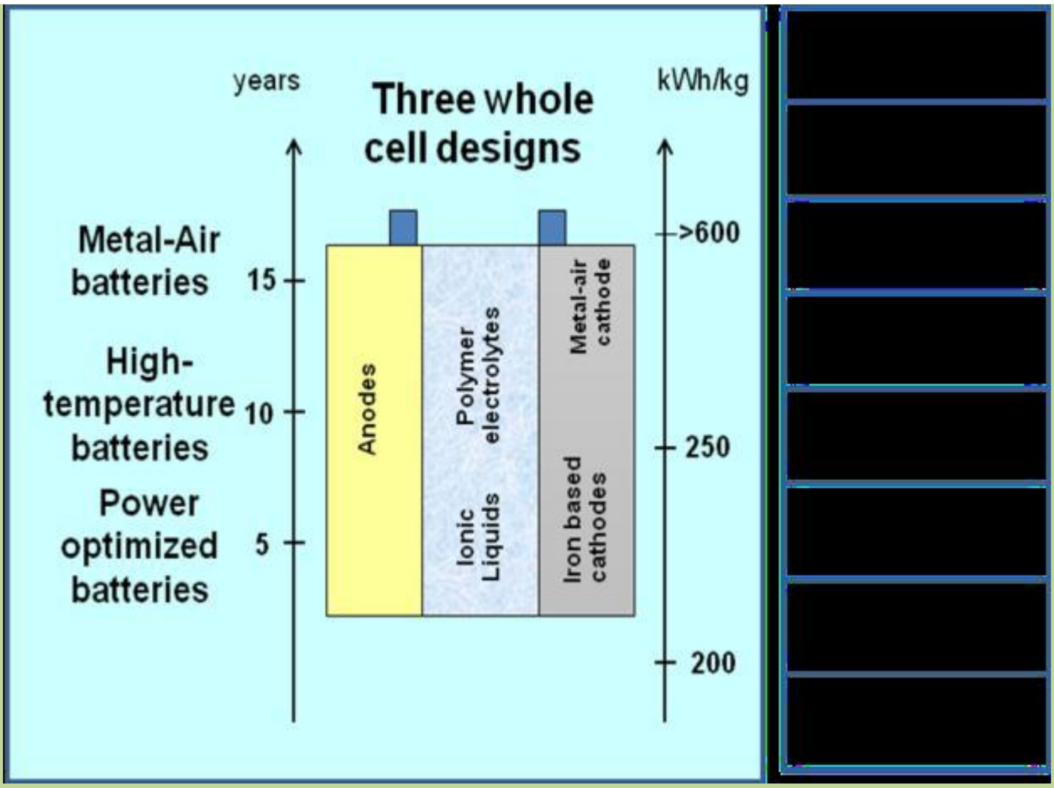

Project Report
25967

Life cycle assessment of high temperature batteries

– 5Ah cell

2017-01-20

Mats Zackrisson

swerea IVF

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Swerea IVF AB

P O Box 104
SE-431 22 Mölndal
Telephone +46 (0)31-706 60 00
Fax +46 (0)31-27 61 30
www.swereaivf.se

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Preface

This report contains a life cycle assessment of lithium batteries. It was performed in the context of the Swedish project *From road to load* funded by Stiftelsen för Strategisk Forskning, SSF. The LCA has been carried out by Mats Zackrisson at Swerea IVF. Members of the From road to load consortium have delivered detailed data about raw materials, manufacturing, use and recycling related to lithium batteries. Kristin Fransson at Swerea IVF has reviewed the report.

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Summary

This report contains a life cycle assessment of a 5Ah LiFeSO4F high-temperature battery cell weighing 110 grams. It was performed in the context of the Swedish From road to load 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. It has also been compared to other lithium battery cells. The results indicate that:

- Production in Sweden is favourable due to that electricity is a main driver of climate impact and toxicity in the production phase.
- Electricity is a main driver of climate impact and toxicity also in the use phase which emphasizes the need to keep the charge/discharge efficiency high.
- Indium tin oxide in the anode dominates abiotic depletion.
- Comparison with lithium-air cells reflects that the lithium air technology is still very far from commercial reality, while indicating that it is an interesting technology for the future.

Introduction

This report contains a life cycle assessment, LCA, of lithium batteries. The LCA has been carried out in the context of the From road to load project funded by SSF. Two of the most challenging strategic needs in the battery area are addressed by this consortium: energy storage for high power hybridization of heavy duty vehicles ("road") and load leveling for energy from intermittent sources like the wind and sun ("load"). The aim is to demonstrate three different Swedish battery concepts based on new materials with energy densities ranging from 200 Wh/kg to more than 600 Wh/kg. Environmental ambitions of the From road to load project are expressed as:

- To develop new Li-ion and metal-air batteries with 200 Wh/kg to > 600 Wh/kg energy densities.
- Syntheses of electrode materials and electrolytes that are energy efficient and low in CO_2 emission.
- New polymer electrolytes for safe low-cost batteries working at 60°C < T < 150°C: to allow the batteries to be cooled by the regular cooling fluid of hybrid vehicles, or to be used un-cooled in generators for large scale storage.

The purpose of the LCA is to highlight environmental hotspots with different combinations of iron-sulphate based cathodes, a tin-oxide anode, LiPF6 and ionic liquid electrolytes. 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). Though, 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.

Method in general

The LCA was performed in the context of the Swedish From road to load project. The LCA has been carried out by Mats Zackrisson and reviewed by Kristin Fransson at Swerea IVF. Members of the From road to load 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 8.2.3.0 was used for the calculations, project Battery systems. 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.

This study and report

Data about the cell and battery configuration was decided by the From road to load project consortium in several meetings during 2016, for example

- 4 March 2016 at Ångström laboratory in Uppsala
- 20 May 2016 at Ångström laboratory in Uppsala
- 20 September 2016 on the telephone
- 21 September 2016 informal meeting in Uppsala

In addition e-mail and telephone were used to deliver and discuss data and results. The first part of the study (not reported here) was carried out as a per unit of weight comparison of all the ingredients in a life cycle perspective. These results were used to decide which combinations to focus in the final LCA calculations reported here.

Functional unit

Life cycle assessments of batteries use a variety of functional units. This reflects that batteries are used in different applications and it is the application context that decides which unit that best describes the desired function. From load to road stretch the application from that of energy storage for high power hybridization of heavy duty vehicles ("road") to load leveling for energy from intermittent sources like the wind and sun ("load"). The most suitable functional unit for this broad application is **per delivered kWh over the lifetime.** This functional unit will be mostly used in this study. In addition, some aggregated figures will be given per vehicle kilometre for a hybrid bus, per nominal battery capacity (kilowatthour) and per kilogram battery.

System boundary

The system boundary for the study is shown below. The use of a small hybrid battery[1] in a heavy vehicle is almost as using it in a stationary application because the battery is so small compared to the vehicle that its weight does not matter. Thus the same model and system boundary is used in the whole study, i.e. from road to load.

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 included but the other parts of the drive train to deliver electricity from plug to wheel: charger, inverter and motor are not included.

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

[1] to support the diesel engine

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
- 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 below zero 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 in the main study while remembering that it will happen many years in the future, if at all.

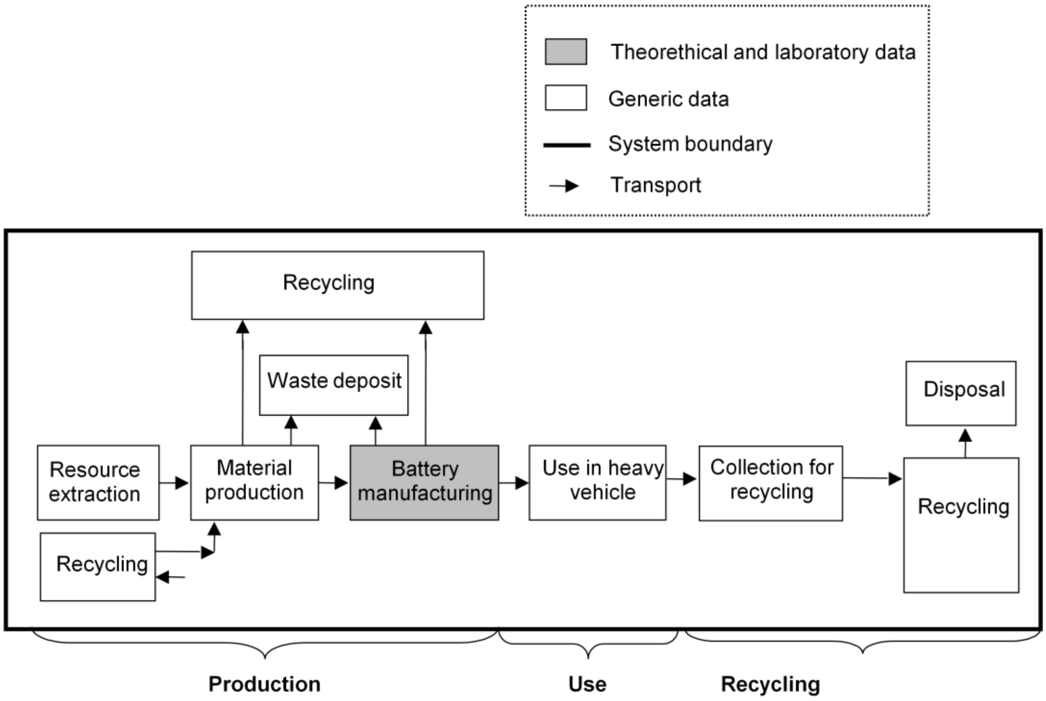

Figure 1 System boundary

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 (calculated with the method CML-IA baseline, version 3.02) 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. It should be mentioned that there is no universal consensus within the LCA community on methodology and on the relative ranking of resource depletion impacts (Klinglmair et al., 2014). (Peters and Weil, 2016) cautions against far-reaching conclusions regarding abiotic depletion while confirming that the recommended CML method is the best available today.
- Toxicity has been evaluated with the method USEtox (recommended+interim) 1.04 as presented in the LCA-software SimaPro 8.2.3.0. This is the method currently being recommended by the ILCD handbook (Wolf and Pant, 2012). USEtox calculates characterization factors for human toxicity and freshwater ecotoxicity at midpoint level:
  - The characterization factor for human toxicity impacts is expressed in comparative toxic units (CTUh), and is the estimated increase in morbidity in the total human population, per unit mass of a chemical emitted.
  - The characterization factor for freshwater ecotoxicity impacts is expressed in comparative toxic units (CTUe), and is an estimate of the potentially affected fraction of species (PAF) integrated over time and volume, per unit mass of a chemical emitted.

Modelling

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

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

As mentioned above, when using a small battery in a heavy vehicle as in this study, the extra electricity needed to carry the battery weight is very small compared to the charge/discharge losses. Thus, as used in this study, the model also represents stationary application. Modelling of the recycling was based on a literature survey.

The model was parameterized in order to enable easy change of parameters such as depth of discharge, efficiency, electricity mix and other.

Production phase

The complete battery system consists of:

- Battery cells
- Battery management system, BMS
- Packaging
- Cooling system

This study focuses on different cell designs and chemistries. However, the other parts, the rest-of-pack, make up roughly half the battery weight and are considered in the calculations by using data from (Ellingsen et al., 2013). Packaging is dominating the rest-of-pack (80%) while BMS and cooling system are approximately 10% each. The bill of material of the studied 5 Ah cell is given in the figure below.

Table 1 Bill of Material (BOM) for Triplite/LiPF6/pp 5 Ah cell

Part of cell	Material	Weight (g)	Recycling	Recycled weight (g)
Cathode	$LiFeSO_4F$, Triplite	35.8	Incinerated	
Cathode	$PEDOT^{1/3+}$	2.4	Incinerated	
Cathode	$TFSI^-$, bis(trifluoro-methane)sulfonimide	1.6	Incinerated	
Cathode	C, Carbon black	1.8	Incinerated	
Cathode	PVdF-HFP, poly-(vinylidene fluoride-co-hexafluoro-propylene)	1.8	Incinerated	
Cathode	Al, Aluminium foil	12	80% recyc.	9.6
	Cathode total mass	**55.4**		

Part of cell	Material	Weight (g)	Recycling	Recycled weight (g)
Anode	SnO_2, tin oxide	9.04	80% recyc.	7.2
Anode	Carbon black	0.94	Incinerated	
Anode	SBR, styrene butadiene rubber	0.1175	Incinerated	
Anode	CMC, carboxy-methyl-cellulose	0.3525	Incinerated	
Anode	Copper foil	16.92	80% recyc.	13.5
Anode	Nickel foil	5.41	80% recyc.	4.33
	Anode total mass	**32.8**		
Separator	Solupor	1.2	Incinerated	
Electrolyte	$LiPF_6$	1.5	Incinerated	
Electrolyte	Ethylene carbonate	5	Incinerated	
Electrolyte	Diethyl carbonate	5	Incinerated	
Electrolyte	Vinylene carbonate	0.1	Incinerated	
	Electrolyte total mass	**11.6**		
Housing	Aluminium (30%)	2.0	80% recyc.	1.6
Housing	Polypropylene (30%)	2.0	Incinerated	
Housing	Nickel (40%)	2.6	80% recyc.	2.1
	Housing total mass	**6.6**		
Current collectors	Aluminium	1	80% recyc.	0.8
	Nickel	3	80% recyc.	2.4
	Collectors total mass	**4**		
Cell total mass		**110.4**		**41.5**

A Tavorite version of the same cell as above is also calculated. It is exactly the same, except that Triplite is exchanged for Tavorite $LiFeSO_4F$.

Cathode

The cathode materials and their representation in the LCA-calculations are shown in the table below.

Table 2 Cathode materials

Cathode materials	Weight (gram)	LCA process name	Description and comment
$LiFeSO_4F$	35.8	Tavorite, LiFeSO4F, 1g	Tavorite or Triplite, see below
$PEDOT^{1/3+}$	2.4	PEDOT, 2.4 g	See below
$TFSI^-$, bis(trifluoro-methane)sulfonamide	1.6	Chemical, inorganic {GLO}| market for chemicals, inorganic | Alloc Rec, S	
C, Carbon black	1.8	Carbon black {GLO}| market for | Alloc Rec, S	

Cathode materials	**Weight (gram)**	**LCA process name**	**Description and comment**
PVdF-HFP, poly-(vinylidene fluoride-co-hexafluoro-propylene)	1.8	PVDF, Fischer, system	
Al, Aluminium foil	12	Aluminium sheet EAA00	LCA for production of aluminium sheet in Europe. Cradle to aluminium sheet ready for delivery at gate. Made from 60% primary and 40% recycled aluminium which corresponds to the world average 1998. Surface treatment not included. Average data.
NMP	110	NMP use for battery electrodes, per kg NMP	
Total slurry **Total wet cathode** **Total cathode**	**153** **165** **55,4**		Slurry excludes metal
Processing	**Weight (gram)**	**LCA process name**	**Description and comment**
Heat treatment 120 ^{0}C, 10 h	165		See below. 165 gram assumed heat treated.
Milling in planetary mill 1h	153	Milling of spin dye pigment, UCTE, Systems	153 gram assumed milled.

Heat treatment

The manufacturing process needs energy for heat treatment involving a temperature increase to 120 °C maintained for 10 hours. The required energy is the sum of heating up the mass of the cathode plus heating up the mass of the oven plus the oven losses. The energy required to heat something up can be calculated as: Temperature increase * Average specific heat capacity * Mass. The oven losses can be calculated as: Temperature difference between oven surface and ambient air * Overall heat transfer coefficient * holding time * oven surface area.

The required energy for heating up the mass of the cathode or any substrate Q_{subs} equals:

$$Q_{subs} = (T-20)*C_{subs}/3600 \text{ kWh per kg substrate},$$

where T-20 is the temperature rise and C_{subs} is the specific heat capacity of the substrate. The specific heat capacity for the cathode material mix above is 1.9 kJ/kgK, since it mostly consists of NMP. Since we calculate per mass unit, the mass as such is not in the equation.

The calculation of the energy to heat up the oven and maintain its losses rests on the following assumptions:

- the oven has a cubic shape so that its volume can be calculated as L^3 and its surface area as $6*L^2$, where L is the length in meter.

- a quarter of the volume L^3 can be filled; a quarter is empty unoccupied space and the remaining half is structural: ¼ insulation, 1/8 steel and 1/8 stone. The assumption means that the thickness of the wall is 3 cm for L=0.3, 10 cm for L=1 and 20 cm for L=2.
- the temperature difference between the oven surface and ambient air equals the holding temperature T divided by four
- 40 W/m^2K is a typical value for the overall heat transfer coefficient H_{trans} between metal and gas (Roetzel, 2010).
- A density of 1200 kg/m3 is assumed for the substrate, the cathode, since it mostly consists of NMP, henceforth denoted ρ_{subs}.

The required energy for heating up the mass of the oven Q_{oven} equals:

$$Q_{oven} = (T-20)*S/\rho_{subs}/3600 \text{ kWh per kg substrate,}$$

where S is a factor containing the heat capacities and the densities of the oven shell materials. S is equal to 2812 with the above assumptions. The heat losses per kg substrate Q_{loss} can be calculated as:

$$Q_{loss} = T * H_{trans} * time * 6/(L* \rho_{subs} * 1000) \text{ kWh per kg substrate}$$

Thus the total energy requirement Q for oven heat treatment of any substrate with density ρ_{subs} is per kg substrate:

$$Q = Q_{subs} + Q_{oven} + Q_{loss} =$$

$$= (T-20)*C_{subs}/3600 +(T-20)*S/\rho_{subs}/3600+T*H_{trans}*time*6/(L*\rho_{subs}*1000)$$

The diagram below shows the energy requirement for heat treatment of the cathode (i.e. 120 ^oC in 10 hours) per kg cathode for different size ovens (L=1, 0.8 and 0.3 m), where L=1 represents industrial size and L=0.3 represents laboratory size. In the LCA calculations, the values corresponding to L=0.8 has been used in order to represent industrial production, though it could be argued that in a process industry the oven is not reheated between batches and thus Q_{oven} is only a fraction of what is shown in the figure above.

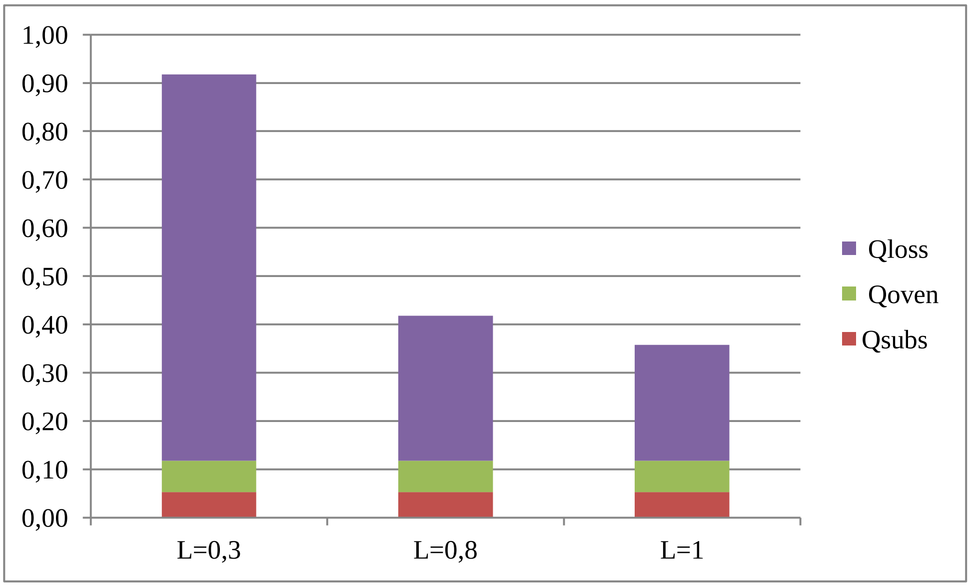

Figure 2 Energy requirement in kWh/kg substrate for heat treatment of the cathode (120 ^oC in 10 hours) for different size ovens

Tavorite

The $LiFeSO_4F$ comes in two forms: Tavorite and Triplite. The synthesization of Tavorite is described here. Triplite and PEDOT are described in the following chapters

Tavorite (35.8 gram of it) is synthesized from FeSO4FH2O and LiF using the following materials and process steps.

Table 3 Tavorite

Material/energy	Weight (gram)	LCA process name	Description and comment
$FeSO_4 \cdot 7H_2O$, Iron sulfate hepta hydrate	52.3	Iron sulfate {GLO}| market for | Alloc Rec, S	Iron sulphate is a by-product of steel and iron manufacturing. Rough estimation of the electricity use for purification of the by-product. No data for infrastructure and emissions.
LiF, Lithium fluoride	5.5	Lithium fluoride {GLO}| market for | Alloc Rec, S	Includes the reaction of lithium carbonate with hydrogen fluoride in an autoklave to lithium fluoride, carbon dioxide and water. The reaction temperatur is 21°C (no need to cool or heat). Energy consumption to evaporate water to dry the salt and CO2 emissions to air from the reaction are calculated. For infrastructure, the ecoinvent dataset "chemical plant, organics" is accounted.
$N_2(g)$ Nitrogen gas	17	Nitrogen, liquid {RER}| market for | Alloc Rec, S	Nitrogen, liquid is produced always only as a by-product of different activities.
TEG Tetraethylene glycol	1200	TEG solvent use for battery electrodes, per kg solvent Ethylene glycol {GLO}| market for | Alloc Rec, S	In the laboratory process the solvents are wasted (emissions to air) but in the model they are assumed to be recycled in a similar way to NMP, see below. Solvent production based on actual plant throughputs and measurements. The oxidation of ethylene oxide leads to the production of 1 kg of three coproducts: ethylene glycol, diethylene glycol (DEG) and triethylene glycol (TEG). Raw materials, energy consumption and emissions are modelled with literature data. Infrastructure is

Material/energy	Weight (gram)	LCA process name	Description and comment
			included with a default value.
CH_3COCH_3 Acetone	425	Acetone use for battery electrodes, per kg acetone Acetone, liquid {GLO}| market for | Alloc Rec, S	In the laboratory process the solvents are wasted (emissions to air) but in the model they are assumed to be recycled in a similar way to NMP, see below. Solvent production from the Eco-profiles of the European plastics industry (PlasticsEurope). Not included are the values reported for: recyclable wastes, amount of air / N2 / O2 consumed, unspecified metal emission to air and to water, mercaptan emission to air, unspecified CFC/HCFC emission to air, dioxin to water.
Total slurry	**1680**		
Processing	**Weight (gram)**	**LCA process name**	**Description and comment**
Heat treatment 100 ^{o}C 4h	**1680**	Heat treatment, per g	See below
Milling in planetary mill 1h	1680* 0.75= **1260**	Milling of spin dye pigment, UCTE, Systems	Electricity and waste treatment for millling of 300 kg dye per hour. Per kg substance.
Heat treatment 215 ^{o}C 70h	**1260**	Heat treatment, per g	See text below

In the laboratory process the solvents are wasted (emissions to air) but in the model they are assumed to be recycled in a similar way to NMP, see below.

The manufacturing process needs energy for two temperature increases: first to 100 °C followed by milling and then a final temperature rise to 215 °C maintained for 70 hours. Since the mix mostly consists of solvents a specific heat capacity of 2 kJ/kgK and a density of 1200 kg/m^3 are assumed. For the milling and the second heat treatment it is assumed that the mass is reduced by 25% by solvent evaporation. For further details about the heat treatment model, see chapter above.

Triplite

Triplite (35.8 gram of it) is synthesized from $FeSO_4FH_2O$ and LiF using the following materials and process steps.

Table 4 Triplite

Material/energy	Weight (gram)	LCA process name	Description and comment
$FeSO_4 \cdot 7H_2O$, Iron sulfate hepta hydrate	52.3	Iron sulfate {GLO}| market for | Alloc Rec, S	Iron sulphate is a by-product of steel and iron manufacturing. Rough estimation of the electricity

Material/energy	**Weight (gram)**	**LCA process name**	**Description and comment**
			use for purification of the by-product. No data for infrastructure and emissions.
LiF, Lithium fluoride	5.3	Lithium fluoride {GLO}| market for | Alloc Rec, S	Includes the reaction of lithium carbonate with hydrogen fluoride in an autoklave to lithium fluoride, carbon dioxide and water. The reaction temperatur is 21°C (no need to cool or heat). Energy consumption to evaporate water to dry the salt and CO2 emissions to air from the reaction are calculated. For infrastructure, the ecoinvent dataset "chemical plant, organics" is accounted.
N_2(g) Nitrogen gas	55	Nitrogen, liquid {RER}| market for | Alloc Rec, S	Nitrogen, liquid is produced always only as a by-product of different activities.
Total slurry	**112.6**		
Processing	**Weight (gram)**	**LCA process name**	**Description and comment**
Heat treatment 270^{o}C, 8h	112.6	270 deg, 8 h, c=1KJ/kgK, η=1000, per kilogram	Density assumed to 1000 kg/m^3, c assumed to 1 kJ/KgK. Other details see Heat treatment above.
Milling in planetary mill 1h	57.6	Milling of spin dye pigment, UCTE, Systems	Electricity and waste treatment for millling of 300 kg dye per hour. Per kg substance. No gas left.
Heat treatment 250^{o}C 8h	57.6	250 deg, 8 h, c=1KJ/kgK, η=1000, per kilogram	Density assumed to 1000 kg/m^3, c assumed to 1 kJ/KgK. No gas left. Other details see Heat treatment above.

PEDOT

PEDOT (2.4 gram of it) is synthesized from the following materials and process steps and the LiFeSO4F is coated with it.

Table 5 PEDOT

Material/energy	**Weight (gram)**	**LCA process name**	**Description and comment**
$NOBF_4$, Nitronium tetrafluoroborate	5.3	Hydrogen fluoride {GLO}| market for | Alloc Rec, S + Boron trifluoride	See below.

Material/energy	**Weight (gram)**	**LCA process name**	**Description and comment**
		{GLO}| market for | Alloc Rec, S + Nitric acid, without water, in 50% solution state {GLO}| market for | Alloc Rec, S	
CH_3CN Acetonitrile	280	Acetonitrile use for battery electrodes, per kg solvent Acetonitrile {GLO}| market for | Alloc Rec, S	In the laboratory process the solvents are wasted (emissions to air) but in the model they are assumed to be recycled in a similar way to NMP, see below. The "Sohio process" delivers the co-products acrylonitrile, hydrigen cyanide, and acetoinitrile. The allocation is based on mass balance. Including materials, energy uses, infrastructure and emissions.
EDOT 3,4-ethylenedioxythiophene	2.4	Chemical, inorganic {GLO}| market for chemicals, inorganic | Alloc Rec, S	Proxy for EDOT. An unweighted average of 20 common inorganic substances
LiTFSI Lithium bis(trifluoromethane)sulfonimide	6.5	Lithium chloride {GLO}| market for | Alloc Rec, S	Proxy for LiTFSI.
CH_3OH, Methanol	110	Methanol use for battery electrodes, per kg solvent	
CH_3COCH_3, Acetone	280	Acetone use for battery electrodes, per kg acetone	
Total slurry	**684**		
Processing	**Weight (gram)**	**LCA process name**	**Description and comment**
Heat treatment 70 ^{0}C, 4 hours	684	70 degree in 4 hours, c=2KJ/kgK, per kilogram	Details see Heat treatment above.

Nitronium tetrafluoroborate can be synthesized from hydrogen fluoride, boron trigfluoride and nitrix acid according to the formula:

$$HF+BF_3+HNO_3 \text{->} NOBF_4+H_2O+O_2$$

A molar calculation gives that 0.17 kg HF, 0.58 kg BF_3 and 0.54 kg HNO_3 gives 1 kg $NOBF_4$.

In the laboratory process the solvents are wasted (emissions to air) but in the model it is assumed to be recycled in a similar way to NMP, see below.

Anode

The anode materials and their representation in the LCA-calculations are shown in the table below. In addition, 63 g of de-ionized water was used for each 5*5 cm anode. Each 5*5 anode weighs 32.8 grams including nickel foil contact.

Table 6 Anode materials

Anode materials	**Weight (gram)**	**LCA process name**	**Description and comment**
SnO_2, tin oxide	9.04	Indium tin oxide powder, nanoscale, for sputtering target {GLO}| market for | Alloc Rec, S	This dataset describes the production of nanoscaled ITO powder by coprecipitation for the use in sputtering targets with a density close to the theoretical one. No direct process emissions are considered due to a lack of respective information. The input raw materials are prompt scrap from the sputtering process, amounting to 77% of the raw material, and raw materials won from primary metals, making 23%. 8.5% of the total ITO is lost during scrap processing. Transports added to represent market process.
Carbon black	0.94	Carbon black {GLO}| market for | Alloc Rec, S	The functional unit represent 1 kg of solid carbon black. Large uncertainty of the process data due to weak data on the production process and estimation of data on process emissions. Transports added to represent market process.
SBR, styrene butadiene rubber	0.1175	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, S	Production data are from the Eco-profiles of the European plastics industry (PlasticsEurope). Not included are the values reported for: recyclable wastes, amount of air / N2 / O2 consumed, unspecified metal emission to air and to water, mercaptan emission to air, unspecified CFC/HCFC emission to air, dioxin to water. Transports added to represent market process. This is not the correct rubber. Used as proxy for SBR.
CMC, carboxy-methyl-cellulose	0.3525	Carboxymethyl cellulose, powder {GLO}| market for | Alloc Rec, S	Data based on company information from a former detergent study of EMPA.
Copper foil	16.92	Copper {GLO}| market for | Alloc Rec, S	Contains 30% virgin copper according to unit processes which is in line with world average. Transports added to represent market process.
Nickel foil	5.41	Nickel, 99.5% {GLO}| market for | Alloc Rec, S	96% virgin content according to unit process. Forming missing but probably insignificant.
De-ionized water	63	Water, deionised, from tap water, at	Energy for operation, chemicals used for regeneration, transport of chemicals

Anode materials	Weight (gram)	LCA process name	Description and comment
		user {GLO}| market for | Alloc Rec, S	to plant, emissions from regeneration chemicals, infrastructure of plant and replacement of spent exchagne resin, with a strong cation exchanger a degasser and a strong anion exchanger operated with counterflow regeneration.
Total slurry **Slurry+metal** **Total anode**	**73.5** **95.8** **32.8**		Slurry excludes metal Both slurry and metal are heat treated Anode excludes the water
Processing	**Weight (gram)**	**LCA process name**	**Description and comment**
Milling in planetary mill 2h	73.5	Milling of spin dye pigment, UCTE, Systems	Electricity and waste treatment for millling of 300 kg dye per hour. Per g substance.
Heat treatment 90 ^{0}C, 12 hours	95.8	90 degree in 12 hours, c=4.18 KJ/kgK, per kilogram	Details see Heat treatment above

Anode preparation starts with ball-milling tin oxide, carbon black, binders and de-ionized water for 2 hours. The slurry is spread on a copper foil with Doctor blade technique after which the anode is heat treated for 12 hours in a vacuum oven at 90 ^{0}C.

Separator

The separator Solupor is made of 100% polyethylene (Lydall, 2014). In the LCA-calculations it is represented by processes shown in the table below. The Solupor separator mass used in the cell is 1.2 gram.

Table 7 Separators

Separator materials	Weight (gram)	LCA process name	Description and comment
Solupor	1.2	Separator solupor, 1 g consisting of: • Polyethylene high density granulate (PE-HD), production mix, at plant RER • Thermoforming, with calendering {GLO}| market for | Alloc Rec, S	Raw data for polymerization and intermediate products are collected by several producers in Europé. (ELCD database). 1.05 g/g to account for losses The thermoformning process contains the auxillaries and energy demand for the mentioned convertion process of plastics but not including the plastic material. Information from different European and Swiss converting companies. 1.05 g/g to account for losses
Cellulose, Clodophora algae	Not used	Lime {FR}| production, algae | Alloc Rec, S	The process contains transports connected with the collection of the algae from the sea ground and the

Separator materials	Weight (gram)	LCA process name	Description and comment
			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 production takes place in France.

Cell packaging

Cell packaging was calculated from the coffee bag size (area) needed. So called coffee bags has a density of 0.0141 g/cm2 and consist of 30% aluminium, 30% of polypropylene and 40% nickel. A coffee bag housing a 5*5 cm cell then weighs 1.1*2*25*0.0141= 0.78 g (10% additional size and 2 walls in a bag).

Table 8 Cell packaging

Packaging materials	Weight (gram)	LCA process name	Description and comment
Cell packaging	0.78	Coffee bag, 1 g • Aluminium sheet EAA00 • Polypropylene, granulate {GLO}| market for | Alloc Rec, S • Nickel, 99.5% {GLO}| market for | Alloc Rec, S	Forming missing for polypropylene and nickel, but probably insignifcant

Electrolytes

$LiPF_6$

One of the electrolytes is a 1-molar solution of $LiPF_6$ in 1:1 EC:DEC 2% VC. The amount needed is based on the volume of pores in the separator and in the cathode. In mass for one cell this translates to the numbers in the BOM-list. Per gram LiPF6 the numbers in the table below apply.

Table 9 $LiPF_6$ electrolyte per gram

Per gram LiPF6	Weight (gram)	LCA process name	Description and comment
LiPF6, Lithium hexafluoro-phosphate	0.11	Lithium hexafluorophosphate {GLO}| market for | Alloc Rec, S	Includes the reaction of lithium fluoride, phosphorous pentachloride and hydrogen fluoride in an autoclave to lithium hexafluorophosphate and hydrogen chloride. Transports according to ecoinvent standards.For infrastructure,

Per gram LiPF6	Weight (gram)	LCA process name	Description and comment
			the ecoinvent dataset "chemical plant, organics" is accounted.
Ethylene carbonate, EC	0.48	Ethylene carbonate {GLO}| market for | Alloc Rec, S	Includes the reaction of ethylene oxide with carbon dioxide in a reactor with a reaction temperatur at 120°C under pressure and with the use of a silver based catalyst. Energy consumption, ethylene oxide and CO2 emissions to air are calculated. After heating, process runs adiabatic.
Diethyl carbonate, DEC	0.39	Ethanol, without water, in 99.7% solution state, from fermentation {GLO}| market for | Alloc Rec, S Phosgene, liquid {RER}| market for | Alloc Rec, S Electricity, medium voltage, production UCTE, at grid/UCTE S	See below
Vinylene carbonate, VC	0.020	Chemical, organic {GLO}| market for | Alloc Rec, S	Proxy

DEC can be made by reacting phosgene with ethanol, producing hydrogen chloride as a byproduct[2]:

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

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 $COCl_2$. The reaction was assumed to consume 0.01 kWh electricity per gram.

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).

Ionic liquid

The idea was to calculate the triplite cell also with an ionic liquid electrolyte. However, it was not possible to obtain enough information about the material content of an ionic liquid electrolyte.

Rest of pack

The battery pack consists of approximately 50% battery cells. The rest of the battery pack is considered in the calculations by using data from (Ellingsen et al., 2013) where packaging is dominating (80%) while BMS and cooling system are

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

approximately 10% each. In the table below the model of the rest of pack is shown including the mass of each material and a recycling estimate. All figures relate to 1 kg of rest of pack.

Table 10 Materials content and recycling of rest of pack, including 1kg BMS, packaging and cooling

Process	Weight (g)	BMS	P[3]	C[3]	Recycling rate	Rec. mass (g)	Avoided process
Aluminium sheet EAA00	379	X	X	X	80% rec.	304	Aluminium sheet EAA00
Steel, low-alloyed {GLO}| market for | Alloc Rec, S	330	X	X	X	80% rec.	264	Steel, low-alloyed {GLO}| market for | Alloc Rec, S
Nylon 6-6, glass-filled {GLO}| market for | Alloc Rec, S	135		X		80% rec.	108	Nylon 6-6, glass-filled {GLO}| market for | Alloc Rec, S
Polypropylene, granulate {GLO}| market for | Alloc Rec, S	54		X		80% rec.	43	Polypropylene, granulate {GLO}| market for | Alloc Rec, S
Copper {GLO}| market for | Alloc Rec, S	19	X	X		80% rec.	15	Copper {GLO}| market for | Alloc Rec, S
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, S	17	X	X	X	80% rec.	14	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, S
Cable, ribbon cable, 20-pin, with plugs {GLO}| market for | Alloc Rec, S	13	X			80% rec.	2	Copper {GLO}| market for | Alloc Rec, S
Ethylene glycol {GLO}| market for | Alloc Rec, S	4.8			X	80% rec.	4	Ethylene glycol {GLO}| market for | Alloc Rec, S
Electronic component, passive, unspecified {GLO}| market for | Alloc Rec, S	12	X			Electronics	9	Copper {GLO}| market for | Alloc Rec, S
Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| market for | Alloc Rec, S	8.3	X			Electronics	7	Copper {GLO}| market for | Alloc Rec, S
Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Alloc Rec, S	4.9	X			Electronics	4	Copper {GLO}| market for | Alloc Rec, S
Electric connector, wire clamp {GLO}| market for | Alloc Rec, S	0.94	X			Electronics	1	Copper {GLO}| market for | Alloc Rec, S
Integrated circuit, logic type {GLO}| market for | Alloc Rec, S	0.001	X			Electronics	0.001	Copper {GLO}| market for | Alloc Rec, S
Synthetic rubber {GLO}| market for | Alloc Rec, S	9.0	X	X	X	Incinerated		
Nylon 6 {GLO}| market for | Alloc Rec, S	2.0	X	X		Incinerated		

[3] P=Packaging, C=Cooling system

Process	**Weight (g)**	**BMS**	**P[3]**	**C[3]**	**Recycling rate**	**Rec. mass (g)**	**Avoided process**
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Rec, S	1.9	X			Incinerated		
Nylon 6-6 {GLO}| market for | Alloc Rec, S	1.6	X			Incinerated		
Polyphenylene sulfide {GLO}| market for | Alloc Rec, S	0.90	X			Incinerated		
Silicon, electronics grade {GLO}| market for | Alloc Rec, S	0.60			X	Incinerated		
Tin {GLO}| market for | Alloc Rec, S	0.45	X			Incinerated		
Brass {GLO}| market for | Alloc Rec, S	0.26	X			Incinerated		
Glass fibre {RER}| production | Alloc Rec, S	0.20			X	Incinerated		
Butyl acrylate {RER}| production | Alloc Rec, S	0.10		X		Incinerated		
Polyvinylchloride, bulk polymerised {GLO}| market for | Alloc Rec, S	0.07			X	Incinerated		
Total	**1000**					**774**	

Battery management systems, BMS

The BMS is modelled according to (Ellingsen et al., 2013) and Table 10. The figure below shows all the involved process and their carbon footprint per kg of BMS. The electronic components dominate the carbon footprint of the BMS.

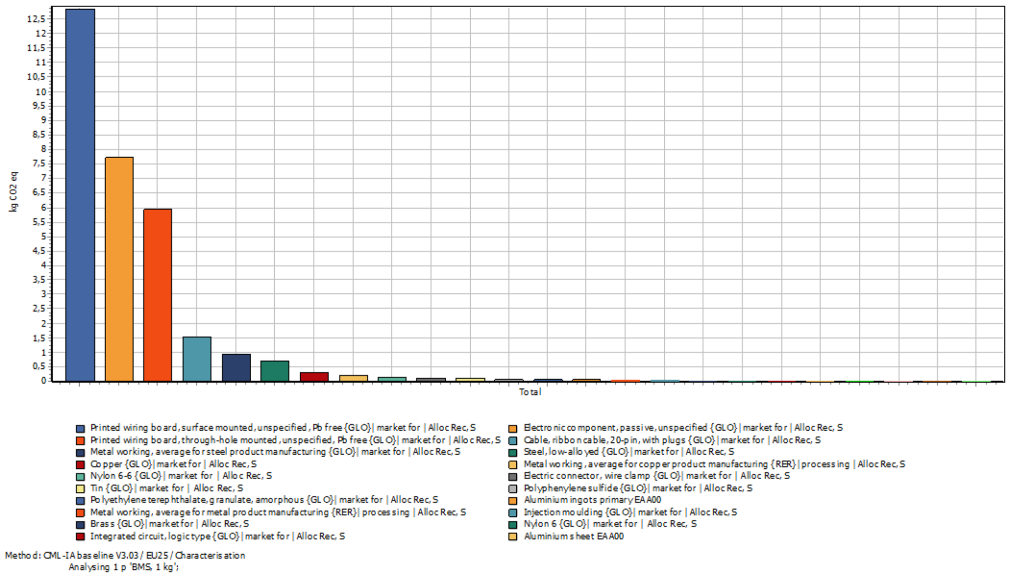

Figure 3 Carbon footprint results for LCA processes used for model of BMS

Battery packaging

The battery packaging is modelled according to (Ellingsen et al., 2013) and Table 10. The figure below shows all the involved process and their carbon footprint per kg of battery packaging. It can be seen that the aluminium material and forming of it dominate the carbon footprint.

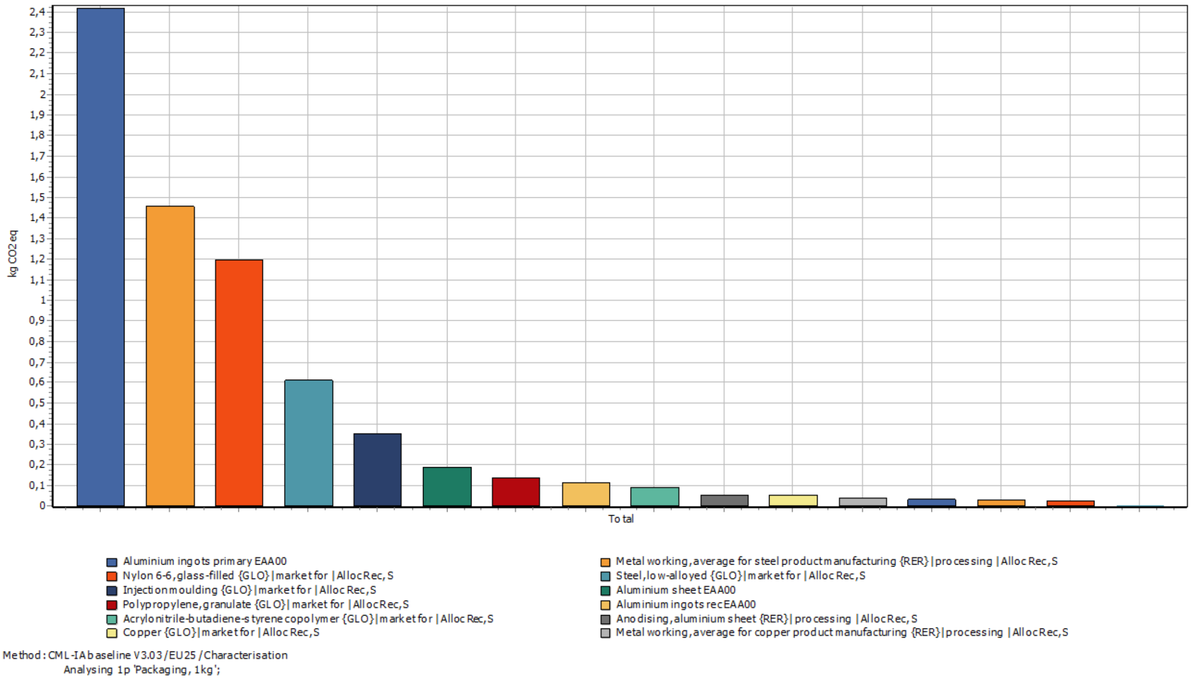

Figure 4 Carbon footprint results for LCA processes used for model of packaging

Battery cooling system

The battery cooling system is modelled according to (Ellingsen et al., 2013) and Table 10. The figure below shows all the involved process and their carbon footprint per kg of battery cooling system. Also here the aluminium material and forming of it dominate the carbon footprint.

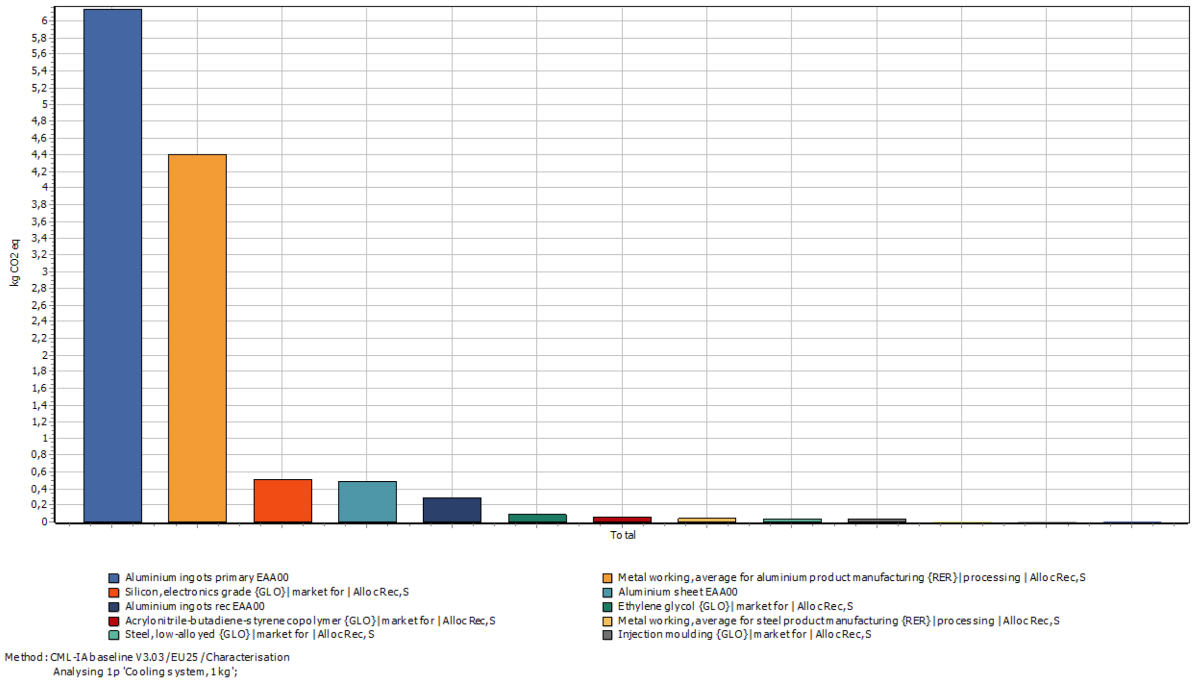

Figure 5 Carbon footprint results LCA processes used for model of cooling system

Cell manufacturing and assembly

Energy requirements for cell manufacturing and battery 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). (Ellingsen et al., 2013) recorded 62 MJ as energy per kg battery during the best month of the year in an Asian battery plant where the average value was 244 MJ/kg. Based on data from Saft's annual report 2008 (Saft, 2008), (Mats Zackrisson et al., 2010) estimated energy consumption for battery assembly to 11.7 kWh electricity and 8.8 kWh gas per kg lithium battery, i.e. 74 MJ/kg energy.

The cells studied here were manufactured and assembled in laboratory conditions where some energy (for heat treatment, milling and mixing) was already included and other energy use, notably for dry and clean room conditions, was not included in the calculations so far. The model of the cells in this report should mimic industrial production, thus, in the base case the, 74 MJ/kg assumption from (Mats Zackrisson et al., 2010) was used.

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/vehicle 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 battery manufacturer to user, in process Battery cell use. There are many battery manufacturers in the world, but customers do not select local producers. 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 and the extra electricity needed to carry the weight of the battery in a vehicle. In addition, the transport of the battery from the battery or vehicle manufacturer to the user was included in the use phase, see transports. In a vehicle, the use phase losses are part of the total propulsion impacts that stems from the plug-to-wheel electricity consumption.

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- η) factored with the total delivered energy. Since the electricity consumption per km in a vehicle will increase with decreasing η, the losses per vehicle km are proportional to (1- η)/η.

Extra power demands to accommodate battery mass

As mentioned above, when using a small battery in a heavy vehicle as in this study, the extra electricity needed to carry the battery weight is very small, i.e. neglible, compared to the charge/discharge losses. Thus, as used in this study, the model also represents stationary application.

The modelling of the extra power to accommodate battery mass in a vehicle is described in (Zackrisson, 2016).

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

As of, 2016, 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 vehicle scrap yard. This is where the battery is removed from the vehicle and ideally sent directly to a chemistry specific disassembly and treatment plant. Batteries for stationary applications will most likely not need this transport since they need not be disassembled from any vehicle.
- 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 lithium batteries are considered as “hazardous materials” and therefore transportation is subject to several laws and regulations. So many of the transports outlined above have to be done by professional dedicated transportation services with specific licences.

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 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 1 above show the resulting recycled mass for a 5 Ah cell and Table 10 show the resulting recycled mass for the rest of the battery pack.

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 used enabling design and test of a battery in a vehicle context. Below is a list of the parameters used. Parameter settings in the figure reflect Road to load ambitions and base case for a 12.7 kWh battery built with 5 Ah cell used in a bus. As explained above this modelling also represents stationary application.

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

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
Prodel	0	Undefined				☐	1=swedish electricity; 0=europeisk el, for the production, i.e. assembly energy
Ahpercell	5	Undefined				☐	Energy content of cell in amperehours
Elsort	0	Undefined				☐	1=swedish electricity; 0=europeisk el, for the propulsion
Weight	16600	Undefined				☐	Vehicle weight without battery in kg. (1176 for Leaf, 1490 for Tesla, 374 for Twizy). 1600 base case for pluginhybrides. 16600 for bus.
Orgbatteryweight	1400	Undefined				☐	Nissan Leaf 294 kg, Tesla 618 kg, Volvo bus 1400 kg
Cellweight	110,4	Undefined				☐	Cell weight in grams.
Voltage	3,2	Undefined				☐	Cell voltage during discharge: 3,2 for LFP, 3,4 for LFP metal, 3,75 for NMC, 4,0 for NMC metal, 3,6-3,7 for NCA. 3,2 for Tavorite and Triplite cells.
Dischargedepth	0,8	Undefined				☐	How much of the total capacity that can be cycled (SOC). 80% base case
Systemvoltage	634	Undefined				☐	System voltage (360 for Leaf, 350 for Tesla, 634 for bus)
NoPstrings	4	Undefined				☐	Number of rows 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
Oldplugtowheel	1,25	Undefined				☐	Original kWh per km of the vehicle. Nissan Leaf 0,1863, Tesla 0,2375, Volvo bus 1,25
Weightofcellsinpack	0,559	Undefined				☐	Relation between cell weight and battery weight. 0,522 for Leaf and 0,517 for Tesla S and 0,258 for Twizy, 0,559 for bus. Base case = 0,5
Cellrecyclemass	41,5	Undefined				☐	Recycled cellmass in grams
Eff	0,9	Undefined				☐	Charge/discharge efficiency; base case 0,9=90%
Restofpackcarboncontent	9,6	Undefined				☐	kg CO2/kg restofpack from Ellingsen et al (BMS+cooling+packaging)
Cellcarboncontent	2,84	Undefined				☐	kg CO2 per cell as calculated by LCA model. Only used in Calculated parameters below!
gCO2perkWh	594	Undefined				☐	53 g/kWh for Swedish average electr. 594 g/kWh for European average electr. Only used in Calculated parameters below!

Calculated parameters

Name	Expression	Comment
Cycles	1331*Dischargedepth^-1,825 = 2E3	Maximum number of cycles at specified SOC (2000, 4000, 600 ealier base case. SOC 0,5 give 4716 cycles; 0,6 give 3381; 0,7 give 2552; 0,8 give 2000; 0,9 give 1613 and 1,0 give 1333)
Plugtowheel	Oldplugtowheel*(1-weightlossdep*(Orgbatteryweight-Batteryweight)/Weight)*0,9/Eff = 1,22	Plugtowheel consumption in kWh/km assuming plugtowheelperkm based on Eff=0,9
Battowheel	Plugtowheel*Eff = 1,1	
Ahpergram	Ahpercell/Cellweight = 0,0453	Energydensity in Ah/gram at cell level
Ahperkg	Ahpergram*1000 = 45,3	Energydensity in Ah/kg at cell level
Whperkg	Ahperkg*Voltage = 145	Energydensity in watthours per kg at cell level: Amperehours*voltage=watthours; Wh/g=kWh/kg. TriLi-target is 250 Wh per kg
Whperkgbatt	Whperkg/Celltobatt = 81	Energydensity in watthours per kg at battery level
Delkwh	Ahpercell*Voltage*Cycles*Dischargedepth/1000 = 25,6	Delivered kwh per cell during life cycle. Amperehours*voltage=watthours
DelkWhperkgcell	Cycles*Dischargedepth*Voltage*Ahpergram = 232	Delivered kwh/kgcell. Wh/g eller kWh/kg.
Nocellsforpackvoltage	Systemvoltage/Voltage = 198	Number of cells connected in series
Nocellsheltal	198 = 198	Heltal för Nocellsforpackvoltage
TotalNocells	Nocellsheltal*NoPstrings = 792	Total number of cell i battery pack
Battcapnom	TotalNocells*Ahpercell*Voltage/1000 = 12,7	kWh nominal battery capacity
BattcapatSOC	Battcapnom*Dischargedepth = 10,1	kWh real battery capacity
RangeatSOC	BattcapatSOC/Battowheel = 9,22	Kilometers at chosen SOC or Dischargedepth
Rangeat100SOC	Battcapnom/Battowheel = 11,5	Kilometers assuming 100% dischargedepth
ServicelifeatSOC	RangeatSOC*cycles = 1,84E4	kilometers life assuming specified SOC equals average SOC
Batteryweight	Cellweight/1000*TotalNocells/Weightofcellsinpack = 156	
Celltobatt	1/Weightofcellsinpack = 1,79	Relation between battery weight and cell weight.
Totalvehicleweight	Weight+Batteryweight = 1,68E4	Total vehicle weight in kg
Restofpackweight	Batteryweight*(1-weightofcellsinpack) = 69	weight in kg of BMS, cooling and packaging for the whole battery systems
Restofpackweightpercell	(1-Weightofcellsinpack)*cellweight/weightofcellsinpack = 87,1	weight in gram of BMS, cooling and packaging per cell weight
Recyclemass	Cellrecyclemass+Restofpackweightpercell*0,774 = 109	cell plus restinpack recycle mass in g per cell
Lossesduetobatteryweight	Batteryweight/(Weight+Batteryweight)*weightlossdep*gCO2perkWh = 1,66	gram CO2 per delivered kWh
Charginglosses	(1-Eff)*gCO2perkWh = 59,4	gram CO2 per delivered kWh
Cellproduction	Cellcarboncontent*1000/Delkwh = 111	gram CO2 per delivered kWh
Restofpackproduction	Restofpackweightpercell*Restofpackcarboncontent/DelkWh = 32,7	gram CO2 per delivered kWh
PropelconsumpCIperkm	Plugtowheel*gCO2perkWh = 726	gram CO2 per km from elec. Total used to propel the vehicle. Can be compared with EU-target 95 g CO2/km. BatteryweightCI & ChargingCI are part of PropelconsumpCI.
BatteryweightCIperkm	Lossesduetobatteryweight*Plugtowheel = 2,03	gram CO2 per km. Part of PropelconsumpCI
ChargingCIperkm	Charginglosses*Plugtowheel = 72,6	gram CO2 per km. Part of PropelconsumpCI
CellproductionCIperkm	Cellproduction*Plugtowheel = 136	gram CO2 per km.

Figure 6 Input parameters and calculated parameters in the LCA model reflecting base case for a 12.7 kWh battery for a bus

Design a battery of size of choice

By size is meant nominal battery capacity and the corresponding weight calculated as:

Battery capacity = Battcapnom = TotalNocells*Ahpercell*Voltage/1000

Batteryweight=Cellweight/1000*TotalNocells/Weightofcellsinpack

The Ahpercell, Voltage and Cellweight depend on the cell design and chemistry. By Voltage is meant cell voltage during discharge: for example 3.2 volt for the LFP cells used here.

The battery size 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 or row is decided by the desired system voltage divided by the cell voltage. For example, a 634 volt battery system requires 634/3.2 = 198 cells connected in series. To obtain a 12.7 kWh battery, four such rows of 198 cells (with 5 Ah in each cell) are required.

The model is built so that it allows to characterize a vehicle by giving its weight (without battery), its original plug-to-wheel electricity consumption, its system voltage, its relation between cell weight and battery weight. As mentioned above, in this report the use of a 12.7 kWh battery in a bus weighing 16600 kg, relation between cell weight and battery weight 0.559 and system voltage 634 volt represents both stationary and mobile application.

Vehicle electric range

The nominal electric range is calculated as:

Nominal range = Battcapnom/Battowheel

The nominal range assumes that the battery is discharged to 100%, which would negatively affect the life of any lithium ion battery. Thus the nominal range is not a very useful figure. Any range figure should be accompanied with information about assumed depth of discharge and calculated as:

RangeatSOC = BattcapatSOC/Battowheel= Battcapnom*Dischargedepth/ Battowheel

Where SOC means state of charge, i.e., depth of discharge or Dischargedepth and Battowheel is the battery-to-wheel electricity consumption defined as:

Battowheel=Plugtowheel*Eff

Where Eff is the batteries internal charge/discharge efficiency and Battowheel and Plugtowheel the batteries electricity consumption calculated in the chosen vehicle, see below.

Battery weight and vehicle electricity consumption

The battery weight is calculated as:

Batteryweight= Cellweight/1000*TotalNocells/Weightofcellsinpack

As mentioned above, the weight of the cell is given by the cell design and the cell chemistry and the number of cells is given by the desired storage capacity of the battery. The weight of cells in a battery pack is often around 50% of the total weight, i.e., the other parts make up roughly half the battery weight and are considered in the calculations by using data from (Ellingsen et al., 2013) where packaging is dominating (80%) while BMS and cooling system are approximately 10% each. The weight of the "other parts" is calculated as:

Restofpackweight=Batteryweight*(1-weightofcellsinpack)

The battery weight influences the electricity consumption. The plug-to-wheel electricity consumption with the new battery in the vehicle chosen is calculated as:

Plugtowheel= Oldplugtowheel*(1-Weightlossdep*(Originalbatteryweight-Batteryweight)/Weight)*0.9/Eff[5]

Where Oldplugtowheel, Originalbatteryweight and Weight is electricity consumption, battery weight and vehicle weight (excluding battery) of the vehicle for which the new battery is designed. Weightlossdep is a parameter that describes how the weight influences the energy consumption, set to 0.3 as a base case, i.e. assuming that 30% of vehicle energy use can be related to car mass (Zackrisson et al., 2014).

Cycles

The relationship between cycles and depth of discharged is calculated according to (Burzio and Parena, 2012) as:

Maximum number of cycles = 1331*Dischargedepth$^{-1.825}$

Parameters as temperature, C-rate, chemistry, cell size, ageing due to calendar life and longevity of discharged status are also important for the cycle life (Burzio and Parena, 2012). However, as can be seen, these parameters are not included in the formula above.

The table below shows some figures for the relation between depth of discharge and cycles and the influence on delivered kWh, range and service life for a 12.7 kWh nominal capacity battery. Henceforth rounded to 13 kWh.

Table 11 Relation between depth of discharge and cycles in a bus

Dischargedepth	Cycles	DelkWh	Range (km)	Service life (km)
1	1331	21.3	11.5	15300
0.9	1613	23.2	10.4	16700
0.8	2000	25.6	9.2	18400
0.7	2552	28.6	8.1	20600
0.6	3381	32.5	6.9	23400
0.5	4716	37.7	5.8	27200

Note that when the depth of discharge increases, the range increases while the delivered kWh and thus the service life decreases. The relationships are also shown in the figure below.

[5] The 0.9 originates from an assumption that the Oldplugtowheel is based on a charge/discharge efficiency equal to 0.9

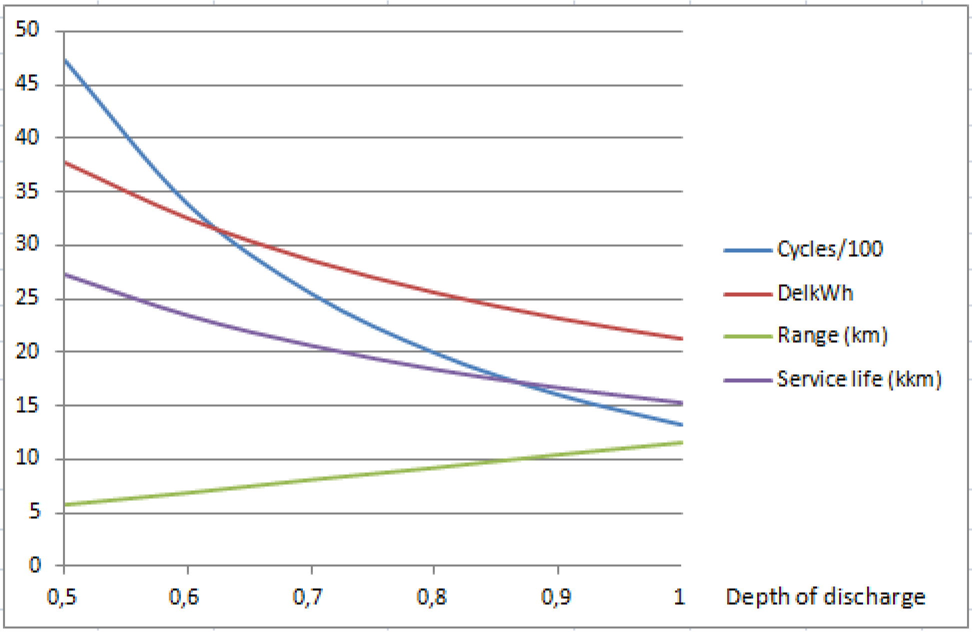

Figure 7 Relation between depth of discharge and cycles in a bus

Depth of discharge does however not affect cell weight nor electricity consumption as long as the size of the battery is not changed.

By DelkWh above is meant delivered kWh per cell during life cycle. The formula is:

Delkwh=Ahpercell*Voltage*Cycles*Dischargedepth/1000

Efficiency

The charge/discharge efficiency is as base case assumed to be 0.9. If the efficiency is lower than 0.9, the vehicle plug-to-wheel consumption and the environmental footprint associated with the electricity consumption will increase, but no other parameters will be affected. The effect on the propulsion carbon footprint in a bus is shown in the figure below.

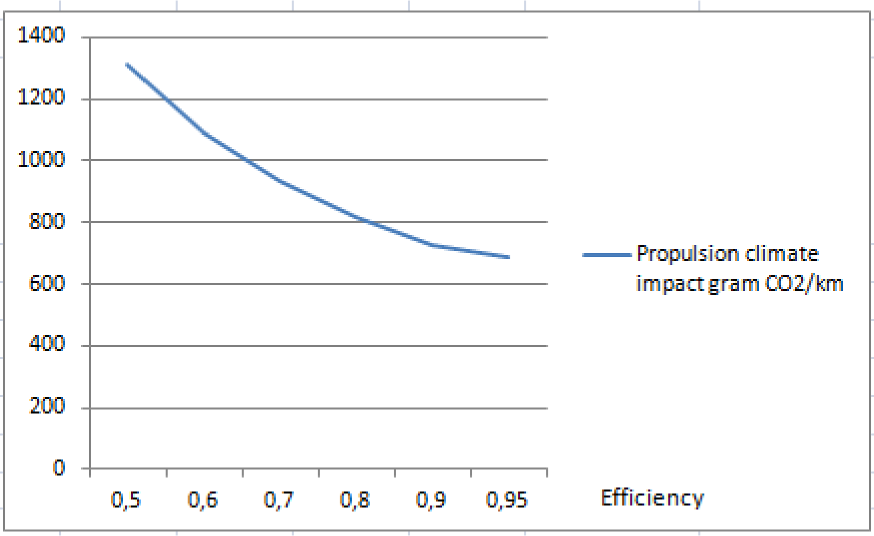

Figure 8 Propulsion climate impact as a function of efficiency in a bus (assuming European average electricity)

The figure above shows the importance of keeping the efficiency high.

Electricity

The climate impact is quite high when feeding the battery with average European electricity at 594 g CO_2/kWh. It is possible to calculate the use phase with average Swedish electricity at 53 g CO_2/kWh by changing the parameter Elsort. The use phase carbon footprint would then be around 10 times lower. It is also possible to change most of the electricity used for cell production between Swedish average mix and European average mix by changing the parameter Prodel. See the table below.

Table 12 Electricity mixes

Name of data set	Gram CO2-eq/kWh	Comment
Electricity, low voltage, production UCTE, at grid/UCTE S	594	Used for propulsion of vehicle. Simulates average global[6] use.
Electricity, low voltage {SE}| market for | Alloc Rec, S	53	Used for propulsion of vehicle. Simulates use in Sweden.
Electricity, high voltage, production UCTE, at grid/UCTE S	523	Used for production of cell. Simulates average global production.
Electricity, high voltage {SE}| market for | Alloc Rec, S	52	Used for production of cell. Simulates production in Sweden.

Note that coal based electricity generation, like in many Asian countries with battery cell production, has above 1000 gram CO2-eq/kWh.

[6] Average west European electricity mix is considered close to the average global electricity mix.

Results

The most important characteristics of the studied batteries are given in the table below.

Table 13 Important characteristics of studied batteries

Characteristic/Battery	*Triplite/LiPF6/pp*	*Tavorite/LiPF6/pp*
Battery capacity, kWh	13	13
Number of cells	792	792
Cell weight, g	110	110
Battery weight, kg	156	156
Energy density, Wh/kg	81	81

To differentiate the specific 5 Ah cells investigated in this report from other 5 Ah cells they are henceforth named the 5 Ah Triplite cell and 5 Ah Tavorite cell respectively.

Figure 9 and figure 10 shows that the distribution of environmental impact between life cycle phases is exactly the same for the functional units per delivered kWh and per vehicle kilometre. Furthermore, the figures show that the use phase losses due to cell weight is negligible, thus the model can also represent stationary application. Henceforth results will mainly be presented per delivered kWh for a 13 kWh bus battery during its life.

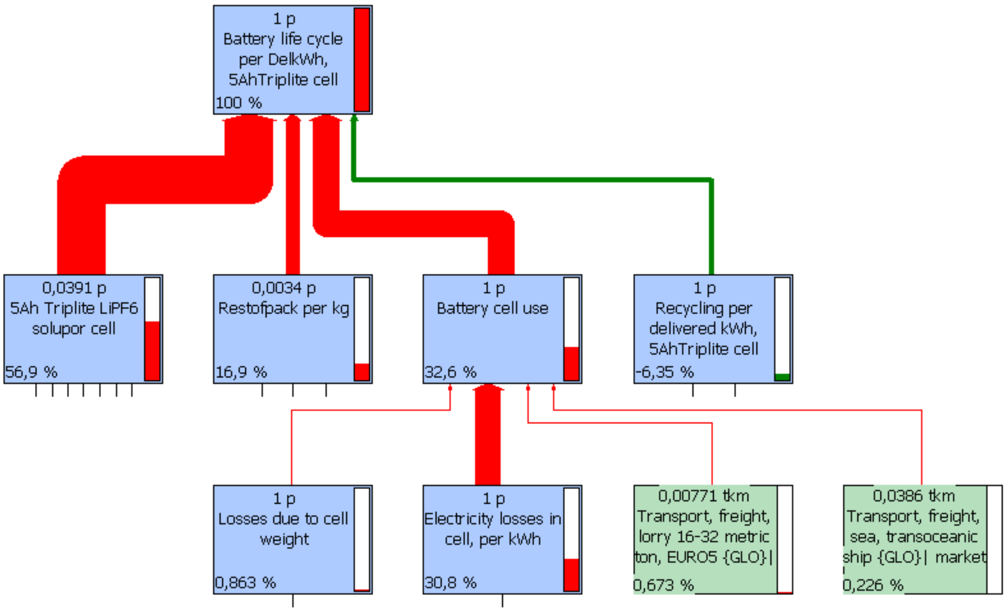

Figure 9 Relative climate impact per delivered kWh for 5AhTriplite battery in Volvo bus (13 kWh battery, European electricity for production and propulsion)

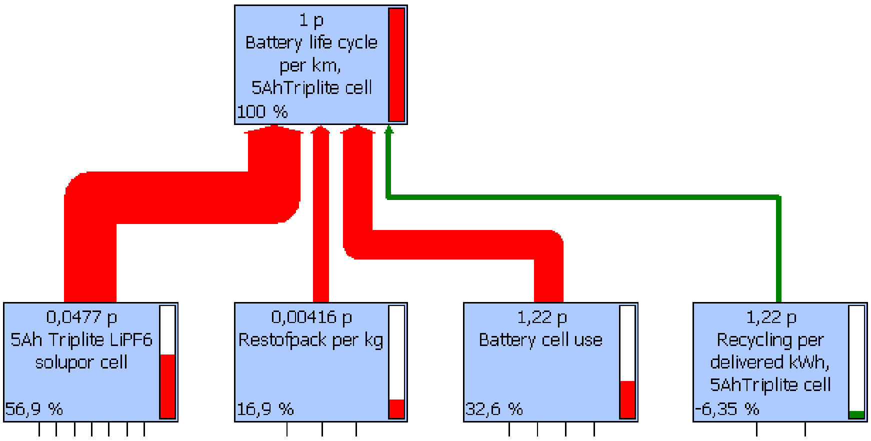

Figure 10 Relative climate impact per km for 5AhTriplite battery in Volvo bus (13 kWh battery, European electricity for production and propulsion)

Climate impacts

The figure below shows the life cycle climate impact calculated as emissions of carbon dioxide equivalents per delivered kWh for 5Ah Triplite cell in a 13 kWh bus battery. 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 110 g CO_2 equivalents per delivered kWh; most of it emanating from the assembly energy, the cathode and the anode. The rest of pack infers emissions of 40 of g CO_2 equivalents per delivered kWh. About 12 gram of this could possibly be avoided through recycling (green or minus means avoided emissions). Use phase impacts accredited to the battery are 63 g CO_2 equivalents per delivered kWh. The use phase impacts stem almost entirely from electricity losses in the battery as can be seen in Figure 9.

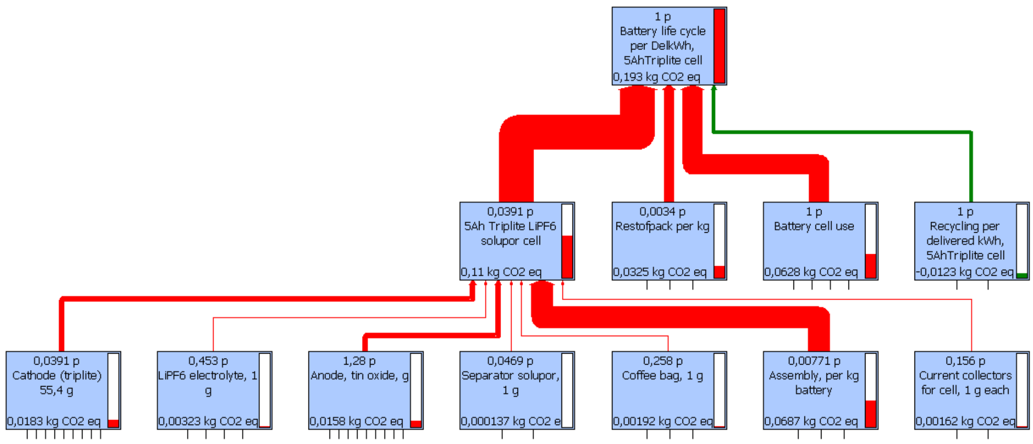

Figure 11 Climate impact per delivered kWh for 5AhTriplite battery in a Volvo bus (13 kWh battery, European electricity for production and propulsion)

As can be seen by comparing Figure 11 with Figure 12 below the Tavorite cell battery gives more than 100 g CO_2 equivalents more per delivered kWh, mostly due to more heat treatment.

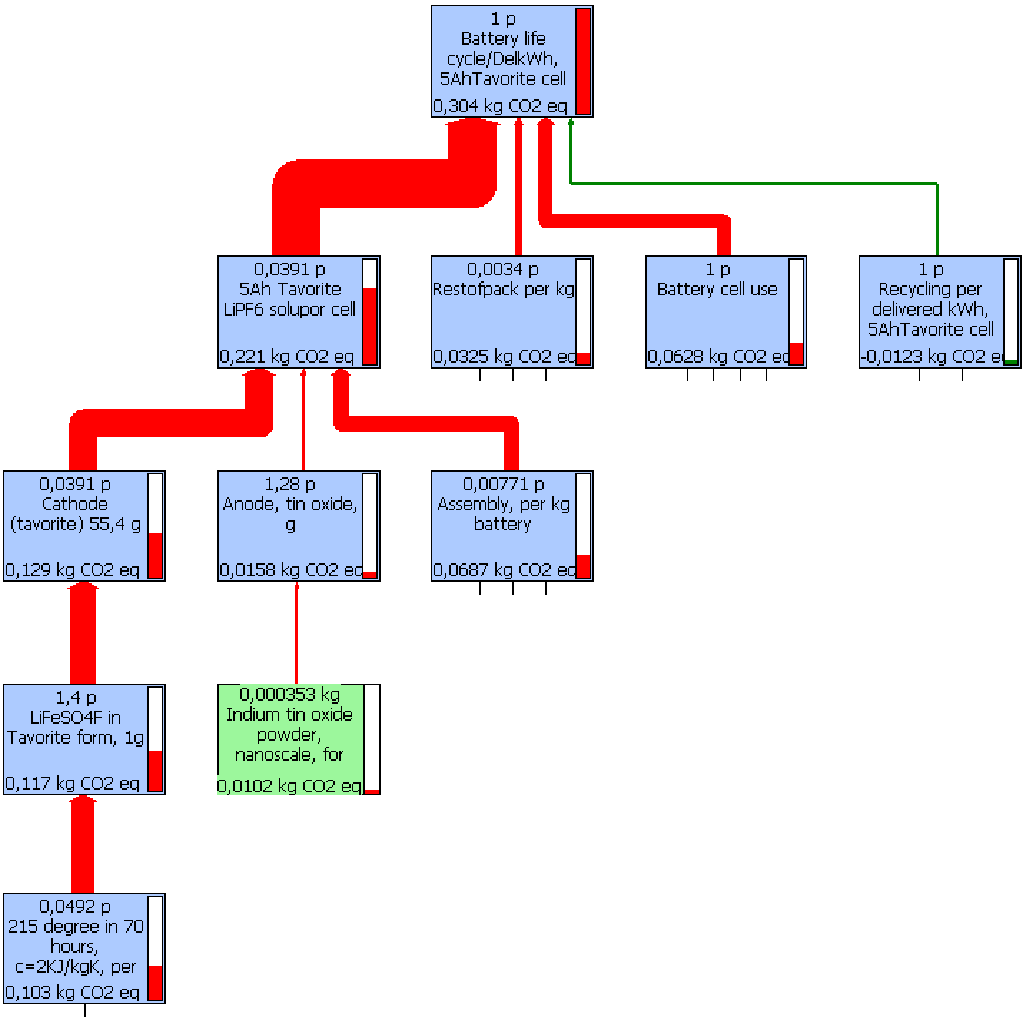

Figure 12 Climate impact per delivered kWh for 5AhTavorite battery in a Volvo bus (13 kWh battery, European electricity for production and propulsion)

The table below contains a summary of climate impact results for the Triplite and Tavorite battery investigated. It should be pointed out that the Climate impact per kWh nominal capacity and per kg battery has no use phase, but recycling is included and recycling credits around 4% are subtracted from the total score. Note also that the unit for Climate impact per kWh nominal capacity and Climate impact per kg battery is *kilogram* CO_2.

Table 14 Climate impact results for the Triplite and Tavorite battery

Characteristic/Battery	***Triplite/LiPF6/pp***	***Tavorite/LiPF6/pp***
Battery capacity, kWh	13	13

Characteristic/Battery	*Triplite/LiPF6/pp*	*Tavorite/LiPF6/pp*
Energy density, Wh/kg	81	81
Battery weight, kg	156	156
Climate impact per delivered kWh, g CO_2/kWh	193	304
Climate impact per vehicle km, g CO_2/km	236	371
Climate impact per kWh nominal capacity, kg CO_2/kWh	218	394
Climate impact per kg battery, kg CO_2/kg battery[7]	18	32

Abiotic depletion potential

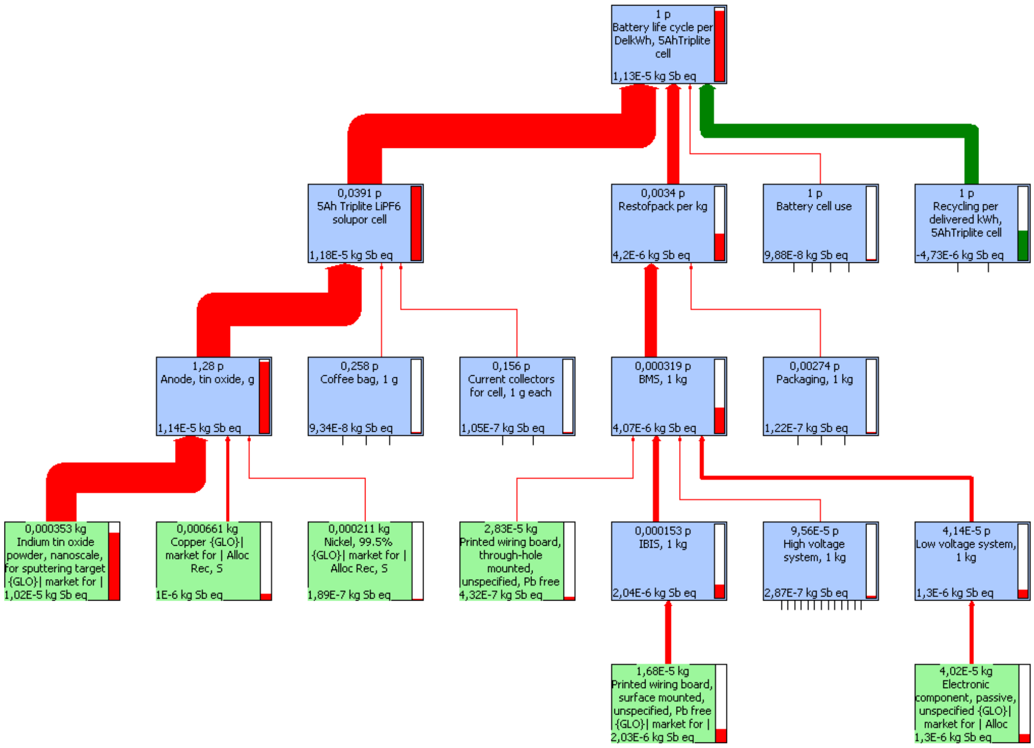

Figure 13 Abiotic depletion per delivered kWh for 5AhTriplite battery in a Volvo bus (13 kWh battery)

The figure above shows the abiotic depletion potential per delivered kWh expressed as kg Sb equivalents (kilogram antimony equivalents, Sb-eq). It can be seen that indium tin oxide in the anode dominates abiotic depletion. The main

[7] Climate impact per kWh nominal capacity multiplied with Energy density above

avoided impact through recycling also stem from indium tin oxide. Electronic components in the BMS also give dominant contributions. Since there is no difference in the anode between the Tavorite and the Triplite cell, the abiotic depletion is the same as can be seen in the figure below.

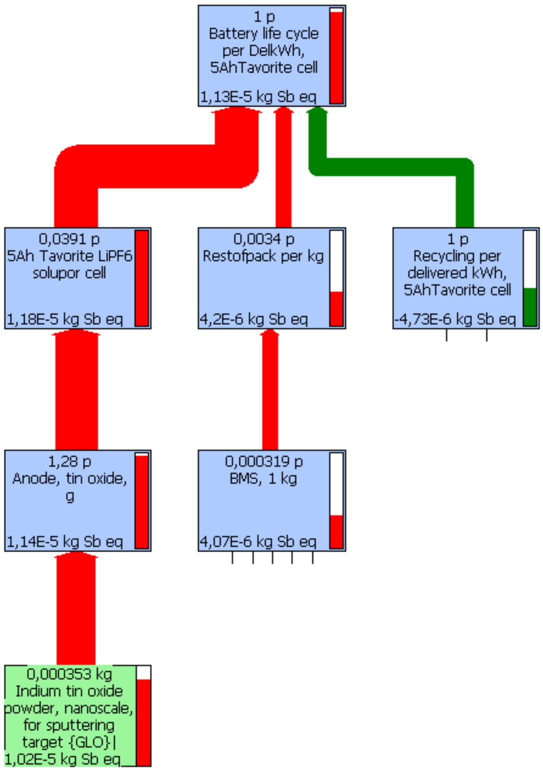

Figure 14 Abiotic depletion per delivered kWh for 5AhTavorite battery in a Volvo bus (13 kWh battery)

Toxicity

The figures below show freshwater and human toxicity per delivered kWh expressed as comparative toxic units, CTUe and CTUh.

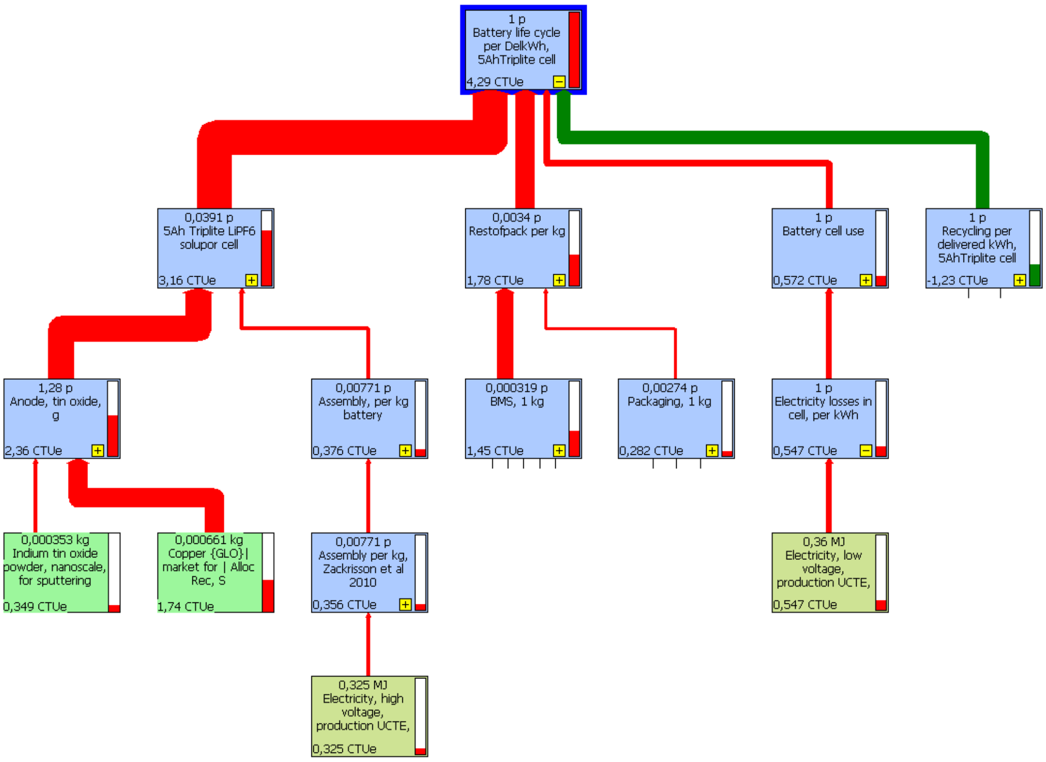

Figure 15   Freshwater ecotoxicity (CTUe) for 5AhTriplite

From Figure 15 and Figure 16 it can be seen that copper and electronics in the BMS dominates freshwater toxicity. The main avoided impact through recycling also stem from copper. Electricity and indium tin oxide also give considerable contributions to freshwater toxicity.

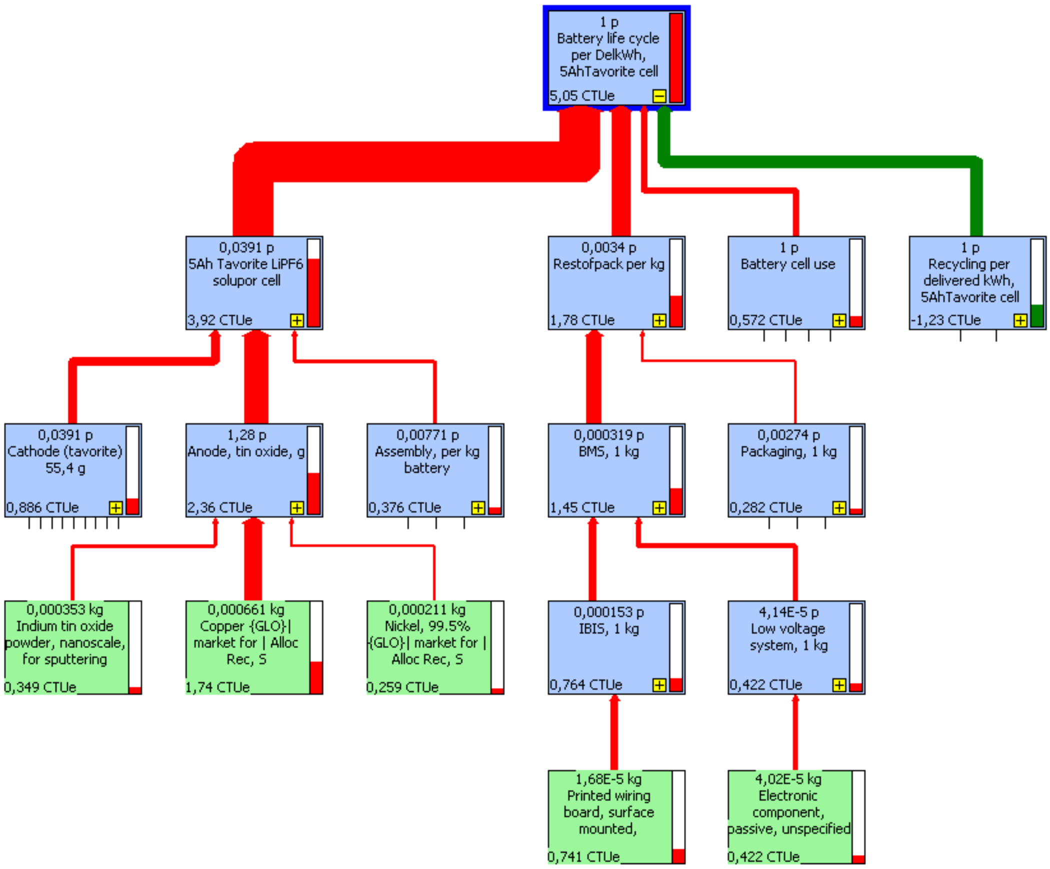

Figure 16 Freshwater ecotoxicity (CTUe) for 5AhTavorite

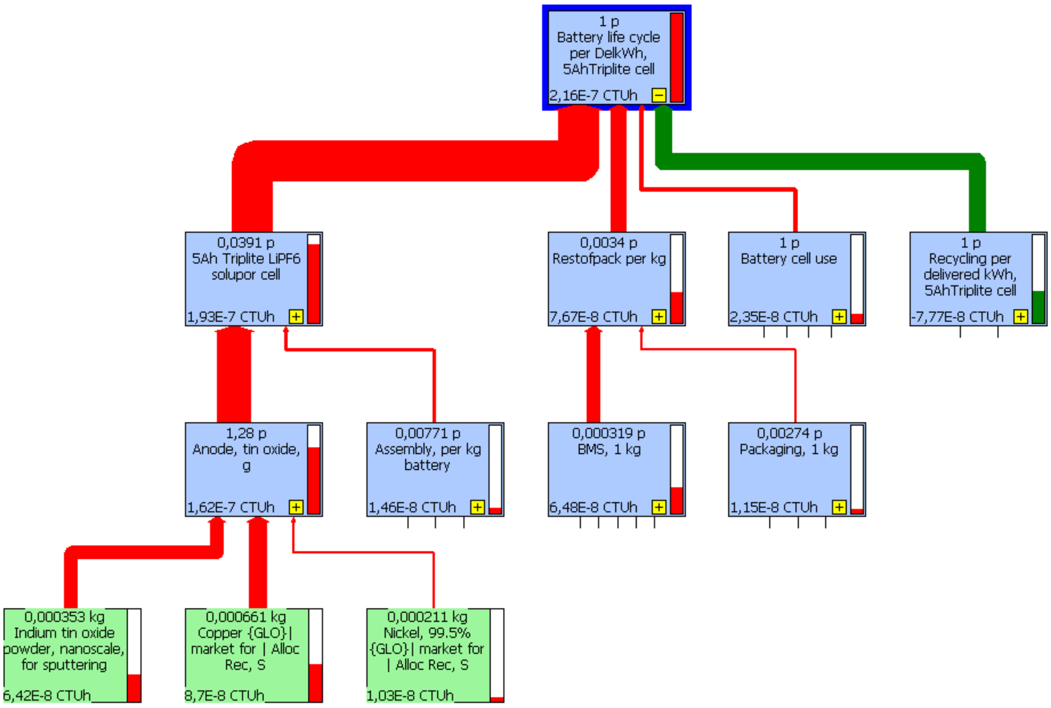

Figure 17   Human toxicity, non-cancer (CTUh) for 5AhTriplite

From Figure 17and Figure 18 it can be seen that copper, electronics in the BMS and indium tin oxide dominate human toxicity, non-cancer. The main avoided impact through recycling also stem from copper. Electricity is less dominant compared to freshwater toxicity and human toxicity cancer below.

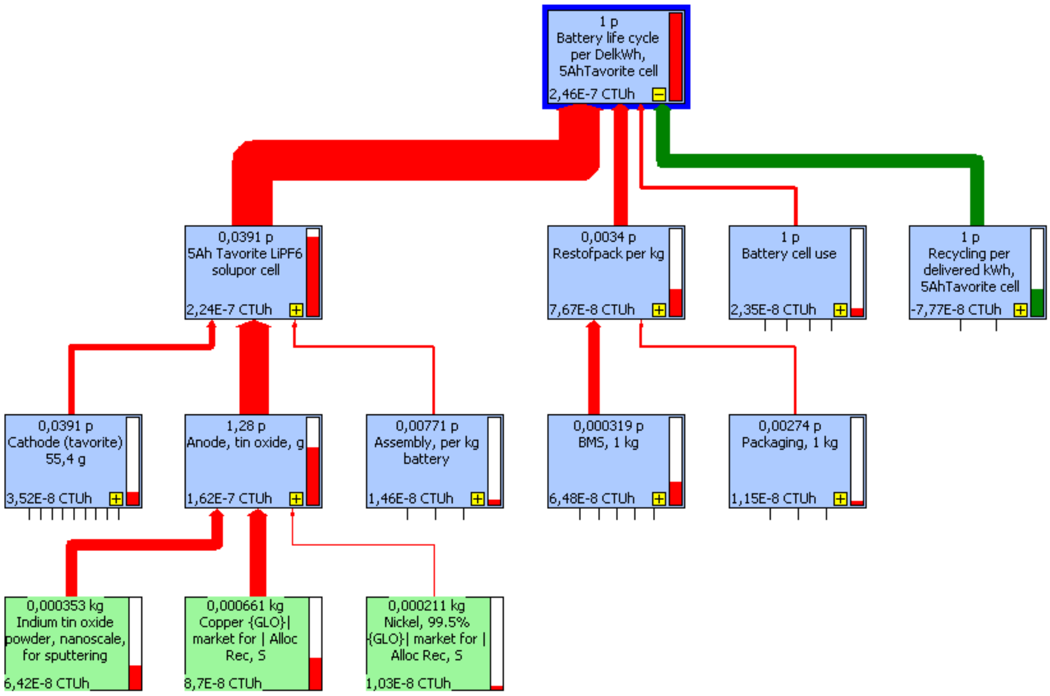

Figure 18 Human toxicity, non-cancer (CTUh) for 5AhTavorite

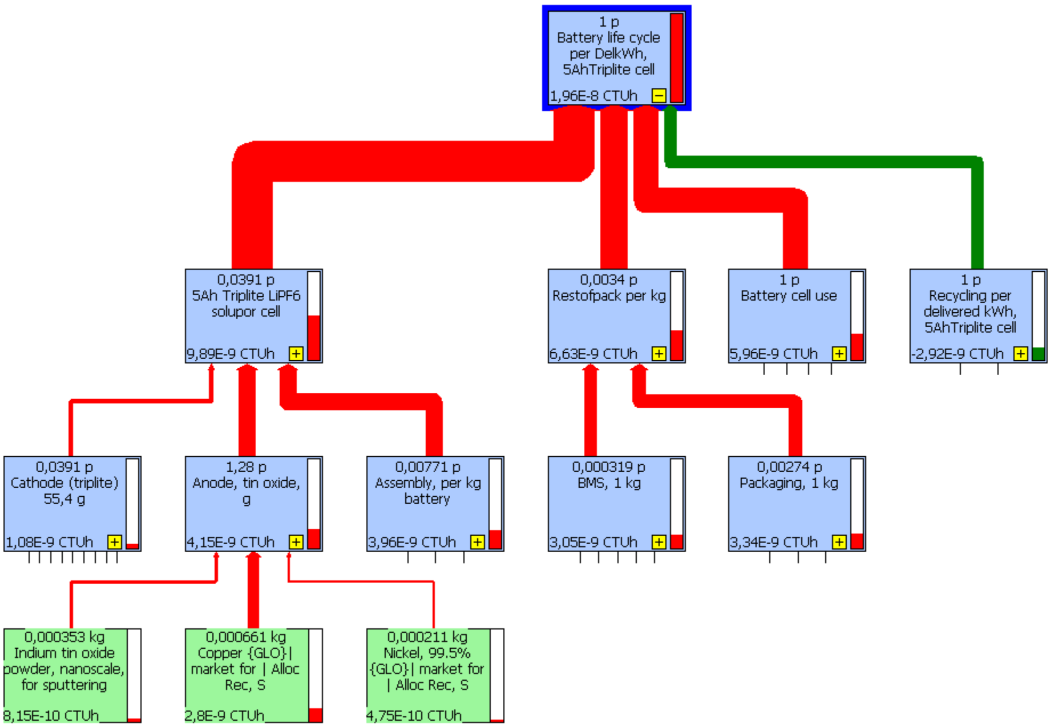

Figure 19 Human toxicity, cancer (CTUh) for 5AhTriplite

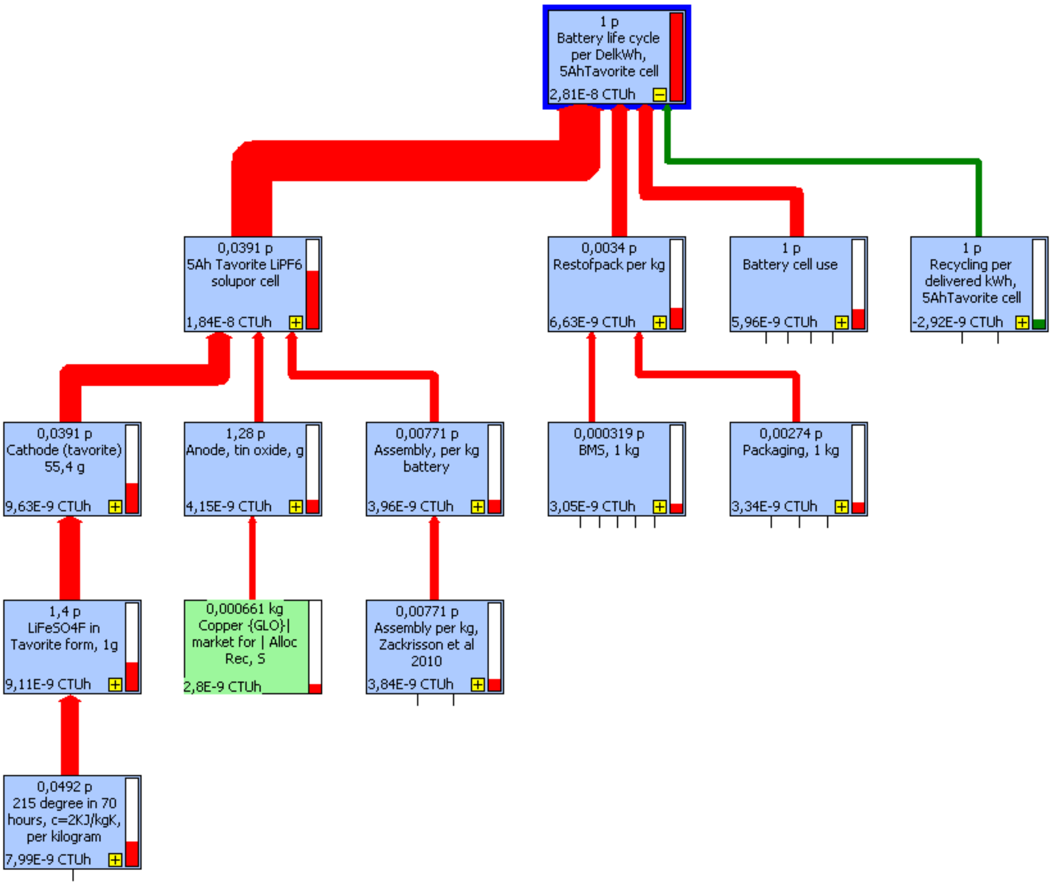

Figure 20   Human toxicity, cancer (CTUh) for 5AhTavorite

From Figure 19 and Figure 20 it can be seen that electricity, electronics in the BMS and copper dominates human toxicity cancer. Note that the CTUh is ten times lower than human toxicity non-cancer.

Sensitivity to electricity mix

The Tavorite cell gives more climate and toxicity impact through more heat treatment. Therefore it is interesting to investigate the battery cells produced with Swedish electricity instead of European electricity.

Table 15   Environmental impacts and influence of electricity mix for production

Characteristic/Battery	***Triplite European electricity mix***	***Triplite Swedish electricity mix***	***Tavorite European electricity mix***	***Tavorite Swedish electricity mix***
Battery capacity, kWh	13	13	13	13
Climate impact per delivered kWh, g CO_2/kWh	193	143	304	156
Abiotic depletion per delivered kWh, kg Sb_{eq}/kWh	1.1E-5	1.1E-5	1.13E-5	1.1E-5
Freshwater ecotoxicity per	4.29	3.98	5.05	4.14

Characteristic/Battery	*Triplite European electricity mix*	*Triplite Swedish electricity mix*	*Tavorite European electricity mix*	*Tavorite Swedish electricity mix*
delivered kWh, CTU_e/kWh				
Human toxicity, non-cancer per delivered kWh, CTU_h/kWh	2.16E-7	2.04E-7	2.46E-7	2.11E-7
Human toxicity, cancer per delivered kWh, CTU_h/kWh	1.96E-8	1.56E-8	2.81E-8	1.64E-8

As can be seen in the table and in the figures below there is hardly any difference in environmental impact between the Triplite and the Tavorite cell when Swedish average electricity is used for the production.

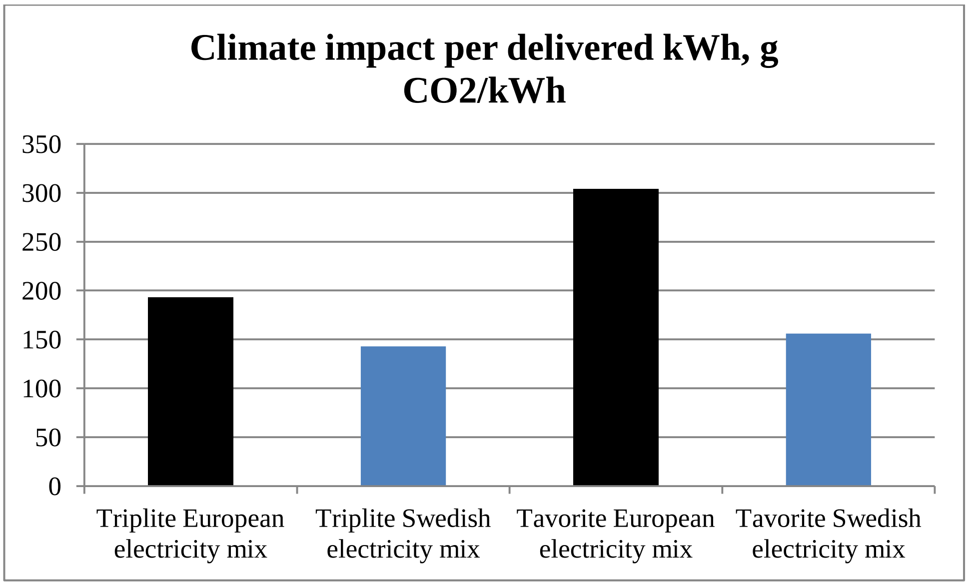

Figure 21 Climate impact per delivered kWh and influence of electricity mix for production

It can be noticed in the figure above that the difference in climate impact between Tavorite and Triplite cathodes is almost gone when the cells are produced with Swedish electricity mix.

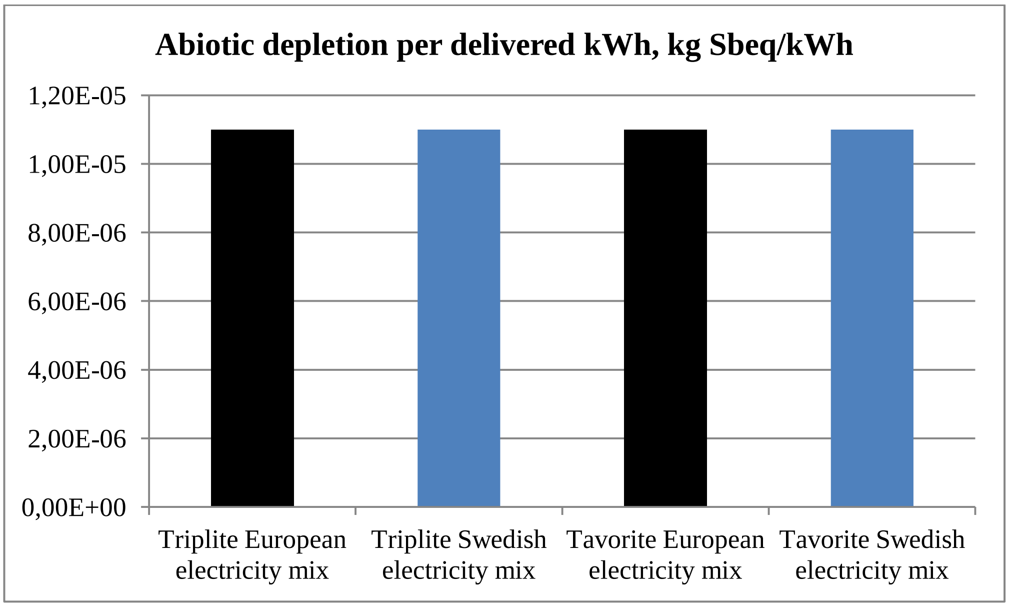

Figure 22 Abiotic depletion per delivered kWh and influence of electricity mix for production

The abiotic depletion is not affected at all by the choice of electricity mix for the production of the batteries as can be seen in the figure above.

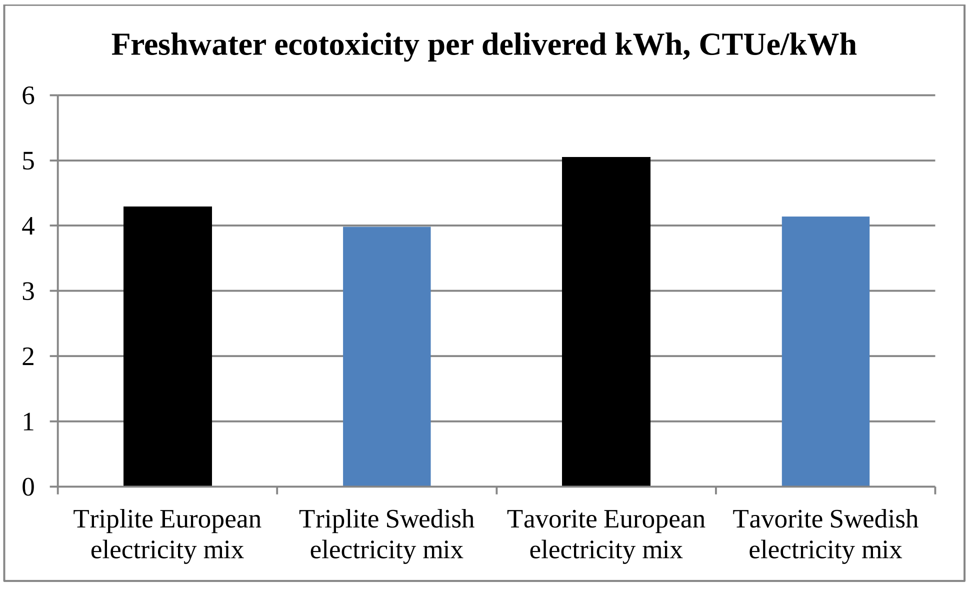

Figure 23 Freshwater ecotoxicity per delivered kWh and influence of electricity mix for production

The difference between the Tavorite and the Triplite cell in toxicity is less when Swedish electricity is used. The reason is that quite a lot of toxicity impact stem from electricity generation by burning of fossil fuels.

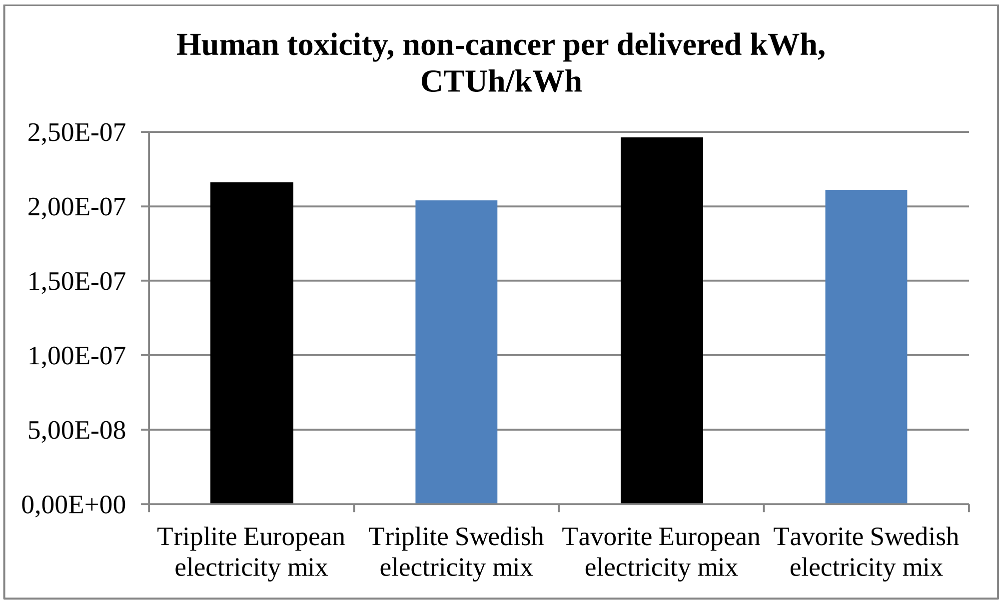

Figure 24 Human toxicity, non-cancer per delivered kWh and influence of electricity mix for production

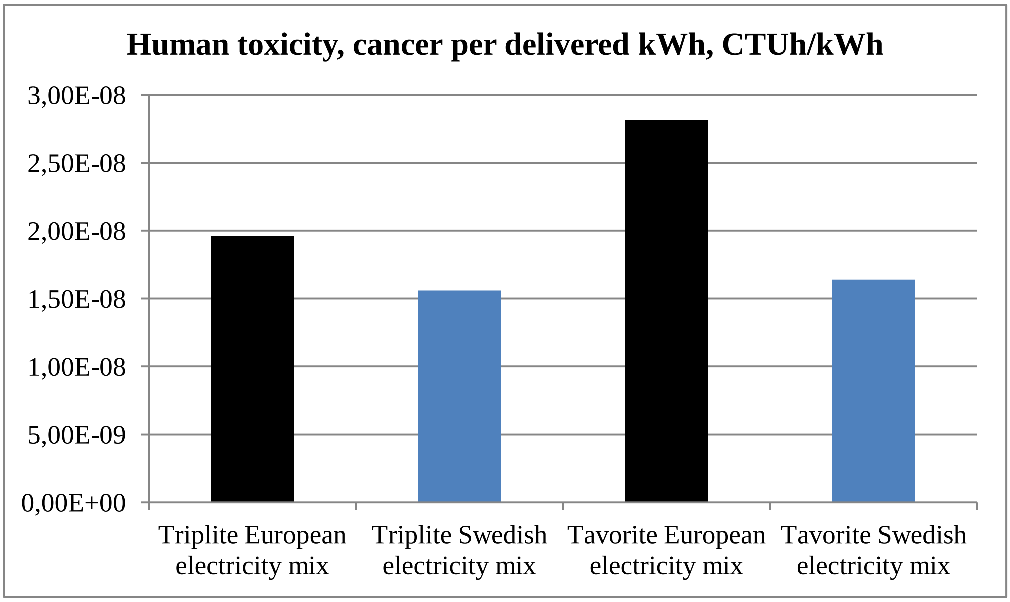

Figure 25 Human toxicity, cancer per delivered kWh and influence of electricity mix for production

Comparisons with other studies

In order to understand and interpret the LCA, results have been compared to three other studies. One of these studies involves two lithium-air cells at different levels of development.

Climate impact

Climate impact for the Triplite and Tavorite batteries are compared to three other lithium battery studies in the table below.

Table 16 Climate impact results from different battery studies

Characteristic/Battery	Triplite	Tavorite	PHEV[8]	Li-metal[9]	Li-air[10]	
					Achie-ved[11]	Long-term[12]
Battery capacity, kWh	13	13	10	76	4550	234
Energy density, Wh/kg	81	81	93	127	1350	5400
Battery weight, kg	156	156	107	599	3370	43
Climate impact per delivered kWh, g CO_2/kWh	193	304	183	152	1299	140
Climate impact per vehicle km, g CO_2/km	236	371	-	187	-	-
Climate impact per kWh nominal capacity, kg CO_2/kWh	218	394	267	159	-	-
Climate impact per kg battery, kg CO_2/kg battery[7]	18	32	25	20	-	-

The PHEV battery is a similar size battery (10 kWh and 107 kg compared to 13 kWh and 156 kg) with similar energy density (93 Wh/kg compared to 81 Wh/kg). It is not relevant to compare per km since the PHEV battery was applied in a light vehicle. The climate impact per delivered kWh is lower for the PHEV battery mainly because it was assumed that it would last 3000 cycles at 80% average depth of discharge, compared to 2000 cycles at 80% depth of discharge for Triplite and Tavorite calculated according to (Burzio and Parena, 2012). Climate impact per kWh nominal capacity and per kg battery for the PHEV battery is in between the Triplite and Tavorite battery.

The Li-metal battery is a much larger battery (76 kWh and 599 kg compared to 13 kWh and 156 kg) with higher energy density (127 Wh/kg compared to 81 Wh/kg) but designed for the same bus with the same assumption about cycle life and depth of discharge (Burzio and Parena, 2012). The energy density of the Li-metal battery is 59% higher than the Triplite battery, but the climate impact is only 21% lower both per delivered kWh and per km. The explanation is that the charge/recharge losses at 10% cause almost half the climate impact and the energy

[8] 10 kWh LFP battery for PHEV investigated in (M. Zackrisson et al., 2010)

[9] 76 kWh LFP battery with metallic lithium anode for Volvo bus investigated in (Zackrisson, 2017)

[10] Lithium air batteries investigated in (Zackrisson et al., 2016)

[11] Only 50 cycles at 20% depth of discharge and 66% efficiency achieved.

[12] 200 cycles at 80% depth of discharge and 80% efficiency feasible in the long-term.

density has little to do with those losses. Climate impact per kWh nominal capacity is lower for the Li-metal battery (since it contains more energy due to higher energy density) compared to the Triplite/Tavorite batteries. For the same reason (higher energy density in the Li-metal battery), the climate impact per kg battery is actually a little higher than in the Triplite battery.

The lithium air batteries are very different in size compared to each other (4550 kWh in 3370 kg at achievement level compared to 234 kWh in 43 kg at long term goal level) and also compared to the Triplite/Tavorite batteries with 13 kWh in 156 kg. The corresponding climate impact at achievement level 1299 g CO_2 per delivered kWh (most of it emanating from 33% electricity losses) reflects that the lithium air technology is still far from commercial reality, while the climate impact at long-term goal level 140 g CO_2 per delivered kWh indicates that lithium-air technology is an interesting future technology that is worth further pursuit. It is not relevant to compare per km since the lithium-air battery was calculated for a light vehicle. Climate impact per kWh nominal capacity and per kg battery were not available for the lithium-air batteries.

Abiotic depletion

Abiotic depletion for the Triplite and Tavorite batteries are compared to other lithium battery studies in the table below.

Table 17 Abiotic depletion results from different battery studies

Characteristic/Battery	**Triplite**	**Tavorite**	**Li-metal**[9]	**Li-air**[10]	
				Achie-ved[11]	**Long-term**[12]
Battery capacity, kWh	13	13	76	4550	234
Energy density, Wh/kg	81	81	127	1350	5400
Battery weight, kg	156	156	599	3370	43
Net abiotic depletion per delivered kWh, kg Sb_{eq}/kWh	1.1E-5	1.1E-5	2,9E-6	1.4E-6	5.3E-8
Recovered abiotic depletion by recycling per vehicle km, kg Sb_{eq}/km	-4.7E-6	-4.7E-6	-1,3E-7	-7.7E-7	-1E-8

The dominance of the indium tin oxide in the Triplite/Tavorite battery has no correspondance in the Li-metal battery in which electronics in the BMS dominate abiotic depletion. Recovery by recycling are around 4% of net abiotic depletion for both battery types.

For the lithium-air battery cells copper dominates abiotic depletion but at a lower level. Rest-of-pack including BMS electronics was not included in the analysis. Recovery by recycling are between 19-45% of net abiotic depletion for both achieved and long-term lithium-air cells (Zackrisson et al., 2016).

Toxicity

Toxicity, represented by freshwater toxicity, for the Triplite and Tavorite batteries are compared to other lithium battery studies in the table below.

Table 18 Freshwater toxicity results from different battery studies

Characteristic/Battery	**Triplite**	**Tavorite**	**Li-metal**[9]	**Li-air**[10]	
				Achieved[11]	**Long-term**[12]
Battery capacity, kWh	13	13	76	4550	234
Energy density, Wh/kg	81	81	127	1350	5400
Battery weight, kg	156	156	599	3370	43
Freshwater ecotoxicity per delivered kWh, CTU_e/kWh	4.31	5.19	2.23	3.1	0.2

The main reason that the Triplite and Tavorite batteries has higher toxicity score per delivered kWh is that they have quite a lot of copper in the anode. It should be emphasized that many metals, among them lithium, is missing from the USEtox method used to assess toxicity (Zackrisson et al., 2016). Toxicity results from LCA of lithium batteries should be interpreted with that in mind.

Discussions and conclusions

In order to model both stationary application and application in a heavy vehicle the functional unit per delivered kWh over the lifetime has been used. It was shown that the distribution of environmental impact between life cycle phases is exactly the same for this functional unit and the functional unit per vehicle kilometre which is the preferred one in vehicle contexts. Furthermore it was shown that heavy vehicle use phase losses due to cell weight is negligible, thus the “vehicle” model can also represent stationary application.

Looking at the whole life cycle of the Triplite/Tavorite cells, electricity use is the main driver of both climate impact and toxicity impacts, both in the production phase and in the use phase. Indium tin oxide in the anode dominates abiotic depletion followed by electronic components in the BMS. There is hardly any abiotic depletion in the use phase.

The possibilities to use existing cooling systems or do without cooling have not been evaluated. However, in this context the importance to maintain a high efficiency should be emphasized. Lowering of the charge/discharge efficiency is not a good idea since use phase electricity losses dominate both climate impacts and toxicity impacts.

Electricity for heat treatment in connection to the Tavorite cell increases the climate impact drastically but also toxicity impacts of this cell compared to the Triplite cell. Production in Sweden with Swedish carbon lean electricity would almost level out this difference between the Tavorite and Triplite cell.

The comparison with lithium-air cells reflects that the lithium air technology is still far from any form of commercial reality, while it indicates that lithium-air technology is an interesting future technology that is worth further pursuit.

Conclusions

In short, the study points towards the following conclusions:

- Production in Sweden is favourable due to that electricity is a main driver of climate impact and toxicity in the production phase.
- Electricity is a main driver of climate impact and toxicity also in the use phase which emphasizes the need to keep the charge/discharge efficiency high.
- Indium tin oxide in the anode dominates abiotic depletion.
- Comparison with lithium-air cells reflects that the lithium air technology is still far from commercial reality, while indicating that it is an interesting technology for the future.

List of acronyms and abbreviations

BMS	Battery Management System
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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