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Life Cycle Assessment of Li-ion Batteries for Electric Vehicles

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MASTER THESIS

for

Student Bjørn Grimsmo

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Life Cycle Assessment of Li-ion Batteries for Electric Vehicles*Livsløpsanalyse av li-ion batterier for elektriske kjørelø***Background**

Concerns about global climate change have made reducing emissions of greenhouse gases (GHG) a priority for both domestic and international policy in many developed countries. Light duty vehicles used for personal mobility are responsible for approximately one-tenth of the energy usage and GHG emissions worldwide. The population of light duty vehicles is expected to grow dramatically over the next several decades, making it particularly difficult to reduce GHG emissions. Because of their reduced tailpipe emissions, electric vehicles (EVs) have been promoted as an attractive alternative to conventional fossil fuel vehicles. When the batteries of these vehicles are charged with grid electricity they offer the possibility of using low-carbon energy sources.

However, EVs have been criticized for the additional environmental impacts associated with battery production. Life cycle assessment studies suggest that lithium-ion (Li-ion) battery production have large impacts. There are different Li-ion chemistries on the EV market, and the difference in production impact between these chemistries has not been sufficiently studied.

The Industrial Ecology Group has compiled a detailed life cycle inventory for the production a lithium nickel-cobalt-manganese oxide battery.

Aim

The main objective of this work is to assess the environmental impacts associated with the production of various types of Li-ion batteries for electric vehicles.

The core analysis should include following elements:

- 1) Introduction and motivation including state of the field
- 2) Overview of Li-Ion battery chemistries.
- 3) Development of life cycle inventories for different type Li-ion chemistries through adaption and harmonization of existing datasets.
- 4) Environmental impact assessment and system contribution analysis.
- 5) Analysis and discussion.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department/supervisor.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

- Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
 Field work

Department of Energy and Process Engineering, 29. January 2014



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Summary

Batteries for electrical power storage is emerging as a significant industry branch, as we search for technologies to mitigate anthropogenic global warming. Whether as part of a realistic solution, or just as a superficial consumerist trend that shifts emissions elsewhere, *electric vehicle* production and use is on the rise. As such, the scrutiny of *life cycle assessment* needs to be applied to this field as well, and here my work begins.

This master's thesis is the creation of life cycle inventories on the *cathode* technology of batteries of the *lithium cobalt oxide* (LCO) and *lithium manganese oxide* (LMO) type. I have studied and accounted for the industrial processes needed to create the metal oxides for these cathodes (the most significant components of the battery), and implemented these in a battery inventory model designed by Ellingsen et al. (2013). It was necessary to update the inventory on *synthetic graphite* for the *anode*, so I have done this as well. Key elements in these inventories, such as energy data, comes from industry sources.

The analytical results indicate that, given assumptions of production in mainland China and high energy storage capacity, LCO battery production is less carbon intensive than the NCM battery of the Ellingsen model, whereas LMO production is more. The differences come mainly from variation in battery mass due to different capacity when normalizing the model for 26,6 kWh. Electricity usage accounts for significant parts of the emissions, and changing to cleaner electricity mixes reduces emissions.

Lack of detailed production data prevents the application of results in other impact categories. Cobalt is a toxic metal, and appears in lower abundance than manganese, yet appears superior in most respects in this study. Is this right? More research must be done on cathode production, particularly on metal extraction, refining and industrial heating.

Sammendrag

Batterier for lagring av elektrisk effekt er på vei framover som en fornyet industrigren, et element i vår leting etter tekniske løsninger for å begrense menneskeskapte klimaendringer. *Elektriske kjøretøyer* er i vinden, uavhengig av om de representerer en genuin løsning, eller bare er et motepåfunn som flytter problemet annensteds. Som sådan må nye, store batterier granskes med *livssyklusanalyse*.

Denne masteroppgaven handler om å skape et livssyklusinventar for katode-teknologien i batterier av typen *lithium-kobolt-oksid* (LCO) og *litium-mangan-oksid* (LMO). Jeg har studert og gjort rede for de industrielle prosessene som brukes for å lage metalloksidene til disse katodene (som er batteriets viktigste komponenter), og satt disse inn i et inventar utviklet av Ellingsen et al. (2013). Det var nødvendig å oppdatere dette inventaret med *syntetisk grafitt* for *anoden*, så dette har jeg også gjort. Nøkkelelementer i disse inventarene, først og frems energi-data, kommer fra kilder i prosessindustrien.

Resultatene indikerer at, gitt antagelser om produksjon på det kinesiske fastlandet, og høy energilagringsskapasitet, produksjon av LCO-batterier fører til mindre karbonutslipp enn Ellingsen-modellens NCM-batteri. LMO-batteriets produksjon er mer karbonintensiv enn begge disse. Forskjellen kommer primært fra ulik størrelse på det modellerte batteriet, på grunn av ulik kapasitet, når batteriet normaliseres til 26,6 kWh. Elektrisitetsforbruk utgjør størstedelen av utslippene, og om man flytter produksjonen til et sted med en renere strøm-miks, går utslippene ned.

Mangel på fin-detajler om produksjon gjør at resultatene for andre typer miljøeffekter blir vanskelige å anvende. Kobolt er et giftig metall, og finnes i mindre forekomster enn mangan, men framstår i denne modellen som det beste alternativet. Stemmer dette? Mer forskning må gjennomføres på katodeproduksjon, og da særlig innen metallutvinning og -prosessering, samt industriell varmebehandling.

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1: Introduction

1.1: Battery sciences

This is the conundrum of the Life Cycle Assessment sciences: Even as we strive to enhance knowledge and understanding of the materials and energy flows passing through the industry, we are fully aware that all of this information is already known, by thousands of people all through the system.

The mine foreman knows exactly how much explosives and chemicals he needs to extract the copper-cobalt-containing ore from the Congolese rock, and he has first-hand experience with the durability of his machinery. The book-keepers of the wholesale traders have precise knowledge of the distances their lithium carbonate is hauled by truck, train and ship from Atacama, Chile to the battery factory. As the rotary kiln is fired up, and the Gabonese manganese dioxide is reduced to monoxide, there are people present who could tell the exact amount of fuel used, and they will be acquainted with people knowing how much steel and alloys went into making the kiln in the first place. In a file somewhere in France, there is written down the optimal mixing proportions of coal, coke, pitch and soot for making graphite. This is the nature of all the things we research: *they are already known*. But in the great ever-evolving enigma that is human society, with its crude competitive conditions and irrational traditions and practices, this information is all hoarded up and salted down, kept out of sight behind physical and legal walls, to stay there.

With this in mind, I have set out to produce this master's thesis on lithium ion battery cathode materials, with a little synthetic graphite on the side. My hope is that this thesis will count as a small but significant advance in our shared understanding of electric energy storage and its place in the great struggle against anthropogenic global warming. A golden age of battery application is about to commence. As Nissan, Tesla and other producers are churning out new electric vehicles at prices and with characteristics appealing to Western motorists, the need to properly map the impacts of lithium ion battery production is greater than ever. The use of consumer gadgets and machines reliant on lithium ion batteries does not seem to slow down either.

The materials in question are lithium cobalt oxide (LCO), lithium manganese oxide (LMO) and synthetic graphite. The two lithium compounds LCO and LMO give batteries with different safety, reliability, power and energy capacity, and have complementary applications in consumer goods. We will have a closer look at the environmental impacts from batteries with these different chemistries. Synthetic graphite is a substance used in the anode (negative electrode) in both battery types. Thus, it is not actually part of the model comparisons, but a supplement that has been

assessed because there was an opportunity. It turns out that the Ecoinvent entry on battery-grade graphite is just an approximation from naturally mined graphite, and does not properly reflect the energy- and materials-intensive production process of battery graphite, so I have set as my secondary task to provide a better attempt at a synthetic graphite inventory.

The purpose of this thesis is twofold: First and foremost, I wish to produce insight on the impacts of lithium cobalt and lithium manganese battery production, as an end in itself. This is the major strength of this master's thesis. But it is also important to be able to place these battery types in a larger context, with several other types used in similar applications. Several studies have already been published comparing different technologies and their impacts, yielding large differences. The second purpose of this thesis is thus to provide a comparison between different technologies on a more standardized basis, where I use one battery model and change only the cathode materials. Several studies have been published for different cathode materials, but my study is an attempt to make these comparisons with the same basis. In addition to LCO and LMO, I will include the impacts from the nickel-cobalt-manganese (NCM) model by Ellingsen, Majeau-Bettez, Singh, Srivastava, Valøen and Strømman (2013). With the NCM model, I will also make a comparison before and after synthetic graphite has been implemented.

Ellingsen et al.'s established NCM model will serve as a vessel for my analyses. It is a comprehensive electric vehicle battery model based on industrial data from Miljøbil Grønland which in addition to cathode and anode materials also includes the rest of the battery, with structures, management systems and cooling. This allows me to simulate an entire battery pack. This is useful because different cathode materials have different energy capacities. A material with high energy capacity (like LCO) would be required in smaller amounts to provide the same energy storage as a material with low capacity (like LMO). This would also equal fewer cells and cell modules, leading to less material and energy usage in the complete battery.

An important part of this thesis is the research behind the numerical impact assessments: Describing the methods and technologies applied by real world industry in the production of the cathode materials. This part has its own dedicated chapter, where I try to explain all the industrial processes in simple terms, and to help making sense of some ambiguous terminology.

The thesis has this setup: Following this introduction, I will give a brief overview of battery essentials. This will be followed by a review of existing research on LCO and LMO battery life cycle assessment.

Chapter 2, *Methodology*, will be an introduction to the Leotief inverse method for estimating

environmental impacts from production, followed by an introduction to the ReCiPe impact category classification, which provides meaning to the figures presented in this thesis.

Chapter 3, *System description*, will be a large chapter dedicated to the specific issues I have been researching. First there will be an introduction to the comprehensive Ellingsen (2013) model of NCM batteries, so that my work within this model can be understood. Second, there will be some notes on how my data has been implemented in the Ellingsen model. Following this will be one of the main innovations in my project: A thorough description of production systems used for LCO and LMO cathode manufacture, as well as synthetic graphite. Finally, I will introduce the different scenarios that I have made to check the sensitivity of my models.

Chapter 4, *Results*, will be a compilation and description of statistical results, with appropriate graphs and tables. First I will look at my results in comparison with one another and with the Ellingsen NCM model, and in the second part I will compare my model with those of other researchers.

Chapter 5, *Discussion*, will be just that – some reflections over what was demonstrated in the previous chapter, and what implications this might have for battery manufacture and use. But I will also go through weaknesses of my model.

There is an appendix as well, beyond the bibliography, which contains complete tables of my LCO, LMO and synthetic graphite inventory contributions. I will also provide a justification of all numerical values in the inventory in the appendix.

1.2: Battery essentials

The battery is a form of energy storage where specific chemicals are stored inside a box, with an internal connection between certain chemical parts. When a conductor is connected between the battery's positive and negative side, a series of chemical reactions are allowed, which induce a flow of electrons (electric current). When connected to a load, this allows the battery to deliver energy to the load, until there is no more potential for the chemical reactions to happen. When connected to a source, this allows the (rechargeable) battery to absorb and store energy, until all the chemicals have had their reactions reversed.

A battery is composed of any number of voltaic cells. A voltaic cell is the basic unit of a battery. It contains two half-cells, with a connection that allows the passage of ions (atoms with non-neutral charge) from one half-cell to the other. Inside the half-cell is an electrode, which is a

rod of conductive material, and some electrolyte, which is a fluid or paste with ions floating freely around. One half cell is positive, in which the electrode is known as a *cathode*. The other is negative, and holds the *anode*.

When an external conductor is set up, a series of chemical reactions is allowed to happen in the half-cells. The conductor allows the passage of electrons from the anode (where negative ions accumulate and give away their surplus electrons) to the cathode (where positive ions are attracted and absorb their missing electrons). The ions are allowed to travel through a membrane that keeps the electrolytes separate. When electrical current is forced upon the half-cells, in the opposite direction, positive ions are created at the cathode and are attracted through the membrane, to the anode where negative charge is building up, and the negative ions go the other way. Thus, the battery sets itself up to be used again.

This is the basic model of the battery, and the principles that the lithium-ion battery is a continuation of. This set of battery chemistries gained popularity from the 1980s, through the 90s and beyond 2000 as production costs went down and capacity was increased (Battery University, no year). In this battery, the cathode is covered with a compound of lithium and some other metal, together in oxide form, and the anode is covered with graphite, a porous form of carbon. The electrolyte also contains lithium, in the form of a lithium salt, along with some organic solvents (National Power Corporation 2011). The lithium and graphite electrodes have structures that allow ions to be absorbed into them. With this technology, lithium ion batteries have storage capacities from 100 to 190 Watt-hours per kg cathode material (Battery University, no year).

1.3: The ones that came before

A number of studies have been made in recent years regarding the environmental impacts of lithium-ion batteries, in the context of batteries for electrical vehicle use. First among these I will count Ellingsen et al. (2013), a study of lithium nickel-cobalt-manganese oxide batteries delivered by Miljøbil Grenland, based on a battery recipe delivered by said corporation. The purpose of this article is to provide “a transparent inventory for [an NCM] traction battery”. The dataset of the article connects with the Ecoinvent database, and allows the article to provide analysis of environmental impacts. For a battery pack of 253 kg, with a storage capacity of 26,6 kWh, the greenhouse gas emissions are around 4600 kg carbon dioxide equivalents (ibid.). The Ellingsen article also provides a comparison with other, similar studies. In this comparison, the GHG emissions per kWh storage capacity is 172 kg/kWh. Particular to the Ellingsen et al. (2013) study,

aside from the inventory, is the range of estimations of energy demand for battery cell manufacture, based on data from manufacturer.

Another home-grown scientific effort in this field is the article “Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles”, by Guillaume Majeau-Bettez, Troy R. Hawkins and Anders Hammer Strømman (2011). This is a study of NCM, lithium iron phosphate (LFP) and nickel metal hydride (NiMH) batteries. Some of the most important information for the Ellingsen et al. (2013) work originates from this study. Energy demands are estimated from sets of production assumptions, and for the NCM battery the global warming potential is 200 kg CO₂-eq per kWh storage capacity.

Next, Notter, Gauch, Widmer, Wager, Stamp, Zah & Althaus (2010) should be mentioned. Their article, “Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles”, is a study of the environmental impacts of internal combustion engine vehicles and electric vehicles, where the latter is powered by a lithium manganese oxide battery pack. The battery has a mass of 300 kg, with an energy capacity of 0,114 kWh/kg (ibid.). The article and its background material report 6 kg CO₂ equivalents per kg battery produced, which is 53 kg CO₂-eq per kWh storage capacity. Of interest in Notter et al. (2010) are also some brief descriptions of key processes in cathode material production.

In 2013, the United States Environmental Protection Agency (EPA) published their report “Application of Life-Cycle Assessment to Nanoscale Technology”, which concerns several lithium ion chemistries, including NCM and a chemistry that is LMO or very similar. In addition, the report deals with single-walled carbon nanotube materials as a replacement of current graphite in anodes. The results are presented as kg CO₂-eq both per kWh energy storage, and per km vehicle usage for electric and hybrid vehicles. The LMO (presented as LiMnO₂) ends up at a battery total of 63,4 kg CO₂-eq per kWh, while the equivalent NCM value is 121.

“Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries” is the name of a 2012 article written by Jennifer B. Dunn, Linda Gaines, John Sullivan, and Michael Q. Wang. This article considers recycling of cathode materials, instead of virgin resource use, and presents the environmental impacts of different recycling methods for production of LMO batteries for hybrid and electric vehicles. The main findings of the study are that for an electric vehicle, GHG emissions come at about 5,1 kg CO₂-eq per kg battery, the total energy use is 75 MJ per kg produced battery, and the energy use can be reduced by as much as 48% in a closed loop recycling scenario. Using the data on the battery Dunn et al. studied, which has a mass of 210 kg and a storage capacity of 28 kWh, it can be

calculated that the storage-specific global warming potential is 38 kg CO₂-eq per kWh capacity.

Some additional sources of LCA research can be found from producers of electric vehicles. Companies like Volkswagen and Daimler-Benz publish brochures extolling the virtues of their “green” alternatives, usually verified by independent research institutions, providing information of cradle-to-grave environmental impacts. Background information material is usually available, allowing readers to review assumptions and some data, like in Volkswagen's “The e-up Environmental Commendation – Background Report” (2013). This material is, however, of limited analytical use, as the breakdowns of impacts do not give specifics about the battery – often not even the chemistry, so that numerical information for scientific purposes will have to be founded in assumptions.

1.4: Ground left to be broken

Upon reviewing this previous research, it becomes clear that there are at least three contributions that my research can provide to the field: An LCO inventory, more precise inventories overall, and a unified model to analyze both NCM, LMO and LCO in the same context.

First, we notice the gaping hole in the literature where lithium cobalt oxide should have been. This cathode chemistry seems widespread use is electronics, yet has been subject to few scientific studies. Research on LCO batteries should be brought up to speed along with the others, so that the impacts can be compared.

Second, things can be done to improve the accuracy of existing research. The Ecoinvent database does not have an explicit inventory for synthetic graphite, which is used in the anodes of lithium ion batteries. For this master's thesis, I have collected an inventory of synthetic graphite, which includes all the most significant materials and energy inputs. But there are other fields as well that could do with updating. Notter et al. (2010) includes a section on the production of lithium manganese oxide (LiMn₂O₄): “*lithium manganese oxide (LiMn₂O₄) is made from Mn₂O₃ and Li₂CO₃ by means of several roasting stages in a rotary kiln*”, using a 2003 patent claim as the source. It is true that the precursors are mixed and heated at high temperature to produce the cathode material. But settings and temperature control is important to produce the optimal particle size, which is not something that can be consistently achieved in a rotary kiln – a crude industrial machine usually associated with large-scale cement production and ore roasting. There is work to be done on the updating of inventory data with more direct industry sources.

Finally, we have seen that although there are many studies of both LMO, NCM and other

chemistries, they are usually part of separate projects, and environmental impact results fluctuate between models – as seen in the previous chapter, Majeau-Bettez, Ellingsen and the EPA, and all of their associates, get very different values for NCM. Notter, Dunn and the EPA get more consistent results for LMO – but these values are noticeably much smaller than those of the NCM. This leaves an important question: Are lithium manganese oxide batteries consistently more climate friendly than their counterparts of other chemistries, or can these large differences be attributed at least in part to different assumptions in different models? The Ellingsen et al. (2013) model allows me to assess this question, and compare NCM, LMO and LCO side by side, keeping battery technology constant, altering only cathode material and the scaling required to produce similar energy storage capacities.

2: Methodology

2.1: Number crunching

The goal determining the choice of method for this thesis, is a numerical estimation of the total emissions of GHG, as well as the emissions of or increases in other environmental impact stressors, caused by the studied activity. I have chosen the standard process-chain life cycle assessment approach. An LCA is assembled by creating a large numerical table with quantification of all product and energy inputs required to produce a given amount of the product in question, and applying existing data on the stressor impacts caused by production of these inputs. The results of this can be represented in a number of ways, to single out which processes contribute more to impacts, or which stressors are the most important.

To flesh out the methodology a little more, we can do a summary of the mathematics behind the process-based LCA (Strømman 2010). We start with the main matrix, designated \mathbf{A} . This is a square matrix where each row represents the output of a process, and each column the input of the same process. Each cell in the matrix has one value, a_{ij} , which shows the number of units of process i activity required to produce one unit from process j . It is common practice to divide the \mathbf{A} matrix into foreground and background areas, although this is only a cosmetic/conceptual alteration of the matrix, with regard to its data sources, not a mathematical one. Here, the foreground is understood as a set of processes that are integral to the case studied, and which usually need to be constructed by the researcher for this particular model. The background is composed of processes that are already mapped in the greater datasphere. Four different relations exist between foreground and background, established as sub-matrices of \mathbf{A} . The foreground processes are usually used by each other by a specific hierarchy, in the matrix represented by \mathbf{A}_{ff} . The backgrounds are similarly reliant on one another, though usually in a far more complicated manner, detailed in the much larger \mathbf{A}_{bb} sub-matrix. There are also two interface matrices between these: Background processes required in the foreground, as \mathbf{A}_{bf} , and foreground feeding into the background, as \mathbf{A}_{fb} , although the latter tends to have very small values and is usually neglected.

We have another mathematical property, the demand array \mathbf{y} . This array shows how many units of activity from the foreground processes we want to simulate, from one particular foreground process. This is called the *functional unit* of the LCA. For the other processes, the \mathbf{y} values are usually zero.

With these tools, we can find the total units of activity from each process required to

produce the functional unit. We know that the required output must be both the external demand (functional unit), as well as the internal demand mapped in the \mathbf{A} matrix:

$$\vec{x} = \mathbf{A} \cdot \vec{x} + \vec{y}$$

This is a linear system of equations, which has the solution:

$$\vec{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \vec{y}$$

Now x is the total units of output/activity from each process. The inverted term is known as the *Leontief inverse*, where \mathbf{I} is the identity matrix with the dimensionality of \mathbf{A} .

If we now have a stressor matrix \mathbf{S} (for multiple different stressors), or stressor array \mathbf{s} (for one stressor), we can create the emissions, as an array or a scalar, by multiplying with the \mathbf{x} . These results, again, can be multiplied with categorization data \mathbf{C} to finally produce an impact array or scalar. Impacts can be disaggregated into matrices allowing for comparisons of the impacts caused by specific processes (\mathbf{D}_{pro}) or specific stressors (\mathbf{D}_{str}). Assuming data in matrix form, we have:

$$\vec{e} = \mathbf{S} \cdot \vec{x} = \mathbf{S} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \vec{y}$$

$$\vec{d} = \mathbf{C} \cdot \vec{e} = \mathbf{C} \cdot \mathbf{S} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \vec{y}$$

$$\mathbf{D}_{\text{pro}} = \mathbf{C} \cdot \mathbf{S} \cdot \vec{x} = \mathbf{C} \cdot \mathbf{S} \cdot \text{diag} [(\mathbf{I} - \mathbf{A})^{-1} \cdot \vec{y}]$$

$$\mathbf{D}_{\text{str}} = \mathbf{C} \cdot \vec{e} = \mathbf{C} \cdot \text{diag} [\mathbf{S} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \vec{y}]$$

This study is mostly oriented around producing the impacts array \mathbf{d} , with some use of \mathbf{D}_{pro} . In practice, the Ellingsen et al. (2013) model, with my data added, consists of a series of foreground processes, assembled in a chain-like structure, each with a significant number of background processes feeding into it. This composes the \mathbf{A} matrix. The \mathbf{y} array has one entry, the functional unit, which is the mass in kilograms of the battery pack.

2.2: Making sense of numbers

To ease the implementation of data and do the necessary calculations, I will use the MATLAB-based computer program Arda version 1.7.0, which in addition to providing \mathbf{d} , \mathbf{D}_{pro} and \mathbf{D}_{str} also calculates the structural path analysis (SPA). The SPA breaks down the results, looking down the chains of foreground and background processes to determine which chains contribute the most to stressor impacts. Arda takes some input: A template spreadsheet where the foreground processes

have their inventories mapped with references to the background, and with direct stressors assigned. The program draws on an internalized version of the Ecoinvent database.

Ecoinvent is a database and a joint effort between a number of Swiss learning institutions, with a wide range of process categories, including energy supply, fuels, heat production, electricity generation, plastics, paper and board, basic chemicals, detergents, waste treatment services, metals, wood, building materials, transport and agricultural products. Ecoinvent bears no responsibility for conclusions made from my data analysis.

The basis of the impact assessment is the ReCiPe method for category indicators at the midpoint level. Arda calculates results with the ReCiPe method, using the hierarchist perspective (100 year time perspective on global warming potential, infinite on many others). The ReCiPe impact categories are given in **table 2.1**:



Name
Agricultural la

Table 2.1: ReCiPe impact categories: (Goedkoop, et al. 2009)

There are potentially many impact categories to consider for the battery LCA, too many to give all a decent review. At any rate, focus will be on global warming potential, this being the most used category for model comparisons.

3: System description

3.1: The 2013 Ellingsen et al. model

For a 2013 article, based on her master's thesis, Linda Ager-Wick Ellingsen developed an inventory for a *lithium nickel cobalt manganese oxide* (NCM) battery package, used in electric vehicles. The inventory is based on industrial data from the Norwegian corporation Miljøbil Grenland, and holds detailed information on the background inventory demand of many components in an NCM battery package. The model also builds upon work by Majeau-Bettez et al. (2011) on NCM cathode materials, and by Notter et al. (2010) on the electrolyte made from lithium hexafluorophosphate. This model is highly useful for my own master's thesis, as it allows me to replace the NCM cathode material inputs with my own LCO and LMO, and adjust the size of the battery pack to create models of similar energy capacity that are directly comparable in terms of environmental impacts.

3.1.1: What's what with the model

The Ellingsen et al. model uses the lithium nickel cobalt manganese oxide chemistry, which (in that specific case) is a metal oxide with equal shares of nickel, cobalt and manganese in compound with lithium.

The model has four main sections, four components of the battery pack: The packaging, the battery management system (BMS), the cooling system and the battery cells. Structurally, the battery pack is composed of a number of modules, each holding a number of cell units. Each module has a management system, and the pack as a whole has a cooling system. In the base NCM model, there are 12 modules with 30 cells each, making out a total of 360 cells. The total energy capacity of the battery pack is 26,6 kWh.

The packaging consists of the battery tray, the retention holding the battery in place, as well as packaging for the modules. The module packaging includes fixings, frames and conductive busbars leading the energy from the cells. The BMS includes low-voltage and high-voltage systems, and some fasteners and interface systems. The cooling system has a radiator and manifolds for coolant pipes from the modules, as well as fasteners, fitting and the coolant fluid in itself.

Finally, there are the battery cells, the most interesting components. Each cell consists of, as indicated in chapter 1.2, the cell container, the separator, the anode and cathode, and the electrolyte. The electrodes (anode and cathode) are each made up from current collector (aluminium foil) and

electrode paste. The electrode paste is made up from glue and, finally, the cathode/anode material.

We can delve slightly deeper into this model, to review the contributions from Majeau-Bettez, Notter and their associates. Majeau-Bettez et al. (2011) have created a nickel-manganese-cobalt inventory, though I will not be using this. Notter et al. (2010) has an inventory on the lithium hexafluorophosphate electrolyte, and, more importantly, on lithium carbonate. As we shall see, this carbonate inventory is a major input in my LCO and LMO models.

3.1.2: Merging the efforts

The actual implementation of the Ellingsen et al. (2013) model is as a Microsoft Office Excel workbook with interconnected spreadsheets. The spreadsheet is set up to be read by the Matlab Arda program, which accesses the \mathbf{A}_{fr} matrix and the \mathbf{A}_{br} matrix (in array form). The values in the matrices are, in this particular setup, pointers to spreadsheets for the different sections. Within the spreadsheets there are several pointers to chains of sub-inventories, at the bottom of which the numerical input and output values are punched in.

For my master's thesis, I am expanding this model by adding spreadsheets of my own. For the LCO models I have added an LCO cathode sheet and a synthetic graphite sheet. For the LMO models I have an LMO sheet and the synthetic graphite. When implementing cathode materials, I am removing the links to the Majeau-Bettez et al. NCM inventory and replacing it with my own **at the same quantity**. When implementing synthetic graphite, I am removing the pointer to the Ecoinvent entry on battery-grade (natural) graphite and replacing it with a pointer to the functional unit of my SG inventory.

In addition to these new spreadsheets, I am making some minor alterations to some of the existing ones. In my thesis I attempt to inventory shipping induced by the real-world locations of the raw material extraction of lithium, cobalt and manganese. Thus, I have implemented some changes of inventory entries to reflect that the lithium carbonate already existing in the model needs to be shipped from Chile to China (or EU or US, depending on scenario).

One final aspect of the implementation should be mentioned. The Ellingsen et al. Model implements inputs and outputs on a per cell scale, and multiplies this with number of cells per module, and number of modules per battery pack, to get the total material and energy demand, and stressor emissions, for the battery unit. This mechanic allows me to easily alter the size of the battery, to compensate for the lesser or greater energy capacity of different chemistries. As can be examined in detail in the appendix, chapter [A.1.3](#), the energy capacity scenarios chosen for LCO

and LMO suit this approach very well, as they can be approximated by the increase or reduction of cell modules by whole numbers and halves. Altering the number of modules like this affects the total number of cells, the amount of module packaging, and the size of the battery management systems.

With these methods, the Ellingsen et al. (2013) model can be readied for examining the impacts of LCO and LMO cathode usage in comparison with NCM.

3.2: Manufacturing processes

As discussed in the introduction, the first purpose of this article is to establish a comprehensive insight in the production chain of Li-ion cathode materials. This chapter is a walk-through of the production of **Lithium Cobalt Oxide** and **Lithium Manganese Oxide**. As the research project also includes creating an inventory on **synthetic graphite**, this process will also be dealt with.

The focus of this chapter is to provide a fluid and easily accessible reference text for understanding materials production. These descriptions do not necessarily exactly match the quantitative production recipe I am using for the data analysis. The details of the recipe, and the assumptions and simplifications used therein, with their sources, are treated in parallel in the appendix. The purpose of this chapter is to give as complete an understanding as possible of the physical facts of cathode and graphite production.

The analysis will be structured from the bottom and up: After acknowledging what specific substance we are interested in, the production chain will be described beginning at natural resource extraction, moving up through various processes, until the substance in question has been acquired.

3.2.1: Lithium Cobalt Oxide introduction

The lithium cobalt oxide (LCO) battery is one of the main lithium ion types. It is used for a number of applications determined from juggling a series of parameters, as with other Li-ion batteries.

These parameters are:

- Cost of production
- Specific energy (how much energy can be stored)
- Specific power (how much energy can be delivered in a given span of time)

- Safety (does the battery need to be designed to counter thermal runaway problems)
- Performance (can the battery be expected to work consistently over time)
- Life span

In this context, the LCO battery, like the others, offers a trade-off: We get high energy content (110 to 200 Watt-hours per kg) (Targray, no year) (Oswal et al. 2010), but moderate power, life span, performance and safety. The characteristics make the LCO battery suitable for mobile phones, laptops and digital cameras (Battery University, no year). We see thus that the LCO battery is widely applied in consumer electronics, and that an understanding of the inputs and impacts of its production is desired.

The LCO battery is composed, like other Li-ion batteries, of a cathode of the lithium compound, and an anode of synthetic graphite, in a lithium-based electrolyte. See Ellingsen et al. (2013) for specific technical details. The cathode is considered to be the positive electrode when the battery is discharged, as it attracts the electron current and pulls it through the load circuit. The lithium cathode compound in powder form is mixed with glue and pasted on an aluminium current collector. At this level in the production chain, my research begins. For a quick overview, consider figure 3.1:

Lithium cobalt oxide production flowsheet

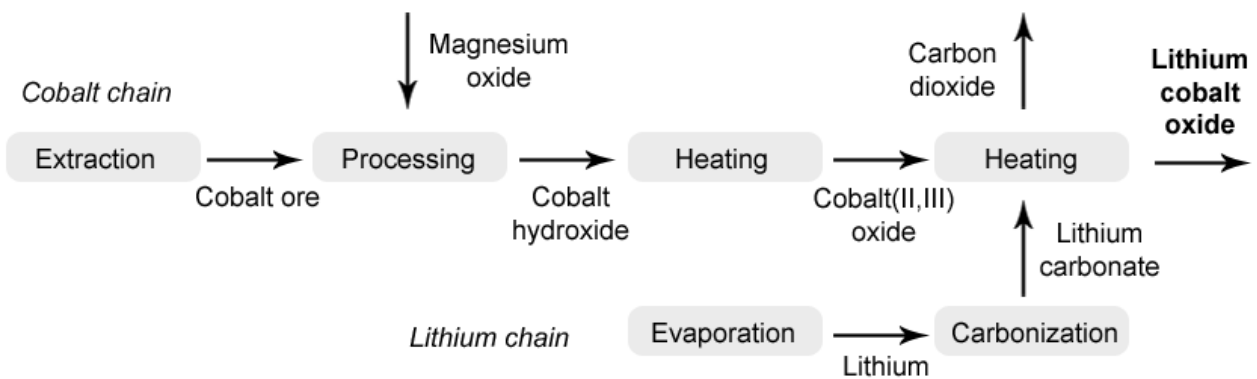


Figure 3.1: Map of major materials and stressor flows associated with production of lithium cobalt oxide.

The cathode material of the LCO battery is **lithium cobalt oxide**, with the chemical formula LiCoO_2 , a compound of one lithium atom, one of cobalt and two oxygen atoms. The *precursor* materials for lithium cobalt oxide are **lithium carbonate** and a cobalt compound (in our case **cobalt(II, III) oxide**) (Hidekazu 2009). Wietelmann & Bauer (2003) describe the cobalt compound

to be **cobalt(III) hydroxide**, which is mixed with lithium carbonate and heated to 900 °C. The more recent Hidekazu (2009) lists cobalt hydroxide along with cobalt(II, III) oxide and **cobalt(II) carbonate** as possible cobalt precursors, and ranks them in order of “preservation stability”. Cobalt(II, III) oxide yields the most stable results, and is reported to be preferred because of the abundance of its supply.

Now we have lithium carbonate and cobalt(II,III) oxide in fine powders. They are mixed at carefully defined conditions (duration, speed) to achieve the optimal molar ratio and homogeneity of the mix. For sensitive electronic equipment such as batteries, homogeneity must be high. Mixing can be done in wet or dry form, but the latter seems to be the norm (*ibid.*). The mixing in itself is not enough to make the precursor materials form lithium cobalt oxide. The mix must be heated to allow the chemical bonds to break and reform.

There are many names for heat treatment in industrial chemistry, and their interchanging usage can be a source of confusion. I wish to clarify the difference between three terms: **roasting**, **sintering** and **calcining**. *Roasting* is a process in the refining of metals from mining, in which the ore is heated and reacted with air. This lets unwanted parts of the ore, like sulfuric compounds, to be converted to gas and vented away. Roasting is a significant source of pollutant emissions to the air. *Sintering* is a process where materials in particle/pebble form are fused together into solid masses, but at temperatures lower than melting point. This process does not necessarily involve air, but relates to internal alteration of chemical bonds. Sintering allows work with materials with very high melting points. *Calcining*, or *calcination*, is a simpler form of roasting with less or no air present, where the purpose is to remove volatile compounds, water, organic matter and other unwanted substances from the treated material. The term originates from the cement industry, where the precursor limestone (calcium carbonate) is broken down to lime (calcium oxide) and carbon dioxide. Obviously, there are often greenhouse gas emissions associated with calcining.

For our LCO process, the method used is a combined calcining and sintering: At high temperatures, carbon and oxygen is removed from lithium carbonate and released as carbon dioxide to the air (calcining). At the same time, the lithium oxide powder is bound together with the cobalt oxide powder to form a lump of lithium cobalt oxide (sintering).

Roasting, calcining and sintering is done in large industrial ovens called kilns. A large number of kiln types have been designed, for various purposes. A standard kiln is the *rotary kiln*, in which materials are heated in a slanted rotating cylinder while hot air flows up through the passage. The rotary kiln has a simple design and relatively low cost, and can be used to produce lithium cobalt oxide. According to Akira Sakai at Kabushiki-gaisha Noritake Kanpanī Rimitedo (Noritake),

however, the rotary kiln offers insufficient conditions for high-end (battery-grade) LCO. High-end companies use the so-called *roller hearth kiln*, in which trays containing the mix are slowly pushed through a large, horizontal oven on ceramic rollers. One producer of such kilns, Daiichi Jitsugyo Co., reports the firing temperature of LCO production to be 1000 °C, with a firing time of twelve hours. The kiln can be both electric and gas-fired (DJK Europe, no year). There are certain CO₂ emissions associated with the removal of carbon from the lithium carbonate, in addition to any emissions from fuel.

After the calcination has been completed, the precursor materials have fused into a lump of lithium cobalt oxide. This lump is crushed and ground into small LCO particles. Again, size must not deviate too much from a set standard (Hidekazu, 2009).

Following Hidekazu's guidance, we determine cobalt(II, III) oxide (Co₃O₄) to be the other precursor, along with lithium carbonate. The following two chapters describe the production of the precursor materials.

3.2.2: Lithium – carbonate from salt water

For the lithium chain, we are looking for the substance lithium carbonate. This is a chemical salt, consisting of lithium and carbon. To start at the beginning, there are two main sources of lithium metal: **rock mining** and **brine evaporation**. Additionally, some lithium is extracted from clay deposits. In **rock**, lithium appears primarily in the mineral *spodumene*, which is extracted from so-called *pegmatites*, mostly from Canada, the US and Australia. Lithium from pegmatites makes up about one fourth of global lithium reserves (Lithium Interesting News, no year).

With the advent of large-scale lithium consumption for battery production, **brine** evaporation is being established as the most important commercial source of the metal. We define “brine” as a solution of a chemical salt in water, which in this case is found (mostly) in salt lakes in South America and the US. Lithium-containing water is pumped from below ground, and evaporated with solar energy to give a concentrate rich in lithium, boron, potassium and other commercial substances. The largest current producer is the Chile-based corporation Sociedad Quimica y Minera de Chile (SQM), working with a brine with an initial lithium concentration of 0,15 %. After precipitating out various salts, the brine concentrate is pumped to a *carbonation plant*. Here, the lithium is purified, and bound up in Li₂CO₃ by the addition of sodium carbonate (Stamp, et al. 2011).

An alternative source of lithium from brine can be found in Tibet. Lake Zabuye has given

the name to the mineral zabuyelite, which is the naturally occurring form of Li_2CO_3 . In 2008, 1500 tons of lithium metal was extracted from the lake, a figure which is expected to increase in the future. Despite this production, the significant lithium demand of Chinese industry comes from the South American salt lakes (LithiumMine.com, no year).

At this point, no more chemical processing is necessary, beyond purification if preferred. Lithium carbonate is shipped to the LCO plant. In my analysis, I will be using brine lithium rather than rock mined lithium.

3.2.3: Cobalt – oxide and hydroxide

Cobalt is a metallic element that sees few uses in its pure form, but which has many purposes in alloys and as a source of chemicals. Alloys with cobalt can give high temperature tolerances, hardness, wear- and corrosion-resistance. Cobalt chemicals have agricultural and medical applications, and are used as pigments in glass, paints and ceramics, as well as catalysts in the petroleum industry. Cobalt is considered a strategic metal, and several nations keep stockpiles (Donaldson 2003).

Cobalt can be found in trace quantities in many rocks, and in sea water. The most significant cobalt ores, however, are the copper-containing carrollite found in the Democratic Republic of the Congo (DRC), linnaeite in DRC and Zambia, and the cattierite found in both these countries and in the US (ibid.). The United States Geological Survey's *2011 Minerals Yearbook* (Shedd 2013) gives a list of newly developed cobalt extraction projects, indicating that the most common cobalt occurrence is with copper and nickel, and that most new projects are opened in the DRC and its surroundings. This region is already producing a significant share of the world's supply, which is dependent on the political stability of the area. Cobalt production is usually *subsidiary* to that of copper or nickel, which means that rules of supply and demand do not apply directly to cobalt – the demand of copper or nickel determines the scale of extraction of the cobalt-containing ores (Donaldson 2003).

Cobalt may be extracted from ore by hydro-, pyro- or electrometallurgical processes, although the hydrometallurgic methods are the most common. Cobalt can be leached from ore with both acidic and alkaline media. Depending on the nature of the ore, processes such as *Gécamines*, *Sherritt Gordon* or *Outokumpu* can be used to separate cobalt and other metals from ore. For DRC copper-cobalt ores, *Gécamines* is the most used process: The ore is roasted at high temperatures to remove sulfuric parts of the ore, leached with sulfuric acid into an aqueous solution, and run

through an *electrowinning* process (a crude form of electrolysis) to remove copper. Adding lime allows for the removal of iron, aluminium and the remaining copper. After removal of nickel and zinc, cobalt is precipitated (creating solid matter from a solution) from the acid leach, and will at this stage be in hydroxide form, Co(OH)_2 (Donaldson 2003). For this precipitation phase, several different agents can be added to the leach to have the cobalt metal precipitate at different purity grades. Calcium hydroxide gives a low-grade cobalt(II) hydroxide, whereas sodium hydroxide gives a considerably better end product. A new development in this field is the use of magnesia, MgO , which also gives a high-grade hydroxide, and is increasing in popularity (Fisher 2011).

The final process to be accounted for is the conversion of cobalt(II) hydroxide to the **cobalt(II, III) oxide** used to produce LCO. Donaldson (2003) reports that Co_3O_4 can be prepared from the thermal decomposition of cobalt salts (like hydroxide) at temperatures below $900\text{ }^\circ\text{C}$, without going into specifics. Paikina et al. (1983) report experiments where Co_3O_4 is synthesized from Co(OH)_2 decomposing in a vacuum at around $150\text{ }^\circ\text{C}$. I have not been able to produce more solid information on this process, nor its material or energy inputs.

3.2.4: Lithium Manganese Oxide introduction

The second battery cathode technology of this thesis is the lithium manganese oxide (LMO). It is relatively similar to the LCO in chemical terms, with the cobalt replaced with two manganese oxides, giving the chemical formula LiMn_2O_4 . This technology offers a more well-rounded set of characteristics than the LCO. It has lower energy content (110 to 160 Watt-hours per kg) (Targray, no year) (NEC 2013) and performance, but higher power output and safety. As with LCO, LMO is widely applied, seeing use in power tools, electric vehicles and medical equipment (Battery University, no year).

The lithium manganese oxide, LiMn_2O_4 , holds one lithium atom, two manganese atoms and four of oxygen. The precursor materials are **lithium carbonate** (Li_2CO_3), as with the LCO cathode, and **manganese(IV) oxide** (MnO_2). Manganese(IV) oxide is a naturally occurring substance, but when high-end lithium ion batteries are produced, natural MnO_2 is not of sufficient purity and quality. Thus, the manganese precursor is synthetic manganese(IV) oxide. There are two main types of this substance: chemical manganese dioxide (**CMD**) and electrolytic manganese dioxide (**EMD**). The latter, **EMD**, is preferred for battery cathode production (Numata 2009).

Again, as with LCO, the precursors are mixed and heated to around $800\text{-}900\text{ }^\circ\text{C}$ (sintering-calcining combination to fuse the materials and remove carbon from carbonate), before crushing

and milling. The next chapter covers the production of the manganese precursor material, as lithium carbonate has already been accounted for. Figure 3.2 gives an overview:

Lithium manganese oxide production flowsheet

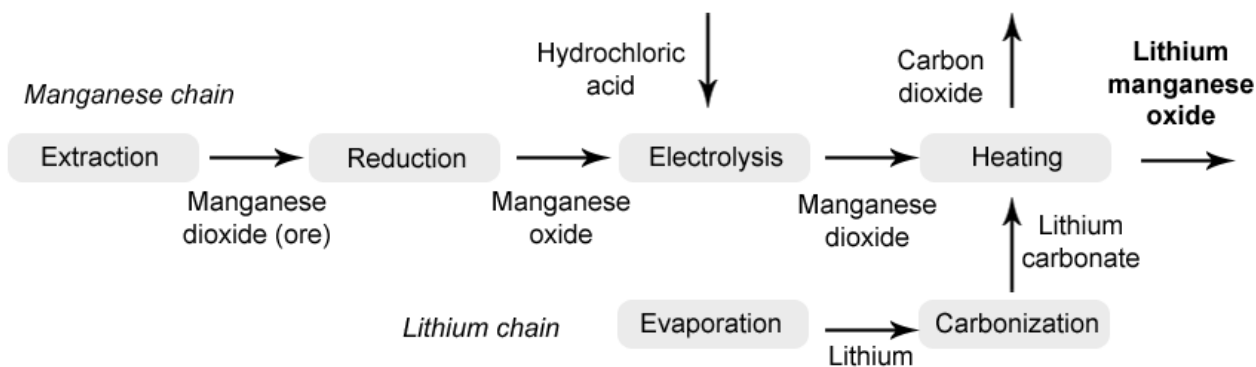


Figure 3.2: Map of major materials and stressor flows associated with production of lithium manganese oxide.

3.2.5: EMD – to monoxide and back again

The production of manganese oxide for lithium ion batteries is rather more complicated than that of cobalt(II, III) oxide. Numerous minerals contain manganese(IV) oxide ore. The most significant, with a manganese content of possibly more than 60 %, are pyrolusite, braumite, manganite, cryptomelane and hausmannite. Ore deposits are largest in South Africa, Gabon, Australia (Wellbeloved, et al. 2003), India and China (Corathers 2009). Only ores where manganese exists as an oxide, are commercially exploited. Current applications, beside battery production, are mostly limited to metallurgy: alloying with manganese gives steel high tensile strength, while aluminium gets increased resistance against corrosion.

The treatment of manganese is very different from that of cobalt, beyond the extraction and crushing of ore-containing rock. We recall how the leaching of cobalt ore in acid allowed for the precipitation and electrowinning of numerous metals. The naturally occurring manganese(IV) oxide (MnO_2), however, is not easily soluble in acid. To get the metal to a state where electrolysis can be applied to it, the dioxide needs to be *reduced* to a monoxide, manganese(II) oxide, or MnO , which is much more readily soluble (Reidies 2003). Reduction can be achieved by reacting the dioxide with several different substances, but the method most readily available and applicable is carbon reduction. Methane, carbon monoxide or carbon is reacted with manganese dioxide in a series of chemical reactions that provide manganese monoxide and carbon dioxide in the end. The process is

mostly exothermic, but parts of it need to be pushed along with addition of heat. Thus, the reduction process takes place in a kiln at temperatures between 800 and 900 °C (Mesa Minerals, no year).

As soon as manganese(II) oxide has been produced, this substance can be leached with acid. The standard procedure described for EMD production is using sulfuric acid, providing manganese sulfate, although as Rethinaraj et al. (1993) have demonstrated, hydrochloric acid is just as applicable, and cheaper. Now, finally, battery grade manganese(IV) oxide can be obtained, as it deposits and accumulates on the graphite electrode of the electrolysis chamber. When the EMD coating on the electrode is 20 to 30 mm thick, which takes between two and three weeks, it is removed mechanically from the electrode, and put through a series of crushing, washing and drying processes.

To sum up this series of refining processes: After extraction, manganese(IV) oxide (two oxygen atoms) is reduced down to manganese(II) oxide (one oxygen), leached with sulfuric or hydrochloric acid, and finally electrolyzed up to manganese(IV) oxide (two oxygen) again, now at sufficient purity. There are two notable energy-intensive steps of the process: the carboreduction of ore with fossil fuels, which is a source of carbon dioxide, and the electrolysis stage, which requires large amounts of direct current.

3.2.6: Synthetic graphite – baking the world's dirtiest cake

In another part of the battery cell, the opposite electrode of the cathode is placed: the anode. In the discharge of the battery, the anode is where the electric current is pushed into the load circuit from, making it the negative electrode. The material of the anode is **graphite**, which is a naturally occurring form of carbon. Apart from being used as the “lead” in pencils, industrial lubricant, and in some unfortunate cases as neutron moderator in nuclear power plants, graphite sees widespread use as electrodes in electric arc furnaces.

As seen before with the lithium ion battery industry, substance quality is everything. Again, the naturally occurring stuff is not of satisfying grade, and an artificial alternative, where production parameters can be easily regulated, is required. Thus, the lithium ion battery industry connects to the substantial industrial effort associated with the production of **synthetic graphite**. Production is illustrated in figure 3.3:

Synthetic graphite production flowsheet

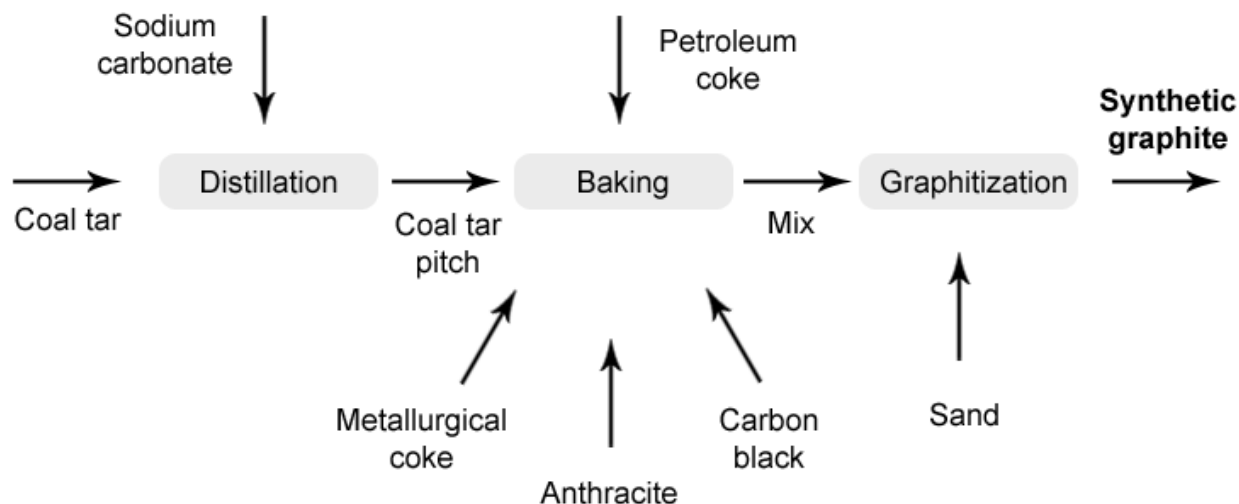


Figure 3.3:

To produce synthetic graphite, a number of precursor materials must be present. Different sources emphasize different mixes, but Jäger, et al. (2012) list **petroleum coke**, **coal-tar pitch**, **anthracite** (hard coal), naturally mined **graphite** and **carbon black** as common raw materials. Matti Rajaniemi at Mersen Group emphasises petroleum coke and coal-tar pitch as the most significant ingredients. The substance with the cryptic name “carbon black” is simply soot, the product of incomplete combustion of carbon fuels – in this case preferably heavy petroleum products. Carbon black is one of the forms pure carbon can take. Petroleum coke is a fuel unit produced from the heavy residual oil left after distilling in the oil refinery. Coal-tar pitch (CTP) is a highly viscous semi-solid, a product of the coal refining industry, traditionally used for water-proofing and sealing wooden vessels and containers.

In the Mersen process, the raw materials are measured out and ground together, to small particle size. After grinding, the precursors are mixed by applying some heat – this causes the pitch to become liquid and bind it all together. After cooling, the mix becomes solid, and is ground once more. After reaching the desired mix, the material is shaped before heat treatment. This is done with extrusion, where the mixture is forced through a die by a piston. Now follows two significant stages of heat treatment, causing the main energy demand of the process.

The first heating is the *baking*. The extruded mix pieces are put in a so-called *ring furnace* for long-term heating to between 800 and 1000 °C. Mersen (2011) reports the length of this heating

to be considerable: one to two months. Jäger, et al. (2012) reports a much shorter duration, about one week. The ring furnace is gas or oil fueled, and has a number of chambers that are being fired and cooled in turn. The purpose of this process is removal of volatile compounds, known as *pyrolysis*. With this process comes an additional material need: The packing and insulation materials that allows the mix piece to retain a stable temperature and keep its shape. In the ring furnace, a mixture of **sand** and **metallurgical coke** is used. The latter is a form of coke different from the petroleum-based form we saw previously, a product of the coal industry primarily used for heating and as a source of carbon in steel production (hence the term “metallurgical”).

After the baking has been completed, the mix is finally ready to be turned into graphite. This happens in the graphitization process, where the pieces are heated in a specialized *Acheson* or *Castner electric furnace* at as much as 3000 °C for one to three weeks (Mersen 2011). Here, the disordered mix of carbon material adopts the hexagonal crystalline structure of graphite. In this furnace type, the pieces are once more supported by packing materials like coke, sand and carbon black (Jäger, et al. 2012), while a powerful electric current is being run through the furnace. When the graphitization phase is finished, we are left with a piece of synthetic graphite that can easily be worked. Both the heating phases are highly energy intensive, and so is the production of the many petroleum- and coal-based precursor materials.

3.2.7: Coal-tar pitch – the special ingredient

Some details should be added regarding the production of CTP. Coal-tar pitch is a by-product of the coal industry. When stone coal is carbonized (pyrolyzed) to produce the purified, carbon-rich fuel known as coke, there is a number of organic by-products, including coke breeze, tar, gas and light oil. “Tar” is the name of a wide array of different liquids of hydrocarbon origin, being produced from wood, oil and peat as well as coal, but we will focus on the coal-tar. Coal-tar is a complex mixture of liquid hydrocarbons as well as solids known as quinoline insolubles (Gray & Krupinski 1997).

Pitch is a product from the continuous vacuum distillation of coal-tar at temperatures between 50 and 400 °C (ibid.) (Jäger, et al. 2012). It forms along with lighter and heavier oils, as well as creosote. Around 50 percent of the tar comes out as pitch. Pitch is a *viscoelastic polymer*, which means that it has characteristics of both liquid and solid matter. At room temperature, it is hard and can be broken, but will flow slowly over long time. When heated to a softening point at about 110 °C, however, it becomes more of a liquid, making it suitable as a binder material in

graphite production (ibid.).

A common issue in pitch production is the presence of ammonium chloride in the tar, which will cause corrosion problems in the distilling infrastructure when it forms hydrogen chloride. Several methods can be used to neutralize the chloride, but a common approach is to add sodium carbonate or sodium hydroxide to the tar, to form relatively inert sodium chloride (table salt). Too much sodium can affect anode reactivity (ibid.).

3.3: Parameter adjusted scenarios

My basic models indicate the difference in environmental impacts of LCO compared with LMO compared with NCM batteries. This in itself is useful enough, but there are several assumptions made along the way that can have had great impact on the final results. My base model assumes that the production of cathode materials takes place somewhere in mainland China. This implies several things: First, that the energy-intensive production will be using the average Chinese electricity mix, which is heavy on coal power, with some hydroelectric power generation. Second, that raw materials will have to be shipped overseas specific distances to China, and from China to Norway. It should however be noted that the first implication is considerably more significant than the second.

The decision to situate LCO and LMO production in China was not made at random. Many suppliers are China-based. According to chemicalbook.com on a web page dated 2010, of 38 global LCO suppliers 18 were Chinese. A similar search for LMO gives 5 Chinese out of a total of 14 suppliers worldwide. China is becoming a major force in the battery industry, and is likely to remain so for a while. Assuming Chinese cathode production is not unreasonable.

However, China is not the only hot spot for battery production in the near future. In 2014, Tesla Motors Inc. revealed plans to build one or more large-scale electric vehicle battery factories in the United States (Wall Street Journal, 05.18.2014). Several locations in the United States have been mentioned as possible sites. It is difficult to find reliable sources for the chemical specifics of the planned plant, but for this thesis I will not go too deeply into this specific case. It is sufficient to say that battery production seems to be a part of the future in the West as well. This is the basis of four more scenarios: LCO production in the United States (west coast) and in the European Union (Germany), and LMO production in the US and in the EU.

There is another most significant assumption that I am making: The energy capacity per mass unit of the cathode material. The Ellingsen et al. (2013) model uses 174 Wh per kg, which is a

relatively optimistic estimate of an NCM battery's specific energy – according to Battery University (no year), it varies between 140 and 180 Wh per kg. For this reason, I have chosen to use optimistic approximations (“high capacity”, HC) of LCO and LMO energy capacity as the base scenarios. They are 200 Wh/kg for LCO and 160 Wh/kg for LMO (see appendix chapter [A.1.3](#) for specifics). The base scenarios are situated in China (see previous paragraphs), although the US- and EU-based scenarios are also HC. To find out how much this assumption means for the environmental impacts, I have set up a “low capacity” (LC) pair of LCO and LMO models, still based in China. For LC, the energy capacity of LCO is 160 Wh/kg and 120 Wh/kg for LMO. This affects the size of the battery pack, as a unit with lower energy content would need more cells to hold the same amount of energy (26,6 kWh in the Ellingsen et al. 2013 model). As seen in [A.1.3](#), this is easily implemented by adjusting the number of modules, not touching the composition of cells within the modules.

These parameter variations, along with the option to compare the base NCM model with an updated NCM model containing synthetic graphite, gives a grand total of 10 models to compare, 9 of which have been modified with my inventories. For all models, it is assumed that synthetic graphite is produced locally, with local raw materials. Consider table **T.3.1** for a summary of the different models.

<i>Model</i>	<i>Cathode</i>	<i>Synthetic Graphite</i>	<i>Production country</i>	<i>Energy content Wh/kg</i>
Ellingsen base	NCM	no	Unspecified, East Asia	174
Ellingsen base SG	NCM	yes	Unspecified, East Asia	174
LCO high capacity	LCO	yes	China	200
LCO low capacity	LCO	yes	China	160
LCO US	LCO	yes	US	200
LCO EU	LCO	yes	Germany	200
LMO high capacity	LMO	yes	China	160
LMO low capacity	LMO	yes	China	120
LMO US	LMO	yes	US	160
LMO EU	LMO	yes	Germany	160

Table T.3.1:

Summary of models (see appendix [A.1.3](#) for details)

4: Results

4.1: My results by themselves

The base model (Ellingsen et al. 2013) has 51 sub-inventories. With synthetic graphite, the model increases to 53. The LCO models have 55 sub-inventories and the LMO models have a total of 56 each. To simplify, I have for each set of models, sorted the sub-inventories into six main fractions.

They are:

- **Battery assembly:** The assembly of packaging, cells, BMS and cooling into a whole.
- **Battery packaging:** All packaging sub-inventories, including assembly.
- **BMS:** All battery management system sub-inventories, including assembly.
- **Cooling system:** All cooling system sub-inventories, including assembly.
- **Cell assembly and structure:** As it says.
- **Cell anode and cathode:** The chemical parts of the cell.

These categories will be recurring in the presentation of my results.

We begin with the most interesting impact category: Global Warming Potential. The amount of CO₂ emissions, or emissions of CO₂ equivalents, from production of such and such batteries, is the most readily understandable of the ReCiPe impact categories.

Let us look at synthetic graphite first, to get it out of the way. When implemented in the Ellingsen et al. (2013) model, synthetic graphite makes so small a difference that there's no meaning trying to demonstrate it graphically. Keep in mind that the battery is the result of a large set of processes, and that the negative electrode paste in the anode is just a small bit of the total mass of the battery. Regard table 4.1 for comparison before and after addition of synthetic graphite.

	Battery assembly	Battery packaging	BMS	Cooling system	Cell assembly and structure	Cell anode and cathode	Sum
NCM + SG	2,31E+01	5,41E+02	2,19E+02	9,66E+01	2,89E+03	8,80E+02	4,65E+03
NCM	2,31E+01	5,41E+02	2,19E+02	9,66E+01	2,89E+03	8,15E+02	4,58E+03

Table 4.1: CO₂-eq. Emissions (kg) from 26,6 kWh nickel-cobalt-manganese oxide battery package production, after and before implementation of synthetic graphite as negative cathode material.

The replacement of the natural graphite in the negative electrode with synthetic graphite does not alter the size or composition of the battery. Thus, the only change we observe is a slight increase in emissions in the anode/cathode category. Synthetic graphite causes the greenhouse gas emissions to increase with about 70 kg, an increase of about 1,5 %. This is not a very significant increase, but over the production of thousands of batteries, it will add up. We now have a slightly more accurate measure of the global warming potential of NCM battery production.

It is time to move on to more important results. Now we look at NCM (with synthetic graphite) in comparison with LCO and LMO, consider figure 4.1:

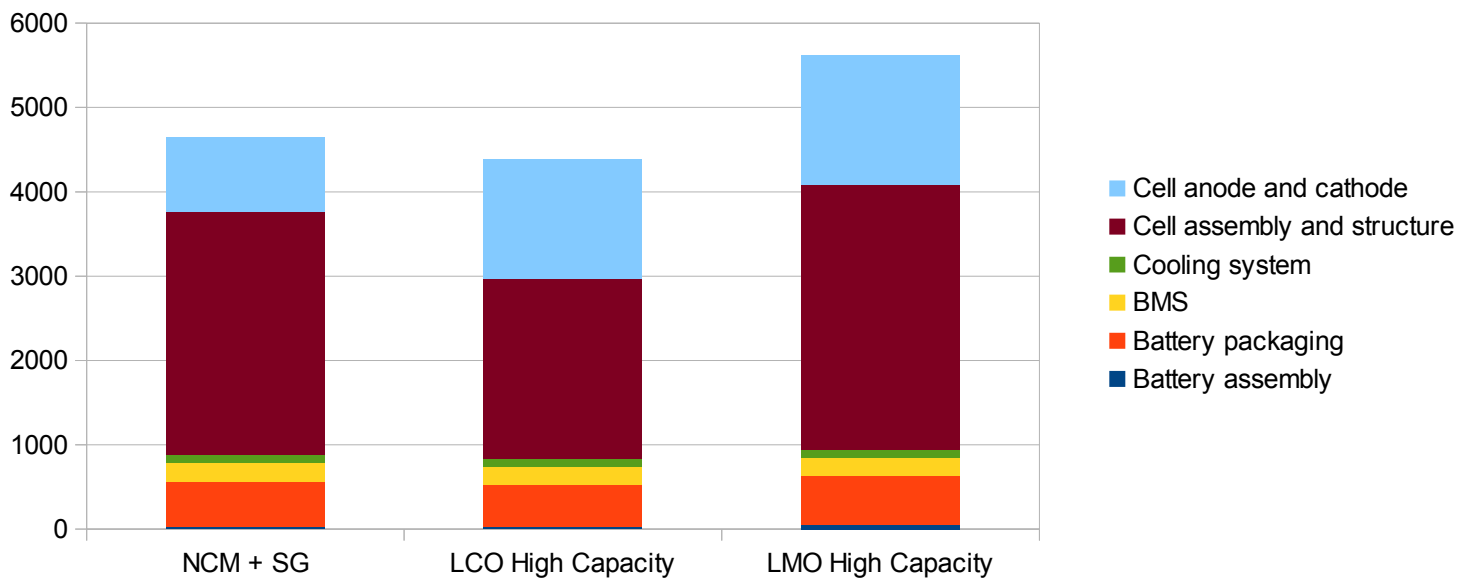


Figure 4.1: Comparison of kg CO₂-eq emissions from NCM, LCO and LMO battery packs at approximately 26,6 kWh, assuming high energy capacity in LCO and LMO.

This primary result shows that the **LCO** battery is slightly less carbon intensive (**4390 kg CO₂-eq**) than the **NCM** battery (**4650 kg CO₂-eq**), although hardly at a significant level. The **LMO** battery, on the other hand, causes significantly larger emissions (**5610 kg CO₂-eq**) in production than both the **NCM** and **LCO** battery. The source for the differences is clearly visible: assembly of voltaic cells. In practice, this category is dominated by the power demand of cell assembly (see structural path analyses in [appendix 3](#)), and altering the chemistry of the cathode does not alter anything here. The actual cause for the large variation is the differences in energy capacity of different materials. The **LCO** battery requires ten and a half modules, compared with the standard twelve of the **NCM** battery, whereas the **LMO** battery uses thirteen modules.

This, however, is not the only result of note. We can see that the relative magnitudes of the “Cell anode and cathode” category are different for the models. Although **LCO** produces less emissions overall than **NCM**, the anode and cathode part is larger. This indicates that the production of a mass unit of lithium cobalt oxide in my inventory is substantially more carbon intensive than that of lithium nickel-cobalt-manganese oxide of the Ellingsen et al. (2013) inventory. Emissions in this category from **LMO** is about the same magnitude. But now we must keep in mind that the **LMO** battery has a lot more modules (and cells) than the **LCO**. The bottom line is that the production of a mass unit of lithium manganese oxide is causing less emissions than an equivalent mass unit of lithium cobalt oxide.

The other categories are of relatively small relevance, and their impacts seem to be following the trend of lower and higher number of modules.

Let us move further through my model sets. The primary issue with the previous comparison was the very optimistic assumption of cathode energy capacity. If we instead implement the lower capacity model (LCO at 160 Wh/kg and LMO at 120 Wh/kg) and compare it with the NCM inventory, we can see significant differences in figure 4.2:

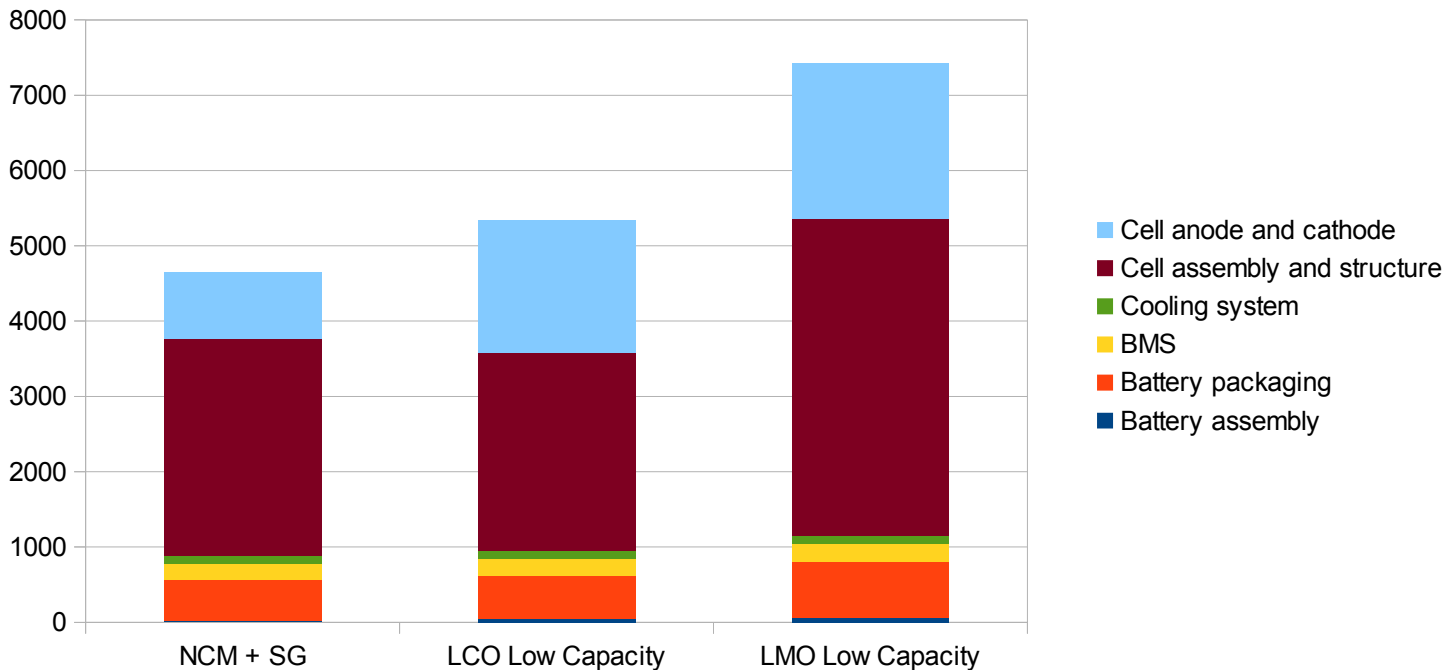


Figure 4.2: Comparison of kg CO₂-eq emissions from NCM, LCO and LMO battery packs at approximately 26,6 kWh, assuming low energy capacity in LCO and LMO.

Now, both models become more GHG intensive than the NCM model. Interestingly, the impacts of the cell assembly part of the LCO model is still lower than the base, even though more modules are required. This is probably because the NCM model uses a general East Asian electricity mix, whereas my high and low capacity base models use a specifically Chinese electricity mix that has a somewhat higher percentage clean hydroelectric power. The final impacts for these battery models come at **5340 kg CO₂-eq for LCO** and **7420 kg CO₂-eq for LMO**, still in comparison with 4650 kg CO₂-eq for the NCM battery.

We return to the optimistic high capacity models for one final set of comparisons: What happens when production is moved out of China, to the US or EU/Germany? Consider figure 4.3:

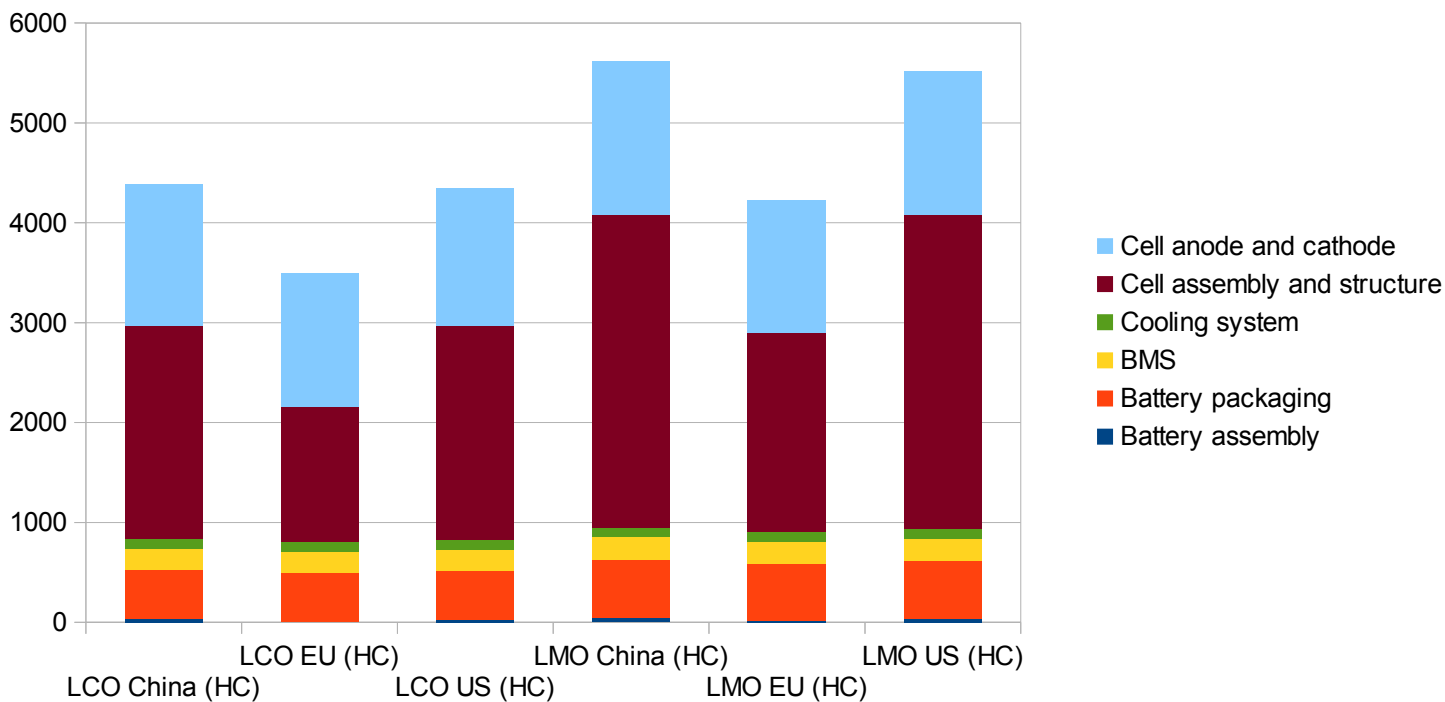


Figure 4.3: Comparison of kg CO₂-eq emissions from LCO and LMO battery packs produced in different countries at approximately 26,6 kWh, assuming high energy capacity in LCO and LMO.

The pattern seen here is quite consistent: The cleaner German electricity mix gives lower GHG emissions for both LCO and LMO, while the Chinese and American electricity mixes do not give significant differences. Notice, however, that LMO batteries produced in the EU give approximately the same GHG emissions as LCO batteries produced in China or the US. The results are: LCO, EU: **3500 kg CO₂-eq.** LCO, US: **4350 kg CO₂-eq.** LMO, EU: **4230 kg CO₂-eq.** LMO, US: **5520 kg CO₂-eq.** Values for China are the same as for figure 4.1.

We shall have one more diagram, to put everything in scale. Figure 4.4 shows the global warming potential normalized by energy: How many kg CO₂-eq each model produces per kWh storage capacity. Here we have all the models together (higher and lower capacity models are both with Chinese electricity mix). The calculation of this diagram is relatively simple: Global warming potential for the entire battery, divided by the energy capacity. The latter value has been adjusted to take into account that the theoretical LCO and LMO models have a number of modules rounded to nearest whole or half, giving them somewhat more or less number of cells than the exact number calculated from the ratio of cathode material energy capacities (see appendix A.1.3 for details).

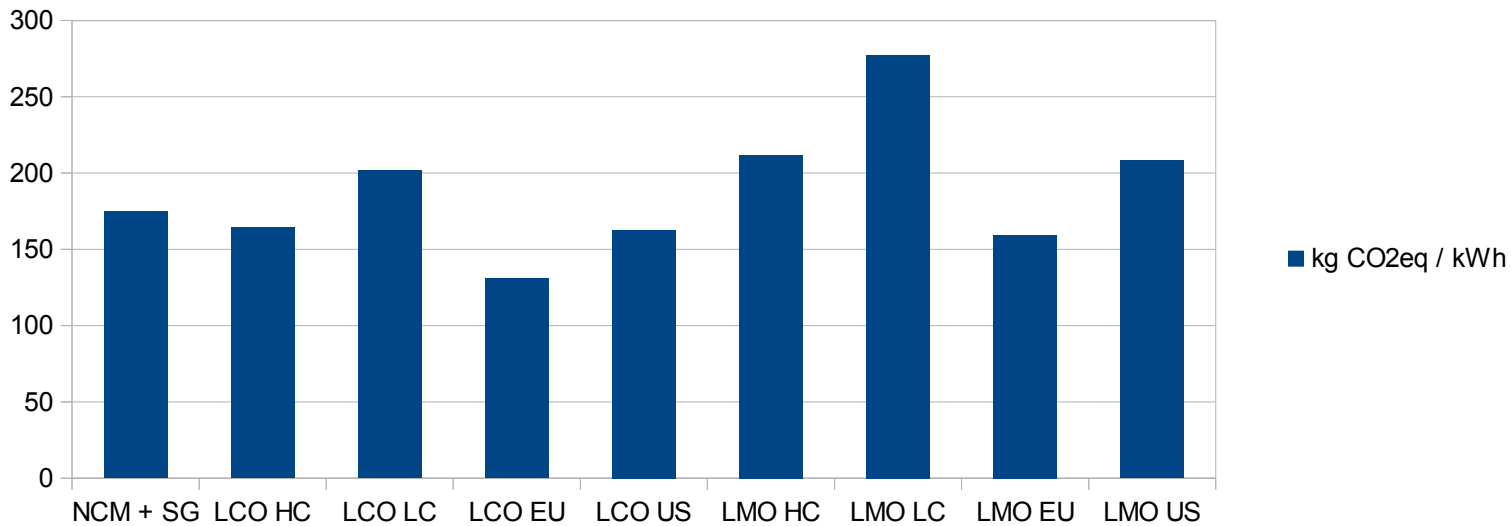


Figure 4.4: Kilograms CO₂-eq emissions for each kWh storage capacity for different battery models, each at approximately 26,6 kWh total energy capacity.

These results do not in themselves show much more than the previous figures, just that the pattern repeats: LCO and European LMO is ecologically competitive with NCM (from a GWP point of view), whereas other LMO scenarios have greater emission rates.

This concludes the comparison of global warming potential impacts. These are the most important results. But we should also have a look at the other ReCiPe impact categories, to see if any of the models have significantly greater impacts in any field, and hopefully determine the cause with the help of the structural path analysis (SPA) technique. I have grouped the ReCiPe impact categories in a series of tables, where the grey fields mark values that differ significantly from the others. Let us begin at *land occupation and transformation*, table 4.2:

Name	Unit	NCM + SG	LCO HC	LCO LC	LCO EU	LCO US	LMO HC	LMO LC	LMO EU	LMO US
Agri land occ	m ² a	1,16E+02	2,81E+02	3,42E+02	2,59E+02	2,78E+02	2,40E+02	3,16E+02	2,05E+02	2,34E+02
Nat land transform	m ²	7,91E-01	2,44E+00	3,00E+00	2,43E+00	2,43E+00	1,92E+00	2,55E+00	1,91E+00	1,91E+00
Urban land occ	m ² a	6,24E+01	3,13E+02	3,85E+02	3,06E+02	3,12E+02	2,15E+02	2,85E+02	2,04E+02	2,13E+02

Table 4.2: Land occupation and transformation impacts, for all models

Looking at these numbers, we immediately notice that the values for the LCO and LMO models are significantly greater than for the base NCM model. The SPA yielded no results for agricultural land occupation, neither for the LCO nor LMO model, but for natural land transformation and urban land occupation there are some indications. The metal working factory infrastructure has the highest values in both models, for both impact categories, followed by copper mine tailings (related to the

anode), cobalt tailings for the LCO model, the electrolysis plant infrastructure for the LMO model, and oil and coal extraction in general.

However, this information is of limited value. It is likely that the significant differences in transformation and occupation can be attributed to different registration practices for different parts of the vast Ecoinvent background process inventory.

Moving on to another cluster of impact categories: *Resource depletion*. These are not necessarily explicitly environmental impacts, but can nonetheless provide useful indicators of a model's place in the industry, and its long-term sustainability. Consider table 4.3:

Name	Unit	NCM + SG	LCO HC	LCO LC	LCO EU	LCO US	LMO HC	LMO LC	LMO EU	LMO US
Fossil depletion	kg oil eq	1,34E+03	1,27E+03	1,54E+03	1,06E+03	1,27E+03	1,67E+03	2,22E+03	1,35E+03	1,68E+03
Metal depletion	kg Fe eq	4,10E+03	2,33E+03	2,79E+03	2,34E+03	2,33E+03	5,41E+03	7,13E+03	5,42E+03	5,41E+03
Water depletion	m3	2,54E+04	2,20E+04	2,62E+04	3,22E+04	2,63E+04	2,56E+04	3,30E+04	4,08E+04	3,17E+04

Table 4.3: Resource depletion, for all models.

The pattern for fossil depletion is predictable: The models with lower energy storage capacity, and thus need for more battery and more energy to assemble this battery, have higher values of fossil depletion. The EU models have cleaner electricity mix, being less dependent on coal and petroleum. For metal depletion, the cobalt models have considerably lower yields than the rest. The SPA shows that the manganese demand counts as a lot more metal depletion than the cobalt demand, by two orders of magnitude. This is a problematic result: There might be a greater need for manganese than cobalt, as the manganese batteries modeled here are larger than the others, but the material inputs per kg cathode metal oxide are roughly similar. There are two possible explanations, both implying that the results of my models may be misleading:

First, it is possible that the unclear implementation of cobalt and manganese in Ecoinvent might have caused me to apply a too large value of manganese, or too small value of cobalt. The Ecoinvent database is not explicit on whether the metal is implemented in pure form, or as an oxide, hydroxide or any other common industrial form. Nor is there a clear connection between metal and mining, which can be problematic when my models start at resource extraction.

Second, the source could again be in different practices of data gathering in the Ecoinvent inventory. Cobalt and Manganese are metals with very different economical backgrounds: Manganese is an abundant element in the Earth's crust, a main product of manganese mines, whereas the rarer cobalt is a by-product of copper and nickel mines. The conceptual distance of these two products can have caused different practices to apply at the time when the metal depletion

coefficients were determined.

Water depletion shows that the EU models have greater impacts than the others. The SPA shows that this comes from the high percentage of hydroelectric power in the battery cell assembly stage – the EU model assumes this happens in Germany, whereas the base models use the general East Asian power mix of the Ellingsen et al. (2013) model for this particular purpose.

The next cluster is the toxicity categories, see table 4.4:

Name	Unit	NCM + SG	LCO HC	LCO LC	LCO EU	LCO US	LMO HC	LMO LC	LMO EU	LMO US
Freshw ecotox	kg 1,4-DB eq	2,56E+02	2,12E+02	2,58E+02	2,05E+02	2,11E+02	2,59E+02	3,41E+02	2,47E+02	2,56E+02
Human toxicity	kg 1,4-DB eq	1,59E+04	1,35E+04	1,64E+04	1,32E+04	1,34E+04	1,66E+04	2,20E+04	1,61E+04	1,64E+04
Marine ecotox	kg 1,4-DB eq	2,76E+02	2,29E+02	2,79E+02	2,22E+02	2,28E+02	2,81E+02	3,71E+02	2,69E+02	2,78E+02
Terr ecotox	kg 1,4-DB eq	1,33E+00	1,01E+00	1,24E+00	1,03E+00	9,94E-01	1,26E+00	1,67E+00	1,29E+00	1,23E+00

Table 4.4: Toxicity categories, for all models.

Name	Unit	NCM + SG	LCO HC	LCO LC	LCO EU	LCO US	LMO HC	LMO LC	LMO EU	LMO US
Freshw eutroph	kg P eq	8,02E+00	6,79E+00	8,27E+00	6,32E+00	6,73E+00	8,50E+00	1,12E+01	7,75E+00	8,37E+00
Marine eutroph	kg N eq	6,40E+00	5,25E+00	6,47E+00	5,05E+00	5,21E+00	6,95E+00	9,31E+00	6,64E+00	6,87E+00

Table 4.5: Eutrophication categories, for all models.

Concerning the emissions of toxics to different biospheres, the pattern is repeating: The LCO processes, except for the LC energy capacity model, have lower impacts than the rest. From the SPA it follows that these results do not relate to the specifics of the data I have added to the inventories, but that they are simply caused by lower energy and resource demands due to the smaller battery. The same is true for the eutrophication categories, as seen in table 4.5.

The final set of impact categories are those not easily grouped, in table 4.6:

Name	Unit	NCM + SG	LCO HC	LCO LC	LCO EU	LCO US	LMO HC	LMO LC	LMO EU	LMO US
Ionising rad	kg U235 eq	2,24E+03	1,86E+03	2,27E+03	1,13E+03	1,35E+03	2,51E+03	3,34E+03	1,48E+03	1,81E+03
Ozone depletion	kg CFC-11 eq	2,93E-04	3,17E-04	3,83E-04	3,25E-04	3,24E-04	4,91E-04	6,47E-04	5,09E-04	5,08E-04
Partic matter form	kg PM10 eq	1,55E+01	1,28E+01	1,56E+01	1,14E+01	1,24E+01	1,41E+01	1,86E+01	1,19E+01	1,35E+01
Photoch oxid form	kg NMVOC	1,81E+01	1,88E+01	2,29E+01	1,61E+01	1,81E+01	2,01E+01	2,65E+01	1,61E+01	1,92E+01
Terr acidification	kg SO2 eq	5,15E+01	3,62E+01	4,42E+01	3,14E+01	3,47E+01	4,23E+01	5,59E+01	3,51E+01	4,00E+01

Table 4.6: Other impact categories, for all models.

Ionizing radiation follows the pattern of cathode energy capacity from above. The values of ozone depletion are small, but with significantly higher values for the LMO models. The SPA indicates that the emissions come from petroleum-related processes, but also from the production of hydrochloric acid for use in production of electrolytic manganese dioxide.

Particulate matter and photochemical oxides formation are highest for the low capacity (LC) LMO model, but generally not very different across the board. These are related to fossil power production and anode copper production, but also to a certain degree cobalt mining. Finally, terrestrial acidification shows highest values for the base model and the LC LMO. Again, power production is the main contributor, but there is also some input from the metal working factory infrastructure, and from mining.

As a summary of impact category review, we can look at how much each section of the battery production contributes to each category. See figures 4.5 and 4.6:

LCO, High Energy Capacity

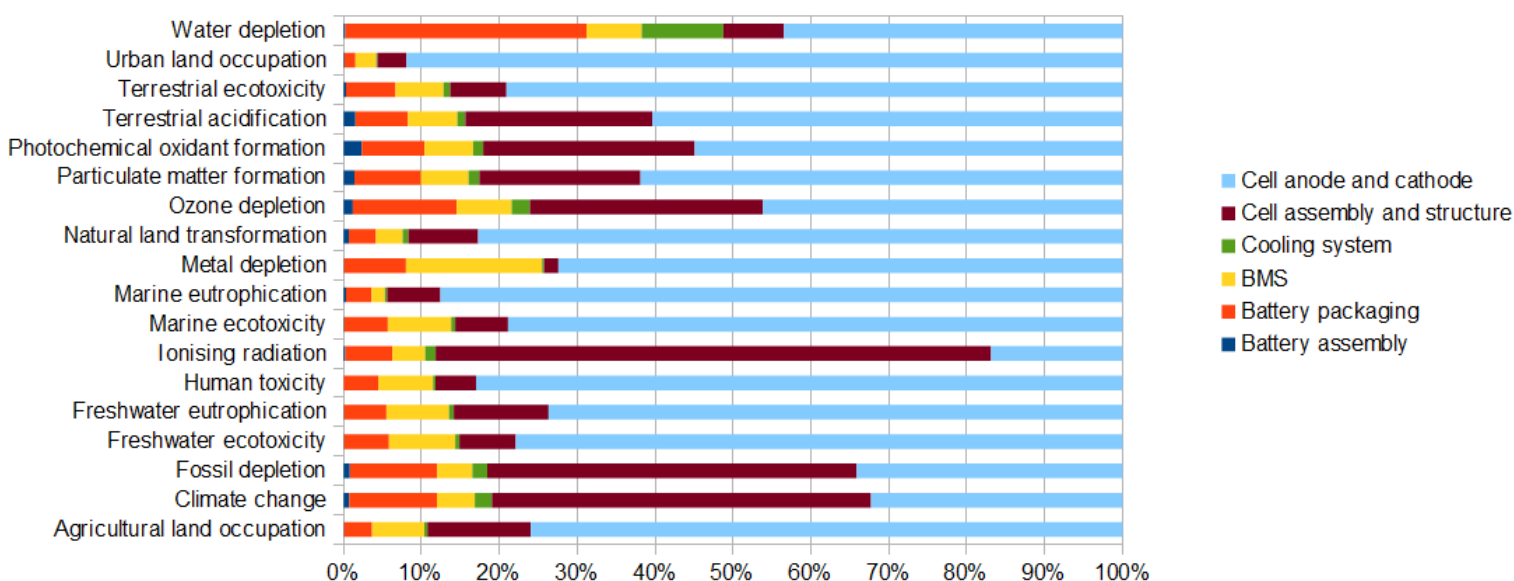


Figure 4.5: Distribution of sub-inventory groups across each ReCiPe impact category, LCO high energy capacity.

LMO, High Energy Capacity

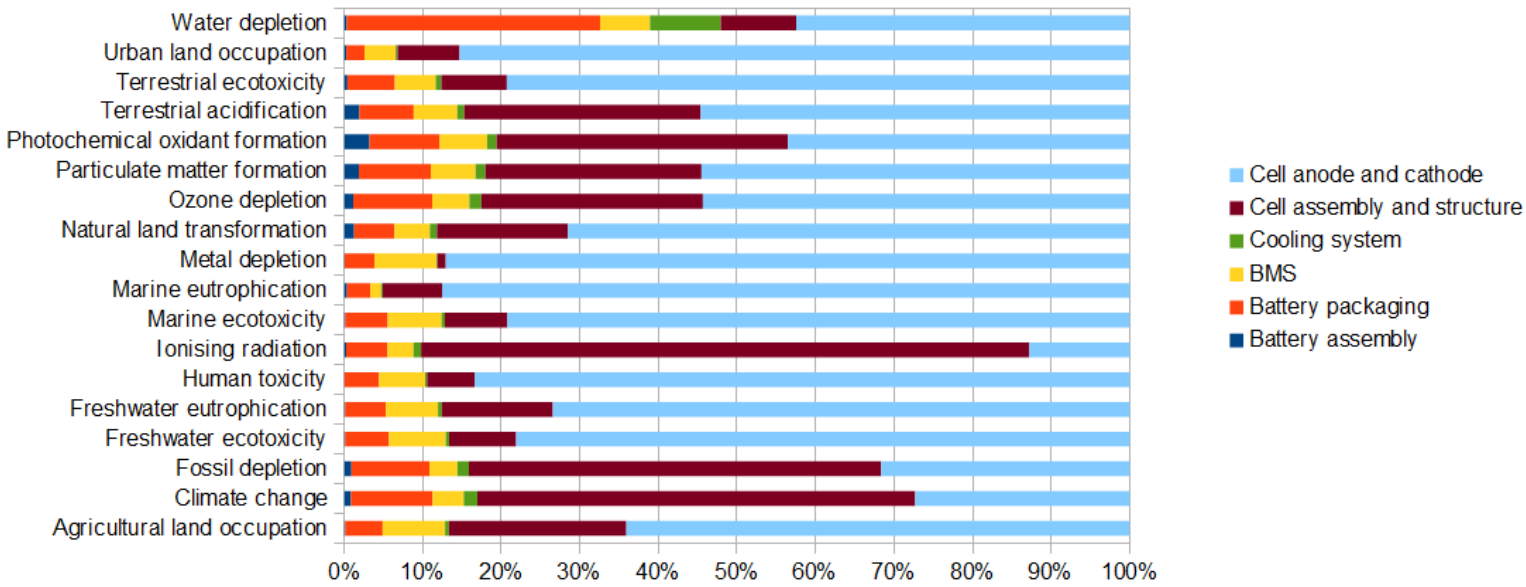


Figure 4.6: Distribution of sub-inventory groups across each ReCiPe impact category, LMO high energy capacity.

These figures let us observe the impacts of various parts of the battery whole, without the distraction of absolute magnitudes. Interestingly, the anode and cathode section – which is where I have made my model contributions – is dominant in most impact categories. However, as we saw while going through the impact categories one by one, many of the most significant inputs come from the production of copper for the anode.

If we directly compare the LCO and LMO models in this perspective, the trend is that the anode and cathode section is a little more dominant in the LCO. Also, impact categories sensitive to electricity production (like ionizing radiation, global warming potential and fossil depletion) are more significant in the LMO model, as this cathode chemistry has two power-intensive processes associated (lithium manganese oxide sinter/calcine and manganese electrolysis), where LCO has only one (lithium cobalt oxide sinter/calcine).

4.2: My results in good company

Now it is time to see how my results compare with previous research. I have taken my two high capacity models of LCO and LMO, adjusted like in figure 4.4, and put these in comparison with the results from previous research as seen in chapter 1.3. This comparison is illustrated in figure 4.7:

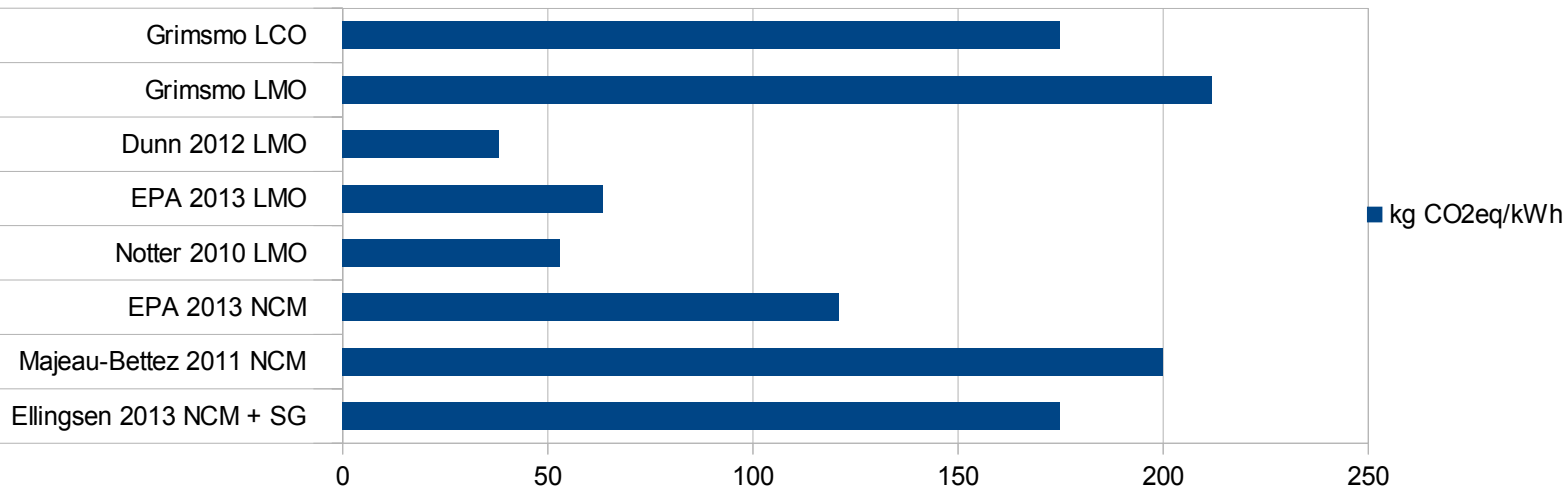


Figure 4.7: Emissions of CO₂-eq per kWh energy storage capacity for

Noticeable immediately is how my LMO model gives results four times higher than the previous LMO research. The lowest value comes from Dunn et al. (2012), but this comparison isn't completely fair – Dunn's study uses recycled metals, whereas EPA (2013), Notter et al. (2010) and my inventory use virgin resources.

However, as we have seen from the previous chapter, figures 4.1 to 4.3, cathode production is far from the only cause of GHG emissions. Substantial amounts come from the scale-adjusted production and assembly of battery components. Here we have the main reason for the large GHG results of my LMO study in comparison with previous research: It comes from the Ellingsen et al. (2013) model, with its comprehensive and detailed battery inventory. The same goes for my LCO research.

The Ellingsen and Majeau-Bettez results on NCM are more consistent, as they partially build on the same data. The EPA results on NCM also cite Majeau-Bettez et al. (2011). The EPA also cites Notter et al. (2010) on LMO. The result of this is that EPA NCM matches the Ellingsen et al. (2013) model, whereas on LMO it matches Notter et al. We cannot disregard the disparity in global warming potential between the Notter-related and the Majeau-Bettez-related sets of models. Looking into the background materials on Notter and Ellingsen, we can see that the latter reports electricity usage three orders of magnitude over the former in the assembly of the cells. As we have seen previously, electricity use for cell manufacture completely dominates the inventory in terms of GHG emissions in the Ellingsen et al. (2013) model.

5: Discussion

5.1: Implications for the industry

As battery production expands to make room for a new renaissance of electric vehicles, some insights may be gleaned from my results. The environmental impacts, particularly global warming potential, are largely related to electricity use at a few key points in battery production: cell factory and cathode material factory (as well as electrolysis plant in LMO production). The results presented in figure 4.3 indicate that the composition of the electricity supply, the degree of renewable power, have significant implications for the total GHG emissions of the battery production.

It thus appears that locating the production of batteries to countries with “clean” electricity mixes, will significantly reduce the carbon footprint of battery production. This sounds fine and dandy for the respectability of the battery industry, but we should reflect on matters like marginal energy consumption and the displacement of other energy intensive industries from the energy pool. Electricity production capacity for a specific location is a fixed quantity on average, and introduction of a battery factory to a grid that is already delivering at full capacity just means that some existing energy intensive industry will be crowded out and must relocate to another, less clean electricity grid. The alternative is to expand the grid with more renewable production capacity – but this is preferable regardless of whether or not a battery industry is part of the grid.

The bottom line of this issue is that battery production can be made less polluting by moving to a country with cleaner energy, but that this is an entirely relative issue. The carbon intensity of battery production is ultimately a question of the global electricity sector as a whole (“global” is here understood as the world in which industry and business can be moved and located more or less freely). If we implement more renewable energy in general, then all industry will be less carbon intensive, including batteries. We should not focus too much on specific emission differences between models only to make ourselves blind to how this industry moves as one part of a whole.

Another important question goes unanswered by this study: What are the implications of using a toxic metal for battery production? We know from school that cobalt has a reputation as toxic and harmful, and although cobalt in trace quantities is beneficial for humans in the form of vitamin B₁₂, and have various medical applications (Lenntech.com, no year), it is a heavy metal and harmful in large concentrations. Cobalt is listed as possibly carcinogenic to humans by the International Agency for Research on Cancer (ibid.).

Yet when we consider the results for ReCiPe toxicity impact categories (table 4.4), we see

that the lithium cobalt oxide models come out more favourably than the in theory more benign lithium manganese models. It would be interesting if the reason for this was that cobalt turned out to actually be less harmful. But the far more likely reality is that any possible stressor emissions from the cobalt value chain simply remain unmapped in the Ecoinvent database. The inventory values related to cobalt production have mostly been approximated with data from nickel mining (Classen et al. 2009), with no stressor emissions. With the limited information access of my work, which is mainly based on specific energy figures from the industry, there are no cobalt-related stressor emissions further downstream in the LCO inventory. The toxicity results in table 4.4 come exclusively from other parts of the total battery inventory. Due to the relative lack of stressor emissions (beside stoichiometric CO₂) from all my added inventories, my work does not provide significant new information about non-GHG environmental emissions beyond what has already been achieved by Ellingsen et al. (2013) in the total battery model.

5.2: Implications for policy

When we move over to consider policy and large-scale preferences, a question that emerges is simply: *which battery cathode chemistry is the best?* Now, we have already seen in the introduction of this text that different chemistries have different purposes – medical equipment, power tools, mobile phones, and so on, yet batteries have many general purposes, and there is bound to be overlapping.

From a global warming perspective, the results in figure 4.4 are explicit: LCO gives less CO₂ per provided kWh storage capacity than both NCM and LMO. Even if we shift to less optimistic energy capacity scenarios, the results are preferable for LCO (keep in mind that the NCM model remains optimistic at 174 kWh/kg). An implication for policy could be that producers should strive to produce batteries at the higher end of the energy capacity scale, as this reduces the overall size requirement. Now, most battery producers would already be aiming for this, to deliver the best product, but it would still be preferable to standardize lithium ion batteries at high energy capacity, to catch them all, so to speak.

Ideally, when putting aside cases where a specific chemistry is required for a specific purpose, lithium cobalt oxide would be the way to go. However, we must keep in mind the economical background of these resources – with cobalt as a subsidiary metal, demand does not really affect supply, as it is the copper or nickel production that needs to be profitable for the mine to increase production, and the cobalt is only a small part of that. The price of LCO batteries would

have to rise significantly before production volume would increase. LMO batteries would not have quite this problem, but there is the GWP issue. NCM is somewhere in-between, containing both cobalt and manganese.

Beyond these considerations, we have already discussed the other impact categories, and found that the lacking implementation of stressors from cathode production makes it difficult to produce additional insights about non-GWP categories. More knowledge is needed on the LCO and LMO processes before policy can be discussed at more than a superficial level.

5.3: Implications for science

There is work to do here, for anyone who is interested. The total Ellingsen et al. (2013) battery model is very good as it is, and with the very recent news of Tesla's release of their patents (Tesla Motors 2014) research on this should have lots of source material to work with. When we focus in on cathode metal oxide production, however, many large holes appear.

Implementation of metal extraction is the most important issue. The Ecoinvent database needs to be made ready for heavy metal-based electronics such as the LCO battery, and such metals need to have their refining processes mapped, even if it is just allocation work with copper and nickel mining.

A second significant issue is industrial heating at temperatures below melting points. In studies such as Majeau-Bettez, the heating energy is estimated with a number of geometric and material assumptions, whereas my study hinges on a handful of values kindly provided by industry representatives. There is number of different kilns and furnaces for calcining, sintering and roasting, all of which have their own inventories for production, operation, maintenance and end-of-life disposal. The kiln is simple on the paper, but likely a lot more complicated in practice. Industrial heating has purposes way beyond the use in battery production, so this would help LCA science a lot in general.

Related to this issue, although probably not as significant, is research on low-temperature chemical heat treatment, which in my study has been given cursory consideration (like the distillation of pitch from tar) or been neglected altogether (like the production of cobalt (II,III) oxide from cobalt hydroxide). These processes are likely not as energy and carbon intensive as the higher temperature versions, but they are necessary to understand to get a complete picture.

While we are at it, transportation should be mentioned. The Ellingsen et al. (2013) base

model implements only some arbitrarily valued truck ton-kilometers for the transport of cathode materials from extraction to the battery factory. My study makes it somewhat less arbitrary by roughly calculating shipping distances from possible extraction countries to possible production countries. Everything in between has been neglected. These neglected transportation phases are likely made up from trucks, which according to IPCC make up more than one fifth of transport energy use – and transport in turn makes up more than one fifth of total global energy use (IPCC 2007). Although the shipping phases of my inventory do not seem to have made significant differences in the overall impacts, properly approximating the many transport distances could mean a great deal.

If we look at battery specific research, the effort should go to ascertain whether the substantial differences between the Ellingsen et al. (2013) model (including my work) and previous research (such as Notter et al. 2010), as observed in figure 4.7, come from better and more complete inventories, or just from different assumptions. Furthermore, research should be done to get accurate results pinpointed from the crude scenarios I have designed: What is the most reasonable energy capacity coefficient for NCM, LCO and LMO? Where is it likely that the main bulk of electric vehicle battery production will be located, and what is the electric production mix like there? Answers to such questions will do much to help properly and accurately determine the environmental impacts of electric vehicles, so that consumers may make their choices and governments may make their policies.

5.4: Model uncertainties

At this point it feels necessary to reiterate what was stated in the introduction: The purpose of this study is first to establish a proper understanding of the industrial processes required for battery cathode production. More specialized work could have been done on the presentation of results. It might have been interesting to implement a summation of direct energy use across processes in each model. Results could have been tweaked and adjusted to more completely create an understanding of the environmental impacts, and to create more complete comparisons with previous research.

We have already been through how the models lack a lot of detail beyond the figures of energy and basic raw materials. The study adds significant information to contemporary research by providing data on energy usage straight from the industry – if these figures can be trusted. They have been given by e-mail (see appendix A) from Michael Harz (DJK Europe, LCO) and Matti Rajaniemi (Mersen, synthetic graphite), as simple numbers without much context, and lacking any

formal documentation. The Mersen number for total specific energy use does match the adding together of numbers from the Riedhammer brochures and the Ullmann's chemical encyclopedia data. A total of 5 kWh per kg synthetic graphite does seem a bit low for a process where materials are raised to high temperatures for two months or more. Compare this with 6,67 kWh/kg for the production of LCO from precursors, which consists of high-temperature heating for just 10 hours. The roller hearth kiln is open ended, and there might be differences in construction and insulation, but the difference is nevertheless striking. Is there a possibility that the matching numbers for graphite production originate from one same misleading source within this very specialized industry? Some research efforts should be made here. Adding synthetic graphite raised the GHG emissions of the Ellingsen et al. (2013) model with about 70 kg CO₂-equivalents, so this is of some relevance.

Other model weaknesses come from the sometimes rather crude assumptions I have had to make. The energy figure on electrolytic manganese dioxide (EMD) production I have used, comes from experimental data, not from the industry. I am assuming that the LMO production process is similar to the LCO, only with a somewhat lower temperature, which I have used to roughly guess a somewhat lower energy figure. I don't really have any idea of whether magnesium oxide is actually being used as a reduction agent for cobalt hydroxide production in today's industry, even though the literature indicates it has a lot of potential, and can be applied with today's technology. The materials input for the production of synthetic graphite remain as guesswork, even if the fraction of coal tar pitch has been determined with additional sources. The assumptions about facility infrastructure are crude, using the nearest-soundingecoinvent industrial plant, always assuming 20 years lifetime.

On the other hand, many assumptions have not been made that could have been. Perhaps my results could have more closely resembled reality if I had made more reasonable assumptions. I could, for instance, have improved the results of toxicity impact categories by assuming probable leakages of cobalt from factory to biosphere. But I have decided to focus on the facts that are known, and to present these.

This project work is, to put it simply, limited by what can be achieved from an office in a city far removed from most of the industrial processes described, using only e-mail and accessible scientific literature.

6: Conclusion

This study had the purpose of increasing knowledge on lithium ion battery cathode production for life cycle assessment purposes. I have adapted the Ellingsen et al. (2013) model for exploring the environmental impacts of lithium cobalt oxide (LCO) and lithium manganese oxide (LMO) cathode materials, while also improving the base model by upgrading the natural graphite anode material to the more correct synthetic graphite.

My work on these three materials has been focused on determining the real-world industrial processes applied for production, and to get numerical values for specific electric and gas energy demands. These numbers have been provided by individuals within the industry, as well as some scientific literature. Using the Arda program for Matlab, applying the Leontief inverse method, I have determined the environmental impacts of batteries with the different cathode materials.

Where the Ellingsen et al. (2013) base scenario of lithium nickel-cobalt-manganese oxide (NCM) gives a total global warming potential of **4650 kg CO₂-eq**, the LCO battery gives slightly less (**4390 kg**), the LMO battery gives quite a bit more (**5610 kg**). Replacing the natural graphite anode with synthetic graphite increases the GHG emissions with about **70 kg**. The differences in numbers come primarily from assumptions on cathode energy storage capacity. Higher capacities means less battery is required to store the same amount of energy, which leads to lower materials and energy demand in production. Some scenarios have been provided with variation of this. I have also set up scenarios with different electricity mixes resembling different countries, showing that production in Germany is less carbon intensive than production in China or in the US.

In comparison with previous research in the field, my LMO model has several times larger GHG emissions than other researchers' LMO models. This is mainly a consequence of my use of the Ellingsen et al. (2013) model, which has a large electricity input. I have found no LCO results to compare with.

My models have limited utility for understanding environmental impacts beyond global warming potential. Due to limitations in the Ecoinvent background database, and lack of information about production processes, stressor data tied to cathode production is low.

It appears that the lithium cobalt oxide battery is the most preferable, from an environmentalist point of view. However, this chemistry is bounded by issues with cobalt extraction. Assembly in a country with a clean electricity production mix will significantly reduce the carbon footprint of the battery. However, more research is needed on metal processing and heating, if we are to find broader insights on the environmental impacts of lithium ion batteries.

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Appendix

Appendix 1: Determining the inventory

A.1.1: Lithium Cobalt Oxide

My research on the LCO inventory has been limited to the cobalt part, and the facts of the lithium-cobalt merging process. The data sheet on LCO powder, as applied in the Ellingsen et al. (2013) battery model, has 18 inputs in the form of materials, energy, transport and infrastructure, and one output in the form of an emission. These 19 flows all relate to one out of two processes: *LiCoO₂ Powder* and *Cobalt(II,III) Oxide*.

To produce one kg of output, *LiCoO₂ Powder* takes in two material inputs: **0,38 kg lithium carbonate** and **0,82 kg cobalt(II,III) oxide**. These values are given by Hidekazu (2009). Hidekazu lists cobalt carbonate and cobalt hydroxide as potential other cobalt precursors, but prefers cobalt(II,III) oxide. This is also verified by professor Yan-Kook Sun from Hanyang University, South Korea, in an e-mail dated 01.23.2014.

The process of merging the precursors have an energy requirement. According to Akira Sakai at Kabushiki-gaisha Noritake Kanpanī Rimitedo (Noritake) in an e-mail dated 02.23.2014, the roller hearth kiln is the recommended equipment for this calcine-sinter process. An estimate for energy demand has been given by Michael Harz in an e-mail dated 03.26.2014. Harz is an employee of DJK Europe GmbH, a corporation producing a range of different kilns. He writes: “Basically we use sagger that contain 5-6kg. For one sagger you need about 40kw/h.” I interpret this answer as meaning kWh, kilowatt hours. From this, we get that the energy demand for one kg of LiCoO₂ is 6,67 kWh, when assuming sagger capacity of 6 kg.

According to a product catalog from DJK Europe GmbH (no year), the roller hearth kiln can be fired by both electricity and gas. I have thus made the assumption that the energy demand of the LCO production is shared equally by these two energy carriers, giving **3,33 kWh electricity and 12 MJ gas**, which is inventoried as “in industrial furnace” in Ecoinvent. The electricity inventory is somewhat more complicated. I have several scenarios where the production is situated in different countries. These scenarios have different mixes of power production types, including peat, coal, oil, gas, waste, nuclear, hydro, solar and wind power. These are all in the inventory pointing to suitable elements in the Ecoinvent database. Consider table **A.1.1** for information of power mix compositions. These elements, however, are all “at power plant”, which means some infrastructure and transformation costs have to be included as well. Some factors for transformation energy

demands are provided in the dataset, as according to Ecoinvent standards, giving a total electric energy demand of **3,4 kWh high voltage**. In addition, there are high and medium voltage networks, and long distance networks, to account for, which are inventoried with small fractions. Finally, there is some sulfur hexafluoride consumption in electrical network circuit breakers. All these infrastructural elements have been given values according to Ecoinvent standard assumptions.

Remaining now is the infrastructure of the LCO factory in itself, which I have modeled as “metal working factory RER”. China Sun Group High-Tech Co. reports in one of their catalogs (2010) that one of their plants, an LCO plant, has a total maximum output of 500 tons per year. Assuming a 20 year life time, this gives **10^{-7} units of production plant per kg LCO produced**.

There is one emission output, CO_2 . The value of this output is given by Hidekazu (2009) as **0,225 kg per kg LCO produced**. The emission is inventoried as “carbon dioxide, fossil / air / unspecified”.

Moving on to the cobalt sub-inventory, we have the cobalt extraction process. The cobalt entry in Ecoinvent has limited documentation regarding the specifics and location of the mine, and the processing of ore. I have decided that it is beyond the scope of this master's thesis to make an inventory of ore processing, seeing as most of this process serves the copper industry anyway. Therefore, I am using only “cobalt, at plant”. The material demand for LCO is in the form Co_3O_4 , which has a different molar mass than pure cobalt. From stoichiometry, I get a demand of **cobalt extraction equivalent to 0,73 kg pure metal per kg Co_3O_4** .

As described in the main text, I am assuming the mine and processing facility to deliver cobalt hydroxide ($\text{Co}(\text{OH})_2$). This is the form the metal has when it is being shipped from mine to LCO factory, and according to stoichiometry the mass of this kg-equivalent batch is 1,16 kg. This means the transport input must be multiplied with 1,16 (from distance in km divided by 1000 to yield ton*km) to get the proper ton*km value. Transport values differ between production location scenarios, as is given in table **A.1.2** below. In the main text I have also specified that the precipitation of cobalt hydroxide is performed by use of an agent. Based on Fisher (2011), I have assumed magnesium oxide (MgO) to be the agent used. Steemson (1999) reports experimental results of different precipitation agents, and finds that a roughly stoichiometric (2 moles MgO to create 1 moles $\text{Co}(\text{OH})_2$) amount of MgO gives a nearly 100 % recovery of cobalt. So to sum up, for 1,16 kg of $\text{Co}(\text{OH})_2$ a total of **1,005 kg magnesium oxide** needs to be added. Production infrastructure has been neglected, as little information could be found, and a proper allocation of copper and nickel would have to be applied. For similar reasons, the conversion of cobalt hydroxide to cobalt(II,III) oxide has been neglected.

	Mix country	China	United States	Germany
<u>Power source</u>				
<u>Peat</u>		0,00%	0,00%	0,00%
<u>Coal</u>		79,00%	43,00%	19,00%
<u>Oil</u>		0,00%	1,00%	5,00%
<u>Gas</u>		2,00%	24,00%	22,00%
<u>Waste</u>		0,00%	0,00%	1,00%
<u>Nuclear</u>		2,00%	19,00%	14,00%
<u>Hydro</u>		15,00%	8,00%	16,00%
<u>Solar</u>		0,00%	0,00%	9,00%
<u>Wind</u>		2,00%	3,00%	13,00%
<u>Total</u>		100,00%	98,00%	99,00%

Table A.1.1: Electricity mix compositions for scenarios China, United States and Germany. Source: International Energy Agency 2011 reports for these respective countries.

	Battery assembly country	China	United States	Germany
<u>Material</u>				
<u>Lithium Carbonate</u>		From Arica, Chile, to Shanghai, 18,3 tkm/kg	From Arica, Chile, to Los Angeles, 7,8 tkm/kg	From Arica, Chile, to Rotterdam, 12,6 tkm/kg
<u>Manganese Oxide</u>		Assumed internal	From Port Gentil, Gabon, to Los Angeles, 12,8 tkm/kg	From Port Gentil, Gabon, to Rotterdam, 6,9 tkm/kg
<u>Cobalt Hydroxide</u>		From Port Gentil, Gabon, to Shanghai, 20,7 tkm/kg	From Port Gentil, Gabon, to Los Angeles, 17,9 tkm/kg	From Port Gentil, Gabon, to Rotterdam, 9,6 tkm/kg

Table A.1.2: Transport values used in my dataset, calculated by portworld.com and stoichiometric considerations

A.1.2: Lithium Manganese Oxide

The inventory on $LiMn_2O_4$ powder is somewhat different in detail from LCO. First of all, it should be clarified that what has been inventoried is the process for production of $LiMn_2O_4$, not $LiMnO_2$. Although the latter substance appears in some sources, my main source, Numata (2009), reports that “[t]he stoichiometric composition of LMO is $LiMn_2O_4$ ”. From Numata, I get the preferred molar ratio of lithium and manganese to be 0,54. For **one kg of $LiMn_2O_4$** , this means we need **0,2 kg of the lithium precursor (Li_2CO_3)** and **0,96 kg of the manganese precursor (MnO_2)**. Numata reports that a powdered mix of these precursors are “heat-treated in a tunnel-type kiln at 700–900°C.” From this I assume a process similar to that of LCO heat-treatment, but since the

temperature is a little lower, I have reduced the **energy demand** from 3,33 to **3 kWh**. I make the same assumptions as with LCO when it comes to electrical infrastructure. The production facility is “metal working factory, RER”. A company presentation by Wuxi Jewel Power & Materials Co., Ltd. gives annual plant production capacity as 2000 tons (2012), which translates to **$5 \cdot 10^8$ units of infrastructure per kg LMO**. Finally, a stoichiometric evaluation of the chemical reaction indicates a CO₂ emission output of **0,12 kg per kg LMO produced**.

The LMO inventory has a sub-inventory called *Electrolytic manganese dioxide*, which is the MnO₂ manganese precursor. This inventory takes in manganese(II) oxide (MnO) from the mining industry, which is being dissolved in hydrochloric acid. Ecoinvent provides background information for hydrochloric acid at 30 % aqueous solution. The determination of these two inputs is again a matter of stoichiometrics. Although the manganese chain involves conversion from MnO to MnCl₂ and then to MnO₂, we can assess the demand by looking at the difference in manganese content for these two different molecules: One kg MnO₂ holds 0,63 kg Mn, one kg MnO holds 0,77 kg Mn. To get the manganese equivalent of one kg MnO₂, we need **0,83 kg MnO**. There is a certain manganese loss in the EMD production process, between 2 and 3 %, according to Rethinaraj, et. al. (1993), but I have chosen to neglect this difference. There is a shipping input present, which is presented in table **A.1.2**. The assumption is that reduced manganese(II) oxide is shipped to an electrolysis facility near the LMO factory.

Within these 0,83 kg MnO, there is 0,63 kg Mn that is being dissolved in hydrochloric acid before electrolysis. We know from the formula MnCl₂ that two moles of HCl are needed per mole Mn. Stoichiometrics gives a total demand of 0,8 kg HCl for this. Hydrochloric acid is at 30 % in water, which means a total of **2,67 kg** of this solution is needed.

These are the material and transportation inputs. In addition, we have a significant demand for electric power, for the electrolysis process. Rethinaraj et. al. (ibid.) kindly provides this data straight up: 2,11 or **2,6 kWh per kg EMD** deposition on electrode, depending on cell size. I have used the larger value, assuming large industrial facilities. As with the LMO powder production, this electric energy is being provided by the local grid mix, with the necessary infrastructure, and is being modeled the same way. Finally, we have the production facility, inventoried as “aluminium electrolysis plant, RER”, which I have given an infrastructure coefficient based on Jones (no year). He describes Broken Hill Pty. Co. Ltd.'s EMD production facility in Newcastle, New South Wales (Australia) with a production capacity of 22 000 tons annually. Assuming the usual 20 years lifetime, the infrastructure coefficient becomes **$2,3 \cdot 10^9$ units**.

The EMD inventory has one final sub-inventory called *Manganese Oxide*, which concerns

the production of manganese(II) oxide (MnO) at the mine. The mine produces ore containing MnO₂, which you need **1,22 (0,77 / 0,63) kg** of to produce one kg MnO. This substance is given in Ecoinvent as “manganese, concentrate, at beneficiation” (Classen et. al. 2009). Here, it is stated that

The module describes the production of manganese ore in 1994 for a world-wide production average. It is designed for the use of manganese ore as intermediary product in the production of ferromanganese and manganese metal. For the use of this module in the battery manufacture, the data quality may not be sufficient. (ibid.)

This is ore, which I assume means manganese(II) oxide. The data may not be of the preferable quality, but is the Ecoinvent process that best suits this project.

It is here assumed that the reduction process is happening at the mine, and that a rotary kiln is being used. I have approximated the energy demand of the kiln by assuming the process is similar to the calcination of cement clinker in the concrete industry. I am assuming that the most of the energy demand comes from heating and maintaining the kiln in itself, and that differences in specific heat capacity of different products can be neglected. Engin & Ari (2004) report a total heat demand of **3,7 MJ per kg** clinker, which is the value I have used in my inventory as well. The reduction process is carboreduction, which means carbon is directly involved in the chemical process. For simplicity, I am assuming this carbon is provided in the natural gas that is also used for heating. Finally, there is a matter of production infrastructure, but I have neglected this due to lack of data and information of proper allocation (a reduction plant would be part of a larger mining process).

A.1.3: Energy content scenarios

Along with electricity mix, a significant parameter for sensitivity analysis is the energy content of each specific battery chemistry. Different sources provide different values, often at continuous intervals. From information provided by supervisor, energy capacity per kg of battery cathode is given as voltage (V) divided by mass (kg), multiplied with current capacity (Ah), with the unit Watt-hours (Wh).

We look at LCO first: Oswal (2010) gives 2,55 Ah and 3,7 V for the 47 gram Panasonic CGR18650E battery. Using the formula, we get about **200 Wh** for one kg of such battery. At Targray (no year), the capacity of the LCO battery is **between 110 and 190 Wh** per kg. For LMO, the same industry reports **110 to 120 Wh** per kg. Nippon Electric Company (NEC 2013) has a more optimistic value of **159 Wh** per kg for their standard LMO battery.

The cathode chemistry of the NCM battery of the Ellingsen 2013 model has an energy capacity of **174 Wh** per kg. This value is the mathematical basis of this parameter variation. The Ellingsen model has 360 cell units – 30 cells per module, with a total of 12 modules in one battery pack. As mentioned in the main text, I have chosen the upper and lower bound LCO scenarios to be **200 and 160 Wh per kg**, and the upper and lower bound LMO scenarios as **160 and 120 Wh per kg**. With these numbers, I have adjusted the model to contain more or fewer modules and cells to simulate a battery pack of the same total energy capacity as Ellingsen's base NCM model. A battery with a more efficient cathode material would require less materials than the base. Note that I am here assuming the amount of cathode material in the cell to be the same, regardless of chemistry. As an example, here is how the upper bound LCO battery pack is estimated:

If we find the ratio between Ellingsen's 174 Wh and my 200 Wh, and multiply it with 360 cells, we get 313,2 cells. This is the number of LCO cells required to provide the same total energy content as Ellingsen's NCM base. This is a difference of 47 cells, which is a little more than a module and a half. Thus, we approximate the upper bound LCO model to have **10,5** modules, a total of 315 cells (rounded up from 313,2). Using a similar logic, we get lower bound LCO and upper bound LMO at **13** modules (390 cells rounded down from 391,5) and lower bound LMO at **17,5** modules (525 cells rounded up from 522).

A.1.4: Synthetic graphite

The production of one kg *synthetic graphite* requires a number of material inputs, including coal tar pitch (CTP), anthracite, carbon black and petroleum coke, according to Jäger, et. al. (2012). In his e-mail at february 6th, Matti Rajaniemi at Mersen Group specified the precursors to be “mainly pitch and petroleum cokes”, which implies these make up the majority of the mass demand. Assuming conservation of mass in the graphite production process (everything is heat-treated in isolated kilns), I made the initial assumption of 0,4 kg each of coke and CTP, and 0,1 kg each of anthracite and carbon black. These values I have since moderated with data from Rütgers Chemicals (Sutton 2008). In his presentation, Sutton provides data on CTP usage for different graphite electrode plants, with given graphite electrode outputs. They give an average of about 25 % CTP of total mass. This gives me the estimate I have used for the inventory: **0,25 kg CTP, 0,55 kg petroleum coke, 0,1 kg anthracite and 0,1 kg carbon black**.

There are two additional material inputs, related to the heating processes: sand and metallurgic coke as packing/refractory materials (Jäger, et. al. 2012). The Riedhammer brochure (no

year) gives some numbers on these materials: **0,006 kg sand** and 0,008 kg coke per kg graphite produced. The Ecoinvent entry on hard coal coke is given in MJ, which makes it necessary to convert my value by multiplying with the energy content of coke, 29,6 MJ/kg. The result is a demand of **0,237 MJ equivalent of coke**.

Now we move on to the energy demand of graphite production. This is a land of conspicuously low values, for a set of processes that heat materials up to thousands of degrees and maintains this state over many weeks. But several independent sources come up with somewhat similar figures, so these are what I have used. Matti Rajaniemi at Mersen Group states straight forward that 5 kWh/kg of “direct energy” is used, in the form of both electricity and gas, without specifying the amounts for baking and graphitization respectively. Jäger et. al. (2012) reports 3-4 kWh per kg for the graphitization process. This value can be combined with information from Riedhammer's brochure, stating 3 MJ energy (about 0,8 kWh) demand for a ring furnace. Together, this becomes almost 5 kWh. On the basis of Jäger and Riedhammer information, I have split this in a **gas-powered process of 3,6 MJ** (1 kWh) and an electric process of **4 kWh**, which have been implemented in the inventory. The electricity, again, has been implemented similarly to previous parts of the model, with high and medium voltage infrastructure. A graphite production facility, inventoried as “ceramical plant, CH”, has been given an **infrastructure coefficient of $4,17 \cdot 10^{-9}$** , based on data from Matti Rajaniemi about Mersen's plant's annual production of 12 000 000 kg.

There is one final sub-inventory: *Coal tar pitch*. It concerns a few inputs related to CTP production. The first is coal tar, which is required in approximately twice the amount of CTP product, according to Gray and Krupinski (1997). So I have inventoried **2 kg coal tar per kg CTP**. The heating of 2 kg tar from 20 to 400 °C (700 K in Jäger et. al.), with a heat capacity of 1,47 kJ/(kg*K) gives about **1,1 MJ**, which is inventoried as “heat, unspecific, in chemical plant”. There is an input of sodium carbonate, determined on the basis of information given by Walter Cremers in an e-mail dated 02.14.2014. Cremers states that about 100 mg Na is required per kg CTP, which can be recalculated to sodium carbonate or sodium hydroxide. Using elementary stoichiometrics, we get **0,212 g Na per kg CTP**. Finally, there is the infrastructure coefficient of the CTP facility, which I have set to 10^{-10} . This an average of annual production rates, at about 500 000 000 kg provided by Gray & Krupinski and by the Rütgers presentation.

A.1.5: Errors discovered beyond point of no return

- Forgot to remove Ecoinvent graphite from models, is now counted together with synthetic graphite.
- Was unable to find proper source for data on electricity conversion and infrastructure inputs, which was part of the Ellingsen et al. (2013) model.
- Forgot to implement sulfur hexafluoride emissions to atmosphere from electricity infrastructure as stressor in Arda.

Appendix 2: Inventory entry evaluations

Here I present numerical evaluations of each of the inventory entries that I have created for this thesis. Please note that there is only one table each for LCO and LMO, although I have used these in several different models. I have deemed the differences between models too small to justify complete tables of all, since the only differences are different power mixes and transportation distances. Number of cell and module differences are implemented elsewhere in the Ellingsen et al. (2013) model. The LCO and LMO tables are for the high energy capacity Chinese model.

A.2.1: Lithium Cobalt Oxide powder

Substance	Input	Output	Dimensions/μ	Proxy or description
52 LiCoO2 Powder				
Functional Unit				
52 LiCoO2 Powder		1 kg		
Materials				
51 Lithium Carbonate	0,38	kg		
53 Cobalt(II, III) Oxide	0,82	kg		
Energy				
Electricity, peat	0	kWh		electricity, peat, at power plant/ NORDEL/ kWh
Electricity, coal	2,686234498	kWh		electricity, hard coal, at power plant/ UCTE/ kWh
Electricity, oil	0	kWh		electricity, oil, at power plant/ UCTE/ kWh
Electricity, gas	0,068005937	kWh		electricity, natural gas, at power plant/ UCTE/ kWh
Electricity, waste	0	kWh		electricity from waste, at munic. waste incin. plant/ CH/ kWh
Electricity, nuclear	0,068005937	kWh		electricity, nuclear, at power plant/ UCTE/ kWh
Electricity, hydro	0,510044525	kWh		electricity, hydropower, at power plant/ CH/ kWh
Electricity, solar	0	kWh		electricity, production mix photovoltaic, at plant/ US/ kWh
Electricity, wind	0,068005937	kWh		electricity, at wind power plant/ RER/ kWh
Natural gas, industrial furnace	12	MJ		heat, natural gas, at industrial furnace >100kW/ RER/ MJ
Emissions				
Carbon dioxide, fossil	0,225	kg		Carbon dioxide, fossil/ air/ unspecified
Infrastructure				
LiCoO2 Production Facility	0,0000001	p		metal working factory/ RER/ unit
HV network	2,8699E-008	km		transmission network, electricity, high voltage/ CH/ km
Long distance network	1,0779E-009	km		transmission network, long-distance/ UCTE/ km
MV network	1,0789E-007	km		transmission network, electricity, medium voltage/ CH/ km
Circuit breaker gas	2,5117E-007	kg		sulphur hexafluoride, liquid, at plant/ RER/ kg
53 Cobalt(II,III) Oxide				
Functional Unit				
53 Cobalt(II, III) Oxide		1 kg		
Materials				
Magnesium Oxide (Magnesia)	1,005	kg		magnesium oxide, at plant/ RER/ kg
Processes				
Cobalt mining	0,73	kg		cobalt, at plant/ GLO/ kg
Transport				
Transoceanic freighter	20,7	tkm		transport, transoceanic freight ship/ OCE/ tkm
Infrastructure				
Oxide production facility	neglected	p		

Table A.2.1: Numerical evaluation of lithium cobalt oxide inventories, for Chinese high energy capacity model. Input cells marked where values may be altered between different models.

A.2.2: Lithium Manganese Oxide powder

Substance	Input	Output	Dimensions/uProxy or description
52 LiMn2O4 Powder			
Functional Unit			
52 LiMnO2 Powder		1 kg	
Materials			
51 Lithium Carbonate	0,2	kg	
53 Electrolytic Manganese Dioxide	0,96	kg	
Energy			
Electricity, peat	0	kWh	electricity, peat, at power plant/ NORDEL/ kWh
Electricity, coal	2,420031079	kWh	electricity, hard coal, at power plant/ UCTE/ kWh
Electricity, oil	0	kWh	electricity, oil, at power plant/ UCTE/ kWh
Electricity, gas	0,06126661	kWh	electricity, natural gas, at power plant/ UCTE/ kWh
Electricity, waste	0	kWh	electricity from waste, at munic. waste incin. plant/ CH/ kWh
Electricity, nuclear	0,06126661	kWh	electricity, nuclear, at power plant/ UCTE/ kWh
Electricity, hydro	0,459499572	kWh	electricity, hydropower, at power plant/ CH/ kWh
Electricity, solar	0	kWh	electricity, production mix photovoltaic, at plant/ US/ kWh
Electricity, wind	0,06126661	kWh	electricity, at wind power plant/ RER/ kWh
Natural gas, industrial furnace	10,8	MJ	heat, natural gas, at industrial furnace >100kW/ RER/ MJ
Emissions			
Carbon dioxide, fossil	0,12	kg	Carbon dioxide, fossil/ air/ unspecified
Infrastructure			
LiMnO2 Production Facility	5,00E-008	p	metal working factory/ RER/ unit
HV network	2,5855E-008	km	transmission network, electricity, high voltage/ CH/ km
Long distance network	0,000000001	km	transmission network, long-distance/ UCTE/ km
MV network	9,72E-008	km	transmission network, electricity, medium voltage/ CH/ km
Circuit breaker gas	2,2628E-007	kg	sulphur hexafluoride, liquid, at plant/ RER/ kg
53 Electrolytic Manganese Dioxide			
Functional Unit			
53 Electrolytic Manganese Dioxide		1 kg	
Materials			
56 Manganese Oxide	0,83	kg	
Hydrochloric acid	2,67	kg	hydrochloric acid, 30% in H2O, at plant/ RER/ kg
Energy			
Electricity, peat	0	kWh	electricity, peat, at power plant/ NORDEL/ kWh
Electricity, coal	2,097360269	kWh	electricity, hard coal, at power plant/ UCTE/ kWh
Electricity, oil	0	kWh	electricity, oil, at power plant/ UCTE/ kWh
Electricity, gas	0,053097728	kWh	electricity, natural gas, at power plant/ UCTE/ kWh
Electricity, waste	0	kWh	electricity from waste, at munic. waste incin. plant/ CH/ kWh
Electricity, nuclear	0,053097728	kWh	electricity, nuclear, at power plant/ UCTE/ kWh
Electricity, hydro	0,398232962	kWh	electricity, hydropower, at power plant/ CH/ kWh
Electricity, solar	0	kWh	electricity, production mix photovoltaic, at plant/ US/ kWh
Electricity, wind	0,053097728	kWh	electricity, at wind power plant/ RER/ kWh
Infrastructure			
Electrolysis plant	2,30E-009	p	aluminium electrolysis, plant/ RER/ unit
HV network	2,2407E-008	km	transmission network, electricity, high voltage/ CH/ km
Long distance network	8,4160E-010	km	transmission network, long-distance/ UCTE/ km
MV network	8,424E-008	km	transmission network, electricity, medium voltage/ CH/ km
Circuit breaker gas	1,9611E-007	kg	sulphur hexafluoride, liquid, at plant/ RER/ kg
56 Manganese Oxide			
Functional Unit			
56 Manganese Oxide		1 kg	
Processes			
Manganese mining	1,23	kg	manganese concentrate, at beneficiation/ GLO/ kg
Energy			
Natural gas, industrial furnace	3,67	MJ	heat, natural gas, at industrial furnace >100kW/ RER/ MJ
Infrastructure			
Reduction plant	neglected	p	

Table A.2.2: Numerical evaluation of lithium manganese oxide inventories, for Chinese high energy capacity model. Input cells marked where values may be altered between different models. Transport entry is missing, as Chinese model assumes internal manganese production.

A.2.3: Synthetic graphite

Substance	Input	Output	Dimensions/u	Proxy or description
54 Synthetic Graphite				
Functional Unit				
54 Synthetic Graphite			1 kg	
Materials				
55 Coal Tar Pitch	2,50E-01		kg	
Anthracite	1,00E-01		kg	hard coal, at regional storage/ WEU/ kg
Carbon Black	1,00E-01		kg	carbon black, at plant/ GLO/ kg
Petroleum Coke	5,50E-01		kg	petroleum coke, at refinery/ RER/ kg
Sand	6,00E-03		kg	sand, at mine/ CH/ kg
Metallurgical coke	2,37E-01		MJ	hard coal coke, at plant/ GLO/ MJ
Energy				
Electricity, peat	0,00E+00		kWh	electricity, peat, at power plant/ NORDEL/ kWh
Electricity, coal	3,23E+00		kWh	electricity, hard coal, at power plant/ UCTE/ kWh
Electricity, oil	0,00E+00		kWh	electricity, oil, at power plant/ UCTE/ kWh
Electricity, gas	8,17E-02		kWh	electricity, natural gas, at power plant/ UCTE/ kWh
Electricity, waste	0,00E+00		kWh	electricity from waste, at munic, waste incin. plant/ CH/ kWh
Electricity, nuclear	8,17E-02		kWh	electricity, nuclear, at power plant/ UCTE/ kWh
Electricity, hydro	6,13E-01		kWh	electricity, hydropower, at power plant/ CH/ kWh
Electricity, solar	0,00E+00		kWh	electricity, production mix photovoltaic, at plant/ US/ kWh
Electricity, wind	8,17E-02		kWh	electricity, at wind power plant/ RER/ kWh
Natural gas, industrial furnace	3,60E+00		MJ	heat, natural gas, at industrial furnace >100kW/ RER/ MJ
Infrastructure				
Graphite facility	4,17E-09		p	ceramic plant/ CH/ unit
HV network	3,45E-08		km	transmission network, electricity, high voltage/ CH/ km
Long distance network	1,29E-09		km	transmission network, long-distance/ UCTE/ km
MV network	1,30E-07		km	transmission network, electricity, medium voltage/ CH/ km
Circuit breaker gas	3,02E-07		kg	sulphur hexafluoride, liquid, at plant/ RER/ kg
55 Coal Tar Pitch				
Functional Unit				
55 Coal Tar Pitch			1 kg	
Materials				
Coal Tar	2,00E+00		kg	tar, at coke plant/ GLO/ kg
Sodium Carbonate	2,12E-04		kg	sodium carbonate from amm. chloride prod., at plant/ GLO/ kg
Energy				
Process heat	1,10E+00		MJ	heat, unspecific, in chemical plant/ RER/ MJ
Infrastructure				
Facility	1,00E-10		p	chemical plant, organics/ RER/ unit

Table A.2.3: Numerical evaluation of lithium manganese oxide inventories, for Chinese high energy capacity model. Input cells marked where values may be altered between different models.

A.2.4: Other added entries

In addition to the three tables provided, my inventory contributions include two instances of data alteration. The first is in the battery assembly summary, where shipping distances from the original production site to Norway has been altered to fit the Chinese, American and European models. The

second is an altered line in the Notter et al. (2010) part of the inventory, where the lorry transportation of lithium carbonate is changed to ship, and adjusted according to facts of the Chinese, American and European models. See table A.2.4:

51 Lithium Carbonate				
Functional Unit				
	Li ₂ CO ₃		1 kg	lithium carbonate, at plant/ GLO/ kg
Transport				
	transport, transoceanic freigl	7,8000	tkm	transport, transoceanic freight ship/ OCE/ tkm

Table A.2.4: Ship transport entry for lithium carbonate, in LCO and LMO models.

Appendix 3: Selected structural path analyses (SPA)

A.3.1: Global Warming Potential (all models)

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:									
650,63459595	14,818604334	10001	10005	1406	1407	1432					
		One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ					
650,63459595	14,818604334	10001	10005	2144	2193						
		One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ						
268,89962286	6,1243548092	10001	10005	1406	1401	1427					
		One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ					
268,89962286	6,1243548092	10001	10005	1406	1402	1428					
		One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ					
114,95824069	2,6182448556	10001	10005	1406	1403	1429					
		One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ					
106,257773	2,4200863361	10001	10005	1406	1404	1430					
		One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ					
72,974787462	1,6620458065	10001	10005	2432	2418	2440					
		One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ					
68,016305604	1,549113323	10001	10005	10032	10037	10052	10053	1781	841	837	
		One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiCoO2 powder	Cobalt(II,III) Oxide	cobalt, at plant/ GLO/ kg	portland calcareous cement, at plant/ CH/ kg	clinker, at plant/ CH/ kg	
68,016305604	1,549113323	10001	10005	1406	1407	1432	1449	1385	1466		
		One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg	hard coal, at mine/ WEU/ kg		
66,167172212	1,5069981692	10001	10005	1406	1405	1431					
		One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ PT/ kWh	hard coal, burned in power plant/ PT/ MJ					

Table A.3.1: Global Warming Potential SPA for high capacity LCO, Chinese model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:								
805,5475949916	15,0742813124	10001	10005	1406	1407	1432				
805,5475949916	15,0742813124	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ				
332,9233425877	6,2300230959	10001	10005	2144	2193					
332,9233425877	6,2300230959	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ					
317,8747864982	5,9484181737	10001	10005	1406	1401	1427				
317,8747864982	5,9484181737	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ				
156,869610768	2,9355144957	10001	10005	1406	1402	1428				
156,869610768	2,9355144957	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ				
142,3292503781	2,6634194833	10001	10005	1406	1403	1429				
142,3292503781	2,6634194833	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ				
131,55724276	2,4618419798	10001	10005	1406	1404	1430				
131,55724276	2,4618419798	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ				
90,3497368573	1,6907223836	10001	10005	2432	2418	2440				
90,3497368573	1,6907223836	One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ				
84,2106640816	1,5758413876	10001	10005	10032	10037	10052	10053	1781	841	837
84,2106640816	1,5758413876	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiCoO2 powder	Cobalt(II,III) Oxide	cobalt, at plant/ GLO/ kg	portland calcareous cement, at plant/ CH/ kg	clinker, at plant/ CH/ kg
81,9212608334	1,532999588	10001	10005	1406	1407	1432	1449	1385	1466	
81,9212608334	1,532999588	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg	hard coal, at mine/ WEU/ kg	
80,4817456954	1,5060618177	10001	10005	1406	1405	1431				
80,4817456954	1,5060618177	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ PT/ kWh	hard coal, burned in power plant/ PT/ MJ				

Table A.3.2: Global Warming Potential SPA for low capacity LCO, Chinese model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:								
382,587864216	10,9352759494	10001	10005	2144	2193					
382,587864216	10,9352759494	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ					
269,3236355337	7,6979134722	10001	10005	1406	1407	1432				
269,3236355337	7,6979134722	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ				
106,277014141	3,0376511788	10001	10005	1406	1401	1427				
106,277014141	3,0376511788	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ				
83,709385696	2,3926143973	10001	10005	2432	2418	2440				
83,709385696	2,3926143973	One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ				
68,0163056044	1,9440686452	10001	10005	10032	10037	10052	10053	1781	841	837
68,0163056044	1,9440686452	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiCoO2 powder	Cobalt(II,III) Oxide	cobalt, at plant/ GLO/ kg	portland calcareous cement, at plant/ CH/ kg	clinker, at plant/ CH/ kg
52,4471727549	1,4990656016	10001	10005	1406	1402	1428				
52,4471727549	1,4990656016	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ				
47,5858054731	1,3601161009	10001	10005	1406	1403	1429				
47,5858054731	1,3601161009	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ				
43,9843345337	1,2571774501	10001	10005	1406	1404	1430				
43,9843345337	1,2571774501	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ				
41,8002094291	1,1947499322	10001	10002	10023	10025	2650				
41,8002094291	1,1947499322	One vehicle battery pack	Battery packaging	Module packaging	Outer frame	nylon 66, glass-filled, at plant/ RER/ kg				
41,8002094291	1,1947499322	10001	10002	10023	10026	2650				
41,8002094291	1,1947499322	One vehicle battery pack	Battery packaging	Module packaging	Inner frame	nylon 66, glass-filled, at plant/ RER/ kg				

Table A.3.3: Global Warming Potential SPA for high capacity LCO, European model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:									
622,4498611055	14,3109151594	10001	10005	1406	1407	1432					
622,4498611055	14,3109151594	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ					
417,3685791447	9,5958352625	10001	10005	2144	2193						
417,3685791447	9,5958352625	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ						
245,6231238662	5,6471884829	10001	10005	1406	1401	1427					
245,6231238662	5,6471884829	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ					
121,2137781073	2,7868591561	10001	10005	1406	1402	1428					
121,2137781073	2,7868591561	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ					
109,9783832512	2,5285431172	10001	10005	1406	1403	1429					
109,9783832512	2,5285431172	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ					
101,6548097127	2,3371735593	10001	10005	1406	1404	1430					
101,6548097127	2,3371735593	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ					
68,0163056044	1,5637815024	10001	10005	10032	10037	10052	10053	1781	841	837	
68,0163056044	1,5637815024	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiCoO2 powder	Cobalt(II,III) Oxide	cobalt, at plant/ GLO/ kg	portland calcareous cement, at plant/ CH/ kg	clinker, at plant/ CH/ kg	
63,3008871783	1,4553680265	10001	10005	1406	1407	1432	1449	1385	1466		
63,3008871783	1,4553680265	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg	hard coal, at mine/ WEU/ kg		
62,1885680512	1,4297943929	10001	10005	1406	1405	1431					
62,1885680512	1,4297943929	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ PT/ kWh	hard coal, burned in power plant/ PT/ MJ					
57,2965282845	1,3173201674	10001	10005	1406	1400	1426					
57,2965282845	1,3173201674	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ BE/ kWh	hard coal, burned in power plant/ BE/ MJ					

Table A.3.4: Global Warming Potential SPA for high capacity LCO, American model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:							
956,445485673	17,0368913691	10001	10005	1406	1407	1432			
956,445485673	17,0368913691	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ			
395,2876652764	7,0411467394	10001	10005	2144	2193				
395,2876652764	7,0411467394	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ				
377,4201629373	6,7228780028	10001	10005	1406	1401	1427			
377,4201629373	6,7228780028	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ			
186,2549550035	3,317706532	10001	10005	1406	1402	1428			
186,2549550035	3,317706532	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ			
168,9908452954	3,0101858567	10001	10005	1406	1403	1429			
168,9908452954	3,0101858567	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ			
156,2009889022	2,7823637829	10001	10005	1406	1404	1430			
156,2009889022	2,7823637829	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ			
107,2743540992	1,9108475547	10001	10005	2432	2418	2440			
107,2743540992	1,9108475547	One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ			
97,2670275374	1,7325898933	10001	10005	1406	1407	1432	1449	1385	1466
97,2670275374	1,7325898933	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg	hard coal, at mine/ WEU/ kg
95,5578575717	1,7021449349	10001	10005	1406	1405	1431			
95,5578575717	1,7021449349	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ PT/ kWh	hard coal, burned in power plant/ PT/ MJ			
88,0408354902	1,5682463588	10001	10005	1406	1400	1426			
88,0408354902	1,5682463588	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ BE/ kWh	hard coal, burned in power plant/ BE/ MJ			

Table A.3.5: Global Warming Potential SPA for high capacity LMO, Chinese model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:							
1287,522769175	17,3445404327	10001	10005	1406	1407	1432			
1287,522769175	17,3445404327	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ			
532,1180109489	7,1682944775	10001	10005	2144	2193				
532,1180109489	7,1682944775	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ				
508,065603954	6,8442785023	10001	10005	1406	1401	1427			
508,065603954	6,8442785023	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ			
250,7278240431	3,3776170689	10001	10005	1406	1402	1428			
250,7278240431	3,3776170689	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ			
227,4876763593	3,0645432415	10001	10005	1406	1403	1429			
227,4876763593	3,0645432415	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ			
210,2705619837	2,8326071985	10001	10005	1406	1404	1430			
210,2705619837	2,8326071985	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ			
144,4077843643	1,9453532898	10001	10005	2432	2418	2440			
144,4077843643	1,9453532898	One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ			
130,9363832234	1,7638766842	10001	10005	1406	1407	1432	1449	1385	1466
130,9363832234	1,7638766842	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg	hard coal, at mine/ WEU/ kg
128,6355775004	1,7328819563	10001	10005	1406	1405	1431			
128,6355775004	1,7328819563	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ PT/ kWh	hard coal, burned in power plant/ PT/ MJ			
118,5165093137	1,5965654643	10001	10005	1406	1400	1426			
118,5165093137	1,5965654643	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ BE/ kWh	hard coal, burned in power plant/ BE/ MJ			

Table A.3.6: Global Warming Potential SPA for low capacity LMO, Chinese model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:						
562,4115868996	13,3088648192	10001	10005	2144	2193			
562,4115868996	13,3088648192	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ			
395,9109721384	9,3688069936	10001	10005	1406	1407	1432		
395,9109721384	9,3688069936	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ		
156,2292737552	3,6969975969	10001	10005	1406	1401	1427		
156,2292737552	3,6969975969	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ		
123,0544218755	2,9119504368	10001	10005	2432	2418	2440		
123,0544218755	2,9119504368	One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ		
77,0983620139	1,8244497477	10001	10005	1406	1402	1428		
77,0983620139	1,8244497477	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ		
69,9520577446	1,6553401495	10001	10005	1406	1403	1429		
69,9520577446	1,6553401495	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ		
64,6578255547	1,5300578435	10001	10005	1406	1404	1430		
64,6578255547	1,5300578435	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ		
51,7526402456	1,2246705244	10001	10002	10023	10025	2650		
51,7526402456	1,2246705244	One vehicle battery pack	Battery packaging	Module packaging	Outer frame	nylon 66, glass-filled, at plant/ RER/ kg		
51,7526402456	1,2246705244	10001	10002	10023	10026	2650		
51,7526402456	1,2246705244	One vehicle battery pack	Battery packaging	Module packaging	Inner frame	nylon 66, glass-filled, at plant/ RER/ kg		
44,1342102006	1,0443885779	10001	10002	10023	10025	1757	1755	1756
44,1342102006	1,0443885779	One vehicle battery pack	Battery packaging	Module packaging	Outer frame	aluminium, production mix, at plant/ RER/ kg	aluminium, primary, at plant/ RER/ kg	aluminium, primary, liquid, at plant/ RER/ kg

Table A.3.7: Global Warming Potential SPA for high capacity LMO, European model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:							
915,0133783443	16,5869961283	10001	10005	1406	1407	1432			
915,0133783443	16,5869961283	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ			
613,5399129813	11,1220058658	10001	10005	2144	2193				
613,5399129813	11,1220058658	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ				
361,0707599309	6,5453461542	10001	10005	1406	1401	1427			
361,0707599309	6,5453461542	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ ES/ kWh	hard coal, burned in power plant/ ES/ MJ			
178,1866067266	3,2300954564	10001	10005	1406	1402	1428			
178,1866067266	3,2300954564	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ FR/ kWh	hard coal, burned in power plant/ FR/ MJ			
161,6703581953	2,9306955165	10001	10005	1406	1403	1429			
161,6703581953	2,9306955165	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ IT/ kWh	hard coal, burned in power plant/ IT/ MJ			
149,4345435229	2,7088895676	10001	10005	1406	1404	1430			
149,4345435229	2,7088895676	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ NL/ kWh	hard coal, burned in power plant/ NL/ MJ			
93,0535329004	1,6868371834	10001	10005	1406	1407	1432	1449	1385	1466
93,0535329004	1,6868371834	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg	hard coal, at mine/ WEU/ kg
91,418402192	1,6571961887	10001	10005	1406	1405	1431			
91,418402192	1,6571961887	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ PT/ kWh	hard coal, burned in power plant/ PT/ MJ			
84,2270087745	1,5268334885	10001	10005	1406	1400	1426			
84,2270087745	1,5268334885	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ BE/ kWh	hard coal, burned in power plant/ BE/ MJ			
44,1342102006	0,8000472901	10001	10002	10023	10025	1757	1755	1756	
44,1342102006	0,8000472901	One vehicle battery pack	Battery packaging	Module packaging	Outer frame	aluminium, production mix, at plant/ RER/ kg	aluminium, primary, at plant/ RER/ kg	aluminium, primary, liquid, at plant/ RER/ kg	

Table A.3.8: Global Warming Potential SPA for high capacity LMO, American model.

A.3.2: Natural land transformation (LCO and LMO high capacity)

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:							
1,6234317125	66,4051647462	10001	10005	10032	10037	10052	3741		
1,6234317125	66,4051647462	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiCoO2 powder	metal working factory/ RER/ unit		
0,0377221467	1,5429939849	10001	10005	10032	10037	10052	10053	1781	3302
0,0377221467	1,5429939849	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiCoO2 powder	Cobalt(II,III) Oxide	cobalt, at plant/ GLO/ kg	disposal, non-sulfidic tailings, off-site/ GLO/ kg
0,027192367	1,1122818405	10001	10005	10033	10038	1796	1782	3315	
0,027192367	1,1122818405	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg	
0,0019253111	0,0787532987	10001	10005	10033	10038	1796	1782		
0,0019253111	0,0787532987	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg		
0,001417453	0,0579797729	10001	10005	1406	1407	1432	1449		
0,001417453	0,0579797729	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg		

Table A.3.9: Natural Land Transformation SPA for high capacity LCO, Chinese model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:										
1,0049815363	52,2467281894	10001	10005	10032	10037	10052	3741					
1,0049815363	52,2467281894	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiMn2O4 powder	metal working factory/ RER/ unit					
0,0336667401	1,7502580474	10001	10005	10033	10038	1796	1782	3315				
0,0336667401	1,7502580474	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg				
0,0316360515	1,6446871146	10001	10005	2432	2418	2440	2352	2350	2472	2460	3858	
0,0316360515	1,6446871146	One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ	heavy fuel oil, at regional storage/ RER/ kg	heavy fuel oil, at refinery/ RER/ kg	crude oil, production RU, at long distance transport/ RER/ kg	crude oil, at production onshore/ RU/ kg	well for exploration and production, onshore/ GLO/ m	
0,0253599912	1,3184088668	10001	10005	10032	10037	10052	10053	3714				
0,0253599912	1,3184088668	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiMn2O4 powder	Electrolytic Manganese Dioxide	aluminium electrolysis, plant/ RER/ unit				
0,0236791985	1,2310282337	10001	10005	2144	2193	2089	2215	2232	2219	3857		
0,0236791985	1,2310282337	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ	natural gas, high pressure, at consumer/ RER/ MJ	natural gas, at long-distance pipeline/ RER/ Nm3	natural gas, production NL, at long-distance pipeline/ RER/ Nm3	natural gas, at production offshore/ NL/ Nm3	well for exploration and production, offshore/ OCE/ m		
0,0098411346	0,5116184361	10001	10005	1406	1407	1432	1449	1385	1466			
0,0098411346	0,5116184361	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg	hard coal, at mine/ WEU/ kg			
0,0023837185	0,1239241618	10001	10005	10033	10038	1796	1782					
0,0023837185	0,1239241618	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg					
0,0020836835	0,1083260139	10001	10005	1406	1407	1432	1449					
0,0020836835	0,1083260139	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg					
0,001144318	0,0594905158	10001	10005	1406	1407	1432	1449	1385				
0,001144318	0,0594905158	One vehicle battery pack	Battery cell	electricity, hard coal, at power plant/ UCTE/ kWh	electricity, hard coal, at power plant/ DE/ kWh	hard coal, burned in power plant/ DE/ MJ	hard coal supply mix/ DE/ kg	hard coal, at regional storage/ WEU/ kg				

Table A.3.10: Natural Land Transformation SPA for high capacity LMO, Chinese model.

A.3.3: Freshwater ecotoxicity (LCO and LMO high capacity)

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:						
123,3109689625	58,0367187511	10001	10005	10033	10038	1796	1782	3315
123,3109689625	58,0367187511	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg
21,5567247573	10,1457443929	10001	10005	10033	10038	1796	1790	3315
21,5567247573	10,1457443929	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper, SX-EW, at refinery/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg
3,4708551219	1,6335695375	10001	10002	10023	10027	1796	1782	3315
3,4708551219	1,6335695375	One vehicle battery pack	Battery packaging	Module packaging	Bimetallic busbars	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg
3,2009694615	1,5065469514	10001	10003	10015	1796	1782	3315	
3,2009694615	1,5065469514	One vehicle battery pack	BMS	High Voltage system	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg	
0,2304941416	0,1084828364	10001	10005	10033	10038	1796		
0,2304941416	0,1084828364	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg		
0,0972755986	0,0457830849	10001	10005	10032	10037	10052	10053	1781
0,0972755986	0,0457830849	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiCoO2 powder	Cobalt(II,III) Oxide	cobalt, at plant/ GLO/ kg
0,0773195495	0,0363907038	10001	10005	10033	10038	1796	1782	
0,0773195495	0,0363907038	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	
0,0064877584	0,0030534851	10001	10002	10023	10027	1796		
0,0064877584	0,0030534851	One vehicle battery pack	Battery packaging	Module packaging	Bimetallic busbars	copper, primary, at refinery/ GLO/ kg		
0,0059832853	0,0028160532	10001	10003	10015	1796			
0,0059832853	0,0028160532	One vehicle battery pack	BMS	High Voltage system	copper, primary, at refinery/ GLO/ kg			
0,0021763267	0,0010242954	10001	10002	10023	10027	1796	1782	
0,0021763267	0,0010242954	One vehicle battery pack	Battery packaging	Module packaging	Bimetallic busbars	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	

Table A.3.11: Freshwater Ecotoxicity SPA for high capacity LCO, Chinese model.

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:						
152,6707234774	59,0180514302	10001	10005	10033	10038	1796	1782	3315
152,6707234774	59,0180514302	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg
26,6892782709	10,317297002	10001	10005	10033	10038	1796	1790	3315
26,6892782709	10,317297002	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper, SX-EW, at refinery/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg
4,2972491986	1,6611912778	10001	10002	10023	10027	1796	1782	3315
4,2972491986	1,6611912778	One vehicle battery pack	Battery packaging	Module packaging	Bimetallic busbars	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg
3,2009694615	1,2374014873	10001	10003	10015	1796	1782	3315	
3,2009694615	1,2374014873	One vehicle battery pack	BMS	High Voltage system	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	disposal, sulfidic tailings, off-site/ GLO/ kg	
0,2853736991	0,1103171536	10001	10005	10033	10038	1796		
0,2853736991	0,1103171536	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg		
0,095728966	0,0370060278	10001	10005	10033	10038	1796	1782	
0,095728966	0,0370060278	One vehicle battery pack	Battery cell	Anode	Negative current collector Cu	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	
0,0080324628	0,003105116	10001	10002	10023	10027	1796		
0,0080324628	0,003105116	One vehicle battery pack	Battery packaging	Module packaging	Bimetallic busbars	copper, primary, at refinery/ GLO/ kg		
0,0059832853	0,0023129637	10001	10003	10015	1796			
0,0059832853	0,0023129637	One vehicle battery pack	BMS	High Voltage system	copper, primary, at refinery/ GLO/ kg			
0,0026944997	0,0010416151	10001	10002	10023	10027	1796	1782	
0,0026944997	0,0010416151	One vehicle battery pack	Battery packaging	Module packaging	Bimetallic busbars	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg	
0,0020071006	0,0007758866	10001	10003	10015	1796	1782		
0,0020071006	0,0007758866	One vehicle battery pack	BMS	High Voltage system	copper, primary, at refinery/ GLO/ kg	copper concentrate, at beneficiation/ GLO/ kg		

Table A.3.12: Freshwater Ecotoxicity SPA for high capacity LMO, Chinese model.

A.3.4: Ozone Depletion SPA (LMO high capacity)

ABSOLUTE	RELATIVE to total impact(%)	SEQUENCE:									
6,6540232E-005	13,5595152442	10001	10005	10032	10037	10052	10053	494	497	475	474
6,6540232E-005	13,5595152442	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiMn2O4 powder	Electrolytic Manganese Dioxide	hydrochloric acid, 30% in H2O, at plant/ RER/ kg	hydrochloric acid, from the reaction of hydrogen with chlorine, at plant/ RER/ kg	chlorine, liquid, production mix, at plant/ RER/ kg	chlorine, gaseous, mercury cell, at plant/ RER/ kg
4,2950732E-005	8,7524658065	10001	10005	2144	2193	2089	2215	2234	2247		
4,2950732E-005	8,7524658065	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ	natural gas, high pressure, at consumer/ RER/ MJ	natural gas, at long-distance pipeline/ RER/ Nm3	natural gas, production RU, at long-distance pipeline/ RER/ Nm3	transport, natural gas, pipeline, long distance/ RU/ tkm		
2,8379228E-005	5,7830963383	10001	10005	10032	10037	10052	10053	494	497	475	471
2,8379228E-005	5,7830963383	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiMn2O4 powder	Electrolytic Manganese Dioxide	hydrochloric acid, 30% in H2O, at plant/ RER/ kg	hydrochloric acid, from the reaction of hydrogen with chlorine, at plant/ RER/ kg	chlorine, liquid, production mix, at plant/ RER/ kg	chlorine, gaseous, diaphragm cell, at plant/ RER/ kg
2,5843212E-005	5,2663090059	10001	10005	10032	10037	10052	10053	494	497	475	473
2,5843212E-005	5,2663090059	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiMn2O4 powder	Electrolytic Manganese Dioxide	hydrochloric acid, 30% in H2O, at plant/ RER/ kg	hydrochloric acid, from the reaction of hydrogen with chlorine, at plant/ RER/ kg	chlorine, liquid, production mix, at plant/ RER/ kg	chlorine, gaseous, membrane cell, at plant/ RER/ kg
0,000025591	5,2149040941	10001	10005	2251	2260	2278	2270	2303	2306		
0,000025591	5,2149040941	One vehicle battery pack	Battery cell	electricity, nuclear, at power plant/ UCTE/ kWh	electricity, nuclear, at power plant pressure water reactor/ UCTE/ kWh	fuel elements PWR, UO2 3.9% & MOX, at nuclear fuel fabrication plant/ UCTE/ kg	U enriched 3.9%, in fuel element for LWR, at nuclear fuel fabrication plant/ UCTE/ kg	uranium, enriched 3.9% for pressure water reactor/ UCTE/ kg SWU	uranium, enriched 3.9%, at USEC enrichment plant/ US/ kg SWU		
1,0032085E-005	2,0443301898	10001	10005	10032	10037	10052	3741	3972	2338	2468	2461
1,0032085E-005	2,0443301898	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiMn2O4 powder	metal working factory/ RER/ unit	roads, company, internal/ CH/ m2a	bitumen, at refinery/ CH/ kg	crude oil, production RAF, at long distance transport/ CH/ kg	crude oil, at production onshore/ RAF/ kg
9,3176801E-006	1,8987494079	10001	10005	2144	2193	2089	2245				
9,3176801E-006	1,8987494079	One vehicle battery pack	Battery cell	electricity, natural gas, at power plant/ UCTE/ kWh	natural gas, burned in power plant/ UCTE/ MJ	natural gas, high pressure, at consumer/ RER/ MJ	transport, natural gas, pipeline, long distance/ RER/ tkm				
6,7878241E-006	1,3832173686	10001	10005	10032	10037	10052	3741	3972	2338	2464	2454
6,7878241E-006	1,3832173686	One vehicle battery pack	Battery cell	Cathode	Positive electrode paste	LiMn2O4 powder	metal working factory/ RER/ unit	roads, company, internal/ CH/ m2a	bitumen, at refinery/ CH/ kg	crude oil, production NG, at long distance transport/ CH/ kg	crude oil, at production/ NG/ kg
5,9068501E-006	1,203693193	10001	10005	10033	10039	491	1383				
5,9068501E-006	1,203693193	One vehicle battery pack	Battery cell	Anode	Negative electrode paste	graphite, battery grade, at plant/ CN/ kg	hard coal coke, at plant/ GLO/ MJ				
5,4009067E-006	1,1005924555	10001	10005	2432	2418	2440	2352	2350	2470	2458	
5,4009067E-006	1,1005924555	One vehicle battery pack	Battery cell	electricity, oil, at power plant/ UCTE/ kWh	electricity, oil, at power plant/ IT/ kWh	heavy fuel oil, burned in power plant/ IT/ MJ	heavy fuel oil, at regional storage/ RER/ kg	heavy fuel oil, at refinery/ RER/ kg	crude oil, production RME, at long distance transport/ RER/ kg	crude oil, at production onshore/ RME/ kg	

Table A.3.13: Ozone Depletion SPA for high capacity LMO, Chinese model.