Project Report
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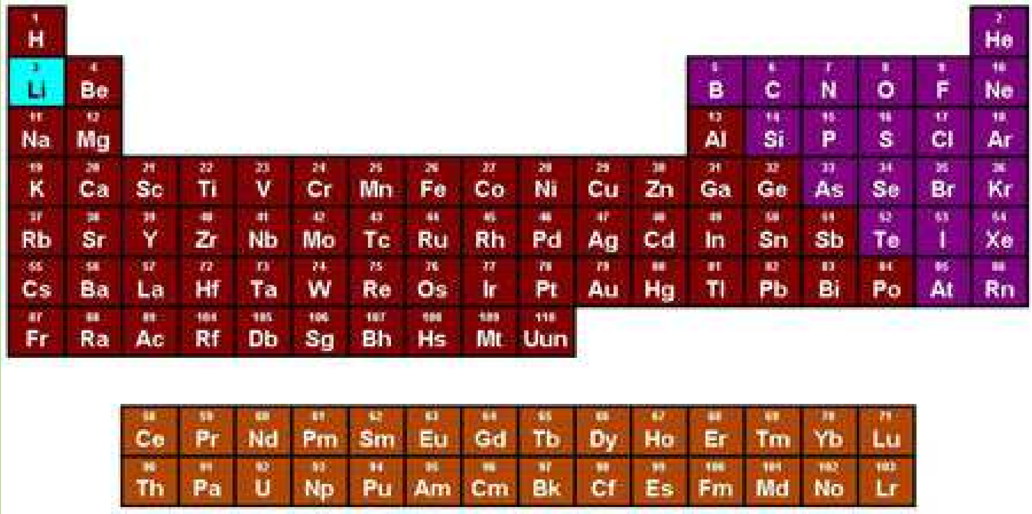

Life cycle assessment of long life lithium electrode for electric vehicle batteries

– 5Ah power cell

2016-04-29

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swerea IVF

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Preface

This report contains a life cycle assessment of lithium batteries. It was performed in the context of the Swedish TriLi - Longlife lithium electrodes for EV and HEV batteries - project. The LCA has been carried out by Mats Zackrisson at Swerea IVF. Members of the TriLi consortium have delivered detailed data about raw materials, manufacturing, use and recycling related to lithium batteries. Kristin Fransson and Jutta Hildenbrand at Swerea IVF have reviewed the report.

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Summary

This report contains a life cycle assessment of a 5Ah lithium battery cell weighing 149.7 grams with metallic lithium in the anode. It was performed in the context of the Swedish TriLi - Longlife lithium electrodes for EV and HEV batteries - project. The 5 Ah cell has been analyzed from cradle to grave, i.e., from raw material production over own manufacturing, use in a typical application and end-of-life. The study aims to highlight environmental hotspots with lithium batteries with metallic lithium in the anode in order to improve them as well as to verify environmental benefits with lithium batteries in vehicles.

A number of LCAs of different depth and detail will be carried out in the TriLi project, each following more or less the steps:

1. Provision of preliminary cell design and data
2. Screening LCA
3. Workshop to present and discuss screening LCA results
4. Revised cell design and data and recalculation of LCA
5. Workshop to present and discuss LCA-results of “final” cell design
6. Manufacturing of cell and testing of cell
7. Calculation of final LCA if needed

This report concerns the final LCA of a 5 Ah power cell weighing 149.7 grams. The results indicate that:

- LCA may be very helpful in the design process of batteries. An example is that the amount of lithium was reduced to a quarter without affecting battery performance, following that the screening LCA results pointed towards the lithium metal as the major source of climate impact.
- The largest non-recyclable contributor to climate impact and abiotic depletion in the production phase is the assembly energy. It therefore warrants special attention in further efforts to minimize cell environmental impacts.
- The cell efficiency is very important to consider. For η=0.95-0.5 electric losses range from 5 to 50% per delivered kWh. These losses are transformed into heat that may require further energy to get rid of.
- Use phase battery weight related losses are not as high and suggests that it is more important to keep the efficiency high than the weight low.
- At 4000 discharge cycles and (η=0.9), production level climate impacts and use phase climate impacts are at the same level, assuming West European electricity mix for the propulsion. However, with carbon-lean electricity for the propulsion, use phase climate impacts are much smaller and not at all dominant.

- Abiotic depletion is dominated by metals depletion related to electricity distribution, not production. Therefore, abiotic depletion is not as sensitive to the choice of electricity mix as climate impact is.

Introduction

This report contains a life cycle assessment, LCA, of lithium batteries with metallic lithium in the anode. The LCA has been carried out in the context of the TriLi (Longlife lithium electrodes for EV and HEV batteries) project funded by the Swedish Energy Agency (Energimyndigheten). The TriLi project aims at safe cells with 250 Wh/kg and 800 Wh/l energy density for electric or hybride electric vehicles. Development focus is to inhibit dendrite formation and to test concepts in battery cells with different cathodes. Environmental ambitions of the TriLi project are expressed as:

- Electrodes with less environmental impact than today's electrodes
- Contribute to Sweden's national goal of a fossil free transport sector 2030
- Energy density 250 Wh/kg and 800 Wh/l at cell level
- Development of recycling methods to recover lithium metal as lithium carbonate to be used in new cells and to
- Explore if it is good or bad from a resource/recycling perspective to have an excess of lithium in the cell

The purpose of the LCA is to highlight environmental hotspots with lithium batteries with metallic lithium in the anode in order to improve them as well as to verify environmental benefits with such batteries in vehicles. LCA is generally considered very useful in the product development stage in order to identify environmental hot-spots and aid in directing development efforts in relevant areas (Rebitzer et al., 2004) (Zackrisson 2009). Nevertheless, caution should always be exercised when drawing more general conclusions from any LCA study because of uncertainties in the data and model and data gaps.

Electric vehicles are seen as the main answer to the transport sector's problems of diminishing oil supplies and contribution to climate change. Potential fuel savings compared to internal combustion engine vehicles between 25% for hybrid electric vehicles to 50%-80% for plug-in hybrids depending on battery size have been reported (Håkansson, 2008), (AEA and Ireland, 2007). Provided that the grid electricity can be generated by renewable energy sources, considerable reductions of CO_2 emissions from the transport sector are possible. Therefore substantial efforts are today being employed to develop battery systems for electric vehicles.

Method in general

The LCA was performed in the context of the Swedish TriLi project. The LCA has been carried out by Mats Zackrisson and reviewed by Kristin Fransson at Swerea IVF. Members of the TriLi consortium have delivered detailed data about raw materials, manufacturing, use and recycling related to lithium batteries. Material needs were determined by experience, theoretical calculations and laboratory tests. Associated resources and emissions were found in existing databases for LCA and represent in general European or global averages. Data has mainly been drawn from the database Ecoinvent 3.1 (Ruiz et al., 2014). General Programme Instructions for Environmental Product Declarations (EPD®, 2013), was used as general guidance for the study.

SimaPro 8.0.4.28 was used for the calculations. The software is also a source of generic data and was also used to store the collected site-specific data in. The study is protected in the software. Only the author of this study has permanent access to the data.

In order to give input to the cell design, a number of LCAs of different depth and detail will be carried out in the project, each following more or less the steps:

1. Provision of preliminary cell design and data
2. Screening LCA
3. Workshop to present and discuss screening LCA results
4. Revised cell design and data and recalculation of LCA
5. Workshop to present and discuss LCA-results of “final” cell design
6. Manufacturing of cell and testing of cell
7. Calculation of final LCA if needed

This study and report

This report concerns the final LCA report of a 5 Ah cell weighing 149.7 grams. Data about the cell and battery configuration was decided by the TriLi project consortium in several meetings during 2015-2016, for example

- 24 March 2015 in Uppsala
- 4 September 2015 at Swerea IVF in Stockholm, corresponding to step 3 above
- 16 October at Ångström laboratory in Uppsala, corresponding to step 5 above
- 4 December at Ångström laboratory during a seminar about Sustainability of lithium batteries.
- 4 March 2016 at Ångström laboratory in Uppsala

In addition e-mail and telephone were used to deliver and discuss data and results.

Functional unit

In order to put the battery in the application context of a vehicle (Andrea Del Duce et al 2013), LCA of traction batteries often present the results as environmental impact per vehicle kilometre. The vehicle context is realized via assumptions about car weight, electricity consumption and total mileage. Thereby, the results can easily be compared to and put in relation with vehicle emission targets, e.g. the European passenger car standards 95 g CO_2-eq/km fleet average to be reached by 2021 by all manufacturers (EC 2000). The principal functional unit of the study is one vehicle kilometre and the corresponding reference flow thus battery capacity and battery electricity losses for one vehicle kilometre. LCA-databases typically contain vehicle emission data per person kilometre, which can be converted to vehicle kilometre. Ecoinvent, for example, uses 1.59 passengers per vehicle to convert from vehicle kilometre to person kilometre. Some argue that larger vehicles carry more passengers. However, according to the IEA[1], occupancy rates of passenger cars in Europe fell from 2.0-2.1 in the early 1970s to 1.5-1.6 in the early 1990s. The decrease is a result of increasing car ownership, extended use of cars for commuting and a continued decline in household size. It shows that the number of passengers per car has very little to do with the size of the car.

It should be noted that the 95 g CO_2-eq/km limit in a legal sense only applies to tail-pipe emissions and does not include a life cycle perspective. However, it is still a useful benchmark.

Using vehicle kilometre as functional unit facilitates comparisons with combustion vehicles and also comparisons of different battery technologies in the same vehicle. However, it does not facilitate comparisons between different size and type of batteries; smaller batteries, e.g. batteries for hybrid vehicles would normally have less environmental impact per vehicle kilometre. Power optimized batteries are probably also in need of an alternative functional unit. For such comparisons, the functional unit per delivered kWh over the lifetime could be more appropriate.

System boundary

The system boundary for the study is shown below. Note that the vehicle itself is not present in the system, only the use of the battery cell in the vehicle. In essence the study will compare the production phase of the battery cell with those use phase losses that can be related to the cell itself and with the recycling of the cell materials. Note that the delimitation is the battery cell including its packaging. Electronics, wiring, packaging of modules and battery casing are not included nor are the other parts of the drive train to deliver electricity from plug to wheel: charger, inverter and motor.

Normally a cut-off approach is used which means that recycled materials are being accounted for as input materials only to the extent that the studied system actually utilizes recycled instead of virgin materials. The system then does not include any credits for material that is recycled after the end of the use phase. The cut-off approach is justified for two reasons:

- recycling, if it happens, happens many years in the future and you cannot really be sure about it happening

[1] http://www.eea.europa.eu/publications/ENVISSUENo12/page029.html

- base materials often have a high recycling content and accounting for it at both ends of the life cycle may lead to double counting and in some cases even negative environmental impact

However, in the case of lithium batteries, only virgin materials are used, at least at the moment. Furthermore, we are interested in the potential of the recycling phase. So we will include the recycling and study it while remembering that it will happen many years in the future, if at all.

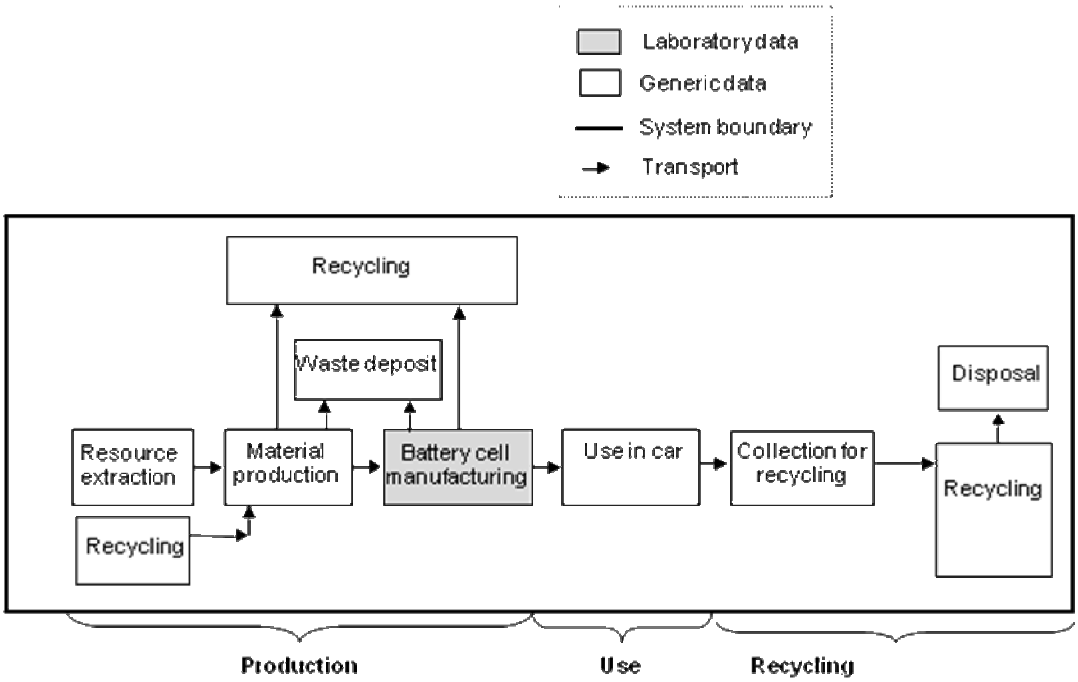

Figure 1 System boundary

All materials were tracked back to the point of resource extraction, mainly by using cradle-to-gate data from the Ecoinvent database (Ruiz et al., 2014). The Ecoinvent data contains associated inputs from nature and emissions, including estimations of losses in production processes. Materials not found in the Ecoinvent database, nor in other available databases, were modelled (from chemicals available in the databases) using molar calculations and estimations of energy use. Some materials that could not be found in the databases were replaced (in the model) with similar materials.

Environmental impact assessment

LCA of traction batteries inevitably leads to comparisons of electric vehicles, EV, with internal combustion engine vehicles, ICEV. Such LCAs should therefore be able to assess tradeoffs between tailpipe emissions, material resource use and toxicological impacts. Thus, relevant environmental impact categories for LCA of vehicles and traction batteries in particular are climate impact, resource depletion and toxicity. The methods used to account for these impact categories in this study are:

- Climate impacts in accordance with the Intergovernmental Panel on Climate Change (IPCC, 2007). The unit is climate impact in grams or kilograms of carbon dioxide equivalents, CO_2-eq. Europe’s emissions in 2005 corresponded to 11200 kg CO_2 equivalents per person [EEA, 2005]. To avoid unwanted climate impact requires global yearly emissions to be reduced by between 50 to 85% by 2050 on current levels, according to (IPCC, 2007). This would translate to a sustainable emission level at approximately 1000 kg CO_2-eq per capita world average.
- Resource depletion, or abiotic resource depletion is calculated with the method CML-IA baseline, version 3.02 as recommended by the ILCD handbook (Wolf and Pant, 2012). Only depletion of mineral reserves is reported since the climate impact indicator, above, is considered to cover environmental impacts of fossil fuels. Abiotic depletion is measured in kilogram Antimony equivalents, abbreviated kg Sb-eq.

Toxicity was not evaluated at this point since current methods have shown considerable inadequacies; among other that there is a lack of data concerning lithium emissions during the life cycle and a lack of characterization factors to translate such emissions into toxic impacts.

Modelling

To encompass a whole life cycle the production of the battery, the use of the battery in the car and the recycling stage must be included. The production phase model is based on the bill of material. The use of the battery in the car can be modelled, (Matheys et al., 2005) and (Zackrisson et al., 2010), by considering:

- The extra electricity needed to carry the batteries weight[2]
- Extra electricity needed to cover charge/discharge losses

Modelling of the recycling was based on a literature survey. The model was parameterized in order to enable easy change of parameters such as cycle life, efficiency, energy density, electricity mix and other.

Production phase

The bill of material of the studied cell is given in the figure below.

Table 1 BOM-list for lithium cell

Part of cell	Material	Weight (gram)	Comment/abbreviation
Cathode	$LiFePO_4$	31.25	LFP
Cathode	PVDF	3.9	
Cathode	Carbon black	3.9	
Cathode	Aluminium foil	33.75	
Anode	Lithium metal	10	
Separator	Cellulose	35	from algae
Electrolyte	$LiPF_6$ in EC:DEC:VC		

[2] Assumptions about vehicle weight and energy consumption are needed to model this.

Part of cell	Material	Weight (gram)	Comment/abbreviation
Electrolyte	$LiPF_6$	3.52	LPF6
Electrolyte	Ethylene carbonate	15.28	EC
Electrolyte	Diethyl carbonate	12.38	DC
Electrolyte	Vinylene carbonate	0.625	VC
Total mass of cell		149.7 g	

Cathode

The cathode is made of $LiFePO_4$, a polyvinylidenfluoride (PVDF) binder and carbon black in a slurry mixed with the solvent N-Methyl-2-pyrrolidone (NMP) which is spread on an aluminium foil. The solvent NMP is dried of. NMP is volatile, flammable, expensive and generally environmentally unfriendly (Posner 2009). According to (Dunn and Gaines, 2012) about 99.5% of the NMP is recovered and can be reused, but the difference is combusted and must be replaced resulting in a net consumption of 0.007 kg NMP/kg battery cell. This net consumption is burnt off and gives rise to 440/198=2.22 g CO_2 per g NMP, by molar calculation.
LCA data for the above cathode ingredients was found in the Ecoinvent database and in the BUWAL database, with the exception of manufacturing of $LiFePO_4$ which is described below. LCA data on PVDF was found in an environmental product declaration from a producer of PVDF piping systems (Fischer, 2012).

Manufacturing of $LiFePO_4$

$LiCO_3$, lithium carbonate, is used to make $LiFePO_4$. A molar calculation yields:

- 73.8 g Li_2CO_3 + 159.6 g Fe_2O_3 + 133 g $(NH_4)_2HPO_4$ > 158 g $LiFePO_4$. In addition 2% graphite is assumed to be used. LCA data for the ingredients was found in the Ecoinvent database.

The manufacturing process needs energy for two temperature increases: first to 400-500 °C followed by grinding and adding graphite and then a final temperature rise to 700-800 °C. Assuming a specific heat capacity of 0.9 kJ/kgK, two temperature rises to first 400 °C then to 800 °C means 0.9*400+0.9*800= 1080 J. In addition, the reactions require some energy and there would be heat losses, so in total 3 kJ electricity/g $LiFePO_4$ was assumed.

Anode

The anode is made of lithium foil. The lithium foil is represented by the Ecoinvent process Lithium {GLO}| market for | Alloc Rec, S. It has a climate impact of 167 kg CO_2-eq/kg, see below. Lithium is produced by electrolysis of lithium chloride.

In a LFP/Li cell the lithium involved in the charge/discharge is from LFP and the electrolyte and the lithium in the anode is not really needed for the electrochemical process. However, to compensate for losses during formation and cycling of the cell a reservoir of lithium is added by the Li-foil as anode. It was assumed that a lithium foil mass of 10 g was needed. This represents around ten times more lithium than is actually needed for the function of the cell but, among other, the thickness of commercially available Li-foils sets a limit today.

Separator

The separator is made of the Cladophora algae harvested in the US. In the calculations it is represented by the Ecoinvent process *Lime {FR}| production, algae | Alloc Rec, S.* This is a rough approximation as can be seen below.

Table 2 Algae dataset

Part of cell	**Process name**	**Description**
Separator of algae	Lime {FR}| production, algae | Alloc Rec, S	The process contains transports connected with the collection of the algae from the sea ground and the delivery to the fertiliser plant as well as the distribution of the usable product to the regional storehouse. Energy requirements for drying of the algae from a water content of 25 % per weight to a final water content of 2.5 %, and milling of the algae were taken into consideration. Demand of the resource calcite contained in the algae was included. Infrastructure and land use were included by means of a proxy-module. The values refer to the market situation in Switzerland. The production takes place in France.

Cell packaging

Cell packaging was not included.

Electrolyte

The electrolyte is a 1-molar solution of $LiPF_6$ in 1:1 EC:DEC 2% VC. In mass for one cell this translates to:

- 3.52 g lithium hexafluorophosphate, $LiPF_6$
- 15.28 g ethylene carbonate, EC
- 12.38 g diethyl carbonate, DEC
- 0.625 vinylene carbonate, VC

$LiPF_6$ and EC are available in Ecoinvent, but not DEC and VC. VC was assumed equal to an average organic product. VC is a fire hazard, acute health hazard and may cause allergic skin reaction, though all toxicological properties have not been fully investigated (Fisher Scientific, 2015).

DEC can be made by reacting phosgene with ethanol, producing hydrogen chloride as a byproduct[3]:

[3] http://en.wikipedia.org/wiki/Diethyl_carbonate

$$2CH_3CH_2OH + COCl_2 \rightarrow OC(OCH_2CH_3)_2 + 2HCl$$

By molar calculation, to get 1 g of $OC(OCH_2CH_3)_2$, requires 92/118 g of $2CH_3CH_2OH$ and 99/118 gram of $COCl_2$.

Cell electronics

The cell electronics were not included in the calculations.

Cell manufacturing and assembly

Energy requirements for cell assembly can vary largely, mainly depending on: 1) which share of the assembly steps require dry room/clean room conditions and 2) assembly plant throughput. Estimations and measurements vary between 1 MJ/kg battery to 400 MJ/kg battery (Dunn et al., 2014).
The 5Ah cell was manufactured and assembled in laboratory conditions. The energy needed for cell manufacturing and assembly was approximated from data in Saft's annual report 2008 (Saft, 2008). Total use of energy was divided by total sales and multiplied with the 2008 price level of a high-quality lithium battery estimated at 750 $/kWh or 500 Euro/kWh (Zackrisson et al., 2010) and multiplied with the energy density 0.11 kWh/kg. This resulted in 11.7 kWh electricity and 8.8 kWh gas per kg lithium battery.

Transports

The following assumptions were made about transport of materials and components in connection to lithium battery manufacturing and use:

- Transport from mines or recycling facilities to raw material producers. These transports are normally included in the generic data used.
- 11000 km transport (1000 km lorry and 10000 km boat) from raw material producers to cell manufacturer. It is expected that there will only be a few cell manufacturers in the world. 11000 km transport (1000 km lorry and 10000 km boat) from cell manufacturer to battery manufacturer/car assembly plant. All these transports (2000 km lorry and 20000 km boat) are included in the model for Assembly.
- 6000 km transport (1000 km lorry and 5000 km boat) from car manufacturer to user, in process Battery cell use. There are many car manufacturers in the world, but customers buy their cars from all over. These transports are included in the model for the Use phase.

Transports related to recycling are presented below.

Use phase

The use phase was modelled as the electricity losses in the battery during the life-time use of the battery in an EV and the extra electricity needed to carry the weight of the battery. This way of modelling the use phase of a car battery has been used in other LCAs (Matheys, Autenboer et al. 2005). In addition, the transport of the battery from the car manufacturer to the user was included in the use phase, see transports. The study includes one main scenario with the following characteristics:

- 5Ah cell cycled 2000, 4000 and 6000 times.
- 90 % charging/discharge efficiency. Varied in the calculations between 0.5 to 0.95.
- Cell weight 149.7 g and discharge voltage 3.2 volt. This would correspond to 5*3.2/149.7= 0.107 Wh/g or 107 Wh/kg energy density at cell level.

Extra power demands to accommodate battery mass

In order to calculate the extra power demands needed to carry the battery mass (M_{batt}), the total number of cells needed for the required range was calculated so that total battery weight could be put in relation to an assumption of vehicle mass excluding battery mass ($M_{vehicle}$). The total weight of the battery was assumed to be double the weight of the cells, but this parameter can be changed. The influence of the battery mass was modelled using the assumption that 30% of energy use can be related to car mass (Zackrisson et al., 2014). Thus the mass related loss or extra power was calculated as: $0.3 \times M_{batt}/(M_{vehicle}+M_{batt})$. This gives a dimensionless factor that can then be factored with the total delivered power.

Excess power requirements to accommodate charge/discharge losses

The charge/discharge efficiency, η, is defined as the relation between battery cell energy output and input $W_{batterytowheel}/W_{plugtowheel}$. The excess energy or loss per delivered kWh is then proportional to the dimensionless factor $(1- \eta)$ factored with the total delivered energy. Since the electricity consumption per km will increase with decreasing η, the losses per km is proportional to $(1- \eta)/\eta$.

Recycling phase

Modelling of the recycling was based on a literature survey of lithium battery recycling. It involves estimation of needs of transport, disassembly and several treatment steps, in order to recover materials in an economic way. The associated environmental impacts are modelled as:

- the environmental impacts from the transportation
- plus the environmental impacts from the involved recycling processes and treatment processes
- minus avoided environmental impacts from avoided virgin production of recycled materials

Today, 2015, recycling of lithium traction batteries has not really started because there are not yet enough of such batteries that have reached the end of their lives. However, quite a few projects have been and are underway that are targeting recycling of lithium batteries. Some conclusions from these studies (Hall, 2014) (Buchert, 2011) (Arnberger et al., 2013) (Dunn et al., 2012) (Georgi-Maschler et al., 2012) (Ganter et al., 2014) (Speirs et al., 2014) (Wang et al., 2014) are:

- Lithium traction batteries will be recycled in the future, among other reason, because it is legally mandatory in for example Europe
- Resource supply considerations will also be a motivation for recycling scarce materials (Jönsson et al., 2014) used in traction batteries as the electrification of vehicles grows
- The presence of several different lithium battery chemistries will necessitate chemistry specific disassembly and treatment. Marking the batteries during manufacturing (Arnberger et al., 2013; Hall, 2014) and sorting them prior to disassembly will become necessary.
- Depending on cell chemistry, recycling will use a mix of manual, mechanical, hydro- and pyrometallurgical processes. The LithoRec project (Buchert, 2011), for example, describes four main process steps: 1) Battery and module disassembly; 2) Cell disassembly; 3) Cathode separation; and 4) Hydrometallurgical treatment.

Transportation

Considering the above conclusions and studies (Hall, 2014) and (Buchert, 2011), the following recycling transportation scenario was estimated:

- 50 km from user to licensed car scrap yard. This is where the battery is removed from the vehicle and ideally sent directly to a chemistry specific disassembly and treatment plant.
- 2000 km from licensed scrap yard to chemistry specific disassembly and treatment plant. There may be intermediate transports and storage but this is covered by the long distance.
- 200 km from chemistry specific disassembly and treatment plant to material market (Buchert, 2011). This is the same (fictional) point at which the cell raw material producer buys precursors. This distance is also used for wastes from the recycling process to further treatment or deposit.

It is important to note that transportation of lithium is a subject to several laws and regulations. So many of the transports outlined above have to be done by professional dedicated transportation services.

Recycling and treatment processes and avoided processes

With respect to recycling efficiency versus energy efficiency and cost it is postulated that legislation and resource supply concerns will drive recycling efficiency[4] to as much as 80% (Kushnir and Sandén, 2012), but at the expense of

[4] 80% recycling efficiency includes also collection rate which cannot be assumed to be 100%

energy efficiency and cost. Thus it is assumed that metallic materials and easily separable plastic parts are recycled to 80%, but at such cost (economic and environmental) that only 50% of environmental impacts of virgin material production is avoided, i.e. the avoided virgin production is used as a proxy for the recycling processes.

Table 3 Materials content of cell

Part of cell	Material	Weight (gram)	Assumed recycling rate	Recycled mass (g)
Cathode	$LiFePO_4$	31.25	80% recycled	25.0
Cathode	PVDF	3.9	Incinerated	
Cathode	Carbon black	3.9	Incinerated	
Cathode	Aluminium	33.75	80% recycled	27.0
Anode	Lithium metal	10	80% recycled	8.0
Separator	Cellulose	35	Incinerated	
Electrolyte	$LiPF_6$ in EC:DEC:VC			
Electrolyte	$LiPF_6$	3.52	Incinerated	
Electrolyte	Ethylene carbonate	15.28	Incinerated	
Electrolyte	Diethyl carbonate	12.38	Incinerated	
Electrolyte	Vinylene carbonate	0.625	Incinerated	
Total mass of cell		149.7 g	Recycled mass	60.0

The environmental impacts of lithium battery recycling are calculated as:

- Transports + Recycling processes – Avoided virgin production, where:
    - Transports are defined as the environmental impacts from the transportation
    - Recycling processes are defined as the environmental impacts from the involved recycling processes and treatment processes
    - Avoided virgin production is defined as avoided environmental impacts from avoided virgin production of recycled materials

Since it is assumed that the sum of Recycling processes – Avoided virgin production = - 50% of Avoided virgin production, i.e. Recycling processes = 0.5 Avoided virgin production, the environmental impacts of lithium battery recycling can be calculated as:

- Transports + 0.5 Avoided virgin production – Avoided virgin production = =Transports - 0.5Avoided virgin production

Parameterized model

The LCA had to be based on various assumptions. A parameterized LCA model was built enabling easy change of parameter values. Below is a list of the parameters used. Parameter settings in the figure reflect TriLi ambitions and base case for a 5 Ah cell with reasonably good power characteristics.

Input parameters

Name	Value	Distribution	SD·	Mir	Ma	Hide	Comment
Zackrisson	1	Undefined					1=Assembly energy according to Zackrisson et al 2010
Argonne	0	Undefined					1=Assembly energy according to Argonne laboratory 2012
Ahpercell	5	Undefined					Energy content of cell in amperehours
Elsort	0	Undefined					1=swedish electricity; 0=europeisk el, for the propulsion
Weight	1600	Undefined					Vehicle weight without battery in kg. (1176 for Leaf, 1490 for Tesla, 374 for Twizy)
Cellweight	149,7	Undefined					Cell weight in grams.
Dischargedepth	0,7	Undefined					How much of the total capacity that can be cycled. 85% base case
Voltage	3,2	Undefined					Cell voltage during discharge
Systemvoltage	360	Undefined					System voltage (360 for Leaf, 350 for Tesla, 58 for Twizy)
NoPstrings	6	Undefined					Number of serial connections. Juggle with this parameter to obtain desired size of battery.
weightlossdep	0,3	Undefined					% of energy consumption that relates to vehicle weight
gCO2perkWh	594	Undefined					63 gram per kwh for Swedish average electricity. 594 for European average electricityl
Cellcarboncontent	3,45	Undefined					3,45 kilogram CO2 for 149,7 grams cell
Plugtowheelperkgkm	0,000093	Undefined					Plugtowheel per km and kg vehicle weight including battery weight. Values can range from 0,000093 to 0,00014 for the same vehicle (LEAF) depending on test driving cycle. (0,000095 to 0,00011 to for Tesla; and 0,00013 for Twizy). These values assume 0,9 efficiency.
Weightofcellsinpack	0,5	Undefined					Relation between cell weight and battery weight. 0,522 for Leaf and 0,517 for Tesla S and 0,258 for Twizy.
Recyclemass	60	Undefined					Recycled mass in grams
Eff	0,9	Undefined					Charge/discharge efficiency; base case 0,9=90%
Cycles	4000	Undefined					Maximum number of charge/discharge cycles: base case 4000. (2000, 4000 and 6000)

(Insert line here)

Calculated parameters

Name	Expression	Comment
Plugtowheel	Plugtowheelperkgkm*(Weight+Batteryweight)*0,9/Eff = 0,168	Plug to wheel consumption in kWh/km

Figure 2 Parameters that can be changed in the LCA model and the base case settings

Note that the battery size and range is set by iteratively changing the factor NoPstrings, i.e., the number of strings of cells connected in series. The number of cells in each string is decided by the desired system voltage divided by the cell voltage. The parameter settings above is the base case examined and correspond to a battery consisting of 6 rows of 113 cells weighing 203 kg with a nominal capacity of 10.8 kWh giving an electric range around 45 km at plug to wheel energy consumption 0.17 kWh/km[5] and depth of discharge 70%. Results related to changes in cycle life, efficiency and weight of the vehicle are presented below in the section Production and use phase.

Results

Results are presented from three perspectives:

- Production and recycling at cell level
- Production and use phase

[5] 0.000093*(1600+203)=0.168=0.17 kWh/km

- Complete life cycle

Production and recycling at cell level

To differentiate the specific 5 Ah cell investigated in this report from other 5 Ah cells it is henceforth named the 149.7 g 5 Ah cell. The climate impact of producing one 149.7 g 5 Ah cell is shown in the figure below. The thickness of the arrows corresponds to the global warming impact measured in carbon dioxide equivalents from respective process. The amount of CO_2-eq in gram is shown in the lower left corner of each box. It can be seen that the production of the cell infers emissions of 3.45 kg CO_2 equivalents, or 3450/149.7=23 g CO_2-eq/g cell. It can further be seen that the lithium metal anode and the assembly energy give major contributions to the climate impact.

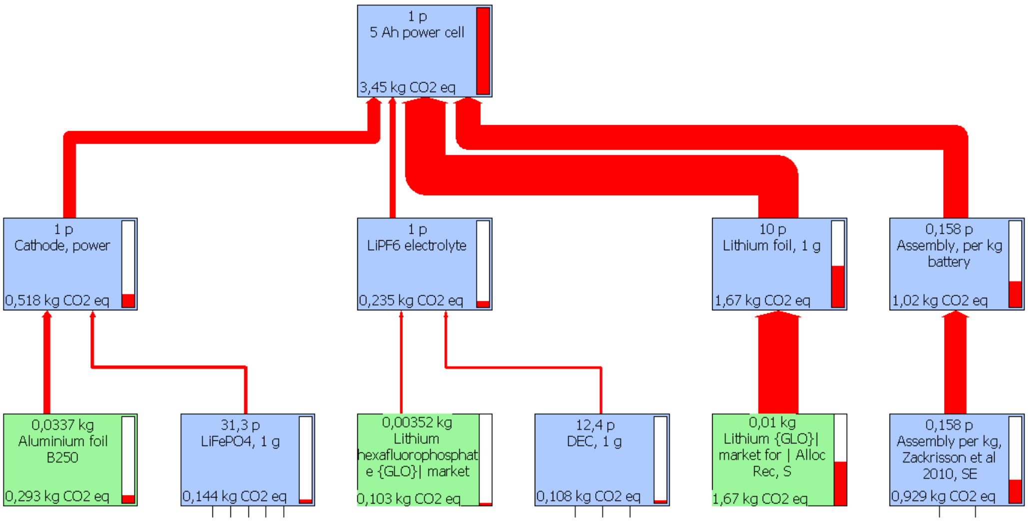

Figure 3 Production of 149.7 g lithium cell – climate impact

As described earlier, the environmental impacts of lithium battery recycling is assumed to correspond to: Transports + 0.5 Avoided virgin production – Avoided virgin production = Transports - 0.5Avoided virgin production. The result is shown in the figure below.

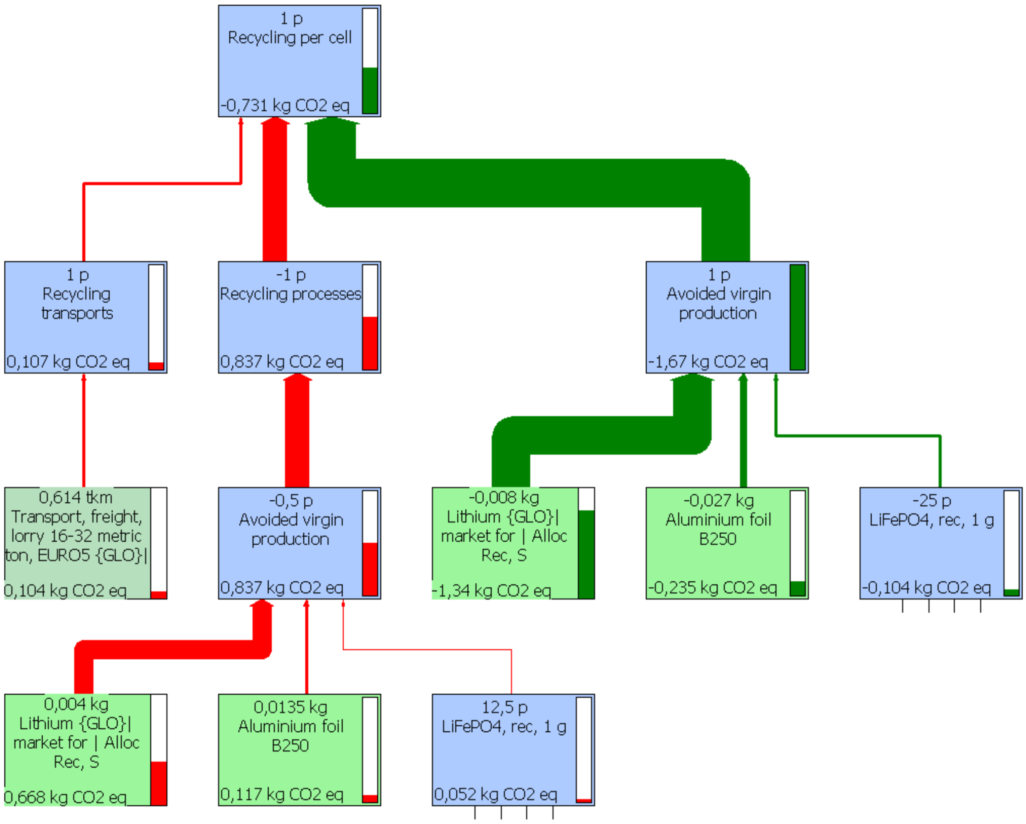

Figure 4 Model of recycling of 149.7 g lithium cell – avoided climate impact

As can be seen from the figure above, recycling avoids 731 g CO_2-eq per cell. Each cell weighs 149.7 gram. 731 g CO_2-eq divided by 149.7 g/cell computes to 4.9 g CO_2-eq/g battery cell. This can be compared to, e.g. the LithoRec (Buchert, 2011) project, which calculated net avoided climate impacts to 1.7 g CO_2-eq/g battery for the recycling of LFP cells. However, the LFP cells examined by (Buchert, 2011) most likely did not have any metallic lithium.

Comparing figure 3 and figure 4 it can be noted that 731/3450=21 % of the climate impact from one cell can potentially be avoided through recycling.

Production and use phase

Below are shown production and use phase climate impacts for variations in maximum number of discharge cycles (2000, 4000, 6000), charge/discharge efficiency (0.5 - 0.95) and cell to battery weight relation (25%, 50%, 75%). The parameter settings in Figure 2 are used as a base case, i.e. a 10.8 kWh battery weighing 203 kg.

Note that the presented use phase impacts below only cover battery related losses. The total operation related climate impact from 1 kWh is 594 g CO_2-eq/kWh with average European electricity. The charge and weight related impacts shown below are part of these 594 grams. The production related impacts adds on. The total operation related climate impact of 0.17 kWh/km plug-to-wheel consumption is

99 g CO_2-eq/vehicle km with average European electricity mix. It should be noted that the recycling phase is not included in the figures below.

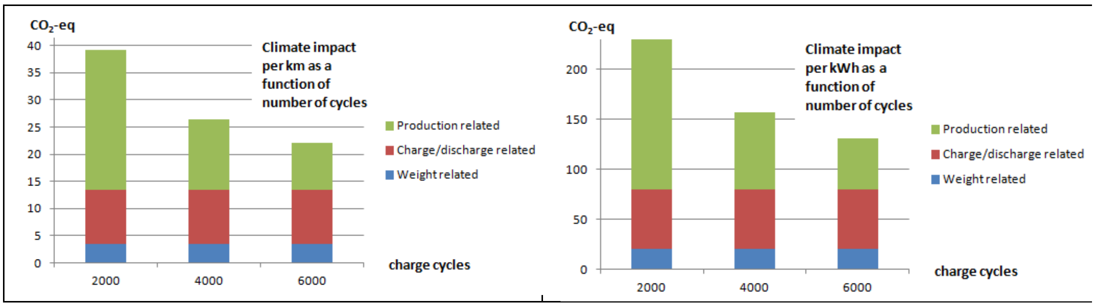

Figure 5 Climate impact CO_2-eq per km and per kWh as a function of number of cycles

It can be seen in the figure above, that the production related impacts decrease with increasing cell life since there are more cycles or kilometres to distribute the environmental burden of production on. The number of discharge cycles does not affect operation losses at all.

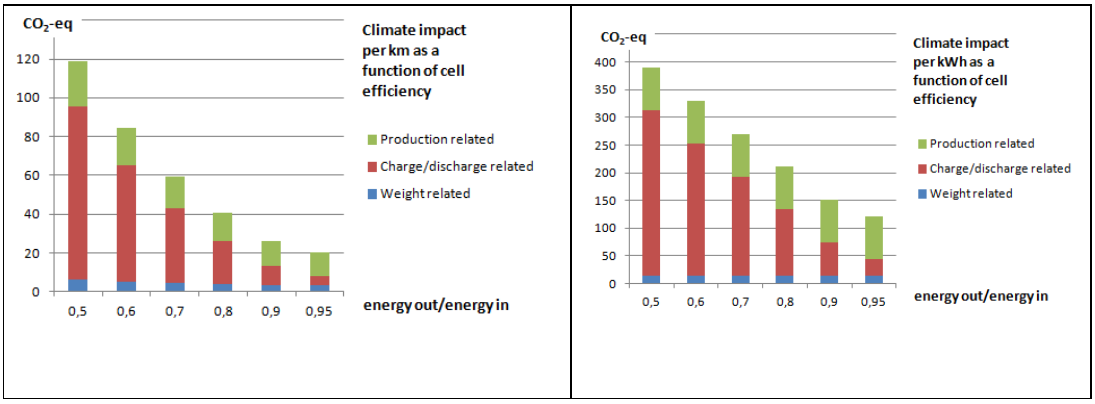

Figure 6 Climate impact CO_2-eq per km and kWh as a function of cell efficiency

Charge/discharge losses are very important to consider since they would always be a percentage of the environmental footprint of the used electricity mix. Here resulting in 5 to 90 g CO_2-eq per km and 30 to 297 g CO_2-eq per kWh with European average electricity mix. Per kilometre, production related and weight related impacts are also affected by the efficiency, since the plug-to-wheel energy consumption per kilometre increases with decreasing efficiency. Per kWh, production related and weight related impacts are not affected by the efficiency.

A way of studying the influence of the battery weight is to change the parameter Weightofcellsinpack. Changing this parameter changes the battery weight while the battery size in kWh remains the same. This is shown in the figure below for 25%, 50% and 75 % weight of cells in 10.8 kWh batteries weighing 407 kg, 203 kg and 135 kg respectively.

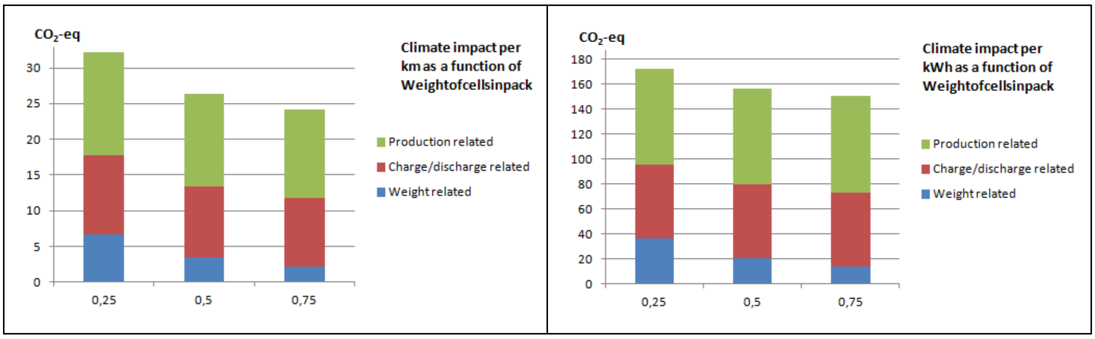

Figure 7 *Climate impact CO_2-eq per km and kWh as a function of the cell weight related to battery weight*

The battery weight affects the energy consumption per kilometre, thus a lighter battery will get an increased range with the same kWh size battery and thus slightly smaller production related impacts per kilometre. For the same reason also the charge related impacts decrease slightly per kilometre with diminishing battery weight. The weight related losses per kilometre are of course reduced by reduced battery weight (i.e. higher percentage of cells in battery). All in all the difference is around 8 g CO_2-eq per km between 25% and 75% weight of cells in pack. Compared to the difference in impact related to efficiency (around 20 g CO_2-eq per km for η[6] from 0.95 to 0.8) this is considerably less difference.

Per delivered kWh the picture is quite similar. The weight related losses will increase with increasing battery weight since they are proportional to $M_{batt}/(M_{vehicle}+M_{batt})$. However the production related and efficiency related impacts will remain the same, per delivered kWh.

Complete life cycle

Climate impact

The figure below shows the life cycle climate impact calculated as emissions of carbon dioxide equivalents per vehicle km for the 149.7 g 5 Ah cell. The thickness of the arrows corresponds to the global warming impact measured in carbon dioxide equivalents from respective process. The amount of CO_2-eq in gram is shown in the lower left corner of each box. It can be seen that the production of the cell infers emissions of 12.9 g CO_2 equivalents per vehicle km; most of it emanating from the lithium metal anode and the assembly (electricity). About 2.7 gram of this, is avoided through recycling (green or minus means avoided emissions). Use phase impacts accredited to the battery are losses due to cell weight (3.4 g CO_2-eq per km) and electricity losses (10.0 g CO_2-eq per km).

[6] Efficiency values commonly used in literature range between 0.8-0.95

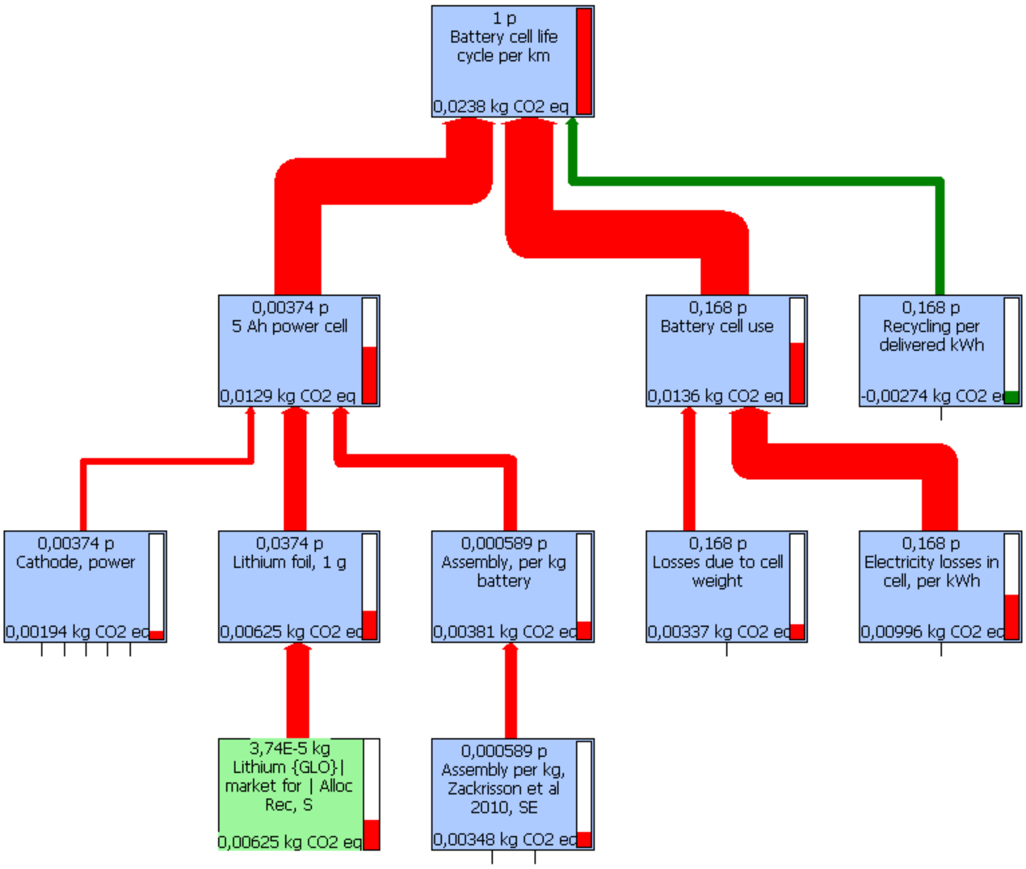

Figure 8 Climate impact per vehicle km for 149.7 g 5 Ah cell (10.8 kWh battery, European electricity)

Note that at 4000 cycles, use phase impacts and production related climate impacts are at the same level. Delivered kWh is probably a more suitable functional unit for power optimized batteries, thus this unit is shown in the figure below. Compared to per vehicle kilometre, the values of course changes, but the same relation between life cycle stages is maintained, as can be seen in Figure 10.

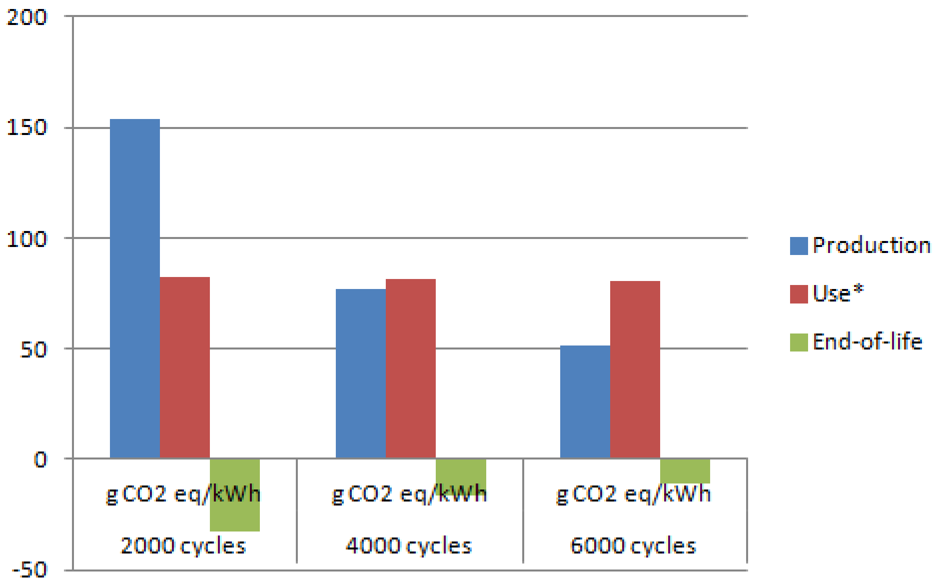

*Figure 9 Climate impact per delivered kWh for TriLi 5 Ah cell (at 2000, 4000 and 6000 cycles at η=0.9). *Use phase impacts cover only battery related losses.*

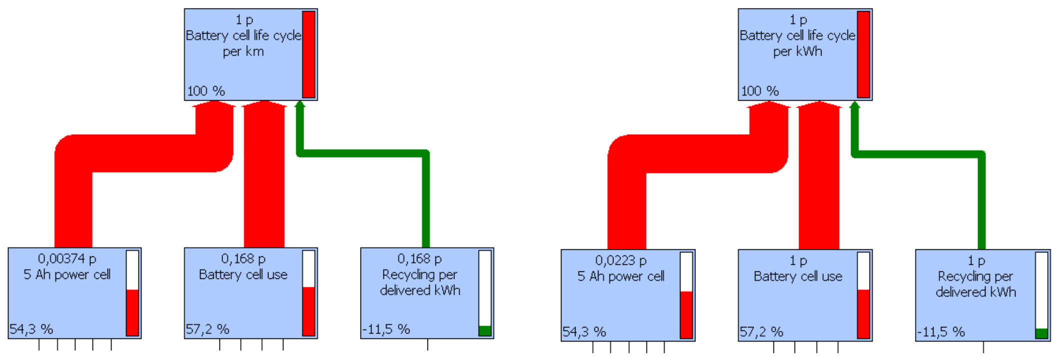

Figure 10 Climate impact per delivered kWh (right) and per vehicle km (left) for 149.7 g 5 Ah cell

Table 4 Climate impact and abiotic depletion per delivered kWh for the 10.8 kWh battery at different cycle life, η=0.9, European electricity

Scenario	**2000 cycles**		**4000 cycles**		**6000 cycles**	
Life cycle stage	kg Sb eq/kWh	kg CO_2 eq/kWh	kg Sb eq/kWh	kg CO_2 eq/kWh	kg Sb eq/kWh	kg CO_2 eq/kWh
Production	2.77E-07	1.54E-01	1.39E-07	7.70E-02	9.25E-08	5.13E-02
Use*	1.31E-07	8.25E-02	1.27E-07	8.10E-02	1.26E-07	8.05E-02
End-of-life	-4.82E-08	-3.26E-02	-2.41E-08	-1.63E-02	-1.61E-08	-1.09E-02
*Note that the presented use phase impacts only cover battery related losses. The operation in terms of propelling the vehicle is not included.						

The more cycles the longer the life and the less impact per kilometer for Production and End-of-life phases. Since the transport of the vehicle equipped with the battery cells belong to the use phase, also the use phase has slightly less impact per kWh the longer the life of the cell is.

Abiotic depletion

The figure below shows the life cycle abiotic depletion potential per delivered kWh for the 149.7 g 5 Ah cell expressed as kg Sb equivalents (antimony equivalents, Sb-eq). It can be seen that the production of the cell causes 1.39E-7 kg Sb-eq/delivered kWh; most of it emanating from the lithium foil and the electrolyte. Some of this, 2.4E-8 kg Sb-eq/delivered kWh, is avoided through recycling. Use phase abiotic depletion accredited to the battery is 1.25E-7 kg Sb-eq/delivered kWh.

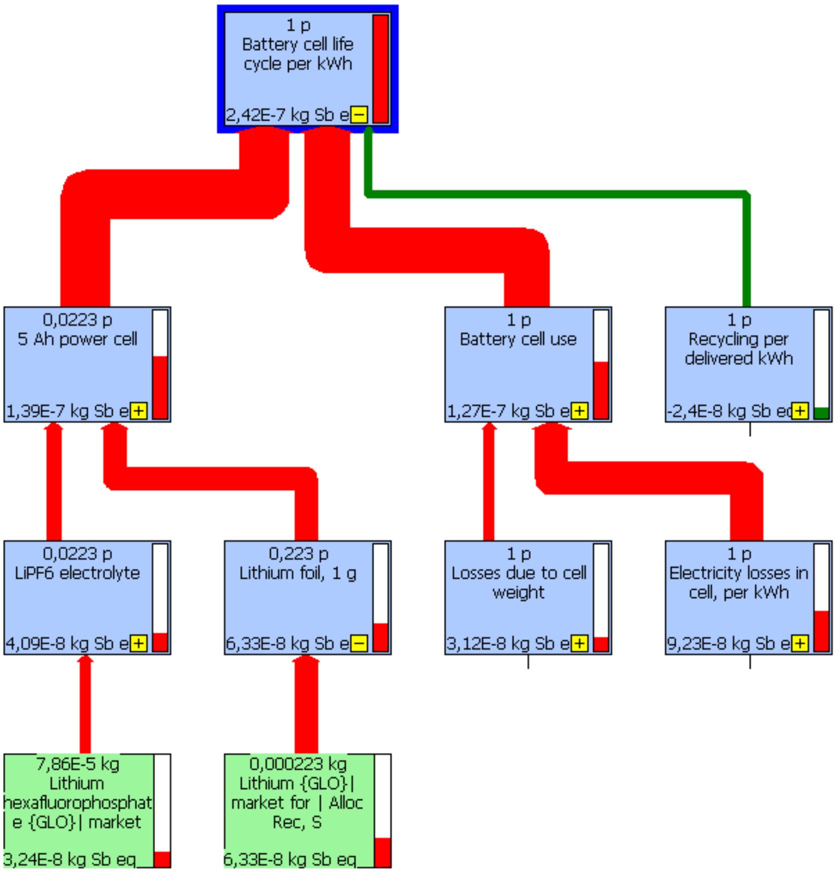

Figure 11 Abiotic depletion, kg Sb-eq per delivered kWh for The 149.7 g 5 Ah cell (4000 cycles, η=0.9, European electricity)

Detailed data about abiotic depletion per delivered kWh is given in Table 4.

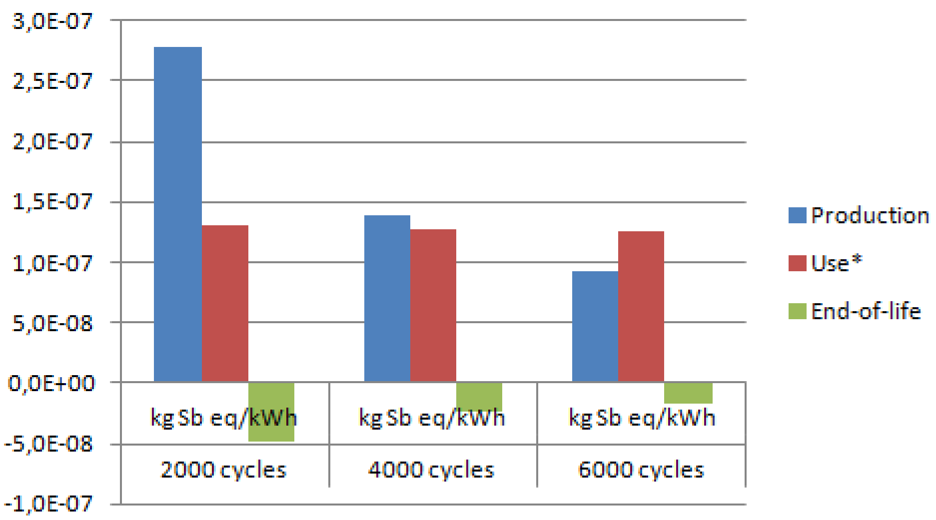

*Figure 12 Abiotic depletion, kg Sb-eq per delivered kWh (2000, 4000 and 6000 cycles at η=0.9). *Use phase impacts cover only battery related losses.*

Note that the use phase electricity is relatively dominant in all scenarios for abiotic depletion, see also the dominance analysis below.

Dominance analysis

In the figures below can be seen that the use phase electricity dominates both impact categories. If the End-of-Life phase had been modelled with recycling process data, electricity would most likely have shown up as significant also in the End-of-Life phase. Now the End-of life phase is dominated by metallic lithium.

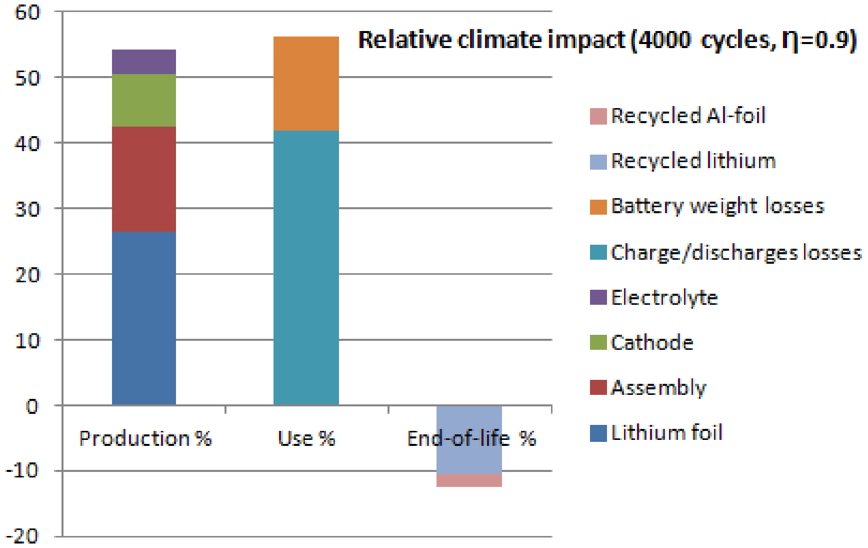

Figure 13 Relative climate impact (18.4 kWh, European electricity)

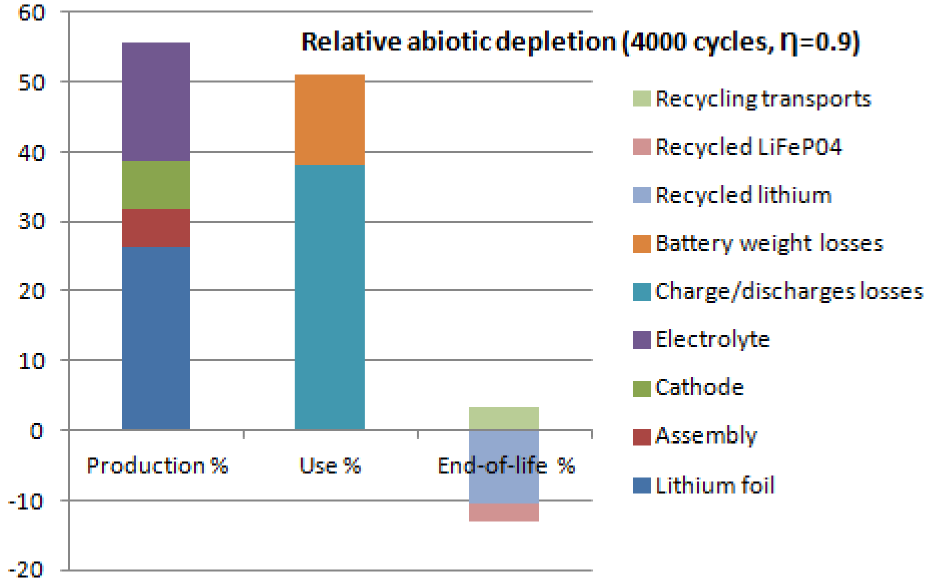

Figure 14 Relative abiotic depletion (18.4 kWh, European electricity)

Sensitivity to electricity mix
As shown above, dominant environmental impact (climate and abiotic depletion) stem from the use phase electricity losses, even when the efficiency is as high as 0.9. This dominance would of course be even more accentuated at lower efficiencies. However, if the vehicle is using Swedish carbon lean electricity at 63 g CO_2-eq/kWh instead of the European average mix at 594 g CO_2-eq/kWh, the charge/discharge losses do not give dominant climate impact as can be seen in the figure below.

For abiotic resource depletion, carbon-lean electricity does not give at all the same drastic reduction of use phase impacts, see figure below. The reason is that the main abiotic resource depletion from electricity stem from the distribution infrastructure (the copper cables) rather than from the electricity generation.

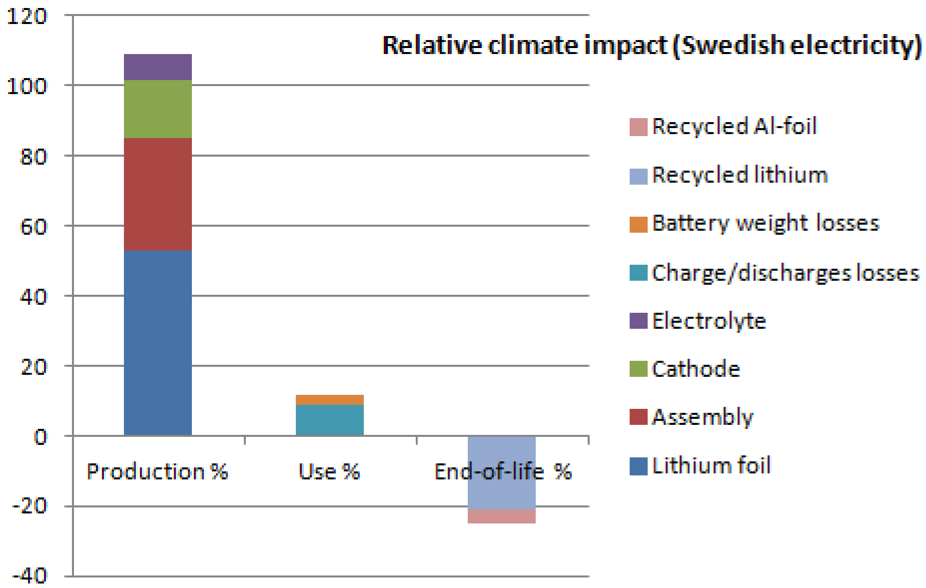

Figure 15 Relative climate impact (18.4 kWh, 4000 cycles, η=0.9)

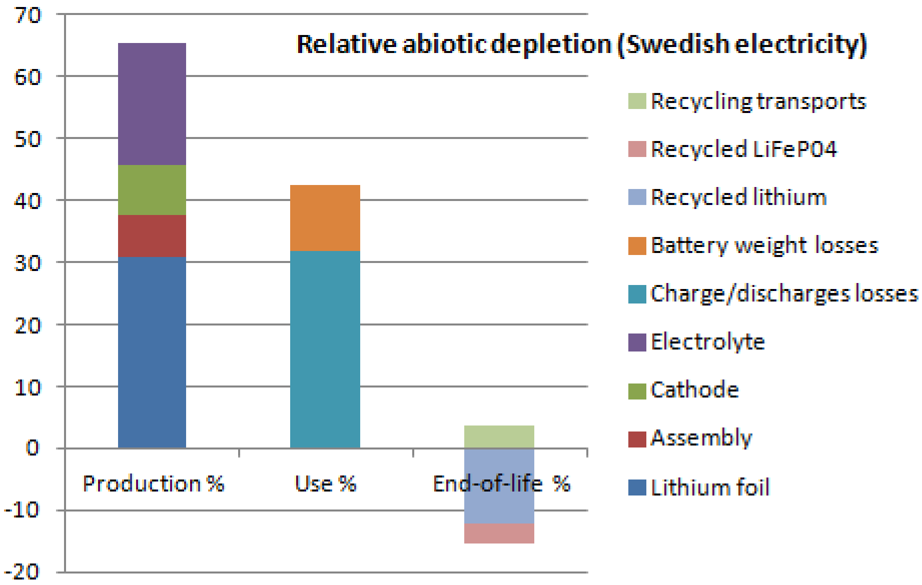

Figure 16 Relative abiotic depletion (18.4 kWh, 4000 cycles, η=0.9)

Discussions and conclusions

The model

The LCA model developed allows the user to design a battery of a given kilowatthour[7] size. Knowledge and assumptions about vehicle electricity consumption and battery depth of discharge decides the vehicle electric range. Furthermore, the plug-to-wheel electricity consumption puts the battery in a vehicle context. Realistic values for vehicle weight and electricity consumption per kilogram and kilometre should be used as input parameters.

The model accounts for that the battery weight affects the energy consumption per kilometre, thus a lighter battery will get an increased range although the same size battery and thus smaller production related impacts per kilometre. Since the energy consumption is decreased, the operation related losses due to efficiency and weight of battery will also decrease.

The model also accounts for that the efficiency affects the energy consumption per kilometre, thus a less efficient battery will get a decreased range although the same size battery and thus higher production related impacts per kilometre. Since the energy consumption per km is affected, the operation related losses per km due to efficiency and weight of battery will also be affected by changes in the efficiency. The base case efficiency is assumed to 0.9.

[7] Amperehours*discharge voltage= Watthours

The desired size in kWh is set by changing the number of strings of cells connected in series until the desired size is achieved. The number of cells in each string is decided by the desired system voltage divided by the cell voltage.

Production and recycling

Results presented at the workshops 4 September and 16 October 2015, resulted in a redesign of the amount of lithium metal in the cell (from 42 to 10 g via 2.3 g) which reduced production related climate impacts from 206 g to 77 g CO_2-eq per kWh. That is, just by identifying a major source of climate impact, it could easily be reduced by more than half, which shows the usefulness of using LCA in a design process.

The lithium content of the cell largely drives both the climate impact and the abiotic depletion potential. However, it should be remembered that some of the impacts from lithium (40% assumed in the model, i.e. 50% of 80%) can be avoided by recycling, if and when recycling takes place. The largest non-recyclable contributor to climate impact and abiotic depletion in the production phase, is the assembly energy. (The lithium foil has a larger production related climate impact than the assembly energy, but the lithium foil can be recycled). It (the assembly energy) therefore warrants special attention in further efforts to minimize cell environmental impacts.

Assembly energy

As mentioned earlier, estimations and measurements of assembly energy in literature vary between 1 MJ/kg and 400 MJ/kg. The number used in the above calculations equals 78 MJ/kg (Zackrisson et al., 2010). Argonne laboratory has calculated the number 2.4 MJ/kg from battery assembly plant equipment specifications (Dunn and Gaines, 2012). These numbers are compared in the below figures which also include a cost estimate of lithium-ion cell manufacturing (Chung et al., 2016).

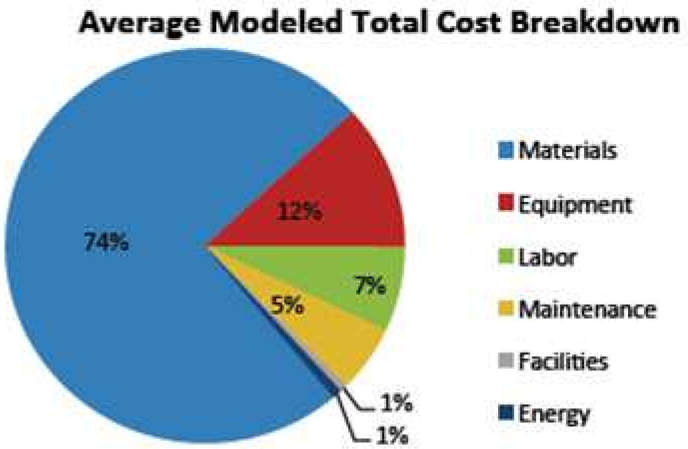

Figure 17 Average costs for lithium-ion cell from (Chung et al., 2016)

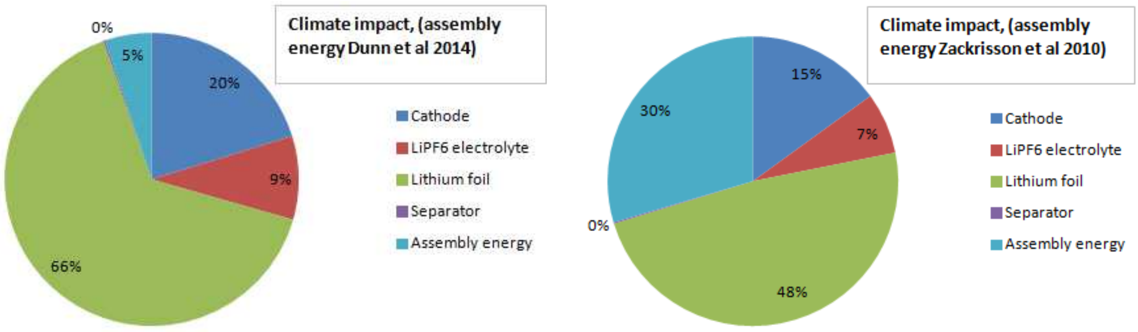

Figure 18 Relative climate impact of production of 5 Ah cell with different assembly energy approximations

Cost is not the same as energy or climate impact, but there is some form of correlation in between. Thus, it can be concluded that the lower energy number (2.4 MJ/kg) from the Argonne laboratory seems to correspond much better to the 1% energy cost number. However, equipment, maintenance, labour and facilities are not included in the LCA and of course they ought to be (especially since they amount to 26% of the cost) in order to calculate the full environmental impact of cell manufacturing. Thus, taken as a proxy for equipment, maintenance, labour and facilities, the higher 78 MJ/kg number correspond better to the 26% of those cost categories.

The issue of assembly energy, maintenance and equipment will be further scrutinized in forthcoming LCAs in the TriLi project.

Production and use phase

The more discharge cycles the cell can withstand, the more kilowatt-hours it will be able to deliver. Therefore production related impacts per kilometre and per delivered kWh decrease with increasing number of discharge cycles. The use phase charge/discharge and weight related losses are not affected by the number of discharge cycles.

The cell efficiency is very important to consider. The associated use phase charge/discharge losses will be a share of the environmental impacts of the used electricity mix. For η=0.95-0.5 these electric losses range from 5 to 50% per delivered kWh. Furthermore, these losses are transformed into heat that may (in reality, not in the model) require further energy to get rid of. Per kilometre, also production related and weight related impacts are affected by the efficiency, since the plug-to-wheel energy consumption per kilometre increases with decreasing efficiency.

The battery weight affects the energy consumption per kilometre, thus a lighter battery will get an increased range with the same size battery and thus slightly smaller production related impacts per kilometre. For the same reason also the charge related impacts decrease slightly per kilometre with diminishing battery weight. The weight related losses per kilometre are of course reduced by reduced battery weight (i.e. higher percentage of cells in battery). All in all the difference is 8 g CO_2-eq per km between 25% and 75% weight of cells in pack. In comparison, impacts related to cell efficiency differ around 20 g CO_2-eq per km for η from 0.95 to 0.8. It emphasizes that it could be more important to keep the efficiency high than the weight low.

Life cycle impacts

At 4000 discharge cycles and η=0.9, production level climate impacts and use phase climate impacts are at the same level, assuming West European electricity mix for the propulsion. Fewer discharge cycles means less service life kilowatthours and kilometers, thus production related impacts would dominate. However, with carbon-lean electricity for the propulsion, use phase climate impacts are much smaller and not at all dominant. This sensitivity to the electricity mix is confirmed by many (Notter et al., 2010) studies.

Abiotic depletion is dominated by metals depletion related to electricity distribution, not production. Therefore, abiotic depletion is not as sensitive to the choice of electricity mix as climate impact is. For abiotic depletion use phase impacts remain at more or less the same level as production related impacts at 4000 cycles even with carbon-lean electricity.

Conclusions

In short, the study points towards the following conclusions:

- LCA may be very helpful in the design process of batteries, here exemplified by potentially halving the climate impact, just by pointing towards lithium metal as a major source.
- The largest non-recyclable contributor to climate impact and abiotic depletion in the production phase is the assembly energy. It therefore warrants special attention in further efforts to minimize cell environmental impacts.
- The cell efficiency is very important to consider. For η=0.95-0.5 electric losses range from 5 to 50% per delivered kWh. These losses are transformed into heat that may require further energy to get rid of.
- Use phase battery weight related losses are not as high and suggests that it is more important to keep the efficiency high than the weight low.
- At 4000 discharge cycles and (η=0.9), production level climate impacts and use phase climate impacts are at the same level, assuming West European electricity mix for the propulsion. However, with carbon-lean

electricity for the propulsion, use phase climate impacts are much smaller and not at all dominant.

- Abiotic depletion is dominated by metals depletion related to electricity distribution, not production. Therefore, abiotic depletion is not as sensitive to the choice of electricity mix as climate impact is.

List of acronyms and abbreviations

CFCs	Chlorofluorocarbons
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
CH_4	Methane
C_2H_4	Ethene
EPD	Environmental Product Declaration
EEA	European Environment Agency
HFCs	Hydrofluorocarbons
ISO	International Organization for Standardization
Kg	Kilogram
KW	Kilowatt
KWh	Kilowatt-hour, 1 kWh = 3.6 MJ
LCA	Life Cycle Assessment
LFP	Lithium iron phosphate, $LiFePO_4$, battery cell
Li	Lithium
LMO	Lithium manganese oxide, $LiMn_2O_4$, battery cell
MJ	Megajoule
MWh	Megawatt-hour
NMC	Lithium nickel manganese cobalt oxide battery cell
NMP	N-Methyl-2-pyrrolidone
NO_x	Nitrogen oxides
PHEV	Plug-in hybrid electric vehicle
PO_4	Phosphorus
PS	Polystyrene
PVDF	Polyvinylidenfluoride
PP	Polypropylene
RER S	RER = Region Europe, S=system process
Sb	Antimony
SO_2	Sulphur dioxide
SF_6	Sulfur hexafluoride

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