Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues

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A B S T R A C T
The main aim of the study was to explore how LCA can be used to optimize the design of lithium-ion batteries for plug-in hybrid electric vehicles. Two lithium-ion batteries, both based on lithium iron phosphate, but using different solvents during cell manufacturing, were studied by means of life cycle assessment, LCA. The general conclusions are limited to results showing robustness against variation in critical data. The study showed that it is environmentally preferable to use water as a solvent instead of N-methyl-2-pyrrolidone, NMP, in the slurry for casting the cathode and anode of lithium-ion batteries. Recent years’ improvements in battery technology, especially related to cycle life, have decreased production phase environmental impacts almost to the level of use phase impacts. In the use phase, environmental impacts related to internal battery efficiency are two to six times larger than the impact from losses due to battery weight in plug-in hybrid electric vehicles, assuming 90% internal battery efficiency. Thus, internal battery efficiency is a very important parameter; at least as important as battery weight. Areas, in which data is missing or inadequate and the environmental impact is or may be significant, include: production of binders, production of lithium salts, cell manufacturing and assembly, the relationship between weight of vehicle and vehicle energy consumption, information about internal battery efficiency and recycling of lithium-ion batteries based on lithium iron phosphate.

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1. Introduction

The purpose of the study was to identify and highlight critical issues regarding life cycle assessment of lithium-ion batteries intended for plug-in hybrid electric vehicles. Electric vehicles are seen as the main answer to the transport sector’s problems of diminishing oil supplies and global warming. Plug-in hybrid electric vehicles, PHEVs, using lithium-ion battery technology were introduced in China 2009 (Conner, 2009) and are expected to be introduced in Europe and in the United States within the next three years (Volvo will bring phevs to US; Honeywill, 2009). PHEVs are generally believed to be playing a major role during the coming decade in the transition from combustion engines to electric motors in automobiles.

Several studies have shown the potential benefits of electric vehicles (including hybrid versions) compared to the traditional internal combustion engine vehicle. Potential fuel savings between 25% for hybrid electric vehicles and up to 50%–80% for plug-in hybrids depending on the battery size have been reported (AEA, 2007). Assuming that the electricity (which is replacing the fuel) can be generated by renewable energy sources, considerable reductions of CO₂ emissions from the transport sector are thus possible. Therefore, substantial efforts are today being made to develop battery systems for vehicles with electric power trains.

Life cycle assessment, 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 (Zackrisson, 2009; Simon et al., 2000; Nielsen and Wenzel, 2002). To facilitate the use of LCA in developing lithium-ion batteries this paper will examine and discuss some critical issues pertaining to LCA of lithium-ion battery technology, in the context of a case study of a lithium iron phosphate, LiFePO₄, battery design.
It should be pointed out that the studied battery does not exist in reality, only as a concept. Thus, the results are only an indication of what results to expect in a real case. As mentioned above, the main aim of the study was to serve as an inspiration and information source to the battery industry to perform an LCA of their specific battery designs and use the results to optimize their products’ environmental performance.

The LCA was carried out at the Swedish research institute Swerea IVF AB as an internal study. The LCA modeling was partly based on in-house laboratory trials with tape-casting of cathodes using water instead of N-methyl-2-pyrrolidone, NMP, as a solvent in the cathode slurry. Also nano-spinning of the separator was tried with success. The studied battery was modeled as a 10 kWh battery system enabling 50 km electric drive range to a plug-in hybrid electric vehicle.

2. Methodology

ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines (ISO, 2006), is the cornerstone standard for how to do an LCA. It should be emphasized that ISO 14044 defines a procedure for carrying out an LCA, rather than defining exactly how to do it. “The scope, system boundary and level of detail of an LCA depend on the subject and intended use of the study. The depth and breadth of LCA may differ considerably depending on the goal of a particular LCA.” (ISO, 2006).

In order to get more guidance (than is provided by ISO 14044) on how to carry out the LCA, the general rules (IEC, 2008) of the International Environmental Product Declaration EPD® system were followed. Though no Product Category Rules exist for vehicle batteries in the EPD© system, the general rules provide helpful guidance on allocation, choice of data, system boundary issues and environmental impact assessment.

The LCA model was built around a theoretical design of a 10 kWh battery for a plug-in hybrid electric vehicle. Material needs were determined based on literature references and laboratory tests. Associated resources and emissions were found in existing databases for LCA and represent in general European or global averages. Data was mainly drawn from the database Ecoinvent 2.0 (Ecoinvent, 2008).

2.1. Functional unit

The functional unit was defined as a 10 kWh battery for a plug-in hybrid electric vehicle capable of sustaining 3000 charge cycles\(^1\) at 80% maximum discharge giving at least a 200 000 km operation during the vehicle design life time. This means that all figures for resource use, emissions and environmental impact are related to one such battery weighing 107 kg, i.e. the energy density is 93 Wh/kg. This functional unit, in effect a battery lasting the life time of a vehicle, has been used in other life cycle assessments of vehicle batteries (Matheys et al., 2005; Ishihara and Kihira).

2.2. System boundary

The system boundary was based on the general rules of the EPD® system (IEC, 2008). The principle is to separate the product systems at the point where the waste products have their lowest value. Furthermore, the product system that pays money at this “lowest-value-point” (either to get rid of the waste or to get the waste resource) should carry future environmental impacts. Applying those principles to metals and other materials that will be recycled as raw materials (e.g. the used battery), means that the transport to the scrap yard should be carried by the studied product. Ensuing recycling processes should be carried by the next product system. Recycling credits are only given to the extent that recycled materials are actually being used in the production of materials for batteries. The system boundary for the study is shown below (Fig. 1).

It should be emphasized that the study focuses on the battery. Only the battery and its casing are inside the system boundary. The battery charger, the electric engine(s) and other hardware in the electric power train are outside the system boundary. In the use phase, only electricity related to internal battery efficiency and the extra electricity needed to carry the weight of the battery is included. In effect, the study compares the production phase of the battery to the use phase of the hybrid electric vehicle and does not include the manufacturing phase of the electric engine(s).

\(1\) 3000 cycles \(\times\) 10 kWh \(\times\) 0.8 = 24000 kWh; 24 000 kWh/0.15 kWh/km = 160 000 km; 75% electric mode: 0.75 \(\times\) 200 000 km – 150 000 km, so there is a 10 000 km margin in the calculations.
battery with those use phase losses that can be related to the battery itself. Those use phase losses are about 7% of the total energy needed to propel a PHEV.

2.3. Cut-off and assumptions

Using the product specifications, all materials were tracked back to the point of resource extraction, mainly by using cradle-to-gate data from the Ecoinvent database (Ecoinvent, 2008). The Ecoinvent data contains associated inputs from nature and emissions, including estimations of losses. So in that respect a 0% cut-off was used. Materials not found in the Ecoinvent database, nor in other available databases, were modeled (from materials available in the databases) using stoichiometric calculations and estimations of energy use but without estimation of losses. Some materials that could not be found in the databases were replaced (in the model) with similar materials. For details about which material was replaced by which, see Chapter 3.

2.4. Environmental impact assessment

In line with the recommendations in ISO 14044 (ISO, 2006) and the EPD® system (IEC, 2008), five largely accepted impact categories were calculated and reported:

- Global warming
- Acidification
- Ozone depletion
- Photochemical smog
- Eutrophication

The drawback of using five different environmental impact categories is that it is rare that a material or technical solution is better or worse than another in all impact categories. It is then difficult to decide on which is preferable. Unfortunately, there are no generally acceptable methods today that can weigh together different impact categories into one value.

3. Modeling

PHEVs are designed with battery sizes ranging from 4 to 16 kWh. In this study 10 kWh was used to simulate the Volvo PHEV that was conceptually introduced in 2009. It was decided to study LiFePO₄ chemistry. Battery packs are made up of cell modules, containing several cells. A typical content of a LiFePO₄ cell is given in Fig. 2 below.

The modeling was based on a conceptual 10 kWh battery consisting of 100 cells in series thus giving 370 V.² The mass of the cell materials was modeled based on literature (Gaines and Cuenca, 2000) and the recipes used in trials performed at the laboratory of Swerea IVF.

Weights of cell materials used in the calculations are shown in the table below. (Table 1)

3.1. Cathode

The cathode was made of LiFePO₄, a polyvinylidenefluoride (PVDF) binder and carbon black in slurry mixed with the solvent N-methyl-2-pyrrolidone which was spread on an aluminum foil. The solvent NMP was dried off. NMP is volatile, flammable, expensive, easily absorbed by the skin and suspected to cause genetic and reproductive damage (Posner, 2009). In the model it was assumed that no NMP is emitted to the environment. Instead the NMP is burnt off causing CO₂ emissions, see Chapter 3.7. Working environment impacts were not modeled. Due to the problems with NMP, Swerea IVF and other laboratories have tried to replace it with water. The cathode made with water as a solvent has a different binder compared to the cathode made with NMP. See Table 1 above.

LCA data for the above cathode ingredients was found in the Ecoinvent database, with the exception of manufacturing of LiFePO₄ which is described below. No LCA data was found on PVDF. It was approximated with equal proportions of tetrafluoroethylene and polyethylene from the Ecoinvent database. Concerning the cathode made with water a styrene acrylate latex binder was used. It was approximated with equal proportions of polymethyl methacrylate, PMMA, and polystyrene from the Ecoinvent database.

3.1.1. Manufacturing of LiFePO₄

LiCO₃, lithium carbonate, is used to make LiFePO₄. The quantity was estimated to 0.23 g LiCO₃ per gram LiFePO₄, by stoichiometric calculation. LCA data for lithium carbonate and the other ingredients (ferrite, graphite and diammonium phosphate) was found in the Ecoinvent database. The manufacturing process needs energy for two temperature increases: first to 400–500 °C followed by grinding and adding graphite and then a final temperature rise to 700–800 °C. Assuming a specific heat capacity of 0.9 KJ/kgK, the

<table>
<thead>
<tr>
<th>Part of cell</th>
<th>Material</th>
<th>Weight of cells made with NMP as solvent (gram)</th>
<th>Weight of cells made with water as solvent (gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>LiFePO₄</td>
<td>422</td>
<td>422</td>
</tr>
<tr>
<td>Cathode</td>
<td>Aluminum foil</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Cathode</td>
<td>Carbon black</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Cathode</td>
<td>PVDF</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>Cathode</td>
<td>Styrene acrylate latex</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ethylene glycol dimethyl ether</td>
<td>157</td>
<td>157</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Lithium salt (Lithium chloride)</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Separator</td>
<td>Polypropylene</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Separator</td>
<td>Polyethylene</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Electronics</td>
<td>Transistor</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Electronics</td>
<td>Resistor</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Anode</td>
<td>Graphite</td>
<td>169</td>
<td>169</td>
</tr>
<tr>
<td>Anode</td>
<td>Carbon black</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Anode</td>
<td>Copper</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>Anode</td>
<td>PVDF</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>Anode</td>
<td>Styrene butadiene latex</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Packaging</td>
<td>Polypropylene</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Packaging</td>
<td>Aluminum foil</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>967</td>
<td>965</td>
</tr>
</tbody>
</table>

² Modern PHEV and electric vehicles have system voltages between 280 and 400 V. 370 V is used as a mean value between Ford Edge HV Series Drive, 336 V, and Daimler all electric sports car, 400 V.
two temperature rises would need about 1 kJ. In addition, the grinding and the chemical reactions require some energy and there would be heat losses. Consequently, a total of 3 kJ electricity/gram LiFePO₄ was assumed.

3.2. Anode

The anode is generally made of graphite coated on copper foil about 14 μm thick (Gaines and Cuenca, 2000). In addition a binder is needed. As with the cathode, the LCA data used for the anode ingredients was found in the Ecoinvent database. For the anode made with water a styrene butadiene latex binder was used. It was approximated with ABS, acrylonitrile butadiene styrene, from the Ecoinvent database.

3.3. Separator

The separator was assumed to be made of equal proportions of polypropylene and polyethylene (Venugopal et al., 1999). LCA data for these materials was found in the Ecoinvent database.

3.4. Cell packaging

Cell packaging was assumed to be made of polypropylene and aluminum foil (Gaines and Cuenca, 2000). LCA data for these materials was found in the Ecoinvent database.

3.5. Electrolyte

The electrolyte is usually an expensive 1-M solution of a lithium salt in an inexpensive organic solvent such as propylene carbonate or dimethyl carbonate (Gaines and Cuenca, 2000). Salts under consideration are among others lithium hexafluorophosphate, LiPF₆ and Lithium tetrafluoroborate, LiBF₄. In the model, the electrolyte was approximated to lithium chloride in ethylene glycol dimethyl ether. The high price of electrolytes and low price of lithium chloride indicate that this means an underestimation of the environmental impact, since there is very often a strong correlation between price and environmental impact (Gregory et al., 2009). However, immature technologies like these electrolytes may have other causes for commanding a high price.

3.6. Cell electronics

The cell electronics were assumed to be a semiconductor to enable switching on and off and a resistor for temperature measurements. The same ingredients and amounts were assumed for both models.

3.7. Module assembly and battery assembly

In the model, 10 cells were packed in one module and 10 modules in one 10 kWh battery. Both modules and batteries require some electronics and some packaging. The weights of the electronics and packaging were based on the assumption that electronics and packaging, excluding cell packaging, equal 10% of the total weight of the battery (Gaines and Cuenca, 2000), i.e. about 10.7 kg. Calculating reasonable amounts for packaging in 1 mm polypropylene for modules and 4 mm polypropylene for the battery casing, left 4.7 kg for the electronics.

In the model it is assumed that cells are assembled in modules, either at the cell manufacturing facilities or at the battery manufacturing facilities, not in a separate industrial facility. Thus, from cell to battery, only one transport is needed, as explained in Chapter 3.8.

The energy needed for cell manufacturing and module and battery assembly was approximated from data in Saft’s annual report 2008 (Saft, 2008). The total use of energy was divided by total sales and multiplied with the current price level of a high-quality lithium-ion battery. This resulted in a total energy corresponding to 11.7 kWh electricity and 8.8 kWh natural gas per kg lithium-ion battery. In addition, CO₂ emissions from burning of NMP were estimated by stoichiometric calculation.

3.8. Transports

Estimating transports involves guessing about what the vehicle battery industry will look like in a few years. It is expected that there will only be a few cell manufacturers in the world and as many battery manufacturers as manufacturers of combustion engines, roughly one per car assembly plant. Thus, long transports from raw material producers to cell manufacturers, and long transports between cell manufacturers and battery manufacturers but relatively short transports between battery manufacturers and car assembly plants.

From car manufacturer to user, long transports were assumed. There are many car manufacturers, but customers buy their cars from all over. Lastly there is a short transport from the user to a nearby sorting facility. Recycling facilities would be much fewer and thus entail longer transports, but this transport would be booked on the next product system. The long transports, mentioned above, were assumed to be carried out by truck, 10%, and by boat, 90%. The short transports were assumed to be carried out exclusively by truck.

3.9. Use phase

The use phase was modeled as the electricity losses in the battery during the lifetime use of the battery in the car and the extra electricity/fuel needed to carry the weight of the battery. This way of modeling the use phase of a car battery has been used in other LCAs (Matheys et al., 2005). In addition, the transport of the battery from the car manufacturer to the user was included in the use phase.

The influence of the battery weight of 107.2 kg was modeled using the following assumptions:

- 30% of vehicle energy consumption can be related to car weight (Zackrisson et al., 2004).
- mid-size car weighing 1600 kg, running 200000 km during design life time
- car consuming 0.5 l petrol per 10 km in petrol mode (Lyle, 2009) or 0.15 kWh electricity (battery-to-wheel) per km in electric mode (Honeywill, 2009; Pesaran, 2007)
- a PHEV runs on electricity half the time or distance and on fuel the other half according to Kågesson (2006). However, with such a large battery as 10 kWh (allowing maybe 8/0.15 = 50 km electric drive range assuming 80% maximum discharge), 75% electric mode was assumed, a figure which is supported by Håkansson (2008) and Pesaran (2007). Note that a PHEV in reality will operate partly in dual-mode, i.e. the combustion engine and the electric engine(s) are operating at the same time. This dual-mode operation was not modeled. It should also be noted that more braking energy could be regenerated to electricity if the vehicle is driven carefully and with planning ahead so that the electric engine is used for

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1600 kg correspond to Volvo PHEV concept car presented in 2009 and in the same class as GMs Chevy Volt. A typical mid-size car.
braking (Håkansson, 2008). Such influence by driving behavior was not modeled.

- 90% charging efficiency was assumed (Rydh and Sandén, 2005), thus plug-to-wheel consumption is 0.15/0.9 = 0.167 kWh/km
- Using the figures above the extra electricity needed to carry the battery weight was calculated to 107.2 kg/1600 kg × 30% × 0.167 kWh/km efficiency × 200000 km × 75% = 504 kW h at plug. Low voltage average West European electricity mix was assumed including 11% grid losses. The extra fuel needed and the extra combustion emissions due to the battery weight was calculated to 107.2 kg/1600 kg × 30% × 200000 km × 0.05 L/km × 25% = 50 L of petrol being combusted in a vehicle.

The internal energy efficiency for lithium-ion batteries was assumed to be 90% (Matheys et al., 2005; Rydh and Sandén, 2005; Campanari et al., 2009) in the base case including discharging and conditioning. The losses due to internal battery efficiency was calculated as 200000 km × 75% × 0.15 kW h/km × 10% losses = 2250 kW h. Van Mierlo et al. calculate with 80% charging efficiency (Van Mierlo et al., 2006) supposedly including the charger as well as charging losses in the battery. Note that the charging losses were not included in the losses due to the internal battery efficiency mentioned above.

3.10. Recycling phase

The recycling phase was represented by a 500 km transportation of the used battery to a recycling scrap yard. Environmental burdens and benefits of using recycled materials should be booked on the next product life cycle. This is in line with the principle of separating product systems at the point where the material/scrap has its lowest value. Pyrometallurgical and hydrometallurgical recycling technologies used for lithium-ion batteries with high cobalt content are not suitable for LiFePO4 batteries. Since the new recycling technology needed for LiFePO4 batteries is not yet commercially available (Kotaich and Sloop), the model assumes a virgin lithium raw material source (spodumene), see also Chapters 2.2 and 3.1.1.

4. Results

4.1. Water versus NMP

Fig. 3 below shows the life cycle emissions of carbon dioxide equivalents of the two batteries. The battery made using NMP leads to emissions of about 4400 kg CO2 equivalents, while the battery made using water leads to about 3400 kg CO2eq life cycle emissions. The difference occurs in the production phase and is mostly due to the fact that the battery made using NMP uses PVDF as a binder.

Since no LCA data exists for PVDF, it was approximated with equal amounts of tetrafluoroethylene and polyethylene. Tetrafluoroethylene has a very high CO2eq score.

With the used system boundary, the part of recycling accounted for by the studied system is a 500 km lorry transport to a scrap sorting facility. Thus, the recycling phase is negligible in comparison to the use phase and the production phase. There is today a lack of knowledge and data about recycling of LiFePO4 batteries, see Chapter 3.10. If, in the future, recycling of such batteries becomes common, the associated benefits and impacts would get credited to the input materials, i.e. they would show up in the “Battery production column” in Fig. 3; hopefully as a net decrease of CO2eq emissions.

It can further be observed that the manufacturing of the batteries causes more or less the same amount of global warming impact as does the use of the batteries. Whether or not this is true, also for the other environmental impact categories, will be explored below. In the following, only the battery made using water will be examined. It will be referred to as a 10 kWh PHEV battery.

In Fig. 4 it can be seen that the transport to recycling is negligible in comparison to the use phase and the production phase also regarding the other environmental impact categories. The production phase and the use phase are much more similar, with the production phase dominating four out of five environmental impact categories. The use phase slightly dominates the global warming impact. Considering all five impact categories it can be concluded that the production phase and the use phase are more or less in the same order of size. This will be further explored in the sensitivity analysis.

Fig. 5. Global warming, photochemical smog, eutrophication, acidification and ozone depletion of a 10 kWh PHEV battery use phase.
4.2. Use phase of 10 kWh PHEV battery

In Fig. 5 it can be seen that the dominating impacts in the use phase stem from electricity losses in the battery during the use of it in the car, in all impact categories. Here is assumed that 90% of the charged electricity will be used for running the motor, thus the losses are 10%. This percentage is not including charging losses as explained in Chapter 3.9.

Battery weight has traditionally been seen as a very important factor for the development of electric vehicles. Losses due to battery weight are calculated based on the assumption that 30% of the energy used by a car can be related to its weight (Zackrisson et al., 2004). Discussions between Mark Goedkoop and Stephan Francis in 2006 referred to in the LCA discussion list (Goedkoop et al., 2006) run by the SimaPro software provider PRé Consultants bv, indicate that this figure might be doubled, i.e. 60%. However, these discussions relate to vehicles with internal combustion engines. Electric vehicles and plug-in electric vehicles, PHEV, regenerate during braking energy lost during acceleration. Thus, the relation between weight and energy loss should be smaller for a PHEV than for a traditional vehicle with an internal combustion engine. The electricity losses will be further examined in the sensitivity analysis in Chapter 4.4.

4.3. Production of 10 kWh PHEV battery

Fig. 6 below shows that the four most dominating sources of global warming impacts in the production phase stem from energy use during battery manufacturing, electronics and the cathode. More than half of the global warming impact stems from energy use during manufacturing. It should be pointed out that the energy figure is very roughly estimated.

The environmental impacts of electronic components are significant at battery level as well as at module and cell level. Almost 30% of the 1660 kg of CO₂eq during the production phase stems from electronics. Production of the cathode and in particular the LiFePO₄ powder results in around 10% of the global warming impact. Energy use during battery manufacturing, electronics and the cathode shows dominating impacts also concerning the other

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4 The thickness of the arrows is proportional to the global warming impact measured in carbon dioxide equivalents from respective process. The amount of CO₂eq in grams is shown in the lower left corner of each box. At the top of each box the flow is shown, for example “100 p Cell” – 100 pieces of cells or “4.22E4 p LiFePO₄, 1 g” – 42 200 g of LiFePO₄. The cut-off in Fig. 6 is 3.7%, meaning that processes that contribute with less global warming impact (than 3.7% of the total 1660 kg) are not shown.
impact categories, however, the relationships between them differ. Photochemical smog impacts are dominated by electronics (58%). Eutrophication impacts are dominated by the cathode (71%). Acidification impacts are dominated by electronics (48%). Ozone depletion impacts are very small on the whole.

In Fig. 7, it can be seen that transportation of raw materials and components has a small but not negligible impact. However, a transport-dependent battery industry structure was assumed, see previous chapter. In the production phase, transports would be responsible for around 3% of the total 1660 kg CO$_2$eq emissions. Note that transport from mines and the like to raw material producers are included in the raw material data sets and not shown separately in Fig. 7 nor included in the 3%. Transport from the car manufacturer to the user was included in the use phase and amounts to 21.5 kg, see Fig. 10 below. As described in Chapter 3.8, a large share of the transports was assumed to be carried out by boat.

4.4. Sensitivity analysis

Two interesting results presented in the previous chapter are:

- use phase environmental impacts are more or less in the same order of scale as production phase impacts
- the global warming impact from internal battery efficiency losses are three times the impact from losses due to battery weight

The above results were tested by recalculation using extreme, but not unrealistic, data concerning electricity mix, internal battery efficiency and PHEV weight—energy relationship and compared with the base case calculations and results in the previous chapter.

Concerning use phase impacts versus production phase impacts, the sensitivity calculations showed that production phase impacts are almost always larger than the use phase environmental impacts. Only when the PHEV is being driven in countries with a very coal-dependent electricity generation the impacts are similar across all the five impact categories. Concerning the relative importance of battery weight and battery internal efficiency, the sensitivity calculations showed that the environmental impact from internal battery efficiency losses are two to six times the impact from losses due to battery weight in PHEVs, all over the world, at 90% internal battery efficiency.

In the base case calculations, average West European electricity was used in all life cycle phases since Western Europe is a likely location for both production and introduction of PHEVs. Furthermore, West European electricity is sometimes used as an approximation for world average electricity. In the sensitivity calculations it was assumed that the PHEV is being driven in Scandinavia, using northern Scandinavian electricity mainly produced from hydro-power and nuclear power, and being driven in China where the electricity is produced mainly from fossil resources.

It is difficult to find information about internal battery efficiency of lithium-ion batteries and what is included and not included in stated figures. For example, is the energy consumed by the battery management system included? In our model it is considered inside the system boundary and includes temperature conditioning. On the other hand, percentages as high as 97.5% battery efficiency exist (Nelson, 2006) though it is unclear what is included in that figure. In the sensitivity calculations 97.5% battery efficiency was assumed and compared to the 90% internal efficiency used in the base case calculations.

As pointed out in Chapter 4.2, the assumption that 30% of the energy consumption in a vehicle can be related to its weight is very unsure. Calculations were therefore made on the assumptions that 15% and 50% of a PHEV’s weight can be related to energy consumption. These percentages, 15% and 50% respectively, must be considered extremes for PHEVs, i.e. it is very likely that any PHEV has a weight—energy relationship in between those figures.

4.4.1. Production phase versus use phase

The sensitivity calculations only change figures in the use phase. Factors that would increase use phase impacts, compared to the base case are:

![Fig. 7. Global warming impacts of a 10 kWh PHEV battery — transports during the production phase amounts to around 3%.](image-url)
• Chinese electricity mix
• 50% weight—energy relationship

Factors that would decrease use phase impacts, compared to the base case are:
• Scandinavian electricity mix
• 15% weight—energy relationship
• 97.5% internal battery efficiency

As mentioned above, the base case calculations used West European electricity, 30% weight—energy relationship and 90% internal battery efficiency.

In Fig. 8 it can be seen that the production phase and the use phase are quite similar when the car is used in China. Even so, only two out of five categories have a larger impact in the use phase. As for the 50% weight—energy relationship only one category has a larger impact in the use phase.

In Fig. 9 is shown that the production phase dominates in all environmental impact categories when the car is using the Scandinavian electricity mix because the use phase emissions will decrease quite a lot. Note that the electricity mix during production is still equal to the West European mix. A sensitivity calculation with a battery with 97.5% internal battery efficiency produces an almost identical figure, because the use phase emissions decrease when the internal battery efficiency is increased. A calculation with a 15% weight—energy relationship, does not give as much decrease in use phase impacts and gives a figure similar to that of the base case, see Fig. 4.

From the above calculations it can be concluded that the production phase impacts are almost always larger than the use phase environmental impacts. Only when the PHEV is driven in countries with a very coal-dependent electricity generation the impacts are similar across all the five impact categories.

4.4.2. Internal battery efficiency versus battery weight

In Fig. 10 it is shown that the global warming impact from internal battery efficiency losses is three times the impact from losses due to battery weight in the base case. This result was examined by recalculations using Scandinavian and Chinese electricity mixes and different assumptions regarding the relationship between energy consumption and weight in a vehicle. Since the use phase model almost solely contains energy-related processes, global warming is a sufficiently good indicator to study.

In the base case, global warming impacts from internal battery efficiency losses were about three times the impact from losses due to battery weight, see Fig. 10 above and Table 2 below. Table 2 gives the relation between losses due to internal battery efficiency versus

 losses due to battery weight for West European, Scandinavian and Chinese electricity at 90% and 97.5% battery efficiency.

If it can be assumed that the battery efficiency today is 90%, it can be concluded that losses due to battery efficiency today are 2–4 times the losses due to battery weight, i.e. at present battery efficiency is more important than battery weight from an environmental perspective. At 97.5% internal battery efficiency, losses due to battery weight are larger or equal to the losses due to internal battery efficiency.

As pointed out in Chapter 4.2, the assumption that 30% of the energy consumption in a vehicle can be related to its weight is very unsure. Table 3 gives the relation between losses due to internal battery efficiency versus losses due to battery weight for different assumptions regarding the weight—energy relationship in a vehicle at 90% and 97.5% battery efficiency. West European electricity is used.

As in the calculations with different electricity mixes, at 97.5% internal battery efficiency, losses due to battery weight are larger or equal to the losses due to internal battery efficiency, except in the case of 15% weight—energy relationship. At 15% weight—energy relationship, losses due to battery weight are larger than the losses due to internal battery efficiency even with 97.5% internal battery efficiency and six times larger at 90% battery efficiency.

The different electricity mixes used represent well the “carbon extremes” of what can be found throughout the world: from the Scandinavian mix of mostly nuclear and hydropower scoring 196 g CO2/kWh over West Europe’s 570 CO2/kWh to 1250 CO2/kWh in China. Similarly, the weight—energy relationships from 15% to 50%, must be considered extremes for PHEVs, see also Chapter 4.2.

Thus, it can be concluded that the global warming impact from internal battery efficiency losses are two to six times the impact from losses due to battery weight in PHEVs all over the world, at 90% internal battery efficiency. The same result is obtained for the other impact categories, since the use phase only contains energy related processes. At 97.5% internal battery efficiency, the conclusion is different, but considering that the figure should cover both discharging and conditioning, see Chapter 3.9, it is unsure if 97.5% is at all realistic today.

5. Discussion

The main objective of the study was to inspire industry to do life cycle assessments in connection with designing lithium-ion batteries for PHEVs and use the results to improve their products’ environmental performance. A lot of attention was therefore given to identifying general difficulties and issues associated with LCA of
such batteries and to share knowledge about the environmental impact of lithium-ion batteries in a life cycle perspective. In this case study, particular attention was given to lithium-ion cell manufacturing using water as solvent for the anode and cathode paste, compared to using NMP as a solvent. Swerea IVF, which commissioned, carried out and financed the study is carrying out in-house laboratory trials with tape-casting of cathodes using water instead of NMP as a solvent in the cathode slurry.

5.1. Comparison with other studies

The results were compared to three other studies or LCA data related to lithium-ion battery technology. For the production phase, one of the studies (Ecoinvent, 2008) report around five times more global warming impact while two studies (Ishihara and Kihira) and Matheys et al. (2005) report a bit less but in the same order of size global warming impact. For the use phase one study (Matheys et al., 2005) reports the same environmental impact while the two other studies do not model the use phase. The system boundary of the recycling phase in this study seems to be too different from the other studies to allow a meaningful comparison.

It should be noted that the SUBAT study (Matheys et al., 2005) presupposes that three batteries are required to obtain 3000 charge cycles, i.e. 1000 cycles per battery which was equal to the commercialization goal of the United States Advanced Battery Consortium, USABC, at the time of the SUBAT study. Today, the equivalent goal is 5000 cycles, so it is not unreasonable to assume that one lithium-ion battery of today (or tomorrow) can replace three dated year 2004—2005, the time of the SUBAT project. Concerning internal battery efficiency versus battery weight, it should be noted that the SUBAT study also found that the internal efficiency caused more environmental impact than the battery weight during the use phase (Matheys et al., 2008).

5.2. Critical assumptions

The modeling of the use phase contains many critical assumptions. One of them is the assumption concerning internal battery efficiency and associated electricity losses of the battery during the lifetime use. As mentioned above, it is difficult to find information about internal battery efficiency of lithium-ion batteries and what is included and not included in stated figures. Also the assumption concerning the extra electricity and fuel needed to carry the weight of the battery must be considered as very unsure. Therefore, both these assumptions were varied in the sensitivity analysis in order to understand their influence on the results.

With the limited perspective — only looking at the battery and not the whole vehicle — there is a risk that some important aspects related to PHEV battery efficiency might not be included in the study and therefore neglected in the design of the system as a whole. This study included the complete lithium-ion battery with electronics, wiring and casing. It did not include any other hardware in the electric power train: the battery charging equipment was not included and the electric engine and its power regulation were not included as hardware. However, the study use information on efficiencies related to the electric engine and further down the power train (battery-to-wheel), as well as efficiency related to charging (plug-to-wheel), in order to estimate the losses attributable to the battery.

More braking energy can be regenerated to electricity if the vehicle is driven carefully and with planning ahead so that the electric engine is used for braking as much as possible (Håkansson, 2008).
2008). This influence of driving behavior is at least partly covered in the sensitivity analysis by varying the weight—energy relationship: the more regenerative braking, the less percentage of vehicle energy consumption can be related to car weight.

Using NMP is the generally used and mature technology with which manufacturers can achieve the performance characteristics of today’s LiFePO₄ batteries. However, NMP is problematic mainly because it is easily absorbed by the skin and/or inhaled and can give genetic damages. Research (Guerfi et al., 2007; Cai et al., 2009; Lee et al., 2008; Porcher et al., 2009) indicates that it is possible to produce a LiFePO₄ cathode using water as a solvent with equal characteristics to one produced using NMP as solvent. The study assumes that this is possible; however, it has not yet been proven in commercial applications.

Some readers may be missing a comparison with combustion powered vehicles. However, this LCA does not aim to justify and argue for electric vehicles. It aims to explore how LCA can be used to optimize the design of lithium-ion batteries for plug-in hybrid electric vehicles.

5.3. Data gaps

In general, the study lacked cooperation with a battery manufacturer to provide data on battery manufacturing. Furthermore, data for the binders and the lithium salt in the electrolyte had to be approximated. For the following materials it was necessary to make quite rough assumptions and approximations:

- Production of LiFePO₄
- Production of PVDF
- Production of styrene acrylate latex binder
- Production of lithium salt for the electrolyte
- Production of styrene butadiene latex binder
- The battery production processes tape-casting, nano-spinning, cell assembly, module assembly, battery system assembly.

According to literature (Gaines and Cuenca, 2000), the salts used in the electrolyte are very expensive. This indicates a higher environmental impact for the electrolyte than shown by the study results, since there is very often a strong correlation between price and environmental impact (Gregory et al., 2009).

As mentioned in 5.2, there is a lack of documentation concerning the relationship between weight of vehicle and vehicle energy consumption, especially concerning electric and hybrid electric vehicles. Also information about internal battery efficiency of lithium-ion batteries and what is included and not included in stated figures is lacking. Furthermore, there is a lack of knowledge about recycling of LiFePO₄ power train batteries.

The study relied to a large extent on global or regional averages from the Ecoinvent database (Ecoinvent, 2008). This type of data is sometimes more appropriate to use in LCA than specific data, for example when raw materials are traded on a global market, which was the case for commodities like iron, aluminum and copper in the study. A major advantage of using specific data, though, is related to supply chain cooperation. When the battery manufacturers start asking their suppliers about LCA data, things may begin to happen as it sends signals to the suppliers that their performance is being monitored. This, in turn, may lead to improvements (Zackrisson, 2009). On the other hand, a lot of LCAs have been stranded in search of data from suppliers that do not have the data or are unwilling to share them. In this study a lot of effort was spent on asking industry for data with very little result.

Lastly, the studied batteries do not exist in reality, only on the drawing board. The general conclusions presented below are therefore limited to results showing robustness against variation in critical data.

6. Conclusions

The study could confirm that it is environmentally preferable to use water as a solvent instead of NMP in the slurry for casting cathodes and anodes of lithium-ion batteries, even though the impact from the possible solvent emissions at the workplace was not modeled. NMP has been identified as a reproductive toxicant. However, it has not yet been proven in commercial applications that LiFePO₄ made by using water are equal in characteristics to those made by using NMP.

In the production phase, global warming impacts are dominated by energy use in manufacturing (>50%), electronics (30%) and the cathode (10%). Transportation of raw materials and components has little (3%) impact.

Recent years’ improvements in battery technology, especially related to cycle life, have decreased production phase impacts almost to the level of use phase impacts. Nevertheless, the sensitivity calculations showed that the production phase impacts are almost always larger than the use phase environmental impacts. Only when the PHEV is being driven in countries with a very coal-dependent electricity generation the impacts are similar across all the five impact categories.

Concerning the relative importance of battery weight and battery internal efficiency, the sensitivity calculations showed that the environmental impact from internal battery efficiency losses is two to six times larger than the impact from losses due to battery weight in PHEVs, all over the world, at 90% internal battery efficiency. Thus, internal battery efficiency is a very important parameter; at least as important as the battery weight.

References


Ishihara, K., Kihira, N. Environmental Burdens of Large Lithium-ion Batteries Developed in a Japanese National Project. Central Research Institute of Electric Power Industry, Tokyo.


Kotaichi, K., Slop, S. Cradle to Cradle Battery Materials.


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