Life cycle assessment of long life lithium electrode for electric vehicle batteries
– cells for Leaf, Tesla and Volvo bus
2017-01-05
Mats Zackrisson
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Our highly qualified personnel based in Mölndal and Stockholm work in the fields of:

– Working life, environment and energy
– Industrial production methods
– Materials and technology development
– Polymers and textiles
– Business development and efficiency (streamlining).

We work with applied solutions to real industrial needs. Our industry-experienced researchers and consultants are able to deliver the fast and robust results that companies require in order to secure their competitiveness on the market.

Swerea IVF is a member of the Swerea Group, which comprises the Swerea parent company and five research companies’ with materials science and engineering technology as core activities: Swerea IVF, Swerea KIMAB, Swerea MEFOS, Swerea SICOMP and Swerea SWECAST. Swerea is jointly owned by industry through associations of owners and the Swedish state through RISE Holding AB.
Preface

This report contains a comparative life cycle assessment of several different 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. Helena Berg has carried out parallel economic analysis of the investigated batteries and been very helpful in providing data and developing the LCA model.

Jutta Hildenbrand at Swerea IVF has reviewed the report. In an earlier report of this project Life cycle assessment of long life lithium electrode for electric vehicle batteries – 5 Ah power cell focus is on a single cell chemistry and specification.
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Summary

This report contains a life cycle assessment of 10Ah lithium battery cells 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 cells have been analyzed from cradle to grave, i.e., from raw material production over own manufacturing, use in three different vehicles: Nissan Leaf, Tesla model S and a Volvo bus; 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 investigate environmental benefits with such lithium batteries in different vehicles. Battery cells with metallic lithium in the anode and LFP and NMC chemistry were compared to the original vehicle batteries. In short, the study points towards the following conclusions:

- Both the LFP and NMC lithium metal anode battery cells shows lower climate impact potential, lower abiotic depletion potential and lower toxicity potential than the original NMC and NCA cells with copper anodes. The main reason for the difference is higher energy density which gives lower weight and thus lower electricity consumption. However, the lower carbon footprint of the metal anode cells rests on the assumption that they last as many cycles as the original NMC and NCA, something which has not yet been proven.

- For the same reason (higher energy density) the NMC chemistry shows lower environmental impacts per vehicle kilometre than the LFP chemistry for the metal anode battery cells, but here the difference is much smaller and probably within error margins.

- Assembly energy is a main driver for climate impact. Sensitivity calculations with Swedish average electricity mix for production of the cells show that production impacts can be reduced by 25% by producing in Sweden, compared to global average production.
Introduction

This report contains a life cycle assessment, LCA, of lithium batteries in which battery cells with metallic lithium in the anode are compared to traditional lithium cells designs. 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 hybrid 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 et al., 2008). 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 have been reported (Håkansson, 2008), (AEA and Ireland, 2007). Provided that the grid electricity can be generated by renewable energy sources, considerable reductions of CO₂ 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 in close cooperation with Helena Berg at AB Libergreen and reviewed by Jutta Hildenbrand at Swerea IVF. Other 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 3.2 (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. 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**

This report concerns a life cycle assessment, LCA, of lithium batteries in which battery cells with metallic lithium in the anode are compared to traditional lithium cells designs with graphite/copper anodes. Data about the cell and battery configuration was decided by the TriLi 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
- 21 September 2016 at Ångström laboratory in Uppsala
- 23 November 2016 at Swerea IVF in Stockholm

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 data about vehicle weight and electricity consumption from tests or assumptions. 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 CO₂-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 IEA¹, 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. For buses the situation is of course different. However, in this study similar size batteries (with different chemistries) are

compared in the same size bus, thus the per kilometre unit works for relative comparisons between the “bus batteries”.

It should be noted that the 95 g CO₂-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. However, in this study results are presented as environmental impact per vehicle kilometre.

**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 battery itself and with the recycling of the battery materials. Note that the delimitation is the battery 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 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 an environmental impact below zero.

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.
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 neither 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 described below.

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, CO₂-eq. Europe’s emissions in 2005 corresponded to 11200 kg CO₂ 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 CO₂-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 and depletion 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.

It should be noted that earlier studies have shown that current methods for toxicity evaluation have considerable inadequacies related to metals and lithium in particular; among other 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 (Zackrisson et al., 2016a).

**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 by considering:

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

Modelling of the recycling was based on a literature survey. The LCA model is parameterized in order to enable easy adaption to different vehicle contexts and change of parameters such as depth of discharge, efficiency, electricity mix and other.

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2 This CML baseline method contained in SimaPro is also used to calculate the climate impacts.

3 Assumptions about vehicle weight and energy consumption are needed to model this.
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 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 cells are around 50% of the battery system for Leaf, Tesla and the Volvo bus, thus the battery systems consist of 50% cells, 40% packaging and 5% BMS and cooling system. The bills of materials of the studied cells are given in the tables below together with recycling estimations which are discussed later. The cells to be studied were selected on the basis of lowest cost for Nissan Leaf, Tesla model S and a Volvo bus, for each chemistry. They were chosen among 5, 10 and 40 Ah power and energy cells.

*Table 1  BOM-lists for 10 Ah LFP cells including recycling estimation*

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>10AhLFPenergy</th>
<th>10AhLFPpower</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weight (g)</td>
<td>Recycling (g)</td>
</tr>
<tr>
<td>Cathode</td>
<td>LiFePO₄</td>
<td>62.50</td>
<td>50</td>
</tr>
<tr>
<td>Cathode</td>
<td>PVDF</td>
<td>1.99</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Cathode</td>
<td>Carbon black</td>
<td>1.99</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Cathode</td>
<td>Aluminium foil</td>
<td>11.25</td>
<td>9.0</td>
</tr>
<tr>
<td>Anode</td>
<td>Lithium metal</td>
<td>6.68</td>
<td>5.3</td>
</tr>
<tr>
<td>Separator</td>
<td>Cladophora algae</td>
<td>8.80</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF₆ in EC:DEC:VC</td>
<td>22.28</td>
<td>14.85</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF₆ (11%)</td>
<td>2.47</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ethylene carbonate (48%)</td>
<td>10.70</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Diethyl carbonate (39%)</td>
<td>8.67</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Vinylene carbonate (2%)</td>
<td>0.44</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Housing</td>
<td></td>
<td>6.50</td>
<td>6.50</td>
</tr>
<tr>
<td>Housing</td>
<td>Aluminium (30%)</td>
<td>1.95</td>
<td>1.6</td>
</tr>
<tr>
<td>Housing</td>
<td>Polypropylene (30%)</td>
<td>1.95</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Housing</td>
<td>Nickel (40%)</td>
<td>2.60</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Total mass</strong></td>
<td></td>
<td><strong>122</strong></td>
<td><strong>68</strong></td>
</tr>
</tbody>
</table>

*Table 2  BOM-lists for 10 Ah NMC cells including recycling estimation*

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>10AhNMCenergy</th>
<th>10AhNMCpower</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weight (g)</td>
<td>Recycling (g)</td>
</tr>
</tbody>
</table>

9
### 10AhNMCenergy

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>Weight (g)</th>
<th>Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>NMC</td>
<td>55.6</td>
<td>44.4</td>
</tr>
<tr>
<td>Cathode</td>
<td>PVDF</td>
<td>1.8</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Cathode</td>
<td>Carbon black</td>
<td>1.8</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Cathode</td>
<td>Aluminium foil</td>
<td>10.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Anode</td>
<td>Lithium metal</td>
<td>5.9</td>
<td>4.7</td>
</tr>
<tr>
<td>Separator</td>
<td>Clodophora algae</td>
<td>7.8</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF$_6$ in EC:DEC:VC</td>
<td>19.8</td>
<td>13.2</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF$_6$ (11%)</td>
<td>2.2</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ethylene carbonate (48%)</td>
<td>9.5</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Diethyl carbonate (39%)</td>
<td>7.7</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Vinylene carbonate 2%</td>
<td>0.4</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Housing</td>
<td>6.5</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Housing</td>
<td>Aluminium (30%)</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Housing</td>
<td>Polypropylene (30%)</td>
<td>2.0</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Housing</td>
<td>Nickel (40%)</td>
<td>2.6</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Total mass (g)</strong></td>
<td><strong>109</strong></td>
<td><strong>61</strong></td>
<td><strong>134</strong></td>
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### 10AhNMCpower

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>Weight (g)</th>
<th>Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>NMC</td>
<td>55.6</td>
<td>44.4</td>
</tr>
<tr>
<td>Cathode</td>
<td>PVDF</td>
<td>1.8</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Cathode</td>
<td>Carbon black</td>
<td>1.8</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Cathode</td>
<td>Aluminium foil</td>
<td>10.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Anode</td>
<td>Lithium metal</td>
<td>5.9</td>
<td>4.7</td>
</tr>
<tr>
<td>Separator</td>
<td>Clodophora algae</td>
<td>7.8</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF$_6$ in EC:DEC:VC</td>
<td>19.8</td>
<td>13.2</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF$_6$ (11%)</td>
<td>2.2</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ethylene carbonate (48%)</td>
<td>9.5</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Diethyl carbonate (39%)</td>
<td>7.7</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Vinylene carbonate 2%</td>
<td>0.4</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Housing</td>
<td>6.5</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Housing</td>
<td>Aluminium (30%)</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Housing</td>
<td>Polypropylene (30%)</td>
<td>2.0</td>
<td>Incinerated</td>
</tr>
<tr>
<td>Housing</td>
<td>Nickel (40%)</td>
<td>2.6</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Total mass (g)</strong></td>
<td><strong>109</strong></td>
<td><strong>61</strong></td>
<td><strong>134</strong></td>
</tr>
</tbody>
</table>

The BOM-list for the original 33 Ah Nissan Leaf NMC cell was constructed by using data from (Ellingsen et al., 2013) for a smaller NMC cell (20 Ah) and scaling it to a 33 Ah cell by distributing the known total weight of the 33 Ah cell in the same proportions as the 20 Ah cell. The results are shown in the table below.

**Table 3**  
*BOM-list for 33 Ah Leaf original NMC cell (from AESC) including recycling estimation*

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>Ellingsen %</th>
<th>Leaf original %</th>
<th>Weight (g)</th>
<th>Recycling (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>NMC</td>
<td>35.84</td>
<td>286.7</td>
<td>229.4</td>
<td></td>
</tr>
<tr>
<td>Cathode</td>
<td>PVDF</td>
<td>1.41</td>
<td>11.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathode</td>
<td>Carbon black</td>
<td>0.71</td>
<td>5.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathode</td>
<td>Aluminium foil</td>
<td>4.91</td>
<td>39.3</td>
<td>31.4</td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>Copper</td>
<td>22.25</td>
<td>178.0</td>
<td>142.4</td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>Graphite</td>
<td>15.71</td>
<td>125.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>CMC</td>
<td>0.33</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>PAA</td>
<td>0.33</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separator</td>
<td>PP separator</td>
<td>2.16</td>
<td>17.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF$_6$ in EC:DEC:VC</td>
<td>15.71</td>
<td>125.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>LiPF$_6$ (11%)</td>
<td></td>
<td>13.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ethylene carbonate (48%)</td>
<td></td>
<td>60.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Diethyl carbonate (39%)</td>
<td></td>
<td>49.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Vinylene carbonate 2%</td>
<td></td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Housing</td>
<td>0.65</td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Housing</td>
<td>Aluminium (30%)</td>
<td>1.6</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Housing</td>
<td>Polypropylene (30%)</td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The BOM-lists for the original 3.1 Ah Tesla NCA cell was constructed by using data from (Bauer, 2010) for a NCA cell (20 Ah) and scaling it to a 3.1 Ah cell by distributing the known total weight of the 3.1 Ah cell in the same proportions as the 20 Ah cell. The results are shown in the table below. The 20 Ah NCA cell modelled by Bauer was a pouch cell while the Tesla cell has a cylindrical shell, assumed to be in aluminium.

Table 4  BOM-list for 3.1 Ah Tesla original NCA cell (NCR18650A from Panasonic) including recycling estimation

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>Bauer</th>
<th>Tesla original</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>%</td>
<td>Weight (g)</td>
</tr>
<tr>
<td>Housing</td>
<td>Nickel (40%)</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Total mass (g)</td>
<td></td>
<td>100</td>
<td>800</td>
</tr>
</tbody>
</table>

The BOM-lists for the original 30 Ah NCA cell for the Volvo bus was constructed by using data from (Bauer, 2010) for a NCA cell (20 Ah) and scaling it to a 30 Ah cell by distributing the known total weight of the 30 Ah cell in the same proportions as the 20 Ah cell. The results are shown in the table below. The 20 Ah NCA cell modelled by Bauer was a pouch cell while the Volvo bus cell has a cylindrical shell, assumed to be in aluminium.

Table 5  BOM-list for 30 Ah Volvo bus original NCA cell (VL30P from SAFT) including recycling estimation

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>Bauer</th>
<th>Volvo bus original</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>%</td>
<td>Weight (g)</td>
</tr>
<tr>
<td>Cathode</td>
<td>NCA</td>
<td>26</td>
<td>290.7</td>
</tr>
<tr>
<td>Cathode</td>
<td>Aluminium foil</td>
<td>7</td>
<td>78.8</td>
</tr>
<tr>
<td>Binder</td>
<td>PVDF</td>
<td>7</td>
<td>78.3</td>
</tr>
<tr>
<td>Anode</td>
<td>Copper</td>
<td>14</td>
<td>156.8</td>
</tr>
<tr>
<td>Anode</td>
<td>Graphite</td>
<td>19</td>
<td>207.0</td>
</tr>
<tr>
<td>Connection</td>
<td>Nickel</td>
<td>0</td>
<td>2.7</td>
</tr>
</tbody>
</table>
LFP cathode

The cathode is made of LiFePO₄, 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 CO₂ 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 LiFePO₄ 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 LiFePO₄

LiCO₃, lithium carbonate, is used to make LiFePO₄. A molar calculation yields:

- 73.8 g Li₂CO₃ + 159.6 g Fe₂O₃ + 133 g (NH₄)₂HPO₄ -> 158 g LiFePO₄. 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 from room temperature. 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 for one gram of material. In addition, the reactions require some energy and there would be heat losses, so in total 3 kJ electricity/g LiFePO₄ was assumed.

NMC cathode

The NMC cathodes are made of Li(Ni0.3Co0.3Mn0.3(O2)), a polyvinyliden fluoride (PVDF) binder and carbon black in a slurry mixed with the solvent N-Methyl-2-pyrrolidone (NMP) which is spread on an aluminium foil, in a process very similar to LFP cathode manufacturing, see above. The solvent NMP is dried of. LCA data for Li(Ni0.3Co0.3Mn0.3(O2)) from (Ellingsen et al., 2013) was used, but adapted to Ecoinvent 3.2.
**NCA cathode**

The NCA cathodes are made of LiNi$_{0.8}$Co$_{0.15}$Al$_{0.05}$O$_2$, a polyvinyliden fluoride (PVDF) binder and carbon black in a slurry mixed with the solvent N-Methyl-2-pyrrolidone (NMP) which is spread on an aluminium foil, in a process very similar to LFP and NMC cathode manufacturing, see above. The solvent NMP is dried off. LCA data for NCA from (Bauer, 2010) was used, but adapted to Ecoinvent 3.2.

**Anodes**

The metallic lithium anodes are 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 59 kg CO$_2$-eq/kg. Lithium is produced by electrolysis of lithium chloride. In a Lithium ion battery cell the lithium involved in the charge/discharge is from the LFP and NMC cathode respectively 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 30 µm lithium foil was needed. This is more lithium than is actually needed for the function of the cell, but the thickness of commercially available Li-foils sets a limit today among other factors.

The more traditional anodes, for the original battery cells, were made of graphite spread on copper with polymer binders.

**Separators**

The separator is made of 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. The Cladophora species are also very common on Swedish coasts. Alternatively, a 100% polyethylene separator Solupor (Lydall, 2014) could be used. In the LCA-calculations it is represented by processes shown in the table below.

**Table 6 Separators**

<table>
<thead>
<tr>
<th>Separator materials</th>
<th>LCA process name</th>
<th>Description and comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose, Cladophora algae</td>
<td>Lime (FR)</td>
<td>production, algae</td>
</tr>
</tbody>
</table>

---

4 In the database update from Ecoinvent 3.1 to Ecoinvent 3.2 it was changed from 167 to 59 kg CO$_2$-eq/kg.
Separator materials | LCA process name | Description and comment
---|---|---
| 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.
Solupor | 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 thermoforming process contains the auxillaries and energy demand for the mentioned conversion 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

**Cell packaging**

Cell packaging was calculated from the coffee bag size (area) needed. So called coffee bags have a density of 0.0141 g/cm² and consist of 30% aluminium, 30% of polypropylene and 40% nickel.

**Electrolytes**

The electrolyte is a 1-molar solution of LiPF₆ 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. LiPF₆ 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 not all toxicological properties have been fully investigated (Fisher Scientific, 2015).

DEC can be made by reacting phosgene with ethanol, producing hydrogen chloride as a byproduct⁵:

\[
2\text{CH}_3\text{CH}_2\text{OH} + \text{COCl}_2 \rightarrow \text{OC(OCH}_2\text{CH}_3)_2 + 2\text{HCl}
\]

By molar calculation, to get 1 g of OC(OCH₂CH₃)₂ requires 92/118 g of 2CH₃CH₂OH and 99/118 gram of COCl₂.

**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 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 7  
Materials content and recycling of 1kg BMS, packaging and cooling

<table>
<thead>
<tr>
<th>Process</th>
<th>Weight (g)</th>
<th>BMS</th>
<th>P</th>
<th>C</th>
<th>Recycling rate</th>
<th>Rec. mass (g)</th>
<th>Avoided process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium sheet EAA00</td>
<td>379</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>80% recycled</td>
<td>304</td>
<td>Aluminium sheet EAA00</td>
</tr>
<tr>
<td>Steel, low-alloyed (GLO) market for Alloc Rec, S</td>
<td>330</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>80% recycled</td>
<td>264</td>
<td>Steel, low-alloyed (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Nylon 6-6, glass-filled (GLO) market for Alloc Rec, S</td>
<td>135</td>
<td>X</td>
<td></td>
<td></td>
<td>80% recycled</td>
<td>108</td>
<td>Nylon 6-6, glass-filled (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Polypropylene, granulate (GLO) market for Alloc Rec, S</td>
<td>54</td>
<td>X</td>
<td></td>
<td></td>
<td>80% recycled</td>
<td>43</td>
<td>Polypropylene, granulate (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Copper (GLO) market for Alloc Rec, S</td>
<td>19</td>
<td>X</td>
<td>X</td>
<td></td>
<td>80% recycled</td>
<td>15</td>
<td>Copper (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Acrylonitrile-butadiene-styrene copolymer (GLO) market for Alloc Rec, S</td>
<td>17</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>80% recycled</td>
<td>14</td>
<td>Acrylonitrile-butadiene-styrene copolymer (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Cable, ribbon cable, 20-pin, with plugs (GLO) market for Alloc Rec, S</td>
<td>13</td>
<td>X</td>
<td></td>
<td></td>
<td>80% recycled</td>
<td>2</td>
<td>Copper (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Ethylene glycol (GLO) market for Alloc Rec, S</td>
<td>4.8</td>
<td>X</td>
<td></td>
<td></td>
<td>80% recycled</td>
<td>4</td>
<td>Ethylene glycol (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Electronic component, passive, unspecified (GLO) market for Alloc Rec, S</td>
<td>12</td>
<td>X</td>
<td></td>
<td></td>
<td>Electronics</td>
<td>9</td>
<td>Copper (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Printed wiring board, through-hole mounted, unspecified, Pb free (GLO) market for Alloc Rec, S</td>
<td>8.3</td>
<td>X</td>
<td></td>
<td></td>
<td>Electronics</td>
<td>7</td>
<td>Copper (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Printed wiring board, surface mounted, unspecified, Pb free (GLO) market for Alloc Rec, S</td>
<td>4.9</td>
<td>X</td>
<td></td>
<td></td>
<td>Electronics</td>
<td>4</td>
<td>Copper (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Electric connector, wire clamp (GLO) market for Alloc Rec, S</td>
<td>0.94</td>
<td>X</td>
<td></td>
<td></td>
<td>Electronics</td>
<td>1</td>
<td>Copper (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Integrated circuit, logic type (GLO) market for Alloc Rec, S</td>
<td>0.000</td>
<td>1</td>
<td></td>
<td></td>
<td>Electronics</td>
<td>0.001</td>
<td>Copper (GLO) market for Alloc Rec, S</td>
</tr>
<tr>
<td>Synthetic rubber (GLO) market for Alloc Rec, S</td>
<td>9.0</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Incinerated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nylon 6 (GLO) market for Alloc Rec, S</td>
<td>2.0</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Incinerated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene terephthalate, granulate, amorphous (GLO) market for Alloc Rec, S</td>
<td>1.9</td>
<td>X</td>
<td></td>
<td></td>
<td>Incinerated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nylon 6-6 (GLO) market for</td>
<td>1.6</td>
<td>X</td>
<td></td>
<td></td>
<td>Inciner-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6 P=Packaging, C=Cooling system
<table>
<thead>
<tr>
<th>Process</th>
<th>Weight (g)</th>
<th>BMS</th>
<th>Recycle rate</th>
<th>Rec. mass (g)</th>
<th>Avoided process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloc Rec, S</td>
<td>0.90</td>
<td>X</td>
<td></td>
<td></td>
<td>rated</td>
</tr>
<tr>
<td>Polyphenylene sulfide (GLO) market for Alloc Rec, S</td>
<td>0.60</td>
<td>X</td>
<td></td>
<td></td>
<td>Incinerated</td>
</tr>
<tr>
<td>Tin (GLO) market for Alloc Rec, S</td>
<td>0.45</td>
<td>X</td>
<td></td>
<td></td>
<td>Incinerated</td>
</tr>
<tr>
<td>Brass (GLO) market for Alloc Rec, S</td>
<td>0.26</td>
<td>X</td>
<td></td>
<td></td>
<td>Incinerated</td>
</tr>
<tr>
<td>Glass fibre (RER) production Alloc Rec, S</td>
<td>0.20</td>
<td>X</td>
<td></td>
<td></td>
<td>Incinerated</td>
</tr>
<tr>
<td>Butyl acrylate (RER) production Alloc Rec, S</td>
<td>0.10</td>
<td>X</td>
<td></td>
<td></td>
<td>Incinerated</td>
</tr>
<tr>
<td>Polyvinylchloride, bulk polymerised (GLO) market for Alloc Rec, S</td>
<td>0.07</td>
<td>X</td>
<td></td>
<td></td>
<td>Incinerated</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1000</td>
<td></td>
<td></td>
<td>774</td>
<td></td>
</tr>
</tbody>
</table>

**Battery management systems, BMS**

The BMS is modelled according to (Ellingsen et al., 2013) and Table 7. 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.

![Battery management systems](image)

**Figure 2**   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 7. 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.

![Battery packaging carbon footprint](image)

**Figure 3** 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 7. 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.
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 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), (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 model of the cells in this report should mimic industrial production, thus the 74 MJ/kg battery figure is used as a base case.

Transports
The following assumptions were made about transport of materials and components in connection to lithium cell 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

Figure 4  Carbon footprint results LCA processes used for model of cooling system
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 and do not select a local production. These transports are included in the model for the Use phase.

Transports related to recycling are presented below.

**Cycling**

Production related environmental impacts, modelled as described above, are calculated per km and per delivered kWh by assuming that the maximum number of cycles can be calculated (Burzio and Parena, 2012) as:

\[
\text{Maximum number of cycles} = 1331 \times \text{Dischargedepth}^{-1.825}
\]

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). Note that when the depth of discharge increases the range increases while the delivered kWh and thus the service life decreases. Since the production related impacts are calculated per km or per delivered kWh, discharge depth 0.8 is used as an average base case setting. Discharge depth 0.8 corresponds to 2000 cycles.

**Use phase**

The use phase was modelled as the electricity losses in the battery during the lifetime 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 use phase losses are part of the total propulsion impacts that stems from the plug-to-wheel electricity consumption.

**Extra power demands to accommodate battery mass**

In order to calculate the extra power demands needed to carry the battery mass ($M_{\text{batt}}$), 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 ($M_{\text{vehicle}}$). The total weight of the battery is around double the weight of the cells based on figures for Leaf and Tesla current packs\(^7\). This parameter can be changed. The other parts 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 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

---

\(^7\) 0.522 for Leaf and 0.517 for Model S
power was calculated as: \(0.3 \times \frac{M_{\text{batt}}}{M_{\text{vehicle}} + M_{\text{batt}}}\). 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, \(\eta\), is defined as the relation between battery cell energy output and input \(\frac{W_{\text{battery to wheel}}}{W_{\text{plug to wheel}}}\). 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 \(\eta\), the losses per km are proportional to \((1 - \eta)/\eta\).

**Use phase electricity**

The use phase electricity is as a base case equal to average Western European electricity mix. It can, for the use phase, easily be changed to Swedish average electricity mix by changing the parameter Elsort. See page 45 for further information about sensitivity to different electricity mixes.

**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 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 completed 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 by (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 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\(^8\) 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 and Table 2 below show the resulting recycled mass for a 10 Ah LFP energy cell, a 10 Ah LFP power cell, a 10Ah NMC energy cell and a 10 Ah NMC power cell. Table 3, Table 4, Table 5 and Table 7 show the resulting recycled mass from the other cell chemistries and the rest of the 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

\(^8\) 80% recycling efficiency includes also collection rate which cannot be assumed to be 100%
o Recycling processes are defined as the environmental impacts from the involved recycling processes and treatment processes

o 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 design and test of a battery in a vehicle context. Below is a list of the parameters used. Parameter settings in the figure reflect TriLi ambitions and base case for a 10 Ah LFP energy cell designed for a Nissan Leaf.
Design a battery for your vehicle

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 and then design a battery for it of a size of choice. By size is meant nominal battery capacity and the corresponding weight calculated as:

\[
\text{Battery capacity} = \text{Battcapnom} = \frac{\text{TotalNocells} \times \text{Ahpercell} \times \text{Voltage}}{1000}
\]
Batteryweight=Cellweight/1000*TotalNocells/Weightofcellsinpack

The Ah per cell, Voltage and Cell weight depend on the cell design and chemistry. By Voltage is meant cell voltage during discharge: for example 3.4 volt for LFP and 4.0 volt for NMC with lithium metal anodes.

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 360 volt battery system requires 360/3.4 = 106 cells connected in series. To obtain a 25 kWh battery, seven such rows of 106 LFP cells (with 10 Ah in each cell) are required.

Range

The nominal range is calculated as:

\[
\text{Nominal range} = \frac{\text{Battcapnom}}{\text{Battowheel}}
\]

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:

\[
\text{RangeatSOC} = \frac{\text{BattcapatSOC}}{\text{Battowheel}} = \frac{\text{Battcapnom*Dischargedepth}}{\text{Battowheel}}
\]

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

\[
\text{Battowheel}=\text{Plugtowheel}*\text{Eff}
\]

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 electricity consumption

The battery weight is calculated as:

\[
\text{Batteryweight}=\frac{\text{Cellweight}}{1000}\ast\frac{\text{TotalNocells}}{\text{Weightofcellsinpack}}
\]

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:

\[
\text{Restofpackweight}=\text{Batteryweight}\ast(1-\text{weightofcellsinpack})
\]
The battery weight influences the electricity consumption. The plug-to-wheel electricity consumption with the new battery in the vehicle chosen is calculated as:

$$\text{Plugtowheel} = \text{Oldplugtowheel} \times (1 - \text{Weightlossdep} \times (\text{Originalbatteryweight} - \text{Batteryweight})/{\text{Weight}}) \times 0.9/Eff^9$$

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).

A way of studying the influence of the battery weight is to change the parameter Weightofcellsinpack. Changing this parameter changes the battery weight by changing the rest of pack weight while the cell weight and thus battery size in kWh remains the same. This is shown in the figure below for 25%, to 75% weight of cells in a 25 kWh battery for Leaf weighing from 362 kg to 121 kg.

![Figure 6](image)

*Figure 6  Range, plug-to-wheel consumption and propulsion climate footprint as a function of weight of cells in pack in a Nissan Leaf*

It should be emphasized that any weight reduction in the vehicle would give a corresponding range increase and plug-to-wheel consumption reduction. This effect is not limited to the battery. It must be taken into account that the efficiency might be negatively affected by a too tightly packed battery system which would drastically increase the propulsion carbon footprint as can be seen below.

---

9 The 0.9 originates from an assumption that the Oldplugtowheel is based on a charge/discharge efficiency equal to 0.9
Cycles

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

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

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 25 kWh battery.

<table>
<thead>
<tr>
<th>Dischargedepth</th>
<th>Cycles</th>
<th>DelkWh</th>
<th>Range (km)</th>
<th>Service life (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1331</td>
<td>45</td>
<td>155</td>
<td>206600</td>
</tr>
<tr>
<td>0.9</td>
<td>1613</td>
<td>49</td>
<td>140</td>
<td>225400</td>
</tr>
<tr>
<td>0.8</td>
<td>2000</td>
<td>54</td>
<td>124</td>
<td>248400</td>
</tr>
<tr>
<td>0.7</td>
<td>2552</td>
<td>61</td>
<td>109</td>
<td>277300</td>
</tr>
<tr>
<td>0.6</td>
<td>3381</td>
<td>69</td>
<td>93</td>
<td>314900</td>
</tr>
<tr>
<td>0.5</td>
<td>4716</td>
<td>80</td>
<td>78</td>
<td>366000</td>
</tr>
</tbody>
</table>

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.

![Figure 7](image_url)

Figure 7  Relation between depth of discharge and cycles

Depth of discharge does however affect neither cell weight nor electricity consumption as long as the capacity of the battery is not changed.
By DelkWh above is meant delivered kWh per cell during life cycle. The formula is:

\[ \text{DelkWh} = \text{Ahpercell} \times \text{Voltage} \times \text{Cycles} \times \text{Dischargedepth} / 1000 \]

**Efficiency**

The charge/discharge efficiency is as base case assumed to be 0.9. If the efficiency is lower than 0.9, the plug-to-wheel consumption and the environmental footprint associated with the electricity consumption will increase. The effect on the propulsion carbon footprint is shown in the figure below for a Nissan Leaf.

![Figure 8](image_url)

*Figure 8  Propulsion climate impact as a function of efficiency*

The figure above and the figure below together shows the importance of keeping the efficiency high in any attempt to pack the battery more tightly. It is counterproductive to increase the weight of cells in pack at the expense of efficiency in a climate perspective and also for fire safety reasons.
Electricity

As can be seen above the propulsion climate impact of an electric vehicle is similar to an ICE vehicle, when fed with average European electricity at 594 g CO₂/kWh. As can be seen in the figure it is possible to calculate the use phase with average Swedish electricity at 53 g CO₂/kWh by changing the parameter Elsort. It is also possible to change most of the electricity used for cell production between Swedish average mix and European average mix, see page 45. This can also be used as an indication to evaluate the effect of a future energy mix compliant with the European Energy Strategy 2050, which aims for a reduction of greenhouse gas emissions of 80-95% compared to the levels of 1990.

When changing cell design

The life cycle impacts are calculated in four parts or phases: production of cell, production of rest-of-pack, use phase losses and recycling of battery pack. The figure below shows the four parts and gives an idea where changes need to be introduced when changing cell design. Only those boxes having the cell name (in this case 10AhNMCenergy) need changes when modelling a new cell. Restofpack and battery cell use are adapted to the right vehicle context by parameters Plugtowell and weightofcells_inpack.
Figure 10  Boxes that need to be changed when modelling new cell

Results

The most important characteristics of the batteries studied for respective vehicle are given in the table below.
Table 9  Important characteristics of studied batteries

<table>
<thead>
<tr>
<th>Characteristic/Battery for Leaf</th>
<th>10AhLFPenergy</th>
<th>10AhNMCenergy</th>
<th>Leaf original (33AhNMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery capacity, kWh</td>
<td>25.2</td>
<td>25.2</td>
<td>24</td>
</tr>
<tr>
<td>Number of cells</td>
<td>742</td>
<td>630</td>
<td>192</td>
</tr>
<tr>
<td>Cell weight, g</td>
<td>122</td>
<td>109</td>
<td>800</td>
</tr>
<tr>
<td>Battery weight, kg</td>
<td>173</td>
<td>132</td>
<td>294</td>
</tr>
<tr>
<td>Energy density, Wh/kg</td>
<td>145</td>
<td>192</td>
<td>81</td>
</tr>
<tr>
<td>Plug-to-wheel, kWh/km</td>
<td>0.181</td>
<td>0.179</td>
<td>0.186</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic/Battery for Tesla</th>
<th>10AhLFPenergy</th>
<th>10AhNMCenergy</th>
<th>Tesla original (3.1AhNCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery capacity, kWh</td>
<td>84</td>
<td>84</td>
<td>85&lt;sup&gt;11&lt;/sup&gt;</td>
</tr>
<tr>
<td>Number of cells</td>
<td>2472</td>
<td>2112</td>
<td>7104</td>
</tr>
<tr>
<td>Cell weight, g</td>
<td>122</td>
<td>109</td>
<td>45</td>
</tr>
<tr>
<td>Battery weight, kg</td>
<td>583</td>
<td>445</td>
<td>618</td>
</tr>
<tr>
<td>Energy density, Wh/kg</td>
<td>144</td>
<td>190</td>
<td>138&lt;sup&gt;12&lt;/sup&gt;</td>
</tr>
<tr>
<td>Plug-to-wheel, kWh/km</td>
<td>0.236</td>
<td>0.229</td>
<td>0.238</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic/Battery for Volvo bus</th>
<th>10AhLFPpower</th>
<th>10AhNMCpower</th>
<th>Volvo bus original (30AhNCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery capacity, kWh</td>
<td>76</td>
<td>76</td>
<td>76.9</td>
</tr>
<tr>
<td>Number of cells</td>
<td>2232</td>
<td>1908</td>
<td>712</td>
</tr>
<tr>
<td>Cell weight, g</td>
<td>150</td>
<td>134</td>
<td>1100</td>
</tr>
<tr>
<td>Battery weight, kg</td>
<td>599</td>
<td>457</td>
<td>1400</td>
</tr>
<tr>
<td>Energy density, Wh/kg</td>
<td>127</td>
<td>167</td>
<td>54.9</td>
</tr>
<tr>
<td>Plug-to-wheel, kWh/km</td>
<td>1.23</td>
<td>1.23</td>
<td>1.250</td>
</tr>
</tbody>
</table>

<sup>10</sup> Propulsion impact using average European electricity mix at 594 CO₂/kWh. The difference in propulsion impacts is due to the difference in plug-to-wheel consumption which is due to difference in battery weight. Any similar vehicle weight reduction would give similar impact reduction.

<sup>11</sup> Tesla states 85 kWh; that amount of 3.1AhNCA cells equals only 3.6*7104*3.1=79.3 kWh

<sup>12</sup> 85 kWh/618 kg = 138 Wh/kg; 79.3 kWh/618 kg=128 Wh/kg
Complete life cycle

Climate impact

The climate impact of the batteries applied in the vehicles is summarized in the table and figures below.

Table 10  Summary of climate impacts of nine batteries in three vehicles

<table>
<thead>
<tr>
<th>Characteristic/Battery for Leaf</th>
<th>10AhLFPenergy</th>
<th>10AhNMCenergy</th>
<th>Leaf original (33AhNMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery use, CO₂eq/km</td>
<td>15</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Production-Recycling, CO₂eq/km</td>
<td>12</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Net impact, CO₂eq/km</td>
<td>27</td>
<td>24</td>
<td>39</td>
</tr>
<tr>
<td>Net impact, CO₂eq/kWh&lt;sup&gt;13&lt;/sup&gt;</td>
<td>152</td>
<td>133</td>
<td>217</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic/Battery for Tesla</th>
<th>10AhLFPenergy</th>
<th>10AhNMCenergy</th>
<th>Tesla original (3.1AhNCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery use, CO₂eq/km</td>
<td>26</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>Production-Recycling, CO₂eq/km</td>
<td>16</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>Net impact, CO₂eq/km</td>
<td>42</td>
<td>36</td>
<td>46</td>
</tr>
<tr>
<td>Net impact, CO₂eq/kWh&lt;sup&gt;13&lt;/sup&gt;</td>
<td>180</td>
<td>157</td>
<td>193</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic/Battery for Volvo bus</th>
<th>10AhLFPpower</th>
<th>10AhNMCpower</th>
<th>Volvo bus original (30AhNCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery use, CO₂eq/km</td>
<td>82</td>
<td>80</td>
<td>95</td>
</tr>
<tr>
<td>Production-Recycling, CO₂eq/km</td>
<td>105</td>
<td>83</td>
<td>234</td>
</tr>
<tr>
<td>Net impact, CO₂eq/km</td>
<td>187</td>
<td>163</td>
<td>329</td>
</tr>
<tr>
<td>Net impact, CO₂eq/kWh&lt;sup&gt;13&lt;/sup&gt;</td>
<td>152</td>
<td>132</td>
<td>263</td>
</tr>
</tbody>
</table>

Overall the lithium metal anode batteries with NMC gives the least climate impact in all vehicles. However, the difference compared to lithium metal anode batteries with LFP chemistry is not large. As expected the benefit of having a lighter battery is much more accentuated in Nissan Leaf and Tesla compared to in the heavy bus. Battery use in Table 10 and Figure 12 to Figure 14 correspond to Battery cell use in Figure 15 to Figure 24. Production-Recycling in Table 10 and Figure 12 to Figure 14 is the net production related impacts, i.e. Battery life cycle per km minus Battery cell use in Figure 15 to Figure 24.

It is important to keep in mind that the Battery use figures above and in the following figures is only part of the total propulsion impact as shown in the figure below.

<sup>13</sup> Net impact per delivered kWh during life of battery
Figure 11  Total propulsion climate impact (Nissan Leaf, European electricity)

Figure 12  Climate impact of three different batteries in a Nissan Leaf
The figure below shows the life cycle climate impact for a 25.2 kWh Leaf battery built of 10AhLPF energy cells with lithium metal anode calculated as emissions of carbon dioxide equivalents per vehicle km. *Note that all propulsion related impacts are not included.* The study compares the production phase of the battery with those use phase losses that can be related to the battery itself and with the recycling of the battery materials. 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 around 10 g
CO₂ equivalents per vehicle km. The rest of the pack, i.e. the BMS, the cooling system and the packaging amounts to almost 4 g CO₂-eq per km. More than 1 gram of these production related impacts are avoided through recycling (green arrows or minus in the box means avoided emissions in the Sankey diagram). Use phase impacts accredited to the battery are losses due to cell weight and electricity losses (15 g CO₂-eq per km). These use phase impacts are part of the total propulsion impacts (107 g CO₂-eq per km) given in Table 9.

![Sankey diagram](image)

**Figure 15** Climate impact per vehicle km for 10AhLPF energy cell for Leaf (25.2 kWh battery at SOC 0.8, European electricity)

When SOC or depth of discharge increases, the battery will deliver fewer kWh during its lifetime thus the battery climate footprint will increase with increasing SOC, see Table 8. Neither the use phase losses nor the plug-to-wheel electricity consumption will be affected by the SOC. Results will in general be shown for SOC=0.8.
Figure 16  Climate impact per vehicle km for 10AhLPF energy cell for Tesla (84 kWh battery at SOC 0.8, European electricity)

The Tesla battery is more than three times larger than the Leaf battery but the climate footprint is less than double despite being built with the same cells. The largest difference is losses due to battery weight which are about three times larger in the Tesla and almost the same size as the electricity losses.

A similar size battery in a Volvo bus gives much higher carbon footprint per km (187 g CO₂/km) due to almost five times higher electricity consumption per km and thereby less service life (and higher use phase losses).
Figure 17  Climate impact per vehicle km for 10AhLPF power cell for a Volvo bus (76 kWh battery at SOC 0.8, European electricity)

Figure 18  Climate impact per vehicle km for 10AhNMC energy cell for Leaf (25.2 kWh battery at SOC 0.8, European electricity)

The NMC battery above gives a smaller carbon footprint than the LFP battery in Figure 15, 24 gram compared to 28 gram CO$_2$eq per kilometre. As can be seen
below both the batteries with metallic lithium give less climate footprint than the original Leaf cell which gives 39 gram CO$_2$eq per kilometre, see figure below.

![Climate impact per vehicle km for original 33Ah NMC cell for Leaf](image)

*Figure 19  Climate impact per vehicle km for the original 33Ah NMC cell for Leaf (23.8 kWh battery at SOC 0.8, European electricity)*

Applied at the Tesla, the NMC battery gives a smaller carbon footprint than the LFP battery in Figure 16, 39 gram compared to 42 gram CO$_2$eq per kilometre.

![Climate impact per vehicle km for 10AhNMC energy cell for Tesla](image)

*Figure 20  Climate impact per vehicle km for 10AhNMC energy cell for Tesla (84.5 kWh battery at SOC 0.8, European electricity)*

The original Tesla battery gives the largest climate footprint, 46 gram CO$_2$eq per kilometre, see figure below.
Figure 21  Climate impact per vehicle km for Tesla original 3.1AhNCA cell (84.5 kWh battery at SOC 0.8, European electricity)

Figure 22  Climate impact per vehicle km for 10AhNMC power cell for a Volvo bus (76 kWh battery at SOC 0.8, European electricity)

A power battery in a Volvo bus will most probably not average 80% SOC. Recalculating with 60% SOC gives a total climate footprint of 145 g CO₂/km, i.e. not that much lower, see figure below. When SOC or depth of discharge...
decreases, the battery will deliver more kWh during its lifetime thus the battery climate footprint will decrease with decreasing SOC, see figure below. Neither the use phase losses nor the plug-to-wheel electricity consumption will be affected by the SOC. Results will henceforth in general be shown for SOC=0.8.

![Diagram showing climate impact per vehicle km for 10AhNMC power cell for a Volvo bus](image)

Figure 23 Climate impact per vehicle km for 10AhNMC power cell for a Volvo bus (76 kWh battery at SOC 0.6, European electricity)

The original NCA Volvo bus battery gives the highest climate footprint of the modelled bus batteries, see figure below.
Abiotic depletion and toxicity

The general trend that the metal lithium anodes and especially the NMC chemistry give the smallest impact, is valid also for Abiotic resource depletion, Eco-toxicity and Human toxicity, non-cancer. For Human toxicity, cancer, the LFP battery scores highest due to a large contribution (>70%) from chromium emissions during ferrite production. See figures below. However, if the two human toxicity scores are summed up, the general trend is the same as for climate impact, i.e. the NMC metal anode chemistry scores lowest followed by the LFP metal anode chemistry.

Figure 24  Climate impact per vehicle km for original 30Ah NCA cell for a Volvo bus (76 kWh battery at SOC 0.8, European electricity)
The figure above shows the life cycle abiotic depletion potential per delivered km for the modelled Nissan LEAF batteries expressed as kg Sb equivalents (antimony equivalents, Sb-eq). The figures below shows Human toxicity, cancer and non-cancer expressed as Comparative Toxic Units, CTUh as well as Freshwater toxicity expressed as CTUe.

**Figure 26  Human toxicity, cancer in CTUh per km for Nissan Leaf batteries**
The same trend (that the metal lithium anodes and especially the NMC chemistry give the smallest Abiotic resource depletion, Eco-toxicity impact and Human toxicity, non-cancer impact) is valid also for the investigated Tesla batteries, as can be seen in the figures below. Since there is more difference between the climate impacts of the bus’ batteries compared to the Leaf batteries or the Tesla batteries and the chemistries are the same, it can be concluded that the batteries with metal lithium anodes and especially the NMC chemistry give the smallest abiotic depletion and toxicity (except Human toxicity, cancer) also for the bus batteries, i.e. for all the vehicle batteries modelled.
Figure 29  Abiotic depletion, kg Sb-eq per km for Tesla batteries

Figure 30  Human toxicity, cancer in CTUh per km for Tesla batteries
### Dominance analysis

As can be seen in Figure 15 to Figure 24, climate impact during cell production is dominated by assembly energy, the cathode and the lithium foil. Power cells have more lithium foil than energy cells which make the lithium foil dominate over the cathode. During the use phase the charge/discharge losses dominate over the losses due to the battery weight. This effect is more pronounced the heavier the vehicle is relative to the battery. In the Tesla, where the battery weight is 30% of the total vehicle weight, the losses are almost equally large. Recycling benefits are dominated by lithium foil.
Sensitivity to electricity mix
If the cell is manufactured with the Swedish carbon lean electricity instead of the European average mix, the production impacts decrease from 12 to 8 g CO$_2$eq/km, see figure below and Figure 15.

Figure 33  Climate impact per vehicle km for 10AhLFP energy cell for Leaf produced with Swedish average electricity

If the vehicle is also driven on Swedish average electricity mix, the total battery related carbon footprint reduces from 27 to 9 g CO$_2$eq/km, see figures below.

Figure 34  Climate impact per vehicle km for 10AhLFP energy cell for Leaf produced and used with Swedish average electricity
Figure 35  Climate impact of 10AhLFP lithium metal anode battery in Nissan Leaf produced and used with European electricity mix (left), produced with Swedish electricity mix and used with European electricity mix (middle) and both produced and used with Swedish electricity mix (left)

Note that the Battery use is only part of the total propulsion impacts, see Figure 11. The data sets used in the calculations are given in the table below.

<table>
<thead>
<tr>
<th>Name of data set</th>
<th>Gram CO2-eq/kWh</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, low voltage,</td>
<td>594</td>
<td>Used for propulsion of vehicle. Simulates average global(^{14}) use.</td>
</tr>
<tr>
<td>production UCTE, at grid/UCTE S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity, low voltage (SE)</td>
<td>53</td>
<td>Used for propulsion of vehicle. Simulates use in Sweden.</td>
</tr>
<tr>
<td>market for Alloc Rec, S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity, high voltage,</td>
<td>523</td>
<td>Used for production of cell. Simulates average global production.</td>
</tr>
<tr>
<td>production UCTE, at grid/UCTE S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity, high voltage (SE)</td>
<td>52</td>
<td>Used for production of cell. Simulates production in Sweden.</td>
</tr>
<tr>
<td>market for Alloc Rec, S</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussions and conclusions

Life cycle environmental impact of battery cells with lithium metal anodes

Both the LFP and NMC lithium metal anode battery cells show lower climate impact, lower abiotic depletion potential and lower toxicity than the original NMC

\(^{14}\)Average west European electricity mix is considered close to the average global electricity mix.
and NCA cells with copper anodes. The difference is largest for the bus battery which has almost twice the carbon footprint per km in its original design. The difference is smallest for the Tesla battery. The main reason for the difference is higher energy density which gives lower weight and thus lower electricity consumption. It should be noted that the lower carbon footprint of the metal anode cells rests on the assumption that they last as many cycles as the original NMC and NCA cells with copper anodes, something which has not yet been proven.

As mentioned above, the scientific base for calculating toxic impacts and resource depletion is not very solid (Klinglmair et al., 2014; Peters and Weil, 2016; Zackrisson et al., 2016b). These impacts are included in the study for reasons of completeness but not further discussed here.

The NMC chemistry shows lower environmental impacts per vehicle kilometre than the LFP chemistry for the metal anode battery cells, but here the difference is much smaller and probably within error margins. The main reason is the same as above: the higher energy density of NMC gives lower weight and thus lower electricity consumption.

The model

The model is built so that it allows to characterize a vehicle by providing its weight (without battery), its original plug-to-wheel electricity consumption, its system voltage, its relation between cell weight and battery weight and then design a battery for it of a size of choice. By size is meant nominal battery capacity and the corresponding weight.

The model accounts for that the battery weight affects the energy consumption per kilometre, thus a lighter battery will result in an increased range even with 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 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). This is a simplification of real world conditions and can therefore easily be modified and subject to sensitivity calculations.

The model also accounts for that the efficiency affects the energy consumption per kilometre, thus a less efficient battery will result in a decreased range for 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. The importance of maintaining high efficiency is shown in Figure 8.

Production and recycling

The assembly energy, the lithium foil and cobalt and nickel in the cathode is dominating the climate impact of the cells. However, it should be remembered that some of the impacts from the metals can be avoided by recycling, if and when recycling takes place.
The assembly energy cannot be recycled and therefore warrants special attention. The sensitivity calculations with Swedish average electricity mix for production of the cells show that production impacts can be reduced by 25% by producing in Sweden.

Conclusions
In short, the study points towards the following conclusions:

- Both the LFP and NMC lithium metal anode battery cells show lower climate impact, lower abiotic depletion potential and lower toxicity than the original NMC and NCA cells with copper anodes. The main reason for the difference is higher energy density which gives lower weight and thus lower electricity consumption.

- For the same reason (higher energy density) the NMC chemistry shows lower environmental impacts per vehicle kilometre than the LFP chemistry for the metal anode battery cells, but here the difference is much smaller and probably within error margins.

- Sensitivity calculations with Swedish average electricity mix for production of the cells show that production impacts can be reduced by 25% by producing in Sweden, compared to global average production.
List of acronyms and abbreviations

CFCs  Chlorofluorocarbons
CO2  Carbon dioxide
CO2-eq  Carbon dioxide equivalents
CH4  Methane
C2H4  Ethene
CTU  Comparative Toxic Unit
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, LiFePO4, battery cell
Li  Lithium
LMO  Lithium manganese oxide, LiMn2O4, battery cell
MJ  Megajoule
MWh  Megawatt-hour
NCA  Lithium nickel cobalt aluminium oxide battery cell
NMC  Lithium nickel manganese cobalt oxide battery cell
NMP  N-Methyl-2-pyrrolidone
NOx  Nitrogen oxides
PHEV  Plug-in hybrid electric vehicle
PO4  Phosphorus
PS  Polystyrene
PVDF  Polyvinylidenfluoride
PP  Polypropylene
RER S  RER = Region Europe, S=system process
Sb  Antimony
SO2  Sulphur dioxide
SF6  Sulphur hexafluoride
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