# Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles

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Battery-powered electric cars (BEVs) play a key role in future mobility scenarios. However, little is known about the environmental impacts of the production, use and disposal of the lithium ion (Li-ion) battery. This makes it difficult to compare the environmental impacts of BEVs with those of internal combustion engine cars (ICEVs). Consequently, a detailed lifecycle inventory of a Li-ion battery and a rough LCA of BEV based mobility were compiled. The study shows that the environmental burdens of mobility are dominated by the operation phase regardless of whether a gasoline-fueled ICEV or a European electricity fueled BEV is used. The share of the total environmental impact of E-mobility caused by the battery (measured in Ecoindicator 99 points) is 15%. The impact caused by the extraction of lithium for the components of the Li-ion battery is less than 2.3% (Ecoindicator 99 points). The major contributor to the environmental burden caused by the battery is the supply of copper and aluminum for the production of the anode and the cathode, plus the required cables or the battery management system. This study provides a sound basis for more detailed environmental assessments of battery based E-mobility.

## Introduction

Society's current individual mobility behavior is creating a plethora of looming problems, such as fossil carbon intensity and the concomitant consequences regarding fossil resource supply or the emissions of pollutants such as nitrogen oxides ($NO_x$), sulfur dioxide ($SO_2$), and particulate matter. While pollutant problems can partially be solved technically by catalytic converters and filters, expectations run high that the greenhouse gas and resource problems can be addressed by massively substituting internal combustion engine cars (ICEV) with battery powered electric cars (BEV).

The widely used term "electric car" covers many types of currently discussed and tested variations of electrical propulsion systems for passenger cars, such as battery car, fuel cell car, and serial hybrid (range extender) car. Most of the major car manufacturers recently announced that battery cars will soon become part of their product lines (*1*).

In the past, the BEVs' on-board energy supply has been based on lead-acid, on nickel−metal hydride (NiMH), or on sodium−nickel−chloride (ZEBRA) batteries. New electric cars typically use lithium ion (Li-ion) batteries. Major reasons are the favorable material characteristics of lithium: it is the lightest of all metals and offers the greatest electrochemical potential, which results in a high power and energy density (*2*). Additionally, extensive experiences gained in the Information and Communication Technology (ICT) industry have led to safe, long-lasting, and affordable products. The Li-ion battery requires little maintenance, an advantage that most other battery chemistries cannot claim. There is no memory effect, little self-discharge, and no scheduled cycling is required to prolong the battery's life. Li-ion battery chemistries and cell construction are rapidly developing and changing: For instance, the commonly used, but expensive, cobalt is being replaced by chemistries using iron phosphate or manganese (*3*). Another development is the increase in the content of active material by, for example, using bipolar electrodes (*4*).

Commercial Li-ion cells are currently using various types of cathode materials (*5*); one of them is lithium manganese oxide ($LiMn_2O_4$). Spinel type $LiMn_2O_4$ is attractive for BEVs in many aspects, such as low cost, rather easy production process (*3*) and, last but not least, thermal safety (*6*). In addition, manganese is abundant in nature (*7*) and well established in the battery industry (*8*).

The question remains as to whether the need for batteries is causing an overcompensation of the potential benefits of the higher efficiency of BEVs compared to ICEVs. The study presented in this paper aims at establishing a sound basis for answering this question from an environmental point of view.

## Methods and Definitions

**Life Cycle Assessment (LCA).** LCA is an established but still evolving method primarily designed for accounting for and assessing the potential environmental impacts caused by products, processes, or activities (*9*). LCA aspires to quantify and evaluate the energy and material flows used in all stages of a product's lifetime and the associated wastes and emissions released to the environment. LCA is based on a perspective called the functional unit. This is especially important when competing products are analyzed to allow for comparative assessment.

This study analyzes the use of lithium-ion batteries in electric vehicles as an environmentally viable option and evaluates whether the burdens related to the battery are likely to offset the benefits related to the electric drivetrain. For this end it is necessary to model electric mobility (E-mobility) including the vehicle's production, use and disposal with a strong focus on the Li-ion battery. The functional unit is chosen as one average kilometer driven by a vehicle with electric drivetrain and Li-ion batteries on the European road network. The corresponding reference flow is one vehicle-kilometer. The study encompasses a cradle-to-grave system without predefined cutoff limits. Materials and processes are only neglected when their contribution to the potential environmental burdens is considered negligible based on a combination of mass, energy demand, and expected burdens per mass or energy unit. LCI data for the battery production and for the production and use of an electric vehicle are compiled specifically for this study (see Figure 1), while LCI data for the materials and processes in the background system are taken from the ecoinvent database version 2.01.

**Battery.** We chose to model a $LiMn_2O_4$ battery since it seems reasonable to assume that manganese will in the near future be substituted for the nickel and cobalt commonly

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used in many of today's batteries because of the much lower price, and better availability of manganese. Calculations were done on different cathode materials containing nickel, cobalt or iron-phosphate in order to check the sensitivity of the results. Details on the production of the battery and its components are given in the paragraph below headed Description of Unit Processes.

**Electric Vehicle.** The vehicle we studied was comparable to a Volkswagen Golf in size and power, had a range of around 200 km per charge (battery weight, 300 kg; battery capacity, 0.114 kWh/kg battery (*10*)) and an assumed lifetime of 150 000 km. These assumptions were tested with a sensitivity analysis for an extension of vehicle life to 240 000 km. In this case the BEV would require a battery replacement. The energy consumption of the electric vehicle's operation was estimated based on existing vehicles and theoretical considerations (for details see Supporting Information); 14.1 kWh of electric energy is needed per 100 km to propel a Golf-class vehicle with an overall efficiency of 80% (including charging losses and recuperation gains) in a standard driving cycle (New European Driving Cycle, NEDC). Heating, cooling, and electronic devices consume 2.9 kWh/100 km (for details see Supporting Information). The BEV thus required a total of 17 kWh/100 km. The influence of energy consumption on the environmental burden was tested by varying energy demand by $\pm 20\%$.

The average electricity production mix (UCTE) in Europe (*11*) was chosen for the operation of the BEVs in agreement with the criteria used in the rest of the study and in the ecoinvent database. The environmental burden for the operation of BEV depended mainly on the choice of electricity production. This was tested by replacing the UCTE-mix with electricity from hard coal and hydropower. It is important to state that neither the vehicle nor the battery was meant to represent specific products but rather a technically sensible option.

**Reference Vehicle.** A new efficient gasoline car (Euro 5 standard (*12*)) was chosen as a basis for comparison. This ICEV consumes 5.2 L of gasoline per 100 km in the NEDC, resulting in a direct emission of 0.12 kg $CO_2$ per km (*13*). The car chosen was representative of neither the European fleet nor the fleet of new cars sold in Europe in 2009: 51.4% of the latter consists of diesel fuel cars with an average fuel consumption of 5.7 L/100 km diesel or 6.6 L/100 km gasoline (calculated from $CO_2$ emissions reported in ref *14*). However, the ICEV was chosen to represent a technological level similar to that of the BEV.

**Allocation and System Boundary.** Allocation of the inputs and output flows to the various products is a critical issue in LCA studies because the choice of allocation principles can predetermine the outcome of the LCA. Thus, it is very important that allocation procedures are in line with the goal of the study (*15*). Since a present study aimed to determine the potential contribution of batteries to the overall burdens of mobility, allocation in the foreground system was chosen in such a way as to result in the highest possible environmental burdens for the battery. Thus, all expenditures for the exploitation of the lithium salts were allocated to the lithium salts, even though the saline brine yields other byproduct as well.

In line with this principle, end-of-life (EOL) products that are being recycled are not allocated any expenditure from their production. Thus, all the burdens from material production are allocated to the first life of a product even though the product might even be reused (e.g., after 5 years in a vehicle the batteries might be used in stationary applications).

**Environmental Impact Assessment.** The environmental burdens are expressed as global warming potential (GWP) applying a time frame of 100 years (*16*), the cumulative energy demand (CED) of which only the nonrenewable (fossil fuel and nuclear) are disclosed (*17*) and the Ecoindicator 99 using the hierarchic perspective and an average weighting (EI99 H/A) (*18*). Resource depletion is indicated as abiotic depletion potential (ADP), one of the impact categories in the CML method (*19, 20*). All impact assessment methods are used as implemented in the ecoinvent database version 2.01. The first two indicators were chosen for their broad acceptance and relevance in decision making. The EI99 H/A was chosen since the other indicators are almost exclusively energy driven and exclude (toxic) effects on human health and ecosystems, as well as damage to resource quality. ADP was evaluated to include the use of resources, especially metals. Apart from the impact assessment results, we also present cumulative particulate matter ($PM_{10}$), $SO_2$, and $NO_x$ emissions, since these indicators are widely used in discussions on environmental issues of mobility.

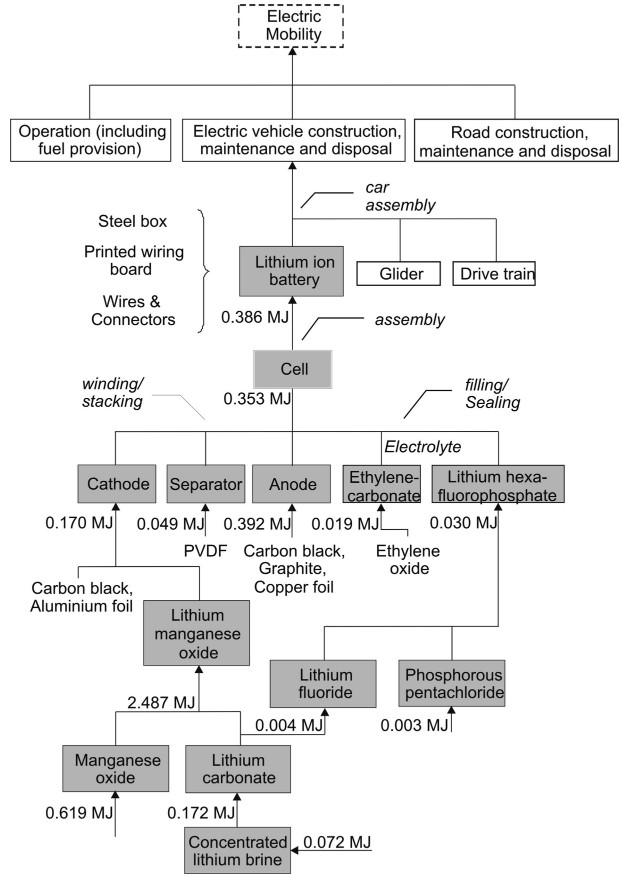


**FIGURE 1. Model structure of electric mobility. The present study considers all relevant processes to deliver a journey of 1 km but focuses on the materials and components in the gray boxes.**

**Description of Unit Processes.** Figure 1 depicts the production steps required for the Li-ion battery ranging from the extraction of lithium and the electrode production to the battery pack, the components of the electric vehicle, and the mobility with the electric vehicle. The dashed line refers to the functional unit chosen for this study. For all productions steps, the required thermal and electrical energy to produce a 1 kg Li-ion battery is quoted. The mass used for the calculation are based on a Kokam battery (*21*) and the cathode material is assumed to be $LiMn_2O_4$. Detailed input−output tables for all gray boxes and the assumptions for transport distances, infrastructure, and electricity mixes are provided in the Supporting Information.

The production of concentrated lithium brine includes inspissations of lithium containing brine by solar energy in the desert of Atacama. Diesel fuel is required for pumping

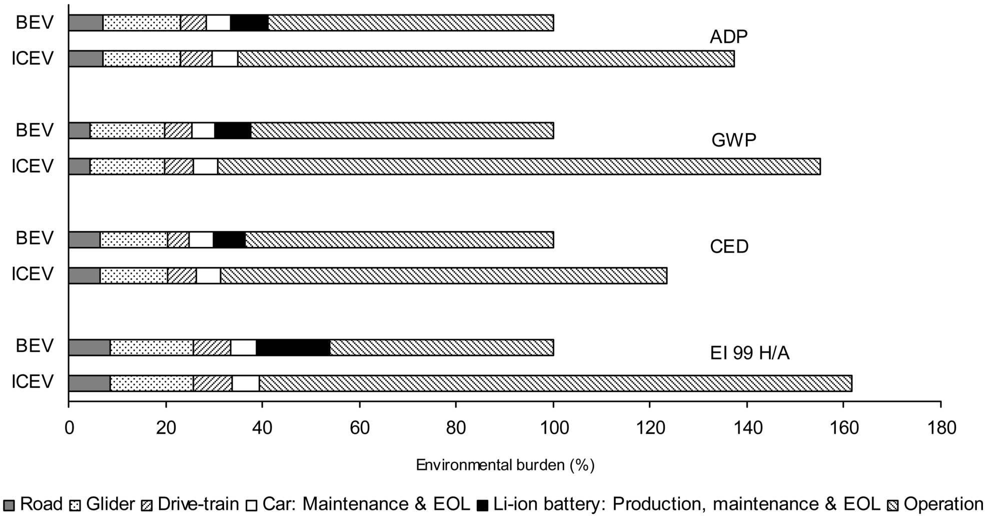


**FIGURE 2. Shares correlating with the components of an internal combustion engine car (ICEV, value in % of the BEV) and an electric battery powered car (BEV, the BEV is set as 100%) assessed with four impact assessment methods: abiotic depletion potential (ADP), nonrenewable cumulated energy demand (CED), global warming potential (GWP), and Ecoindicator 99 H/A (EI99 H/A). Road includes construction, maintenance, and end of life treatment (EOL). The absolute values of the components are provided in the Supporting Information.**

the brine (*22*) between different basins. The concentrated lithium brine is further treated with additives for the removal of boron, followed by a purification step. Finally, the addition of soda for carbonation results in the precipitation of lithium carbonate ($Li_2CO_3$). The salt is filtered, washed and dried which results in a purity of 99% or higher (*23*).

Manganese oxide ($Mn_2O_3$) is produced by a two stage roasting process whereby manganese carbonate is roasted in an atmosphere low in oxygen content, followed by roasting in an atmosphere high in oxygen content (*24*). Subsequently, lithium manganese oxide ($LiMn_2O_4$) is made from $Mn_2O_3$ and $Li_2CO_3$ by means of several roasting stages in a rotary kiln (*3*). During the different stages, the atmosphere in the rotary kiln changes from an inert (addition of $N_2$) to an oxidizing (addition of $O_2$) condition. The powder is then suspended with water followed by spray drying (evaporation of the water).

Base materials for the electrolyte are an organic solvent, typically ethylene carbonate ($C_3H_4O_3$) (*25*), and the electrolytic salt, typically lithium hexafluorophosphate ($LiPF_6$) (*26*). For the production of the $LiPF_6$, lithium fluoride (LiF) is manufactured with a reaction of $Li_2CO_3$ and hydrogen fluoride at room temperature. The filtrate is titrated with ammonia (pH 7.5), washed with water, and dried (*27*). Phosphorus pentachloride ($PCl_5$) (*28*) and LiF are then combined in an autoclave and cooled down to −78 °C. Thereafter, hydrogen fluoride is added in excess for complete chlorine-fluorine exchange in $PCl_5$ (*29*). The reaction in the autoclave occurs in an inert nitrogen atmosphere.

The production of the cathode and anode requires the mixture of a few components (binder and solvent, black carbon, $LiMn_2O_4$ and graphite respectively) in a ball mill to a slurry (*26, 30*), followed by coating the collector foil (aluminum and copper respectively) with the slurry. The binder (modified styrene butadiene copolymer (*31*)) is water-soluble and has the advantage that no organic solvent is needed. For the production of the separator, a porous polyethylene film is coated with a slurry consisting of a copolymer, dibutyl phthalate and silica dissolved in acetone (*32*). Thermal heat energy for anode, cathode and separator is used to heat up the slurry to 130 °C, to evaporate the solvent and to completely dehumidify the components of the electrode in a dry channel ($H_2O$ content <20 ppm) (*33*).

Cathode, separator, and anode are calendared, slit to size, winded, and packed to a single cell in a polyethylene envelope. In an inert atmosphere, the electrolyte ($LiPF_6$ dissolved in $C_3H_4O_3$) is added to the electrode (*26*). Finally, single cells, the battery management system and cables are assembled in a steel box.

The electric car represented in this LCI was derived from the existing Golf LCI (*34*). The glider (chassis, car body parts, wheels, interiors, safety devices, acclimatization devices) remained unaltered, but the drivetrain was replaced by an electric drivetrain (composed of the electric power control, an electric motor and the transmission) and by a Li-ion battery (see Scheme S1 for Supporting Information). The use of the car takes into account electricity consumption and all infrastructures needed (vehicle, road and electricity network) including EOL treatment. The data set for a new efficient gasoline passenger car with reduced fuel consumption (Euro 5 standard) based on the ecoinvent Database was used as a reference.

**Emissions and Impacts.** The Li-ion battery plays a minor role regarding the environmental burdens of E-mobility irrespective of the impact assessment method used. Transport services with an ICEV cause higher environmental burdens than with a BEV (ADP, + 37.47% or 261 kg antimony equivalents; GWP, + 55.3% or 37,700 kg $CO_2$ equivalents; CED, +23.5% or 593,000 MJ-equivalents; EI99 H/A, +61.6% or 2530 points; Figure 2). The share of the total environmental impact of E-mobility caused by the battery is between 7 (CED) and 15% (EI99 H/A). Analysis with EI99 H/A showed a relative share of E-mobility caused by the battery that is twice as high as analysis with the other impact assessment methods, and this is mainly at the expense of the operation phase.

There are no differences between ICEV and BEV with respect to the environmental burden related to road use (infrastructure, maintenance, and disposal) and the glider. Small differences are related to the drivetrain, maintenance, and disposal of the car. The main difference is reflected in the operation phase, which rises far above the impact of the battery. Operation obviously dominates the LCA of both E-mobility and mobility with an ICEV, while it is distinctly higher for mobility with an ICEV.

$PM_{10}$-, $NO_x$-, and $SO_2$-emissions caused by E-mobility ($PM_{10}$ 100%, 16.2 kg; $NO_x$ 100%, 49.5 kg; $SO_2$ 100%, 83.7 kg)

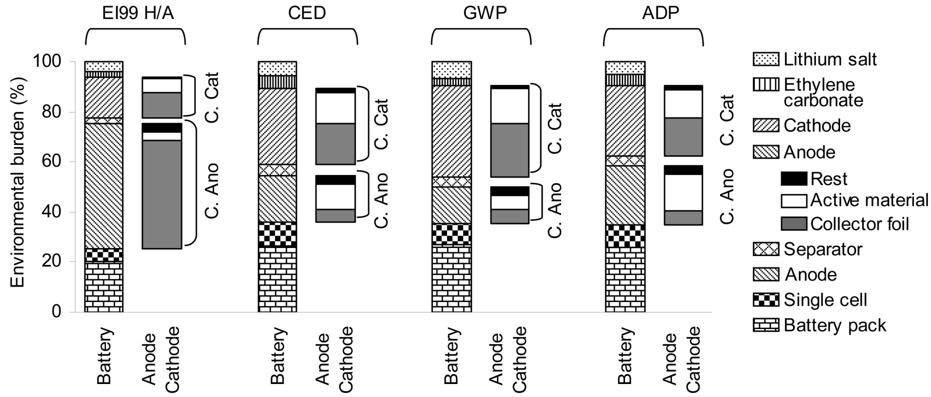


**FIGURE 3. Environmental burden of the main components of the Li-ion battery and the electrodes expressed with Ecoindicator 99 H/A (EI99 H/A), cumulated energy demand (CED), global warming potential (GWP), and abiotic depletion potential (ADP). Components of the anode (C. Ano), components of the cathode (C. Cat). Absolute values are provided in the Supporting Information.**

are higher compared to mobility with an ICEV ($PM_{10}$ 79.0%, 12.8 kg; $NO_x$ 87.9%, 43.5 kg; $SO_2$ 74.7%, 62.5 kg; Supporting Information Figure S1 and Table S20). All these emissions result mainly from operation independently of the vehicle type. The production of the battery, the glider, and the drivetrain also emits considerable amounts of $PM_{10}$, $NO_x$, and $SO_2$.

The production of the Li-ion battery is dominated by the production of the anode, the cathode and the battery pack (Figure 3). Single cell, separator, lithium salt, and solvent play a minor role. In addition to its cells, the battery pack contains a steel box, cables, and the printed wiring board. These components cause a relatively high share of more than 20% throughout all impact assessment methods.

Concerning EI99 H/A, the production of the anode generates the highest impact, while CED, GWP, and ADP show the highest impact for the production of the cathode. Copper in the anode is needed as collector foil, which has a share of 43% (EI99 H/A) of the environmental burden of the Li-ion battery. Copper used in other components (e.g., cables) comes in addition. Graphite and all other components of the anode only have a small impact. The results for the anode look different when assessed with the ADP, CED,or GWP. The anode has a much smaller share on the total impact of the battery. Within the anode, graphite shows a higher environmental burden than copper, at least when assessed with ADP and CED.

The cathode causes a higher GWP, CED, or ADP than the anode. The collector of the cathode, made of aluminum foil, has a higher share of the environmental burdens than the active material throughout all impact assessment methods. All other components (binder, carbon black, energy use, etc.) cause a very small environmental burden for the production of the cathode.

Environmental burdens caused by the two lithium containing components $LiMn_2O_4$ and $LiPF_6$ are between 10 (EI99 H/A) and 20% (GWP), whereas the share of $LiMn_2O_4$ (EI99 H/A 5.60%; GWP 13.8%) is higher than the share of $LiPF_6$ (EI99 H/A 3.79%; GWP 6.47%).

The printed wiring board, process heat, and nitrogen are other important contributors to the total impact of a Li-ion battery, besides the copper- and aluminum collector foils and the active materials graphite and $LiMn_2O_4$.

A closer look at the damage categories of the EI99 H/A indicates that the production of a Li-ion battery predominantly causes damage to human health (44%) and resource quality (39%), whereas the quality of ecosystems is affected less (17%). Inorganic emissions affecting the respiratory system, such as $PM_{10}$, $SO_2$, $NO_x$, etc., cause the highest impact, followed by the use of fossil fuels and minerals (for detailed information see Supporting Information Figure S2).

The sensitivity of the $LiMn_2O_4$ as an active material was tested (EI99 H/A) by comparing the environmental burden of $LiMn_2O_4$ compared to the also widely used active material $Li(Mn_{(1/3)}Ni_{(1/3)}Co_{(1/3)})O_2$ and $LiFeO_4$. While the scenario with the active material containing nickel and cobalt results in an increase in environmental burden of 12.8% for the battery, $LiFeO_4$ as cathode material decreases the impact for 1.9%. The difference on the level of transport service is much smaller ($Li(Mn_{(1/3)}Ni_{(1/3)}Co_{(1/3)})O_2$, +2.0%; $LiFeO_4$, −0.30%).

The results of the sensitivity calculated for a vehicle life of 240,000 km (the BEV needs 2 sets of Li-ion battery) shows a decrease of the total environmental burden per vehicle-kilometre (EI99 H/A) of 7.5% (BEV) and 7.1% (ICEV).

A variation of electricity consumption of ±20% (mean, 0.17 kWh/km; −20%, 0.14 kWh/km; +20%, 0.20 kWh/km) results in a modification of ±8.2% of the environmental burden (EI99 H/A) for E-mobility.

The impact (EI99 H/A) of the transportation of a BEV using electricity produced with hard coal (UCTE) increases for 13.4%, while it decreases for 40.2% when applying electricity from hydropower plants. Thus, using hydropower electricity as fuel for the BEV reduces the share of operation on total environmental burden of transport service substantially to 9.6%.

## Discussion

The main finding of this study is that the impact of a Li-ion battery used in BEVs for transport service is relatively small. In contrast, it is the operation phase that remains the dominant contributor to the environmental burden caused by transport service as long as the electricity for the BEV is not produced by renewable hydropower. This finding is in good accordance with other studies showing that the impact of operation dominates in transport service (*35, 36*). In these studies, infrastructure, maintenance, and service have minor shares of the environmental impact imposed by transport services. We found the same pattern for the environmental burden of the different components to transport service (Figure 2).

Another explanation for the small impact of the battery on the overall assessment of transport service is the tiny share of the lithium components on the environmental burden for the Li-ion battery. This finding can be explained first of all by the fact that the lithium content accounts for only 0.007 kg per kg Li-ion battery. Thereby, the lithium content of the active material ($LiMn_2O_4$) and the lithium in the electrolyte is included. In addition, the processes used to extract lithium from brines are very simple and have a low energy demand. Although lithium occurs in average con-

centrations lower than 0.01% in the Earth's crust and hence can be considered to be a geochemically scarce metal (*37*), assessment with ADP does not result in a high impact for the lithium components. $Li_2CO_3$, the base material for the cathode active material and the lithium salt have an impact of only 1.9%. Compared to other components, for example, $Mn_2O_3$ (4.4%), copper (5.3%) or aluminum (15.1%), the abiotic depletion of lithium resources does not seem to be critical. However, these results are valid only as long as $Li_2CO_3$ is produced from brines. If the lithium components were based on spodumene, a silicate of lithium and aluminum, the extraction of the lithium would require a considerable amount of process energy (*38*).

The major contributors to the environmental burden for the production of the battery, regardless of the impact assessment method used, are metal supply (Figure 3) and process energy. Metals appear above all in the production of the anode (copper collector foil), the cathode (aluminum collector foil), and the battery pack. The battery pack requires cables (copper), steel for the box of the battery and a battery management system, which contains different metals, for example, copper, gold, tin. A high energy demand occurs in the production of aluminum, the production of wafers for the battery management system, the production of graphite, the roasting processes of manganese carbonate to $Mn_2O_3$ or $Li_2CO_3$ and $Mn_2O_3$ to $LiMn_2O_4$ or the use of heat to dry the electrodes.

Graphite has a distinctly higher impact regarding CED compared to GWP. Hard coal coke is the base material which is transformed into graphite. The material itself contains a lot of energy and contributes to the CED, but not to the GWP as the carbon remains in the product and only a low level of $CO_2$ emissions are generated in the process.

Another remarkable contributor to the environmental impact of the Li-ion battery is $LiMn_2O_4$ which reaches its highest values when assessed with GWP. The high score is explained with the energy input for the roasting process of $Mn_2O_3$ and $LiMn_2O_4$ and the concomitant high use of the resource. The extraordinarily high value in terms of GWP originates from the fact that the conversion of manganese carbonate to $Mn_2O_3$ and further the reaction of $Li_2CO_3$ and $Mn_2O_3$ to $LiMn_2O_4$ releases considerable amounts of $CO_2$.

The LCA result of BEVmobility mainly depends on the environmental profile of the electricity mixes considered, as the vehicle tailpipe emissions are shifted to the power generation units (*36*). E-mobility causes the highest possible EI99 H/A, CED, GWP ADP results whenever an electricity mix is used that contains a high share of fossil fuel such as the UCTE electricity mix (share of fossil fuel >50% (*11*)). Nevertheless, the operation of an ICEV alone causes impacts that are roughly just as high (CED, 92%; GWP, 125%; Figure 2) as the total environmental impacts of E-mobility (100%). A break even analysis shows that an ICEV would need to consume less than 3.9 L/100km to cause lower CED than a BEV or less than 2.6 L/100km to cause a lower EI99 H/A score. Consumptions in this range are achieved by some small and very efficient diesel ICEVs, for example, from Ford and Volkswagen (*13, 39*).

Transport service affects the environment largely by contributing to global air pollution. $PM_{10}$, $SO_2$, and $NO_x$ traffic emissions contribute significantly to environmental problems such as acidification and eutrophication ($SO_2$ and $NO_x$), photochemical air pollution ($NO_x$) or have adverse effects on human health, for example, cell toxicity, damage to genetic material by means of oxidative stress or by triggering allergies ($PM_{10}$, $SO_2$, and $NO_x$). With respect to the LCI results for the pollutants $PM_{10}$, $SO_2$, and $NO_x$, transport with a BEV leads to higher environmental burden than transport with an ICEV. However, the emissions caused by the production of the vehicle, in particular the Li-ion battery, are located in industrial areas where the population density is rather small. The releases of emissions from operation are prevalent in urban areas with a high population density. The $NO_x$-emissions from an ICEV that originate prevalent from operation, consequently have a high damage potential to human health.

The relationship between operation versus battery production is different when assessed with EI99 H/A compared to the other impact assessment methods, even though the comparisons for transports with BEV or ICEV look very similar regardless of the method used. EI99 H/A indicates copper as being a large contributor to the environmental burden, whereas it has a rather small share when assessed with the other methods. On the contrary, aluminum and $LiMn_2O_4$ which contribute considerably when assessed with CED, GWP or ADP, only account for a small share when assessed with EI99 H/A. This is suggested by the different information that can be inferred when using the EI99 H/A method. GWP, CED and ADP are driven exclusively by the use of minerals and energy, while EI99 H/A also appraises toxicity to humans and ecosystems. The human health damage category within EI99 H/A accounts for 43% of the complete environmental burden caused by the production of a Li-ion battery (see Figure S2 in Supporting Information). When analyzing only copper (43% of overall impact of the entire battery production) with EI99 H/A, the damage to human health (40%) and ecosystem quality (27%) inflicts a greater environmental burden than the extraction of the mineral (30%) including energy consumption (3%). This evidence explains the different pictures produced by EI99 and the other assessment methods.

**Uncertainty and Sensitivity.** The inventory data presented for the Li-ion battery and both the BEV and the ICEV do not rely on performance data representing specific products, hence, uncertainties adhere to the LCI. Also the choice of allocation procedures and other modeling choices elicit variances that might affect the outcome of the study. The most critical points are therefore discussed in the following section.

The chemistry chosen for the Li-ion batteries investigated in this study was based on manganese. Today, numerous other materials are serious contenders for automotive batteries, for example, nickel, cobalt, or iron. The sensitivity analysis of different lithium-based cathode materials showed only small changes in the environmental burden. Hence, for a generic assessment it seems reasonable to neglect the diversity of many different active materials to reduce the complexity of battery chemistry.

The sensitivity analysis on electricity consumption for the BEV or the sensitivity analysis for a modified lifespan showed rather small variances concerning environmental burdens for both, mobility with an ICEV or BEV. However, the choice of the electricity generation led to considerable variations in the results. Propelling a BEV with electricity from an average hard coal power plant increases the environmental burden by 13.4%. On the other hand, using electricity from an average hydropower plant decreases environmental burden by 40.2%. This results in a decrease for the operation from 41.8% (UCTE mix) to 9.6% when charging the battery with electricity from hydropower plants.

The modeling applied to EOL treatment for the vehicles including the Li-ion battery resulted in a worst case scenario, as no benefits were derived from the potentially useful materials in the battery. Batteries are recycled at a very high rate, since recycling and recovery rates prescribed by the EU legislation are 85% for 2006 and 95% for 2015 (*40*). For a conventional car, the EI99 H/A scores would be reduced to 88.8% if the modeling approach included the benefits of recycled material being substituted for other

(virgin) materials (*41*). This reduction is expected to be even higher for electric vehicles since the exergy analysis by Dewulf et al. (*42*) shows that switching from virgin resource supply to recycling for Li-ion battery cathode material results in a 51% natural resource savings. Thus, the EOL modelling approach applied in this study underlines the ecological advantage of E-mobility over mobility with an ICEV.

All the facts taken together, the results of the LCA, the various sensitivity analyses, the modeling applied for EOL, the assumption for the used electricity mix, etc., suggest that E-mobility is environmentally beneficial compared to conventional mobility. The Li-ion battery plays a minor role in the assessment of the environmental burden of E-Mobility. Thus, a Li-ion battery in an BEV does not lead to an overcompensation of the potential benefits of the higher efficiency of BEV compared to an ICEV.

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## Supporting Information Available

Detailed life cycle inventory data for the drive train and the glider of the ICEV and the BEV, input−output tables for the Li-ion battery, and absolute values to environmental burden for E-mobility and conventional mobility. This information is available free of charge via the Internet at http://pubs.acs.org/.

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