	1892	15.2
Occupational Non-Cancer Hazard	3210	4.1

Notes:

¹¹ Impact ratio is the ratio of the SWCNT anode manufacturing impacts to those of the battery grade graphite anode. For example, the energy impacts of manufacturing the SWCNT is 1,599 times greater than the graphite anode.

¹² The break-even metric represents the at-plug electricity consumption during production of 1 kWh capacity of SWCNT anode, below which the impacts would be less than that of the corresponding conventional graphite-based anode. (Note: Current electricity consumption during the production of a 1 kWh capacity SWCNT anode is approximately 28,000 kWh.) For instance, in order to register the same global warming impact as the graphite anode, the SWCNT-based anode would have to be produced using less than 11 kWh of electricity drawn from the average U.S. grid.

3.4 Sensitivity Analysis

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

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

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

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

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

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

Battery Chemistry	LiMnO ₂	LiNCM	LiFePO ₄
Impact Category	Pct. deviation	Pct. deviation	Pct. deviation
Primary Energy	9.9%	18.8%	23.8%
Abiotic Depletion Potential	8.9%	17.9%	20.9%
Global Warming Potential	9.2%	16.0%	20.9%
Acidification Potential	7.8%	16.3%	14.6%
Eutrophication Potential	-28.2%	-7.1%	73.4%
Ozone Depletion Potential	98.1%	97.6%	99.5%
Photochemical Oxidation Potential	9.8%	17.0%	23.2%
Ecological Toxicity Potential	97.7%	97.8%	92.3%
Human Toxicity Potential	9.9%	16.0%	19.2%
Occupational Cancer Hazard	29.9%	55.0%	80.6%
Occupational Non-Cancer Hazard	22.1%	86.6%	72.4%

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

Battery Chemistry	LiMnO ₂	LiFePO ₄
Impact Category	Pct. deviation	Pct. deviation
Primary Energy	2.8%	7.4%
Abiotic Depletion Potential	2.4%	6.3%
Global Warming Potential	2.0%	5.1%
Acidification Potential	4.2%	8.3%
Eutrophication Potential	-8.9%	50.4%
Ozone Depletion Potential	50.5%	78.4%
Photochemical Oxidation Potential	4.7%	12.1%
Ecological Toxicity Potential	92.1%	76.3%
Human Toxicity Potential	4.5%	9.3%
Occupational Cancer Hazard	11.8%	56.6%
Occupational Non-Cancer Hazard	14.7%	61.5%

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

Eutrophication impacts are negative in value and vary significantly between battery chemistries. This has to do with the production of steel being a net sink for phosphate and other nutrients. Increased steel

production appears “beneficial” from a nutrient reduction standpoint, so halving the lifetime of the battery actually improves the outcome.

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

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

Battery Chemistry	LiMnO ₂		LiNCM		LiFePO ₄	
	Low	High	Low	High	Low	High
Impact Category						
<i>Primary Energy</i>	0.2%	-0.2%	0.4%	-0.4%	0.4%	-0.4%
Abiotic Depletion Potential	0.2%	-0.2%	0.4%	-0.4%	0.4%	-0.4%
Global Warming Potential	0.2%	-0.2%	0.4%	-0.4%	0.5%	-0.5%
Acidification Potential	0.1%	-0.1%	1.3%	-1.3%	0.3%	-0.3%
Eutrophication Potential	0.7%	-0.7%	1.7%	-1.7%	2.9%	-2.8%
Ozone Depletion Potential	2.6%	-2.5%	3.4%	-3.4%	2.7%	-2.6%
Photochemical Oxidation Potential	0.2%	-0.2%	0.5%	-0.5%	0.4%	-0.4%
Ecological Toxicity Potential	~0.0%	~0.0%	1.1%	-1.1%	0.2%	-0.2%
Human Toxicity Potential	0.1%	-0.1%	0.3%	-0.3%	0.3%	-0.3%
Occupational Cancer Hazard	4.8%	-4.8%	4.8%	-4.8%	3.9%	-3.9%
Occupational Non-Cancer Hazard	3.3%	-3.3%	27.4%	-27.3%	3.5%	-3.5%

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

Battery Chemistry	LiMnO ₂		LiFePO ₄	
	Low	High	Low	High
Impact Category				
Primary Energy	0.1%	-0.1%	0.1%	-0.1%
Abiotic Depletion Potential	0.1%	-0.1%	0.1%	-0.1%
Global Warming Potential	0.1%	-0.1%	0.1%	-0.1%
Acidification Potential	0.1%	-0.1%	0.2%	-0.2%
Eutrophication Potential	0.2%	-0.2%	2.0%	-2.0%
Ozone Depletion Potential	1.3%	-1.3%	2.1%	-2.1%
Photochemical Oxidation Potential	0.1%	-0.1%	0.2%	-0.2%
Ecological Toxicity Potential	0.0%	0.0%	0.1%	-0.1%
Human Toxicity Potential	0.1%	-0.1%	0.1%	-0.1%
Occupational Cancer Hazard	1.9%	-1.9%	2.8%	-2.8%
Occupational Non-Cancer Hazard	2.2%	-2.2%	3.0%	-3.0%

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

does significantly mitigate impacts overall, especially from the upstream processing and extraction stages, across battery chemistries.

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

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

Table 3-40. Low and High Impacts from Grid and Charging Scenarios for EV Batteries ¹¹

Battery Chemistry	LiMnO ₂			LiNCM					
Impact Category	Low	Scenario	High	Scenario	Low	Scenario	High	Scenario	
Primary Energy (MJ)	1.80E+00	ISO-NE Un	2.20E+00	IL Sm	2.00E+00	ISO-NE Un	2.40E+00	IL Sm	
ADP (kg Sb-Eq.)	8.36E-04	ISO-NE Un	1.05E-03	IL Sm	9.34E-04	ISO-NE Un	1.14E-03	IL Sm	
GWP (kg CO ₂ -Eq.)	1.08E-01	ISO-NE Un	2.04E-01	IL Sm	1.19E-01	ISO-NE Un	2.14E-01	IL Sm	
AP (kg H+ Mol-Eq.)	9.70E-03	ISO-NE Un	8.72E-02	IL Sm	1.55E-02	ISO-NE Un	9.30E-02	IL Sm	
EP (kg N-Eq.)	6.55E-06	WECC Un	3.08E-05	IL Sm	8.67E-06	WECC Un	3.29E-05	IL Sm	
ODP (kg CFC 11-Eq.)	5.38E-10	IL Sm	1.13E-09	ISO-NE Un	4.44E-10	IL Sm	1.04E-09	ISO-NE Un	
POP (kg O ₃ -Eq.)	5.56E-03	WECC Un	1.66E-02	IL Sm	6.27E-03	WECC Un	1.73E-02	IL Sm	
EcoTP (PAF m ³ day)	2.01E-03	ISO-NE Un	2.06E-03	IL Sm	2.10E-03	ISO-NE Un	2.14E-03	IL Sm	
HTP (Cases)	2.16E-12	IL Sm	2.78E-12	WECC Sm	2.37E-12	IL Sm	2.99E-12	WECC Sm	
OCH (Unitless)	5.78E-02	ISO-NE Un	9.82E-02	IL Sm	1.02E-01	ISO-NE Un	1.42E-01	IL Sm	
OnCH (Unitless)	6.38E-02	ISO-NE Sm	9.92E-02	IL Sm	6.17E-01	ISO-NE Sm	6.52E-01	IL Sm	

Battery Chemistry	LiFePO ₄			
Impact Category	Low	Scenario	High	Scenario
Primary Energy (MJ)	2.13E+00	ISO-NE Un	2.54E+00	IL Sm
ADP (kg Sb-Eq.)	9.71E-04	ISO-NE Un	1.18E-03	IL Sm
GWP (kg CO ₂ -Eq.)	1.28E-01	ISO-NE Un	2.23E-01	IL Sm
AP (kg H+ Mol-Eq.)	1.42E-02	ISO-NE Un	9.17E-02	IL Sm
EP (kg N-Eq.)	4.76E-05	WECC Un	7.19E-05	IL Sm
ODP (kg CFC 11-Eq.)	2.93E-09	IL Sm	3.94E-09	ISO-NE Un
POP (kg O ₃ -Eq.)	6.98E-03	WECC Un	1.80E-02	IL Sm
EcoTP (PAF m ³ day)	5.68E-04	ISO-NE Un	6.12E-04	IL Sm
HTP (Cases)	2.50E-12	IL Sm	3.12E-12	WECC Sm
OCH (Unitless)	2.65E-01	ISO-NE Un	3.06E-01	IL Sm
OnCH (Unitless)	2.73E-01	ISO-NE Sm	3.09E-01	IL Sm

Notes: ¹¹ ADP = abiotic depletion potential; AP = acidification potential; EcoTP = ecological toxicity potential; EP = eutrophication potential; HTP = human toxicity potential; IL = Illinois electricity grid; ISO-NE = Independent System Operators – New England grid; OCH = occupational cancer hazard; ODP = ozone depletion potential; OnCH = occupational non-cancer hazard; POP = photochemical oxidation potential; Sm = smart charging scenario; Un = unconstrained charging scenario; WECC = Western Electricity Coordinating Council

Table 3-41. Low and High Impacts from Grid and Charging Scenarios for PHEV Batteries¹¹

Battery Chemistry	LiMnO ₂			LiFePO ₄					
	Low	Scenario	High	Scenario	Low	Scenario	High	Scenario	
Primary Energy (MJ)	1.93E+00	ISO-NE Un	2.11E+00	IL Sm	2.03E+00	ISO-NE Un	2.20E+00	IL Sm	
ADP (kg Sb-Eq.)	9.13E-04	ISO-NE Un	1.01E-03	IL Sm	9.52E-04	ISO-NE Un	1.04E-03	IL Sm	
GWP (kg CO ₂ -Eq.)	1.63E-01	ISO-NE Un	2.05E-01	IL Sm	1.68E-01	ISO-NE Un	2.10E-01	IL Sm	
AP (kg H ⁺ Mol-Eq.)	9.53E-03	ISO-NE Un	4.34E-02	IL Sm	1.08E-02	ISO-NE Un	4.48E-02	IL Sm	
EP (kg N-Eq.)	8.13E-06	WECC Un	1.88E-05	IL Sm	2.00E-05	WECC Un	3.07E-05	IL Sm	
ODP (kg CFC 11-Eq.)	3.01E-10	IL Sm	5.61E-10	ISO-NE Un	6.71E-10	IL Sm	9.31E-10	ISO-NE Un	
POP (kg O ₃ -Eq.)	3.76E-03	WECC Un	8.59E-03	IL Sm	4.18E-03	WECC Un	9.00E-03	IL Sm	
EcoTP (PAF m ³ day)	6.19E-04	ISO-NE Un	6.38E-04	IL Sm	1.96E-04	ISO-NE Un	2.16E-04	IL Sm	
HTP (Cases)	1.53E-12	IL Sm	1.80E-12	WECC Sm	1.62E-12	IL Sm	1.90E-12	WECC Sm	
OCH (Unitless)	4.89E-02	ISO-NE Un	6.66E-02	IL Sm	1.09E-01	ISO-NE Un	1.27E-01	IL Sm	
OnCH (Unitless)	2.76E-02	ISO-NE Sm	4.31E-02	IL Sm	8.83E-02	ISO-NE Sm	1.04E-01	IL Sm	

Notes:¹¹ ADP = abiotic depletion potential; AP = acidification potential; EcoTP = ecological toxicity potential; EP = eutrophication potential; HTP = human toxicity potential; IL = Illinois electricity grid; ISO-NE = Independent System Operators – New England grid; OCH = occupational cancer hazard; ODP = ozone depletion potential; OnCH = occupational non-cancer hazard; POP = photochemical oxidation potential; Sm = smart charging scenario; Un = unconstrained charging scenario; WECC = Western Electricity Coordinating Council

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