Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack

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Life cycle assessment of a lithium-ion battery vehicle pack

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Abstract

Electric vehicles have no tailpipe emissions, but the production of their batteries leads to environmental burdens. In order to avoid problem-shifting, a life cycle perspective should be applied in the environmental assessment of traction batteries. The goal of this study is to provide a transparent inventory for a lithium-ion nickel-cobalt-manganese traction battery based on primary data and to report its cradle-to-gate impacts. The study was carried out as a process-based attributional life cycle assessment. The environmental impacts were analyzed using midpoint indicators. The global warming potential of the 26.6 kilowatt-hour (kWh), 253 kg battery pack was found to be 4.6 tonnes carbon dioxide equivalents. Regardless of impact category, the production impacts of the battery are caused mainly by the production chains of battery cell manufacture, the positive electrode paste, and the negative current collector. The robustness of the study was tested through sensitivity analysis, and results were compared with preceding studies. Sensitivity analysis indicates that the most effective approach to reduce climate change emissions would be to produce the battery cells with electricity from a cleaner energy mix. On a per-kWh basis, cradle-to-gate greenhouse gas emissions of the battery are within the range of those reported in preceding studies. Contribution and structural path analysis allowed for identification of the most impact-intensive processes and value chains. This article provides an inventory based mainly on primary data, which can easily be adapted to subsequent EV studies, and offers improved understanding of environmental burdens pertaining to lithium ion traction batteries.

Introduction

In the hope of mitigating climate change, both national and international goals have been set to reduce anthropogenic greenhouse gas (GHGs) emissions. Reaching these goals is made difficult by our dependence on the combustion of fossil fuels, a primary source of GHG emissions. Globally, light-duty vehicles are responsible for approximately 10% of energy use and GHG emissions (Solomon et al. 2007). A study commissioned by the World Business Council for Sustainable Development (2004) estimates that the number of light-duty vehicles in operation will rise from roughly 750 million currently to 2 billion by 2050. This projection entails a dramatic increase in demand for gasoline and diesel demands, which raises concerns of energy security as well as implications for climate change and urban air quality. As a result, policymakers, advocacy groups, and the automobile industry have promoted novel car technologies such as electric vehicles (EVs), which, depending on the electricity mix used for charging, have the potential to reduce GHG emissions compared to internal combustion engine vehicles (ICEVs) (Hawkins et al. 2012a; Samaras and Meisterling 2008).

The term *electric vehicle* covers several different types of vehicles: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and purely battery-driven electric vehicles (BEVs). Batteries used in PHEVs and BEVs are referred to as traction batteries. Advances in battery technology have made lithium-ion (Li-ion) the preferred option of traction batteries. There are various types of Li-ion batteries, using different composition of cathode materials, such as $LiMn_2O_4$ (LMO), $LiFePO_4$ (LFP), $Li(NiCoAl)O_2$, and $Li(Ni_xCo_yMn_z)O_2$ (NCM) where x,y,z denotes different possible ratios. In connection with these cathode materials, graphite is a commonly used anode material (Cameán at al. 2010; Park at al. 2013).

EVs are, on occasion, promoted as “zero-emission” vehicles, but studies have shown that the environmental contributions of battery production and use phase can be significant (Hawkins at al. 2012a; Samaras and Meisterling 2008). EVs have no tailpipe emissions but in order to avoid problem-shifting, a life cycle perspective should be applied in the environmental assessment of their traction batteries. As limited accessibility to battery industry data makes it difficult to openly evaluate the impacts of EVs, open inventory studies on traction batteries are mostly based on secondary data. The most complete life cycle inventories (LCIs) are provided by Notter and colleagues (2010), Zackrisson and colleagues (2010), and Majeau-Bettez and colleagues (2011). The USEPA (2013) compiled inventories based on both primary and secondary data, but in order to protect the confidentiality of their primary data, they aggregated these data and complete inventories have not been provided. For their batteries, Dunn and colleagues (2012b) included a thorough investigation of the impact of recycling, but like the USEPA (2013), do not provide a complete inventory. Bauer (2010), on behalf of the Paul Scherrer Institut, performed a study commissioned by Volkswagen. The inventory is partly based on primary data, but data have been aggregated and the report is only available in German. In total, the existing literature varies with respect to the importance of impacts associated with Li-ion traction batteries, but more importantly, there is a low degree of transparency.

Thus far, the most complete traction battery inventories are based on secondary data, and do not converge to a consistent conclusion regarding the impacts pertaining to traction batteries. In order to obtain constructive insight into the environmental footprint of these components, an inventory based mostly on primary, rather than secondary, data has been compiled. This provides the opportunity for impact assessment of traction batteries to evolve beyond merely indicative academic studies into documentation based on more robust analysis. This study offers guidance as to where R&D initiatives are likely to be rewarded with impact reductions.

A process-based attributional life cycle assessment (LCA) approach is used to report cradle-to-gate impact contributions in terms of the most relevant components. In order to avoid problem-shifting, multiple impact categories are covered. In addition to the conventional LCA method, the conduction of a structural path analysis (SPA) has allowed for the identification of the most emission-intensive value chains (Peters and Hertwich 2006). The basic idea behind a SPA is the unravelling of the Leontief inverse by means of a series expansion, and this allows for impact investigation of different production chains (Wood and Lenzen 2009). This article is divided into five, including this introduction. First, the system definition, the battery characteristics, and the battery inventory are described. Thereafter, the main results of the cradle-to-gate analysis are presented. Subsequently, the findings are discussed and compared with preceding studies; in this section some of the implications of the study are commented on. Finally, the main conclusions of the study are presented.

Method

System Definition

The study is a cradle-to-gate life cycle analysis of an NCM traction battery and the related background processes; other EV components are outside the system boundary. The functional unit is chosen as the production of one traction battery. Impacts are also reported for functional units based on mass measured in kilograms (kg) and in terms of nominal energy capacity measured in kilowatt-hour (kWh). A sensitivity analysis reporting battery production impacts per km driven is also included in order to investigate the influence of cycle life and powertrain efficiency on the environmental performance of the battery. A sensitivity analysis with respect to the source of the electricity is performed in order to assess how the electricity mix used in production influences the total impact.

Battery Technology

Data in this section is provided by the battery producer, Miljøbil Grenland. The battery is an NCM Li-ion battery for use in BEVs. Each battery cell is made with a cathode based on $Li(Ni_xCo_yMn_z)O_2$ and an anode based on graphite. One battery vehicle pack is made up of two battery sub-packs connected in parallel. The weight of the battery is 253 kg, of which the battery cells makes up 60% of its total weight. The battery's energy capacity is 26.6 kWh, and under normal use the battery efficiency is 95-96%. The number of cycles the battery can perform before its nominal capacity falls below 80% of its initial rated capacity is often referred to as the battery's cycle life (Kalhammer and colleagues 2007). With 100% depth-of-discharge (DOD), the battery is expected to reach a nominal cycle life of 1000 cycles, whereas 50% DOD extends the expected number to 5000 cycles.

Battery Manufacture

The battery components are grouped into four main components: battery cell, packaging, battery management system (BMS), and cooling system. All of these components consist of subcomponents (figure 1). The battery has 12 battery modules, each made up of 30 battery cells, for a total of 360 battery cells. Below, the inventory is described and comments are provided on the different components and subcomponents, beginning with the battery cells, then the packaging, the BMS, the cooling system, and finally the battery assembly process. The full inventory covering battery components can be found in the Supporting Information.

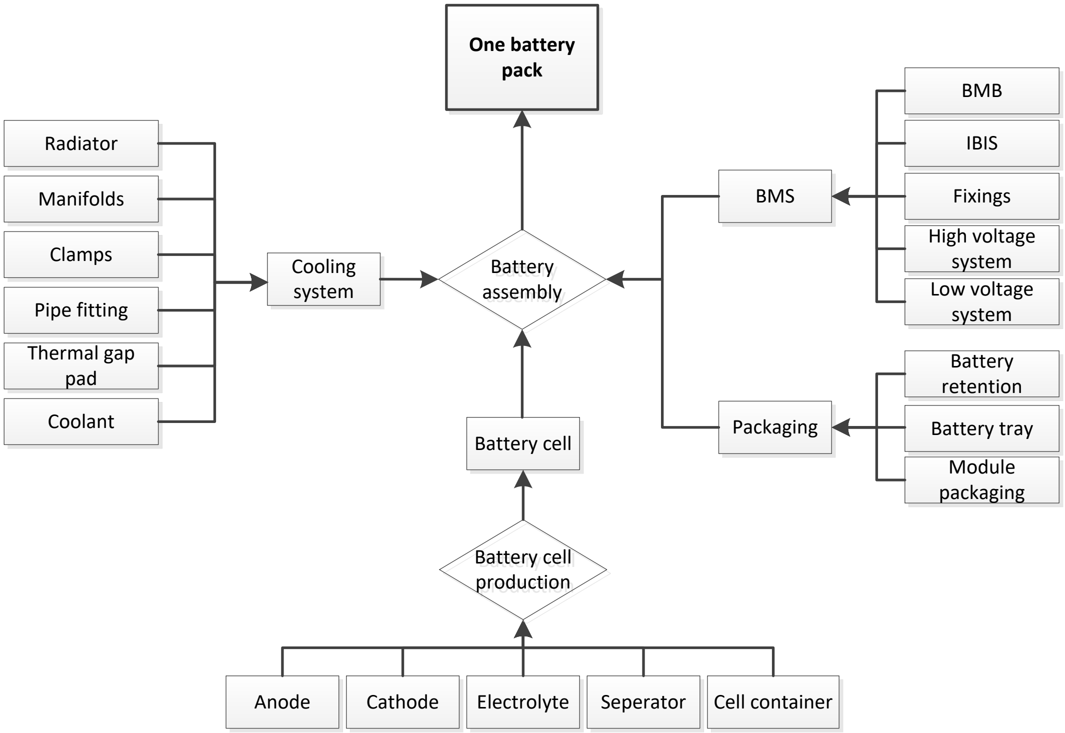


Figure 1 Simplified flow diagram of the battery system. Abbreviations: BMS refers to "battery management system", BMB to "battery management board", and IBIS to "Integrated Battery Interface System".

Cell manufacture

The battery cells consist of five subcomponents: anode, cathode, separator, electrolyte, and cell container. The bill of materials (BOM) for the battery cell identified the material composition and weight of each of the battery cell subcomponents. The anode is composed of a copper current collector with a coat of negative electrode paste. The negative electrode paste consists mainly of synthetic graphite but also contains small amounts of binders. The cathode is composed of an aluminum current collector with a coat of positive electrode paste. The positive electrode paste consists mainly of the positive active material, $Li(Ni_xCo_yMn_z)O_2$, and small amounts of carbon black and a binder. In both the positive and the negative electrode pastes, a solvent is applied to slurrify the mixtures; after the mixtures have been applied to the current collectors, the solvent evaporates. The electrolyte is based on the salt lithium hexafluorophosphate ($LiPF_6$) in a mixture of solvents. The separator is a porous polyolefin film. The cell container consists of a multilayer pouch and tabs. The pouch is placed around the cell components, with one end left open for electrolyte filling. After the electrolyte has been added and evenly distributed between the cathode, separator, and anode, the cell is sealed. For each cell, a copper tab is welded to the negative current collector and an aluminum tab welded to the positive current collector. The tabs pass through the walls of the sealed pouch, and connect the cell to bar-shaped conductors, referred to as busbars.

The battery cell manufacturer provided information on their monthly electricity use for production over an 18 month period; the manufacturer's base cell is a 3.65 nominal voltage and 20 ampere-hour NCM-type, which is the same as the studied battery, but the electricity use also include other types of cells with various capacities. The energy requirements for battery cell manufacture include coating of electrode pastes to metallic foils used as current collectors, welding of current collectors to tabs, filling of electrolyte, and initial charging of the finished cell, but according to the battery cell manufacturer, the predominant energy usage derives from operation of various dry rooms that are vital to the quality of the battery cells. There is significant variation in electricity use relative to production output over time, indicating that there is room for improvement with respect to energy use. Three values for the electricity use are presented in this work: the lower bound value (LBV), the asymptotic value (ASV), and the average value (AVV). The LBV is the value for the most energy efficient month at 586 mega joule (MJ) per kWh battery cell capacity produced, the ASV represents the asymptotic value for the dataset at 960 MJ·kWh battery cell^{-1}, and the AVV is the average value for the dataset at 2318 MJ·kWh battery cell^{-1}.

Packaging

Packaging is divided into three sub-components: module packaging, battery retention and battery tray. The module packaging consists of inner and outer frames, the aforementioned busbars, module fasteners, and a module lid. The inner and the outer frames form nylon cassettes that are placed around the battery cell container to provide protection and structural support. Additionally, each frame includes an aluminum heat transfer plate to ensure optimal thermal conduction. Thirty cassettes stacked after one another form a battery module. At the top of the cassettes, the tabs are welded to the busbars. For the total of 60 tabs per module, there are 30 busbars. There are three types of busbars: copper end-busbars, aluminum end-busbars, and bimetallic busbars. Bimetallic busbars have a copper side and an aluminum side. At the negative terminal of the battery, an end-busbar-holder with a copper busbar is followed by seven double busbar-holders, each with two bimetallic busbars, adding up to a total of 15 busbars. Similarly, on the positive terminal, an end-busbar-holder with one aluminum busbar is followed by seven double busbars-holders each with two bimetallic busbars, also adding up to 15 busbars. The module fasteners include steel screws, caps, nuts, and retention rods, and nylon washers. Together with the module lid, the fasteners are used for assembly of the individual battery modules. There are 12 battery modules in one battery, and the battery retention system keeps the battery modules in place within the battery tray, using straps, restraints, and foams. In addition, eight heat transfer plates made of steel are considered a part of the battery retention system. All battery components are placed inside a steel battery tray which is closed with a sealed lid.

Battery Management System

The BMS includes battery module boards (BMBs), Integrated Battery Interface System (IBIS), fasteners, high voltage (HV) system, and low voltage system. In each battery there are 12 BMBs, one for each module. BMBs are placed under module lids, situated between the two rows of busbars. The BMBs monitor the battery cells for voltage and temperature limits, whereas the IBIS acts as a master controller for the BMBs, as well as overseeing the battery charge and discharge strategies. Additionally, the IBIS provides vehicle-level HV precharge, contactor control, system isolation monitoring, and charge/discharge current measurements. Attached with steel screws, the IBIS box is an integrated part of the HV system, which also contains cables, nylon clips, intermodule fuse, neoprene gaskets, both plastic- and aluminum connectors, and an aluminum lid. The low voltage system consists of nylon clips and harnesses.

Cooling system

For thermal management, the battery is equipped with a cooling system. An aluminum radiator is the main component of the cooling system. For the convective heat medium, the cooling system includes a glycol coolant, which is contained within aluminum manifolds. Clamps and fasteners made of steel, and pipe fittings of plastic and rubber are used for sealing. Thermal conductivity is further ensured with the use of a thermal gap pad made of fiberglass-reinforced filler and polymer.

Battery assembly

Battery assembly is performed at Miljøbil Grenland’s facility. The assembly process itself requires little energy as the assembly of battery components to make one battery pack is mainly performed using manual labor. The only direct energy requirement is for a welding process which only amounts to 0.014 MJ per kWh of battery capacity.

Inventory

An overview of the inventoried battery components are listed in table 1. The inventory list indicates the extent of original data collected for this study, and what data are gathered from literature. Forty-two elements are original data, whereas five are taken from Majeau-Bettez and colleagues (2011) and two elements from Notter and colleagues (2010)/*Ecoinvent 2.2*. The sub-inventory for the positive active material is based on Majeau-Bettez and colleagues (2011), but the ratio of nickel, cobalt, manganese has been modified from $Li(Ni_{0.4}Co_{0.2}Mn_{0.4})O_2$ to $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ (c.f. Ngala et al. 2004; Huang et al. 2011; Väyrynen and Salminen 2012; Wang and Chen 2012; Huang and Hitt 2013). Otherwise no modifications have been made to the original sub-inventories.

Table 1 List of inventories and sub-inventories.

Inventory list	
1	One battery pack
2	Battery packaging
3	BMS
4	Cooling system
5	Battery cell
6	Battery tray
7	Battery retention
8	Tray with fasteners
9	Tray lid
10	Tray seal
11	Strap retention
12	Lower retention
13	Propagation plate
14	Low Voltage system

15	High Voltage system
16	Fasteners
17	Integrated Battery Interface System (IBIS)
18	Radiator
19	Manifolds
20	Clamps
21	Pipe fitting
22	Thermal pad
23	Module packaging
24	Module fasteners
25	Outer frame
26	Inner frame
27	Bimetallic busbars, Al & Cu
28	Busbars, Al
29	Busbars, Cu
30	Module lid
31	Electrolyte
32	Cathode
33	Anode
34	Cell container
35	Separator
36	Positive current collector, Al
37	Positive electrode paste
38	Negative current collector, Cu
39	Negative electrode paste
40	Tab, Al
41	Tab, Cu
42	Aluminum pouch
43	Positive active material*
44	Nickel cobalt manganese hydroxide*
45	Nickel Sulfate*
46	Cobalt Sulfate*
47	Manganese Sulfate*
48	Lithium hexafluorophosphate[+]
49	Synthetic graphite+

* Majeau-Bettez et al. (2011), [+]Notter et al. (2010)

Copper products in our study are modeled as 85% of primary and 15% secondary copper, which is based on the average copper consumption mix (International Institute for Sustainable Development 2010). Aluminum products are modeled as production mix consisting of 68% primary aluminum, 10% secondary aluminum from old scrap, and 22% secondary aluminum from new scrap (Ecoinvent Centre 2010). Steel products are modeled with low-alloyed steel, where 49% is made from recycled material (Ecoinvent Centre 2010). For the manufacture of battery cells, we established a medium voltage electricity mix, based on the following sources: 46% coal, 33% nuclear, 15% gas, 4.4% oil, 1.4% hydro, 0.15% wind, 0.12% solar photovoltaic, and 0.044% waste incineration. The assembly of the battery is performed in Norway, and thus the Norwegian electricity mix, at medium voltage, is used for the welding process. Transport is modeled as receiver input, and is mainly based on standard transport distances of materials (Ecoinvent Centre 2010). The transportation of battery cells and module packaging from the cell manufacturer in East Asia to Miljøbil Grenland in Norway includes road transport and ocean freight. Choice of infrastructure required for production of the battery, battery components and sub-components is estimated based on the recommendations published in the *Ecoinvent* reports (Ecoinvent Centre 2010).

Our inventory is linked to *Ecoinvent 2.2* as a background system (Ecoinvent Centre 2010) and includes materials from resource extraction. Using process-based attributional LCA, the cradle-to-gate impacts of the battery were calculated from the compiled inventory. The battery is not attributed any benefits from second-life or end-of-life treatment. Characterization of environmental releases and resource use was performed using the ReCiPe characterization method (version 1.08) for midpoint indicators from the hierarchical perspective (Goedkoop et al.

2009). SPA was performed to identify the value chain of the most emission-intensive processes and components.

Results and Analysis

In this section, the environmental impacts associated with the production of the battery are presented. The total impact of the battery for 13 impact categories with additional results for two alternative functional units is reported (table 2), and the cradle-to-gate impact contributions are broken down in terms of key components (figure 2). The results of a sensitivity analysis shows how different parameters influence the manner in which production impacts are spread out over the use phase (figure 3). Another sensitivity analysis shows the impact of different electricity sources used for the manufacture of battery cells (figure 4).

Total Impacts and Contribution Analysis

The cradle-to-gate impact of our battery is highly dependent upon the energy requirements of battery cell manufacture. Therefore, impact at the LBV, the ASV and the AVV of the battery are all reported (table 2). At the LBV, the cradle-to-gate global warming potential (GWP) of the battery is 4.6 tonnes carbon dioxide equivalents (CO_2-eq.), whereas at the ASV it is 6.4 tonnes CO_2-eq, and at the AVV it is 13.0 tonnes CO_2-eq.

Table 2 Total impact of production.

Impact	**Units**	**Functional unit**			**Alternative functional units**					
		One battery pack			Mass [kg^{-1}]			Cycle capacity [kWh^{-1}]		
		LBV	ASV	AVV	LBV	ASV	AVV	LBV	ASV	AVV
GWP_{100}	*kg CO_2-eq*	4580	6390	12960	18	25	51	172	240	487
FDP	*kg oil-eq*	1320	1820	3630	5.2	7.2	14	49.5	68.3	136.6
ODP_{inf}	*kg CFC-11-eq*	2.8E-04	3.6E-04	6.5E-04	1.1E-06	1.4E-06	2.6E-06	1.1E-05	1.4E-05	2.4E-05
POFP	*kg NMVOC*	18	22	38	7.2E-02	8.9E-02	1.5E-01	6.8E-01	8.4E-01	1.4E+00
PMFP	*kg PM10-eq*	16	18	26	6.1E-02	7.0E-02	1.0E-01	5.8E-01	6.7E-01	9.7E-01
TAP_{100}	*kg SO_2-eq*	51	59	85	2.0E-01	2.3E-01	3.4E-01	1.9	2.2	3.2
FEP	*kg P-eq*	8.0	8.7	11.0	3.2E-02	3.4E-02	4.4E-02	3.0E-01	3.3E-01	4.2E-01
MEP	*kg N-eq*	6.4	6.7	7.8	2.5E-02	2.6E-02	3.1E-02	2.4E-01	2.5E-01	2.9E-01
$FETP_{inf}$	*kg 1,4-DCB-eq*	256	267	308	1.0	1.1	1.2	9.6	10.0	11.6
$METP_{inf}$	*kg 1,4-DCB-eq*	276	287	329	1.1	1.1	1.3	10.4	10.8	12.4
$TETP_{inf}$	*kg 1,4-DCB-eq*	1.3	1.4	1.6	5.2E-03	5.4E-03	6.2E-03	5.0E-02	5.2E-02	5.9E-02
HTP_{inf}	*kg 1,4-DCB-eq*	15900	16340	18110	63	64	71	596	614	681
MDP	*kg Fe-eq*	4100	4120	4180	16	16	17	154	155	157

Note: Impact categories: global warming potential (GWP), fossil depletion potential (FDP), ozone depletion potential (ODP), photo oxidation formation potential (POFP), particulate matter formation potential (PMFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), freshwater toxicity potential (FETP), marine toxicity potential (METP), terrestrial eutrophication potential (TETP), human toxicity potential (HTP), metal depletion potential (MDP). Suffixes “eq”, “100” and “inf” refer to equivalents, 100 years, and infinity, respectively. *Abbreviations:* CO_2 refers to carbon dioxide, CFC-11 to trichlorofluoromethane, NMVOC to “non-methane volatile organic carbon”, PM10 to “particulate matter less than 10 um in diameter”, SO_2 to sulfur dioxide, P to phosphor, N to nitrogen, 1,4-DCB to 1,4-dichlorobenzene, Fe to iron.

The results will hereafter be discussed in terms of the LBV, as this is likely to better reflect large-scale production volumes. The cradle-to-gate production impacts of the battery are mainly caused by the production chains of three key requirements: the manufacture of battery cells, the positive electrode paste, and the negative current collector (figure 2).

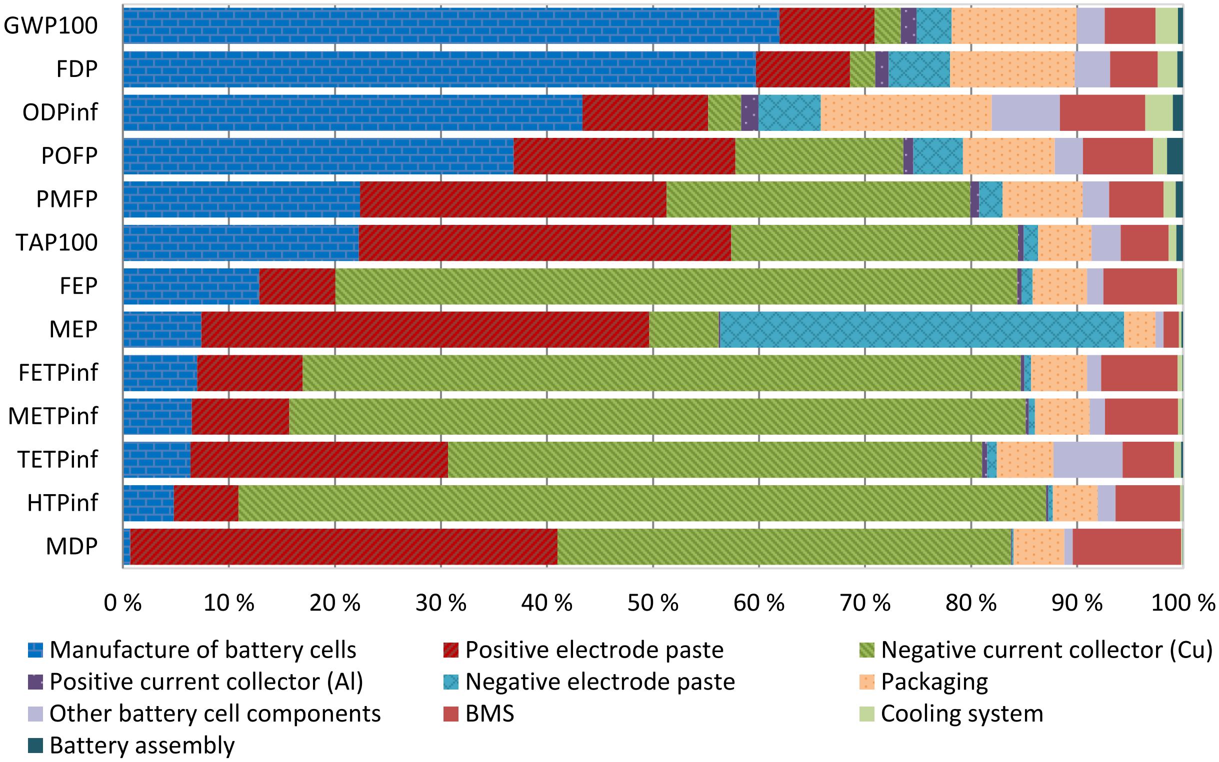


Figure 2 Contribution of cradle-to-gate impacts of the battery. Impact categories: global warming potential (GWP), fossil depletion potential (FDP), ozone depletion potential (ODP), photo oxidation formation potential (POFP), particulate matter formation potential (PMFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), freshwater toxicity potential (FETP), marine toxicity potential (METP), terrestrial eutrophication potential (TETP), human toxicity potential (HTP), metal depletion potential (MDP). Suffixes "eq", "100" and "inf" refer to equivalents, 100 years, and infinity, respectively. Abbreviations: CO2 refers to carbon dioxide, CFC-11 to trichlorofluoromethane, NMVOC to "non-methane volatile organic carbon", PM10 to "particulate matter less than 10 um in diameter", SO2 to sulfur dioxide, P to phosphor, N to nitrogen, 1,4-DCB to 1,4-dichlorobenzene, Fe to iron.

For the various impact categories, these three production chains combined comprise 56-87 % of the battery's total impact. With the use of SPA, the value chains are tracked to find the different sources of impacts. Combustion of hard coal and natural gas in power plant to meet the energy requirements for the manufacture of battery cells make up 51% of the battery's total GWP impact. Extraction of hard coal and natural gas for the same purpose make up 32% of the battery's total fossil depletion potential (FDP). Natural gas, uranium, and crude oil, which are also used to meet the energy requirements for battery cell production, contribute to 31 % of the battery's total ozone depletion potential (ODP). Most impacts from the positive electrode paste are predominantly due to the use of nickel sulfate, but manganese causes 86% of the paste's metal depletion potential (MDP). It should be noted that the ReCiPe method does not include a depletion characterization factor for lithium and therefore the use of lithium has no MDP impact, which in turn results in an underestimated absolute MDP value in this study (see Insights and implications). Primary copper used in the negative current collector adds a large share of the battery's total impact for many midpoint categories; it indirectly causes the disposal of sulfidic tailings that are at blame for 62% of freshwater eutrophication potential (FEP), 65% of freshwater ecotoxicity potential (FETP), 54% of marine ecotoxicity potential (METP), and 53% of human toxicity potential (HTP). The solvent N-methyl-2-pyrrolidone (NMP), used in both the positive and negative electrode paste, causes the only significant contribution of the negative paste; production of dimethylamine used in the solvent contributes to 75% of the battery's total marine eutrophication potential (MEP).

Sensitivity analyses

To establish the GWP impact for a given distance driven, the total production impact of the battery is divided by the total distance the battery covers during its operating life in the vehicle. For a given initial nominal energy capacity, the distance is dependent upon the battery's cycle life and the powertrain efficiency of the EV. For figure 3, an 80 % DOD and a capacity loss of 0.008 % per cycle from its initial capacity (see supporting information) were assumed.

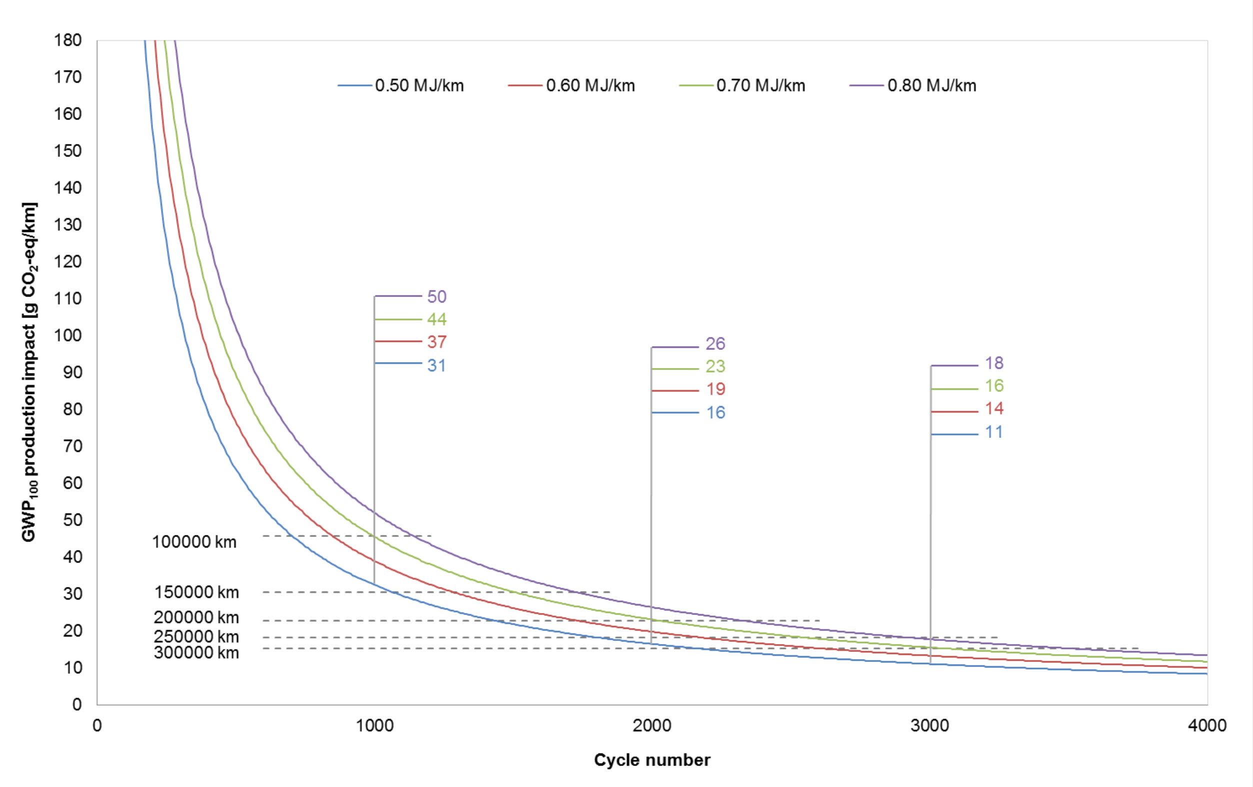


Figure 3 Sensitivity analysis on production impacts spread out over the use phase. Impact category: global warming potential (GWP). Suffixes "eq" and "100" refer to equivalents and 100 years, respectively. Abbreviations: g refers to gram, CO2 to carbon dioxide, MJ to mega joule, km to kilometer.

The impact of production measured in gram (g) per kilometer (km) is a decaying function of cycle number; because the battery deteriorates slowly, doubling the number of charge-discharge cycles in the battery's use phase almost doubles the driving distance for the same initial impact (figure 3). Lower cycle numbers can be crucial for whether a BEV is environmentally preferable to an ICEV or not. Studies assessing the environmental performance of batteries can reach different conclusions all depending on the assumptions regarding battery cycle numbers or range; for our battery, a battery lifetime of 3000 cycles (Majeau-Bettez et al. 2011) with a powertrain efficiency of 0.50 MJ per km results in 11 g CO_2-eq·km^{-1}, whereas a lifetime of 150 000 km (Notter et al. 2010), results in 31 g CO_2-eq·km^{-1}.

Figure 3 also shows how, for a given number of charge-discharge cycles, different powertrain efficiencies allow for different driving distances with the same initial battery production impact. For example, relative to a powertrain efficiency of 0.5 MJ·km^{-1} as a starting point, every 0.1 MJ·km^{-1} change in powertrain efficiency yields a 20 % change in attributed production impact per kilometer for any given cycle number.

Energy requirements met with highly carbon intensive electricity mix result in large GWP impacts (figure 4). The largest energy requirements in the production of the battery are found in the manufacture of battery cells, and thus a sensitivity analysis with respect to the electricity used in the production of the cells is performed.

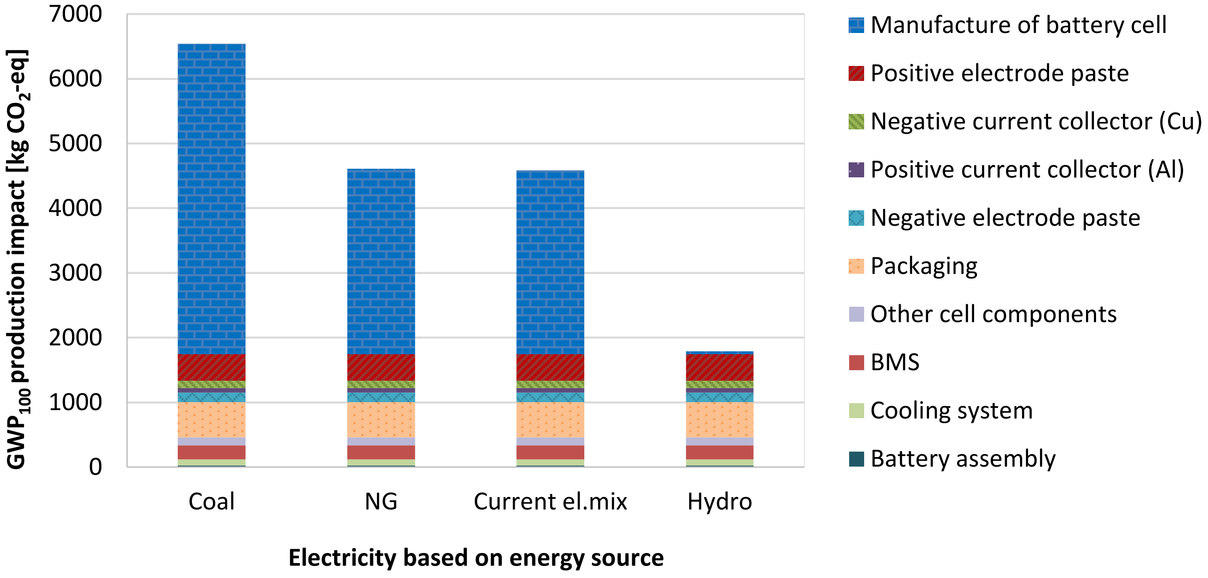


Figure 4 Sensitivity analysis with respect to source of electricity for battery cell manufacture. Impact category: global warming potential (GWP). Suffixes "eq" and "100" refer to equivalents and 100 years, respectively. Abbreviations: kg refers to kilogram, CO2 to carbon dioxide.

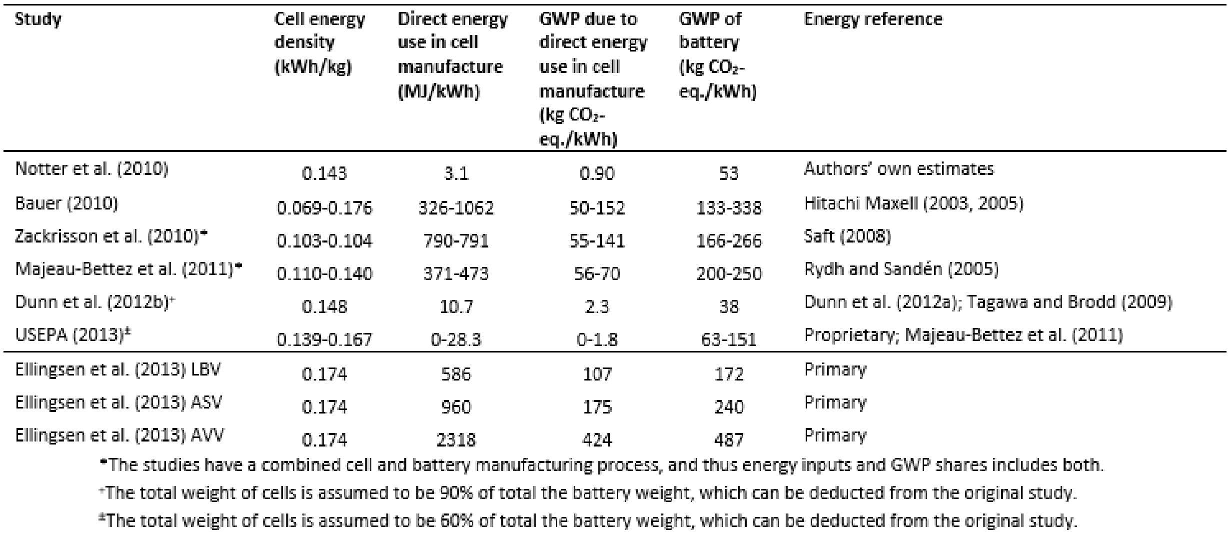
In the first scenario, the battery cells are produced with electricity based on coal, which results in an increase of the battery's GWP by more than 40%. In the second scenario, the electricity is based on natural gas, which has similar carbon intensity as the current electricity mix and thus results in insignificant change in GWP. In the last scenario, the battery cells are produced using electricity based on hydroelectric power, which leads to more than 60% decrease compared to the battery's current GWP.

Discussion

Result analysis and comparison with preceding studies

The objective of the study is to provide a detailed life cycle inventory of an NCM traction battery and to report direct and indirect impacts of production for this battery. Battery capacity measured in kWh is used as a representative functional unit for batteries, which allows a consistent comparison of the studies. Data from preceding Li-ion traction battery studies have been compiled and energy density of cell, direct energy requirements for cell manufacture in terms of MJ per kWh, GWP due to direct energy use in cell manufacture, and GWP of the entire battery (table 3). Note that the focus is on the cell (not the battery), as energy requirements are significantly higher in cell production than in battery assembly.

Table 3 Cell data.



Study	Cell energy density (kWh/kg)	Direct energy use in cell manufacture (MJ/kWh)	GWP due to direct energy use in cell manufacture (kg CO_2-eq./kWh)	GWP of battery (kg CO_2-eq./kWh)	Energy reference
Notter et al. (2010)	0.143	3.1	0.90	53	Authors' own estimates
Bauer (2010)	0.069-0.176	326-1062	50-152	133-338	Hitachi Maxell (2003, 2005)
Zackrisson et al. (2010)*	0.103-0.104	790-791	55-141	166-266	Saft (2008)
Majeau-Bettez et al. (2011)*	0.110-0.140	371-473	56-70	200-250	Rydh and Sandén (2005)
Dunn et al. (2012b)†	0.148	10.7	2.3	38	Dunn et al. (2012a); Tagawa and Brodd (2009)
USEPA (2013)‡	0.139-0.167	0-28.3	0-1.8	63-151	Proprietary; Majeau-Bettez et al. (2011)
Ellingsen et al. (2013) LBV	0.174	586	107	172	Primary
Ellingsen et al. (2013) ASV	0.174	960	175	240	Primary
Ellingsen et al. (2013) AVV	0.174	2318	424	487	Primary

*The studies have a combined cell and battery manufacturing process, and thus energy inputs and GWP shares includes both.

†The total weight of cells is assumed to be 90% of total the battery weight, which can be deducted from the original study.

‡The total weight of cells is assumed to be 60% of total the battery weight, which can be deducted from the original study.

Note: kWh refers to kilowatt hour, kg to kilogram, MJ to mega joule, CO_2-eq to carbon dioxide equivalents, LBV to lower bound value, ASV asymptotic value, AVV to average value.

The reported energy required for manufacture of battery cells from preceding studies vary greatly, from 3.1 MJ·kWh^{-1} to 1060 MJ·kWh^{-1} (table 3). At the LBV, the present study reports the corresponding energy requirements to be 586 MJ·kWh^{-1}. Notter et al (2010) made their own process-based energy estimations. Bauer (2010), Zackrisson and colleagues (2010), and Majeau-Bettez and colleagues (2011) based their energy data on industry reports from Hitachi Maxell (2003, 2005), Saft (2008), and Rydh and Sandén (2005), respectively. Note that energy data reported in Zackrisson and colleagues (2010) and Majeau-Bettez and colleagues (2011) include battery assembly as well as cell manufacture. Dunn and colleagues (2012b) based their energy data on a quote for a dry room (provided by dry room manufacturer SCS Systems) and calculated energy required for formation cycling (Dunn et al. 2012a). The USEPA (2013) based their energy data partly on proprietary industry sources and partly on Majeau-Bettez and colleagues (2011). The process-level approach, used by Dunn and colleagues (2012b) and Notter and colleagues (2010), has the advantage of being process specific and yields detailed results, but runs the risk of leaving out processes and the lack of access to primary data may lead to uncertain estimates. The top-down approach, used by Bauer (2010), Zackrisson and colleagues (2010), and Majeau-Bettez and colleagues (2011) has the advantage of being complete with respect to inclusion of all relevant activities related to the producing industry, but data is often aggregated, which results in a lack of detail, and may include inhomogeneous products. In our study, the system boundaries for the battery cell manufacture are well defined and products are homogenous (produces only Li-ion battery cells), and thus we used a top-down approach to establish the energy usage. The different approaches have resulted in two opposing understandings; we align with Bauer (2010), Zackrisson and colleagues (2010), and Majeau-Bettez and colleagues (2011) and find significantly higher energy requirements than Dunn and colleagues (2012b), Notter and colleagues (2010) and the USEPA (2013).

The environmental impacts of the cradle-to-gate analysis for the LBV are compared with results reported in preceding studies, but only limited comparison can be made with Bauer (2010) and Dunn and colleagues (2012b) as they report results for materials rather than components. There will be a stronger emphasis on GWP than other impact categories, owing both to GWP being the only common impact category in the reviewed literature, and the fact that EVs, to a large extent, are being promoted precisely as an alternative to ICEVs in order to reduce GWP. The preceding studies report a wide range of impacts, 53-338 kg CO_2-eq·kWh^{-1} of nominal capacity. In comparison, our production impact is found to be 172 kg CO_2-eq·kWh^{-1}.

We use the same inventory, with only a small alteration, for the positive active material as Majeau-Bettez and colleagues (2011) did for their NCM battery. Despite the common data, the GWP impact of the positive electrode paste reported in our study is nearly one fifth of what Majeau-Bettez and colleagues (2011) found; their high impact is due to the binder used in their study. The total ODP obtained in their study is more than two orders of magnitude higher than ours and nearly all of their ODP impact is attributed to the binder material. Majeau-Bettez and colleagues (2011) assumed polytetrafluoroethylene (PTFE) as binder, and used tetrafluoroethylene (TFE) as a proxy, which the authors mentioned as having a high GWP, and particularly high ODP impact. In contrast, we use polyvinyl fluoride as a proxy for polyvinylidene fluoride. Our study reports similar overall impact of the positive current collector as Majeau-Bettez and colleagues (2011). We obtain twice as high GWP impact for the positive electrode paste compared to Notter and colleagues (2010), this is likely due to differences in the active materials. Notter and colleagues (2010) estimated the weight of the positive current collector to be more than four times heavier than those in our battery, and consequently report GWP more than four times larger than our study. Zackrisson and colleagues (2010) report the GWP impact of the cathode, made with water rather than NMP, to be similar to ours. Compared to our cathode, the USEPA (2013) reports twice as high impacts for their NCM cathode, likely explained by the higher share of cathode materials in their battery.

Majeau-Bettez and colleagues (2011) report GWP impacts of the negative electrode paste around four times larger than the paste in our battery, which is also likely to be due to the use of PTFE as a binder. For our battery, MEP due to the negative electrode paste is caused by production of dimethylamine used in NMP. The amount of NMP in our battery is larger than what Majeau-Bettez and colleagues (2011) estimated in their study, and this explains their lower

MEP impact. Because our negative current collectors are heavier than those in Majeau-Bettez and colleagues (2011) there is higher overall impact. For the anode, with water as solvent, Zackrisson and colleagues (2010) find the GWP to be nearly seven times smaller than the anode in our battery. A possible explanation is that only 4.8% of the battery cell's weight is due to the negative current collectors in the Zackrisson and colleagues (2010) study, compared to 22% in our battery. Both Notter and colleagues (2010) and the USEPA (2013) obtain similar GWP for the anode as we do.

The lack of access to industry data in the preceding studies is perhaps more evident for the packaging and the BMS components than the other battery components. The reported GWP due to packaging is three to nine times higher for our battery than the preceding studies. For the BMS inventory, there is great variability in the literature. Compared to our BMS, Majeau-Bettez and colleagues (2011) and Zackrisson and colleagues (2010) report three to four times larger GWP, whereas the USEPA (2013) and Dunn and colleagues (2012b) estimate half the impact of ours. The BMS impact reported by Notter and colleagues (2010) is similar to the impact of our BMS.

The USEPA (2013) reported the impact of a cooling system aggregated with the BMS impact. Dunn and colleagues (2012b) included glycol as a coolant fluid, but beyond this did not make an inventory for a cooling system. Because the cooling system is a rather uncomplicated component material-wise and the inventory is based on primary industry data, we are confident in the relatively low (5% of total GWP) impact generated by the cooling system.

Insights and implications

The production of the battery requires five kg of lithium. It is deemed unlikely that lithium in the battery will be recycled as only selected materials, such as nickel and cobalt, are being recycled from Li-ion batteries (Dewulf at al. 2010). At present, the recovery of lithium is not efficient due to the low lithium content in batteries and the present low prices for lithium ore (Ziemann et al. 2012). Grosjean and colleagues (2012) and Mohr and colleagues (2012) assessed the world lithium resources, and concluded that despite the technological breakthrough of EVs, the planet is in no danger of running out of lithium. In the study by Notter and colleagues (2010), it was concluded that although lithium can be considered to be a geochemically scarce metal, assessment with abiotic depletion potential does not result in a high impact for the lithium components of their battery.

By using our findings as a guide, the battery industry can reduce the environmental footprint of traction batteries. GWP of the battery will be reduced if the energy requirements are decreased or met with less carbon intensive electricity. The sensitivity analysis showed that it was possible to reduce the impact of production by more than 60% if the electricity used in cell manufacture was based on hydroelectric power rather than the current electricity mix. For the studied NCM battery, the positive electrode paste and the negative current collector made of copper have particularly high environmental impacts and reuse of these components is desirable as adverse environmental effects can thereby be avoided. The current battery technology has a limited functional lifetime; ideally, the batteries should last at least as long as the vehicles they drive. Extending the battery life may eliminate the necessity of replacement in the vehicle lifetime, making the achievable cycle number of the battery a crucial parameter. The sensitivity analysis performed on cycle number and impact per kilometer driven (figure 3), shows that not only total number of cycles delivered by the battery is important, but that powertrain efficiency is also a crucial parameter. To drive a distance of 160 000 km (total driving distance given for the Mercedes-Benz A 180), 1100 cycles will be demanded of the battery by a vehicle with powertrain efficiency of 0.50 MJ/km, whereas 1800 cycles will be demanded by a vehicle with powertrain efficiency of 0.80 MJ/km. This demonstrates that the number of cycles required from the battery by the vehicle is dependent on the powertrain efficiency of the vehicle. In this way, the powertrain efficiency directly influences the usable lifetime of the battery in the vehicle (figure 3).

The production of the battery causes 4.6 tonnes CO_2-eq. at LBV (table 2). This is close to the cradle-to-gate impact of a small personal vehicle such as the A 180, which emits 6.1 tonnes CO_2-eq (Daimler AG 2012). In fact, production of EVs have been found to be almost twice as large GWP as ICEVs (Hawkins at al. 2012; Volkswagen AG 2013). In order for EVs to be a viable alternative from a GWP perspective, EVs have to make up for the large production phase impacts by emitting less than ICEVs in the use phase.

Conclusion

A high-resolution inventory for an NCM traction battery has been compiled. In addition, the environmental impacts associated with the production of the studied battery are assessed and analyzed (table 2). The most impact intensive production chains are the manufacture of the battery cells, the positive electrode paste, and the negative current collector (figure 2). Our main findings are comparable with those in preceding studies; the observed discrepancies between our study and the preceding studies can, to a large extent, be explained by the differences in battery design or the preceding studies' lack of access to primary data. Sensitivity analysis showed that powertrain efficiency and cycle numbers are crucial when assessing the environmental impact of traction batteries (figure 3). The sensitivity analysis of electricity used for manufacture of battery cells shows that the most effective approach to reduce GWP is to focus on reducing the energy demand in cell manufacture and the carbon intensity of the electricity used in production (figure 4).

If the battery industry and policy makers use our results to prioritize R&D resources – decreasing the manufacturing energy requirements or use cleaner electricity sources, closing the material loop by recycling, and increasing the battery lifetime – impacts may be reduced to the point where EVs offer very clear advantages relative to ICEVs. EV producers, in turn, may improve the battery lifetime by improving powertrain efficiency.

With this work, original primary data is provided and by doing so some of the key gaps in the existing literature on EVs and particularly on traction batteries are filled. Consequently, the study allows for better understanding of the environmental impacts pertaining to traction batteries and ultimately EVs, and permits the discussion of traction batteries to move forward with a greater empirical foundation.

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