THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Using life cycle assessment to support the development of electrified road vehicles

Component data models, methodology recommendations
and technology advice for minimizing environmental impact

ANDERS NORDELÖF

Graduate School of Energy and Environment
Division of Environmental Systems Analysis
Department of Technology Management and Economics

CHALMERS UNIVERSITY OF TECHNOLOGY
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ANDERS NORDELÖF
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Graduate School of Energy and Environment

Division of Environmental Systems Analysis
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000
Cover: The electric motor and the inverter unit brought into the context of an electric passenger vehicle during charging, illustrated by Boid / Product design studio.

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Till Anna, Maja, Melker och Molly

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Abstract

The anthropogenic pressure on the Earth system already overshoots safe limits for climate change, so there is an urgent need to drastically reduce greenhouse gas emissions caused by transportation. Electric propulsion technology is a promising solution that can decouple fossil fuel use from road vehicle traffic. Additional benefits include removed tailpipe exhaust gas emissions, which currently damage human health and the environment, both locally and regionally.

However, electrification of vehicles could lead to problem shifts, e.g. from the use of fossil fuels to the generation of fossil electricity. Even when combined with renewable energy, there are trade-offs between benefits in operation and added environmental load during manufacturing, shifting from airborne emissions to resource related impacts. This is because electric powertrain components require new materials and more advanced processing compared to conventional vehicle parts.

The environmental impacts of vehicle electrification can be analyzed using life cycle assessment (LCA). This is a holistic systems tool, where all life cycle stages, from raw material acquisition to disposal, are investigated for potential contribution to environmental problems. For LCA of vehicles, a well-to-wheels study examines the life cycle of the energy carrier, i.e. a fuel or electricity, whereas complete LCA includes the production, use and disposal of the vehicle as such. A thorough review of the research field exposed short-comings in both methodology and inventory data.

This thesis aims to discuss in what ways LCA support the development of electrified road vehicles, and present contributions on how the methodology can advance to provide better support, with the goal to minimize environmental impact of vehicles in the long term.

Two component data models were developed. These estimate the mass and composition of one electrical traction motor and one inverter unit (the motor controller), calculate full gate-to-gate manufacturing inventories, and point to an existing database to establish cradle-to-gate models. Both are scalable from basic engineering parameters, build on typical design solutions and are easy-to-use. During this work, 45 new unit process datasets for manufacturing were compiled and the thesis discusses and presents useful strategies for data collection.

A critical review of 79 publications was conducted. It was found that most LCA studies of electric vehicles fail to report their purpose and time scope as required by the ISO standard for LCA, making results appear divergent and creating a demand for more restrictive LCA guidelines to enhance comparability. But LCA has utility beyond comparing electric and conventional vehicles, e.g. to guide stepwise improvements in design and manufacturing. Such studies address a technical audience rather than consumers or policy makers. An LCA study in the project evaluated three electric motors with different designs and magnets. Results show that the making of aluminum, electrical steel and copper dominates the environmental load of the production. In particular, copper use is a driver of toxic impacts.

The thesis stresses the importance of framing LCA studies to advise specific actors to take action and avoid future environmental impact. The thesis advises policy makers, automotive and power industries to plan and act for a conjoint development of electrified vehicles with fossil free electricity production, to attain the full climate change mitigation potential of electrification. Policy makers and automotive industries need to be aware that energy efficiency is key to low impact, while the equipment production, especially of primary metals and related toxic emissions, becomes increasingly important.

Keywords: electric vehicle; critical review; LCA; LCI; inventory data; scalable model; electrical machine; motor; inverter; magnet; stepwise improvements

List of appended papers

The thesis is based on the following appended papers:

I. **Nordelöf, A.**, Messagie, M., Tillman, A.-M., Ljunggren Söderman, M. & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment,* 19(11), pp. 1866-1890.

II. **Nordelöf, A.**, Grunditz, E., Tillman, A.-M., Thiringer, T. & Alatalo, M. (2017). A scalable life cycle inventory of an electrical automotive traction machine—Part I: design and composition. *The International Journal of Life Cycle Assessment.* Published online 5 April 2017.

III. **Nordelöf, A.** & Tillman, A.-M. (2017). A scalable life cycle inventory of an electrical automotive traction machine—Part II: manufacturing processes. *The International Journal of Life Cycle Assessment.* Published online 9 April 2017.

IV. **Nordelöf, A.**, Grunditz, E., Lundmark, S., Tillman, A.-M., Alatalo, M. & Thiringer, T. (2017). Life cycle assessment of permanent magnet electric traction motors. Submitted manuscript.

V. **Nordelöf, A.**, Alatalo, M. & Ljunggren Söderman, M. (2017). A scalable life cycle inventory of an automotive power electronic inverter unit—Part I: design and composition. Manuscript to be submitted.

VI. **Nordelöf, A.** (2017). A scalable life cycle inventory of an automotive power electronic inverter unit—Part II: manufacturing processes. Manuscript to be submitted.

Contributions to the appended papers:

Paper I. The author conducted the complete reading and review of articles, including the search for publications and the meta-analysis. He wrote full draft versions of the main manuscript and the supporting information. The author collaborated with A.-M. Tillman in setting up the meta-analysis. She also gave support in structuring texts, drawing conclusions and final phrasing. Co-author M. Messagie supported the content development of texts, the meta-analysis and in the calculations of numerical examples. Other co-authors assisted by advising the review process and by reviewing the manuscripts. The author made calculations for the erratum and phrased the text together with A.-M. Tillman.

Paper II. The author initiated the project, gathered all design data not deriving from theoretical calculations and conducted the validation of the design work. He wrote a full draft version of the manuscript. He edited sections on motor theory and design descriptions in the model report and wrote remaining sections corresponding to paper II. Support was given by A.-M. Tillman in structuring and processing all texts. E. Grunditz conducted all design tool calculations with support by T. Thiringer and M. Alatalo. They also wrote draft sections for the theory chapter and the design descriptions for the model report.

Paper III. The author initiated the project and compiled all manufacturing data. He wrote a full draft version of the manuscript and corresponding sections of the model report. Support was given by A.-M. Tillman in structuring and processing both texts. The author programmed, structured and wrote all texts in the LCI model file.

Paper IV. The author conducted the LCA study and wrote the complete main manuscript. E. Grunditz, S. Lundmark and M. Alatalo conducted the design tool calculations for the new motor options with support by T. Thiringer. E. Grunditz conducted all use-phase drive cycle calculations with support in the setup by the author. E. Grunditz also wrote the corresponding sections in the supplementary report. The author compiled all data required for the modeling of designs and manufacturing, as well as allocation procedures. A.-M. Tillman provided support in the analysis of LCA results and processing texts.

Paper V. The author initiated the project, compiled all design data, and conducted all calculations including the evaluation of the model. He wrote a full draft version of the manuscript and all corresponding sections of the model report. Support was given by M. Alatalo in the theoretical derivations of the design scaling of components and throughout the design theory section of the model report. M. Ljunggren Söderman contributed by structuring and processing texts in the manuscript. A.-M. Tillman commented on the manuscript, but not in the role as a co-author.

Paper VI. The author initiated the project, compiled all manufacturing data, and wrote the manuscript and corresponding sections of the model report. A.-M. Tillman commented on the manuscript, but not in the role as a co-author. The author programmed, structured and wrote all texts in the LCI model file.

Other publications by the author

The following erratum, reports and model files were or will be published in connection to the appended papers:

Nordelöf, A. (2017) Scalable Power Electronic Inverter LCI Model.xlsm [Online]. Version 1.0. Gothenburg, Sweden: Chalmers University of Technology. To be distributed by The Swedish Life Cycle Center (CPM) upon publication of appended papers V and VI (to ensure journal requirements for research novelty).

Nordelöf, A. & Alatalo, M. (2017). A scalable life cycle inventory of an automotive power electronic inverter unit – Technical and methodological description, version 1.0. 2017, Gothenburg, Sweden: Department of Energy and Environment, Divisions of Environmental Systems Analysis & Electric Power Engineering, Chalmers University of Technology. To be uploaded as ESA report no. 2016:5 in the Chalmers publication library (CPL) and distributed via The Swedish Life Cycle Center (CPM) upon publication of appended papers V and VI (to ensure journal requirements for research novelty).

Nordelöf, A. (2016) Scalable IPMSM LCI Model.xlsm [Online]. Version 1.0. Gothenburg, Sweden: Chalmers University of Technology. Distributed by The Swedish Life Cycle Center (CPM).

Nordelöf, A., Grunditz, E., Tillman, A.-M., Thiringer, T. & Alatalo, M. (2016). A scalable life cycle inventory of an electrical automotive traction machine – technical and methodological description, version 1.0. 2016, Gothenburg, Sweden: Department of Energy and Environment, Divisions of Environmental Systems Analysis & Electric Power Engineering, Chalmers University of Technology. ESA report no. 2016:4.

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M. & Van Mierlo, J. (2016). Erratum to: Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment.* 21(1) pp. 134-135. Appended to paper I.

Nordelöf, A. & Tillman, A.-M. (2014). Mindre miljöpåverkan eller bara annorlunda? In: SANDÉN, B. (ed.) *Perspektiv på eldrivna fordon*, E-bok.
Online ISBN 978-91-980974-4-3.

Nordelöf, A., Tillman, A.-M., Messagie, M. & Van Mierlo, J. (2013). Less or different environmental impact? In: SANDÉN, B. (ed.) *Systems Perspectives on Electromobility*, E-book. Online ISBN 978-91-980973-1-3.

The following publications have also been written or contributed to as a part of the project:

Arvidsson, R., Tillman, A.-M., Sandén, B., Janssen, M., **Nordelöf, A.**, Kushnir, D. & Molander, S. (2017). Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. *Journal of Industrial Ecology*.

Nordelöf, A., Björkman, A., Ljunggren Söderman, M. & Tillman, A.-M. (2013) The role of life cycle assessment in evaluating alternatives for electrification of roads and long haul trucks in Sweden. Poster presented at the *SETAC Europe 23rd Annual Meeting*, 12-16 May 2013, Glasgow, United Kingdom. Environmental systems analysis, Chalmers University of Technology.

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Abbreviations

AC	alternating current
BEV	battery electric vehicle
CF	characterization factor
CI	compression ignition
CML	Centrum voor Milieukunde Leiden, *acronym name*
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
DCB	direct copper bonded
EPD	environmental product declaration
E-REV	extended range electric vehicle
EV	electric vehicle
HC	hydrocarbons
HEV	hybrid electric vehicle
ICE	internal combustion engine
IE	industrial ecology
IGBT	insulated gate bipolar transistor
ILCD	International Reference Life Cycle Data System, *name*
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
Nd(Dy)FeB	neodymium-dysprosium-iron-boron
NdFeB	neodymium-iron-boron
NOx	nitrogen oxides
PCB	printed circuit board
PEF	product environmental footprint
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
PM-assisted SynRM	permanent magnet-assisted synchronous reluctance machine
PMSM	permanent magnet synchronous machine
ReCiPe	*acronym name*
REE	rare-earth element
REO	rare-earth oxide
SI	spark ignition
SmCo	samarium-cobalt
Sr-ferrite	strontium-ferrite

This list is continued on the next page.

TTW	tank-to-wheels
VOC	volatile organic compound
WTT	well-to-tank
WTW	well-to-wheels

Contents

Chapter 1

Introduction

Current atmospheric concentrations of carbon dioxide, methane and nitrous oxide have reached levels unsurpassed for at least 800,000 years (IPCC, 2014). Anthropogenic emissions of greenhouse gases increased by more than 80% between 1970 and 2010, and effects on the climate system are becoming increasingly visible (IPCC, 2014). Scientific records dating back to 1850 prove ongoing global warming, and further evidence indicate that the last three decades have been the warmest period in over 1000 years (IPCC, 2014).

The burning of fossil fuels is the fundamental cause of human induced climate change, and road based transports account for more than 17% of global carbon dioxide emissions (IEA, 2016a). Over the last century, vehicle technology has evolved to play a central role in everyday life globally. The total fleet has passed 1.2 billion vehicles and mankind has constructed more than 64 million kilometers of road (CIA, 2016, OICA, 2016c).[1]

However, there are limits to the amount of anthropogenic pressure the Earth system can withstand without being triggered into irreversible and perhaps uncontrollable environmental change (Rockström et al., 2009a, b, Steffen et al., 2015). Due to exponential growth in activity, humans are now capable of altering the stability of natural systems which constitute the foundation of our well-being (Rockström et al., 2009a, b). At worst, such an alteration would lead to societal collapse and a rapid decrease in the world population (Meadows et al., 1972).

The safe limit for climate change has already been overshot, but there is still time to act (Steffen et al., 2015). At best, the technology development which generated the precarious situation also contains keys to a manageable solution. Electrification may be the way out for road transportation, but there are many challenges ahead.

1.1 Combustion based transportation

The internal combustion engine (ICE) is the most common propulsion source in vehicles (Stone, 1999). It is conveniently combined with liquid fuels of high energy density to provide both sufficient power and range for operation of great flexibility regardless of vehicle category and size. The ICE can be divided into two main types depending on how

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[1] In 2014 the road vehicle fleet contained more than 900 million passenger vehicles and 300 million commercial vehicles (OICA, 2016a, b). 30% of all roads in the world are paved (CIA, 2016).

the combustion is ignited: spark ignition (SI) and compression ignition (CI). Each type combines with one of the two dominating liquid fossil fuels used in road vehicles: petrol (gasoline) for SI engines and diesel for (CI) engines. SI engines combust with lower efficiency than CI engines (Stone, 1999).

Any combustion of fossil fuels produces carbon dioxide and varying levels of other airborne emissions, such as carbon monoxide (CO), unburned or volatile hydrocarbons (HC/VOC), nitrogen oxides (NOx), and particulate matter (PM). Differing from carbon dioxide, which contributes to climate change by global accumulation, the other tailpipe emissions cause damage to health and environment regionally and locally. There is a clear link between urban air pollution and both respiratory and cardiovascular diseases, as well as cancer mortality (Demidov and Bonnet, 2009). Secondary effects of especially NOx emissions, are the creation of harmful ground-level ozone, acidification and eutrophication. For these reasons, tailpipe emissions have been subject to increasingly strict regulation over many decades (Stone, 1999, European Parliament, 2007). In response, the automotive industry has developed exhaust gas after-treatment systems to reduce emissions for both SI and CI engines, but typically at the cost of higher fuel consumption and linked emissions of carbon dioxide (Stone, 1999). Nevertheless, continuous development has brought both fuel consumption and exhaust emissions from ICEs down during the last two decades.

The enforcement of tailpipe regulations is exercised via measurements on special test cycles (European Parliament, 2007, US EPA, 2015). However, with increasingly strict requirements, real-world driving emissions and those measured for compliance with the regulations are diverging significantly, especially for diesel vehicles and NOx emissions (Weiss et al., 2013). Clearly, there is large challenge for both SI and CI engine development to further reduce both fuel consumption and regulated emissions (US EPA, 2015).

Both SI and CI engines can be combined with non-fossil liquid fuels, recovered from waste or biofuels from various crops and trees. There are also emerging techniques for making liquid fuels using electricity and captured carbon dioxide, even directly from air (Conrado et al., 2013, Nikoleris and Nilsson, 2013). SI engines run well with alcohols and CI engines can operate on most liquid fuels, although different oils with properties similar to diesel are the most compatible (Stone, 1999). SI engines can also be adopted for gaseous fuels, such as biogas or hydrogen.

Biofuels are not the focus of this thesis, but a few remarks have been included for orientation. Their main benefit is carbon neutrality due to the absorption of carbon dioxide during the photosynthesis. However, the capacity to replace all fossil transport fuels is limited, at least on a global scale (Murphy et al., 2011). Actual reductions of carbon dioxide are decreased due to land transformation when biofuels production expand (Havlík et al., 2011, Timilsina and Shrestha, 2011). When used in ICEs, biofuels cause emissions of other air pollutants, as in any combustion, but sometimes in larger amounts than fossil fuels (Timilsina and Shrestha, 2011). A topic of much discussion concerns the competition over land between biofuels and food production (Rathmann et al., 2010, Timilsina and Shrestha, 2011, Harvey and Pilgrim, 2011).

1.2 Promises and challenges of electrification

Electrification of vehicle propulsion is regarded as promising technology for significant reduction of greenhouse and other exhaust gas emissions from road transport (Nemry and Brons, 2010, Sadek, 2012). Electric powertrains are more energy efficient for propelling vehicles than ICEs, and full electric propulsion does not emit tailpipe emissions (IAE, 2011, 2015, Sadek, 2012). Maybe most important, electric powertrains enable a decoupling of the road transport sector from its heavy reliance on fossil fuels during operation. Together with coming generations of biofuels, this is the main option for a complete phase out of petrol and diesel from vehicle propulsion (IEA, 2015). However, to completely remove carbon dioxide emissions, and not only to reduce and shift them to other sectors, non-fossil electricity production is required. This is offered by flowing renewable energy sources such as solar power and wind power, which, unlike the crucial drawback with biofuels, do not require productive land area.

On the other hand, electric vehicles may necessitate increased electricity production (Tran et al., 2012, IEA, 2015). Furthermore, electric powertrains require new advanced components (Chan, 2007), causing additional, or at least different, environmental impacts compared to conventional vehicles. There is also a general increase in the use of scarce and critical materials in vehicles (Andersson et al., 2016), driven partly by electrification and an overall ambition to reduce energy consumption. As a consequence, there is a shift of focus from emissions caused during operation to other stages in the life cycle of vehicles, especially manufacturing of parts and materials in terms of energy and resource use. Resource constraints as well as emissions relating to resource extraction are of particular interest for electrical and electronic parts and devices (European Commission, 2015, Hawkins et al., 2013). Consequently, the reduction of greenhouse and other exhaust gas emissions by electrification may lead to a shift to new environmental problems and undesired trade-offs.

1.3 Environmental assessment of electric vehicles

The balance of benefits and negative impacts of road vehicle electrification, i.e. the removal of emissions during operation versus the load of producing the electric powertrain and emissions from electricity supply, can be analyzed using life cycle assessment (LCA). It is a systemic tool for evaluating the environmental impact related to goods and services (Baumann and Tillman, 2004). All life cycle stages, from material acquisition and manufacturing, to use and End-of-life are surveyed technically and evaluated in terms of a potential contribution to different environmental problems (ISO, 2006a, b).

Paper I reports a critical review of 79 publications on LCA of fully electric and hybrid vehicles covering the period from 1998 to 2013. The study investigated both assessment results and the selection and reporting of methodology, with the purpose of illustrating typical results and to explain diverging results among studies. A meta-analysis of the assessment results show that the charging electricity, the degree of electrification and how the vehicle is operated, are key factors for the environmental load coupled to the use of electric vehicles. It is also found that the use phase is the most important life cycle stage in terms of total energy use, and that the burden of manufacturing increases with the degree of electrification. In addition, paper I shows that the battery is the most contributing component and that recycling has a large impact on final results.

However, whereas almost all studies examined in paper I included greenhouse gas emission, broader impact assessment was conducted only in about a third of the studies and few included resource depletion. In addition, paper I exemplifies that toxicity issues related to metal extraction is an area where potential adverse environmental impacts of the electric vehicles calls for further assessments and action.

In conclusion, there is little focus in existing literature on assessing the trade-offs of electrification or on providing support for minimizing the environmental impact by technology development.

Chapter 2

Purpose and scope

2.1 Research questions

The facts of Chapter 1 led to the genesis of a project. In brief, research questions evolved out of the following rationale: Climate change and long term sustainable use of Earth's finite resources are unprecedented challenges of the human civilization. For global warming in particular, time is of essence and there is at worst only a few decades available to complete major technical and societal changes to sufficiently curb vast carbon dioxide emissions. Current road bound transportation constitutes a significant part of the problem. Vehicle electrification is a possible path forward with the potential to decouple road transport from the dependency on fossil fuels while still allowing a large scale deployment. But there are tradeoffs. Implementing electric propulsion in the automotive transport sector may enhance other environmental problems.

In systems research, LCA was developed to become an important method for mapping such problem shifts, between different life cycle stages and impact categories. LCA is holistic and informative, but like any tool, its usefulness depends on how it is used.

Two overarching questions were articulated:

- *In what ways* does LCA support the development of electrified road vehicles for minimizing environmental impact in the long term?
- *By what means* can LCA of vehicles advance to better support the development of electrified road vehicles for minimizing environmental impact in the long term?

As expected, insights and conclusions drawn early in the project came to influence the direction of later stages. The review of the research field (paper I) exposed short-comings both in methodology and inventory data. Meanwhile, initial case studies and industrial collaborations (Inunza Soriano and Laudon, 2012, Björkman, 2013) revealed that relevant data can be acquired, although often in such technical formats that expert support and engineering homework is required to obtain datasets applicable for LCA. For this reason, consulting industrial experts and cross-disciplinary dialogues with colleagues in other research field became an important part of the project.

Furthermore, the two questions were phrased with an underlying idea; mapping and describing is important for knowledge building in all environmental research, but not enough in the development of new automotive technology. To support technical change within the time frame available, it is of essence not only to give advice, but also to direct it to someone specific. Behind every action there is an actor.

As a consequence, three detailed research questions were formulated:

1. Is it possible, and if so how, to establish generic LCI data sources as a support to LCA practitioners who conduct studies on electric vehicles or their subsystems?
2. Which are the main methodology recommendations to LCA practitioners who conduct studies on electric vehicles or their subsystems, to better support the development of automotive electrification technology for minimizing environmental impact in the long term?
3. What is the main technology advice to relevant stakeholders, to support the development of automotive electrification technology for minimizing environmental impact in the long term?

2.2 Research process and the scope of the project

As mentioned, the first step of the project was to conduct a thorough review of LCA studies concerning vehicle electrification, in academic literature as well as in company and government reports. In the initial stage, the work was focused mainly on assessment results and reported in writing as two e-book chapter contributions, one in English (Nordelöf et al., 2013b) and one in Swedish (Nordelöf and Tillman, 2014).

In the review process, as well as in dialogues with representatives for both automotive industry and government agencies in Sweden, it was noted that whenever LCA of vehicles was discussed, the numerical results were set in focus. In turn, this causes frustration among stakeholders since there is large variability in numerical results between studies and LCA does not seem to provide incontestable judgement as to whether or not electric vehicles are beneficial in terms of reducing environmental impacts in the short term. Accordingly, other overviewing literature described research results as divergent and inconsistent (Althaus, 2012, Frischknecht and Flury, 2011, Helmers and Marx, 2012).

As a response, the review study was set up to examine the appearance of inconsistency in the research field, now focusing on both methodology and assessment results. The result became paper I which investigates the usefulness of different types of LCA studies to provide relevant information to industrial managers, governmental agencies and other institutions seeking advice and guidance about vehicle electrification from LCA studies. Attention was given to the conclusions of the examined studies. The methodological findings were phrased for an LCA specialist audience.

One other major review article (Hawkins et al., 2012) had surveyed the research field prior to the publication of paper I. Hawkins et al. (2012) identified clear gaps in inventories of the main powertrain components other than the tractions batteries, including electric motors and power electronic converters. Paper I confirmed that LCA of electric propulsion technology is a very active area of research, focusing either on the complete vehicle or the traction battery. But very few in depth LCA studies had been carried out on other subparts. These observations became the starting point for the work leading to papers II-VI.

Ideas for how to construct generic models of two components, the electric motor and the inverter unit, were proposed to research colleagues within the electric power engineering division and became the starting point for a cross-disciplinary collaboration. In parallel, significant efforts were made to collect relevant design data. The aim of the modeling work was to address the general lack of data for electric propulsion components and create models that assist LCA evaluation of electric vehicles or their subsystems, through generation of data for one electric motor and one power electronic inverter unit. Both models were arranged to be scalable in terms of the component size based on input of easily acquired engineering requirements expressed as power, torque and voltage.

However, even scalable models generating design and mass composition data would not fully meet the ambition of creating generic LCI data sources. Manufacturing data was also needed to establish complete inventories and so further efforts were made to collect data, including establishing contacts with Swedish manufactures of both electrical machines and automotive power electronics. The objective, for both models, was to find manufacturing data with sufficient resolution to properly include the production effects when the components change in size. Users receive gate-to-gate inventories with instructions for how to link upstream flows to database data, and calculate cradle-to-gate inventories.

In parallel to being reported in papers II-III and V-VI, both models have been described in detail in extensive model reports (Nordelöf et al., 2016, Nordelöf and Alatalo, 2017) and both model files will be possible to download from the CPM database, distributed via The Swedish Life Cycle Center.

The obvious next step, once the electric motor LCI model and papers II and III had been published, was to use and test the first model when conducting LCA. Such a study is described in paper IV, and the purpose is to compare three different motor designs, i.e. two motor types combined with three different magnet materials. The motor represented in the LCI model is a permanent magnet synchronous machine (PMSM) with neodymium-dysprosium-iron-boron (Nd(Dy)FeB) magnets. In paper IV, it is compared with a similar PMSM using other rare-earth-based magnets, made of samarium-cobalt, and another motor type – a permanent magnet assisted synchronous reluctance machine (PM-assisted SynRM) – with ceramic strontium-ferrite magnets. Again, substantial data compilation and technical investigations were conducted, for the use phase of all motor options and the manufacturing steps for the magnets not covered by the electric motor LCI model.

2.3 Content and outline of the thesis

The final step of the project was to place the work contained in papers I-VI in a larger context, to summarize the empirical contributions and to synthesize methodology and assessment conclusions. This is the role of this thesis. The aim is to answer the research questions asked in section 2.1.

More specifically, following this declaration of the purpose and scope, there is a brief technology presentation of automotive electric powertrains in Chapter 3. Slightly more detailed technical descriptions are given for the components in focus in papers II-VI, the electric traction motor and the power electronic inverter unit.

Following, Chapter 4 provides a methodology background about LCA, explaining different steps in the procedure and how it is applied on vehicles. Inventory data gaps for the assessments of electric vehicles are also discussed. Chapter 5 explains the research approach, including the specific methods used in each step of the project. It also includes a discussion about LCA as a part of systems science, its role in relation to technology transitions and different actors.

The six appended papers are not summarized one by one anywhere in the thesis. Instead, relevant aspects of their content are presented and referred throughout the entire text. Chapter 6 discusses the observations and reflections made during the thesis work, i.e. insights given by combining the content of the six appended papers and the experiences from the overall project. Indeed, the appended papers are partly recapitulated, but not with the aim of covering all specific results and conclusions, as these can be found in each paper.

Finally, Chapter 7 synthesizes the findings of Chapter 6 with the conclusions of the appended papers. Empirical contributions, methodology recommendations and technology advice are reported to answer the three research questions. Questions 1 and 2 are of special relevance for LCA practitioners. The advice given as an answer to question 3 is addressed to various stakeholders that currently influence the development of vehicle electrification. In Chapter 7 there are few references to external sources, and instead it mainly refers to the other chapters and to the appended papers.

Chapter 3

Technical background

3.1 Electric propulsion of road vehicles

The electric powertrain

An automotive electric powertrain can be realized in several different configurations. Whichever way, it requires a set of advanced electrical components including at least one electrical machine to provide motoring and generating capacity. As in conventional vehicles, there is often a mechanical power path to the wheels, including gears and shafts. There is also a need for a portable energy storage which can provide electricity, most commonly realized as a battery (Husain, 2011). Batteries can be made for external charging with electricity from the grid, referred to as “plug-in”, or charging only within the vehicle, for example by brake energy recovery. The choice of battery size and design depends on the desired operating range, and how it is charged and used (Corrigan and Masias, 2011). Other solutions for electrification include fuel cells which generate electricity electrochemically from a fuel stored in a tank, often hydrogen, either to charge the battery or for direct use in propulsion (Husain, 2011).

Power electronic converters play an important role in the electric powertrain. The term converter refers to an electronic circuit that is able to convert electrical energy from one voltage level and frequency to another. In vehicles, converters are used to control electric machines, to modify voltages and to shift between AC (alternating current) and DC (direct current). Inverter units are one of three converter types used in electrically propelled vehicles. The other two are DC/DC converters and on-board chargers. Externally charged electric vehicles contain at least one converter of each type, often more (Çağatay Bayindir et al., 2011, Emadi et al., 2008). The inverter unit then acts as the electric motor controller and the charger enables charging of the battery from the AC grid. The DC/DC converter acts as the link between the vehicle’s high voltage DC system used for propulsion, often 250-450 V for electric passenger cars and 600-700 V for trucks and busses, and the low voltage system used for auxiliaries, often 12 V or 24 V (Emadi, 2005, Grunditz and Thiringer, 2016b, Inunza Soriano and Laudon, 2012, Volvo Bus Corporation, 2015a, b). The final number of converter units in an electrified vehicle depends on how many motors are installed, different auxiliary demands and how, or if, the electric powertrain is combined with a conventional powertrain. A schematic overview of the main components is shown in Figure 1.

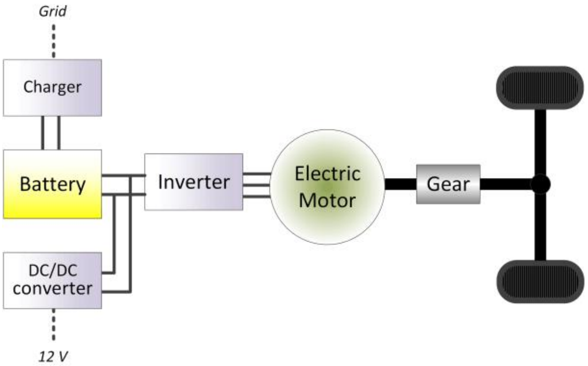

Figure 1: Schematic drawing of a basic setup for an automotive electric powertrain.

Vehicles categories and the degree of electrification

By definition, a hybrid vehicle combines an electric propulsion system with a conventional powertrain, either to achieve better driving performance or to allow the internal combustion engine (ICE) to be downsized (Chan, 2007). Specifically, the term *hybrid electric vehicle* (HEV) is used to describe a vehicle with both propulsion methods, but without external charging. The battery size and the degree of electric propulsion may still vary between HEVs. The span goes from regeneration of brake power and assistance to the ICE (mild hybrids) to include short distances of pure electric driving (full hybrids). *Battery electric vehicles* (BEVs) are adapted for external charging, have no ICE and drive purely on electric energy. The *plug-in hybrid electric vehicle* (PHEV) runs on externally charged electricity, but enters a blended mode of electric motor and ICE operation when the battery has been depleted. There are many, more or less complex ways of realizing PHEVs (Çağatay Bayindir et al., 2011, Emadi et al., 2008). The terms *range extender* and *extended range electric vehicle* (E-REV) are sometimes used when there is a small ICE (without any mechanical connection to the wheels) or fuel cell charging a relatively large battery, in order to provide longer driving range for an electric vehicle.

The terminology presented is applicable for all types of electrified vehicles, regardless of size, i.e. passenger vehicles, light and heavy duty vehicles. Busses and trucks, even long-haulers, can also be electrified, but they are most often found as hybrids without the possibility of external charging (Björkman, 2013, Inunza Soriano and Laudon, 2012, Volvo Bus Corporation, 2013). However, city buses are sold commercially in plug-in hybrid or all-electric versions (Volvo Bus Corporation, 2015a).

The term *electric vehicle* (EV) is not strictly coupled to any vehicle size or degree of electrification. However, very often it is used synonymously with a passenger BEV, i.e. an all-electric car. In this thesis, the term is generally used with a broader denotation, and does not only refer to cars.

Technical scope of appended papers

Paper I reviews LCA case studies covering various degrees of electrification, including HEVs; PHEVs, E-REVs, and BEVs, often in comparison with conventional vehicles. The vast majority of the case studies assess passenger cars, but this was a result of the literature search and not an intentional selection of scope. In contrast, LCAs of fuel cell vehicles were not included in order to limit the scope of the review.

However, papers II-IV, covering electric motors, and papers V-VI, focusing on the inverter unit, are applicable for all electric propulsion systems regardless of the energy storage solution, i.e. these papers are equally valid for fuel cell vehicles. The range of both models extend from small passenger cars up to city busses.

3.2 The electric traction motor

Overview and principle of operation

Electrical machines convert electrical energy to mechanical energy via magnetic energy. Electric traction motors deliver torque to the wheels of the vehicle via a rotating shaft, in turn attached to a core part of the machine referred to as the *rotor*, due to its ability to revolve. A stationary part called the *stator* creates a rotating magnetic field when currents are conducted in its windings (conductors wound into coils through slots of the stator). The stator magnetic flux interacts with flux from the rotor. The rotor is forced to turn and generates a torque, which can be transmitted to the wheels.

There are plenty of ways to classify electrical machines depending on their main characteristics, for example, the type of electric power feeding it (DC or AC) and the way to generate the magnetic field in the different parts (Tong, 2014). In the case of a permanent magnet synchronous machine (PMSM), the rotor flux is generated by permanent magnets, while the stator windings are fed with AC power. The magnetic field from the permanent magnets in the rotor strive to align with the rotating magnetic field produced by the stator, and there is an electromagnetic force acting on the rotor, which can be controlled by regulating the magnitude of the currents in the stator. PMSMs with magnets mounted inside the rotor (instead of on the surface) is the machine type which is most common in electrified vehicles (Chan, 2007, Miller, 2013), and the type modeled in papers II-IV. Figure 2 shows an exploded view of the modeled PMSM design, specifying relevant subparts.

Electrical traction machines can be operated both ways in terms of how the energy flows (Hughes and Drury, 2013). In the motoring mode, electrical energy is converted to mechanical energy to propel the vehicle. In the generating mode, the machine acts as a brake and recuperates mechanical energy into electrical energy, which can be stored in the

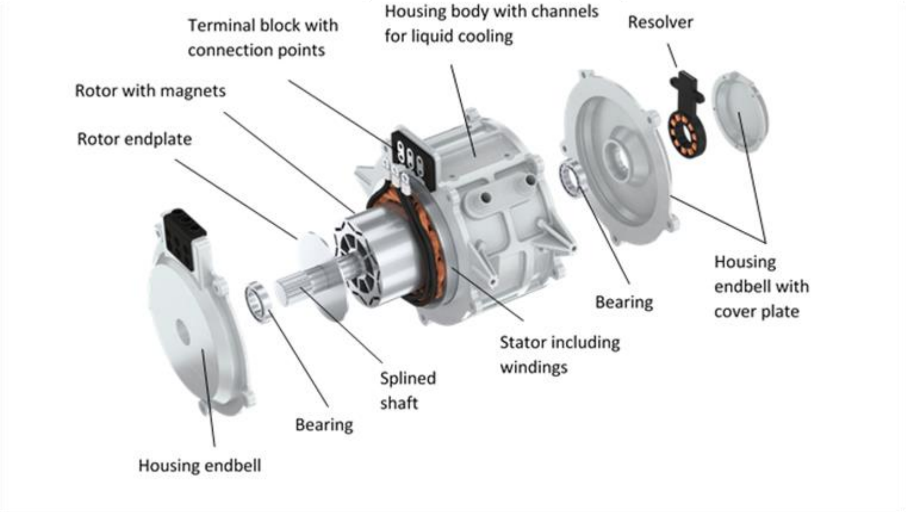

Figure 2: Exploded view of the PMSM modeled in paper II and III, and studied in the LCA case study of paper IV.

battery. This is an important feature provided by the electric powertrain compared to conventional vehicles, which are unable to recover energy during braking.

Modern electrical traction machines have very high efficiency, with peak values reaching up to 96-97% and average efficiencies around 90% depending on the drive cycle (Grunditz and Thiringer, 2016a). The efficiency is defined as the ratio of the power output to the power input. The losses that do occur, for example in conduction resistance, core losses due to magnetic phenomena and mechanical friction, turn into heat, which requires cooling in order not to reduce the performance of the motor.

Torque and power

Torque is the measure of the rotation caused by the electromagnetic force around the motor's central axis. In turn, the output mechanical power is the rate of work made by the torque. The two parameters relate to each other via the angular velocity of the rotation. As a general rule of thumb it can be stated that the torque is proportional to the volume of the electrical machine, while the power also depends on the motor speed (Hughes and Drury, 2013).

Already at take-off an electrical machine can produce maximum torque, which is constant at low speed, and as the speed increases so does the maximum attainable power. At a certain speed level called *base speed*, the power is limited (ideally constant) due to the voltage and power limits of the battery. Hence, the nominal rated voltage of the system (and for which the motor is designed) is fundamental for the relationship between power and torque of the motor (Grunditz and Thiringer, 2016b).

In vehicles, it is common for a lot of power to be required during accelerations, which lasts only for about 5-15 seconds. The remainder of the time much less power is needed. In general, the electromagnetic ability of motors is much higher than their thermal ability, i.e. the amount of heat that can be cooled off and how much heat different parts can withstand during longer operation. However, for a short period of time, the motor is able to store thermal energy temporarily inside the core parts, to be cooled off later. For this reason, the rated maximum power (also called peak power) is often twice as high as the rated continuous power (also called nominal power) for electric vehicles (Grunditz and Thiringer, 2016b). The ratings of vehicle traction motors in vehicle specifications are typically given for the peak value.

Torque and power were used as scaling parameters in the LCI model of the electric motor presented in papers II and III.

3.3 The inverter unit

Overview and principle of operation

Power transistors are primary building blocks of traction inverter units. A transistor is a type of active and controllable semiconductor device which can switch on and off at high frequency. Combined with power diodes they can be structured into a "bridge" of switches that can emulate AC waveforms from a DC voltage supply, and be used to control AC fed electrical machines (Husain, 2011, Hughes and Drury, 2013). Insulated gate bipolar transistors (IGBTs) are the dominating transistor type in automotive inverter unit applications for power ratings higher than 20 kW (Husain, 2011, Volke and Hornkamp, 2012, Hughes and Drury, 2013, Krah et al., 2013, Albanna et al., 2016).

The inverter unit requires several additional parts to become fully functioning. The *power module* contains the semiconductor chips and provides the electrical and mechanical structure, as well as the required ability to dissipate heat, necessary for operation (Volke and Hornkamp, 2012). One or a few large capacitors are connected on the DC side of unit, called the *DC link capacitor*, with the ability to absorb energy and protect the battery and the power module from the switching operation (Grinberg and Palmer, 2005, Volke and Hornkamp, 2012, Wen et al., 2012). Printed circuit boards (PCBs) are also required to control the switching operation, to interpret signals from various sensors and to communicate with other powertrain control units, to act in accordance with different driver demands. Additional components are connectors, a unified conducting structure (called laminated bus bar) and the casing, which provides a compartment and a cooling structure for other parts. Figure 3 shows an exploded view of the inverter design represented in papers V and VI.

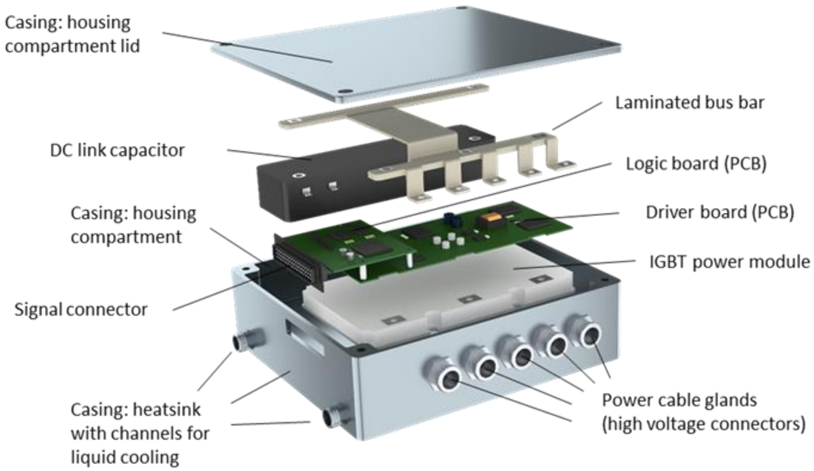

Figure 3: Exploded view of the inverter unit modeled in paper V and VI.

The inverter can be a stand-alone unit or integrated with other power electronics. Two or more converters may share the same casing and other sub-components, e.g. bus bars (Burress and Campbell, 2013). Another trend is that motors and inverters are packaged closely together, not necessarily in one unit, but adjacent, e.g. to reduce electromagnetic interference (Jahns and Blasko, 2001, Shimizu et al., 2013).

Power and voltage

Current handling capability is often the starting point when selecting inverter for a vehicle application (Waern, 2012). In addition, inverter unit specifications often present a voltage operating span (Bosch, 2008, Siemens, 2015, Brusa, 2013a, b, Siemens, 2014, Inmotion, 2016). Power output is generally not expressed as a design requirement. But indeed, power, current and voltage are fundamentally related and there is an overall correlation between the mass, volume, and the power capability of inverter units (Fuji Electric, 2015, 2016, Infineon, 2012, 2014). Power is also closely related to the required cooling capacity of the design.

However, for a certain power level, designing for a higher voltage implies lower currents and a possibility to have smaller conductors in the bus bar structure due to less heat losses, and vice versa. A shift in voltage also means that the capacitor size can change and still store the same charge amount.

Power and voltage were used as scaling parameters in the LCI model of the inverter unit presented in papers V and VI.

Chapter 4

Methodology background

4.1 Life cycle assessment

LCA belongs to a family of tools used in environmental systems analysis. Other examples in the same group are material flow analysis, ecological risk assessment and cost-benefit analysis (Baumann and Tillman, 2004). LCA builds upon a systems approach to describe and explain relationships and components within and across a specifically drawn boundary around a study object. A key feature is the idea of assessing the entire life of a product, from cradle to grave. The framework differentiates components[2] and interacting systems of three types: technical, social and natural (Baumann and Tillman, 2004).

A product or service, including activities for its manufacturing, use and disposal, is part of the technical system, which in turn can be divided into subsystems on many different levels. Technical systems are governed by people and organizations, i.e. the societal system, and provide functions in return. Resources requested by, and emissions leaving the technical system, link to the natural system, i.e. the "environment". As a consequence, the natural system can change, but whether or not this is regarded as a problem is decided by the society (Baumann and Tillman, 2004). In essence, all three systems interact, although the natural system sets the ultimate limit for all activities.

LCA can be either attributional or consequential (Tillman, 2000, Ekvall, 2002). The first type studies the cause-effect chain of a steady state, e.g. an existing product is held responsible for a share of the environmental impact caused by all processes involved in its life cycle. Attributional studies are setup to be additory, which implies completeness in terms of included processes, that the burdens of shared processes are partitioned between products and that data corresponds to average values (Tillman, 2000). Attributional studies are retrospective from the point in time where study object is defined (Sandén and Karlström, 2007).

Consequential LCA studies investigate the effects of a change (Tillman, 2000). Parts in the life cycle, which are not affected by the change, may be excluded; allocation problems are addressed by expanding the system when possible and marginal data is used for the assessment. The study is prospective from the point in time where study object is defined (Sandén and Karlström, 2007).

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[2] Here, the term "component" is referred to in a broad sense, i.e. not a specific technical part.

LCA is conducted in a standardized procedure (ISO, 2006a, b). There are four phases: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a, b). The life cycle interpretation phase is both recurring during the procedure and the final phase where conclusions and recommendations are formulated. This illustrates that LCA is an iterative technique where the different phases influence each other and that modifications are made in a learning process throughout the study. Interpretation is an open phase of the LCA procedure, which includes analyzing the results and checking the validity of the study.

The importance of goal and scope

The goal of an LCA study defines why it is done, often in the form of a question (Baumann and Tillman, 2004, ISO, 2006a). It also specifies for what and whom the answer is intended. Different questions and intended use of the answer require different methodology. Consequently, the selection of scope and other methodological choices are subordinate to the goal formulation. The ISO standard states that the full goal shall be explicitly and clearly stated, and that the scope should be consistent with the goal (ISO, 2006a, b). It allows LCA studies to be conducted in different ways, depending on the purpose, but not arbitrarily.

More specifically, the scope should be defined to ensure that the coverage and the details of the study are compatible and suffice to address the stated goal (ISO, 2006a). The scope definition motivates and specifies the functions of the system being studied, allocation procedures, life cycle impact assessment (LCIA) methods, system boundaries and other limitations. System boundaries are drawn in the technical systems, but also in terms of geography and time. The information provided in the scope definition is required to evaluate the representativeness of the data used and the validity of the results.

Paper I examines the goal and scope of reviewed articles.

The need for inventory data

In the inventory analysis phase a model of the technical system under study is created, referred to as a product system (ISO, 2006a). The product system is in turn divided into a set of unit processes. Each process has inputs and outputs. Typically, a number of inputs are used in the creation of one product output, some to become a part of the product while others are used only within the unit process. The unit process also generates other outputs, for example wastes. The model is created by identifying all relevant processes and by linking their inputs and outputs within the system. Each link is referred to as a flow. Specific inputs and outputs are linked to the natural system in the form of resources and emissions. These links are referred to as elementary flows.

The level of detail in the model, i.e. the precision of flows, and the size and boundary of each unit process, is decided by the goal and scope definition (ISO, 2006a). It should be sufficient to provide an answer to the stated questions. In the final summary, all interconnections are calculated into one life cycle inventory (LCI), the result consisting of only elementary flows, which can be subject to analysis or brought further into the life cycle impact assessment.

The inventory analysis is strongly dependent on an extensive amount of data to describe all parts of the system with sufficient accuracy. For this reason, large databases have been established and built up successively over time. Data collection is a time consuming activity, which requires both strategy and multidisciplinary knowledge. Such strategies are seldom described or even mentioned in literature about LCA (Baumann and Tillman, 2004). Nevertheless, claims made and conclusions drawn in an LCA study are dependent on data quality.

The models presented in papers II-III and V-VI generate inventory data for LCA.

Impact assessment to understand consequences

The LCI quantifies the environmental load for the study object. However, these results can be difficult to interpret. The LCIA phase translates the LCI into potential impacts caused by the environmental load, to make results comprehensible, and evaluate their significance (Baumann and Tillman, 2004, ISO, 2006a, b). To be regarded as complete, LCA should cover impacts on three areas of protection: natural environment, natural resources, and human health (ISO, 2006a).

Environmental problems arise due to complex cause-effect chains where effects occur on many different levels, referred to as primary, secondary, tertiary effects etc. (Baumann and Tillman, 2004). The same pollutant can cause many different primary effects, and one primary effect can cause many different secondary effects etc. In addition, different pollutants can contribute to the same the primary effect, and different primary effects can contribute the same secondary effects, and so on. There are also feedback-loops from higher-order effects back to lower order effects. To make this manageable, methods are often simplified to describe potential effects instead of actual effects (Baumann and Tillman, 2004).

In general, ready-made LCIA methods are used in LCA, i.e. methods developed by specialists within different areas of environmental research. The ISO standard regulates how such methods can be developed (ISO, 2006b). The LCIA methods aggregates emissions contributing to the same type of environmental effect into one indicator per impact category, e.g. climate change, eutrophication and human toxicity, and likewise for resource use, e.g. land use and resource depletion. This characterization step brings the LCIA to the “midpoint” level. Further aggregation of impact, summarized for the three areas of protection, leads to the “endpoint” level. By means of weighting, further aggregation can be achieved all the way to one single number; a one-dimensional measure of environmental impact. However, weighting methods always include value judgments, which can be contested. Instead, LCIA is often stopped at midpoint, where inventory results are aggregated using models based on natural science.

Paper IV presents LCIA results in the evaluation of different electric motor options.

First, results are assessed at the endpoint level, to determine the significance of different impact categories. Next, the results of key midpoint level categories are analyzed.

4.2 LCA of vehicles

The well-to-wheels and equipment life cycles

There is a variation in the scope of LCA studies of vehicles that reflects the transition of the dominant stage for the environmental impact: from tailpipe emissions for ICE vehicles, to the production of the energy carrier for electrified vehicles. And with an increasing degree of electrification and decreasing emissions from electricity production, attention is further shifted to the manufacturing of new and complex vehicle equipment.

Paper I describes different kinds of system boundaries used in LCA studies of vehicles (Figure 4). The well-to-wheels (WTW) study is an LCA that focuses only on the energy carrier used for the propulsion, e.g. a liquid fuel or electricity. The WTW life cycle is subdivided into the well-to-tank (WTT) stage, i.e. the delivery of energy from its source to the storage equipment in the vehicle, and the tank-to-wheel (TTW) stage, when the stored energy is converted to mechanical energy during vehicle operation. The WTT stage covers all processes from harnessing a primary energy flow or stock, to different forms of conversion, distribution and storage of energy carriers. The environmental burden of the WTT stage is very dependent on how the energy carrier is produced. For example, there is a large difference between electricity produced from hydropower and coal fired plants.

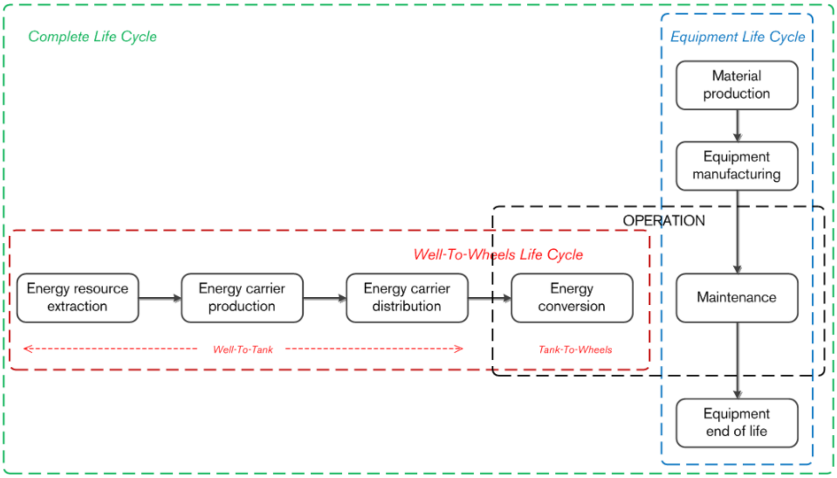

Figure 4: Simplified view of the well-to-wheels and equipment life cycles, from paper I.

In the case of liquid fuels, the TTW stage typically results in both exhaust and evaporative emissions (MacLean and Lave, 2003). For pure electric vehicles charged from the grid, the TTW stage involves no emissions at all. Nevertheless, the TTW is still important as different powertrain configurations have different efficiencies and energy losses, which affect the overall results of the WTW study.

The vertical flow in Figure 4 represents the life cycle of the vehicle itself, defined in paper I as the "equipment life cycle", to comply with general LCA terminology used in the ISO standard (ISO, 2006a). This division of the complete life cycle into two main flows is common in vehicle LCA (Baptista et al., 2011, Gao and Winfield, 2012, Jaramillo et al., 2009, Lane, 2006, Messagie et al., 2010, Van Mierlo et al., 2003). The first processes in the equipment life cycle consist of raw material extraction and material processing. They are followed by manufacturing of parts and the assembly of the vehicle. The WTW life cycle and the equipment life cycle coincide during the vehicle operation. The final stage, the End-of-life, consists of dismantling and recovery of certain parts, as well as shredding, recycling of materials and disposal of residues.

Data gaps

Addressing data gaps is an important part of this project. However, a data gap analysis was not focused upon in the review made in paper I. As mentioned in Chapter 2, Hawkins et al. (2012) had already conducted a major and preceding review of the research field, and identified inventory data gaps for all main powertrain components. Control electronics, electric motors and motor magnets were pointed out among the parts in need of "transparent, rigorous, and publicly available inventories", relating both to the composition of materials and production processes (Hawkins et al., 2012). These gaps were confirmed during the review presented in paper I, and even more so in the work with papers II-VI. Especially, no LCA studies were found that both use and report detailed data for the manufacturing of electric motors or power electronics.

To explain how such a data gap can manifest itself, it is helpful to expand on an example given in paper III about the data for energy use in electric motor production included in the Ecoinvent database (Habermacher, 2011, Weidema et al., 2013, Del Duce et al., 2014). The original source is an environmental product declaration (EPD) published by ABB (2002). The same data was also used in the only two previous electric traction motor LCA studies that were found (Hernandez et al., 2017a, 2017b). Since the information derives from a well-known electrical machine manufacturer (ABB, 2002), it understandable that it was brought to use and has been regarded as the best available data for the production of electrical machines in vehicles. However, the original ABB data was established from energy measurements at factory level representing year 2001 and allocated to the each motor produced based on the sum of all rated output power for all machines produced in the factory during that year (Arnell, 2012). In summary, the ABB (2002) EPD data represents a different type of electrical machine than used in vehicles, which is rated for continuous power instead of peak power (see Chapter 3), and the data relies on a difficult allocation procedure with a decisive effect on the output (Arnell, 2012). Additionally, the factory data used is now considered to be outdated by ABB (Arnell, 2012, Överstam, 2013). There is no doubt that there is a lack of manufacturing data for electric powertrain components.

Hawkins et al. (2012) also requested more detailed and updated data for batteries. Indeed, the battery is the component contributing most to the environmental load of the electric powertrain (paper I). In addition, there is rapid development in battery technology (IEA, 2016b), making continuous publications of battery LCAs both relevant and requested. Paper I shows that there is a response from the research field to this need, as there are many LCA studies conducted on traction batteries, and it was concluded that assessment of batteries is well attended. Therefore, except for paper I, batteries were not focused on in the project, despite their importance. Peters et al. (2017) report that this trend has continued since the publication of paper I. Several recent studies are based on new primary inventory data for batteries (Peters et al., 2017), from laboratory scale (Wang et al., 2017) to industrial scale production for batteries in sold vehicles (Kim et al., 2016).

In terms of study objects and system boundaries, paper I shows that very few studies assess heavy road vehicles, such as trucks and buses, whereas passenger cars are studied frequently. For the life cycle phases, paper IV indicate that there is a lack of representative inventory data for the End-of-life stage of powertrain parts and electrical vehicles, exemplified by the uncertainty about what happens to electric motor materials after disposal. In the choice of LCIA, paper I shows that greenhouse gas emissions are very often studied but other impact categories, such as toxicity or resource depletion, are rarely explored.

Chapter 5

Research approach

This project was conducted within an academic context of previous and ongoing related research. In the following, the ambition is to provide an epistemological background and explicate important points of departure for the thesis, and then to describe the methods used in the work with the appended papers.

5.1 A systems science perspective

The common denominator for all activities within the research division where this thesis has been written, is systems science and systems thinking. The view is holistic in contrary to mechanistic, with the "whole" being more than the sum of its parts, and relationships a fundamental feature (von Bertalanffy, 1969, Churchman, 1968, Meadows et al., 1972). The many directions of systems science investigate parts and relationships of societal, technical and natural systems (as introduced for LCA in Chapter 4) with different frameworks and diverging focus. LCA and other environmental systems analysis tools can be seen as part of the larger concept of industrial ecology (IE), which is based on an analogy of technical systems with ecosystems, where the aim is to assess industrial activities in relation to the capabilities of the natural systems, in order to identify the response needed for long term sustainability (Andrews, 2000, van Berkel et al., 1997). Typically in IE, but not always, the societal level is represented by industrial sectors, the technical systems by products and the anticipated change of the system involves product development or efforts for cleaner production (van Berkel et al., 1997).

Other systems research areas that have influenced the project are oriented towards social aspects of technological transitions (Kushnir, 2012, Sandén and Hillman, 2011), e.g. on forming public policy for the diffusion of environmentally benign technologies. A technology can be defined as a socio-technical system of artefacts combined with the hardware, knowledge and social organization required for their design, manufacturing and use (Grübler, 1998). In turn, a product can be regarded as a subset of a technology, i.e. one step of many in an ongoing development and diffusion process.[3] Important terms and ideas in the studies of technological change derive from economic theory of positive feedback loops in systems (Arthur, 1989, 1994). Small events trigger the diffusion of technologies via specific and often unpredictable pathways, sometimes not only to market dominance, but

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[3] The description is very simplified. A vehicle is a complex product, with multiple technologies and functions combined into one object, possible to discuss and describe on many system levels.

to reshape the societal system as an effect of self-reinforcing adoption. The primary example is how the world came to be "locked in" on the use of fossil fuels (Unruh, 2000). But systems theory also explains how well-considered policy can be used to stimulate new radical technological change towards a desired future state (Sandén and Azar, 2005, Hillman and Sandén, 2008).

Actor oriented LCA

Actors are acknowledged to play a critical role in all systems science about technological change (Kushnir, 2012). Accordingly, they are the key to life cycle management, where information about, and efforts to address, environmental concerns in the different life cycle stages of a product are shared between the different actors involved (Baumann and Tillman, 2004).

However, in LCA studies the actor's perspective is often forgotten (Baumann et al., 2011). A possible reason is that the holistic aspiration of LCA, i.e. the coverage of all life cycle stages from cradle to grave, inspires practitioners to formulate very broad study goals. In turn, conclusions and suggested actions come to address complete value chains beyond the scope of single decision makers, such as product designers, manufacturers or policy makers. At worst, actors are misled by dominance analysis between different life cycle stages, into believing that their efforts in improving the product life cycle are pointless (Baumann et al., 2011).

Actor orientation is a key step in increasing the usefulness of LCA (Andrews, 2000, van Berkel et al., 1997), as it acknowledges there are specific receivers of the information able to take action and thereby contribute to product or process development and improvement.

Technological change

Electric propulsion of road vehicles can be regarded as an emerging technology (Arvidsson et al., 2017). Such technologies are recognized by the trait that they have not yet reached the level of maturity or scale of production for which they show potential (Arvidsson et al., 2017, Sandén, 2008). In analogy with products, technologies go through different phases during their life: a formative phase, a growth phase and a saturation phase (Grübler, 1998). The exact position of a technology on this trajectory is difficult to pinpoint, but it is reasonable to argue that the electrification of road vehicles is somewhere on the border between the formative phase and the growth phase, at least for city buses and cars.

The scale of technology adoption is important when relating to environmental impact and assessments. If significant environmental issues are addressed early in the technology diffusion process, degrees of freedom to act are larger, as are the effects of improvement suggestions (Arvidsson et al., 2017, Collingridge, 1980). For example, if at some point most electric city buses are designed for charging with a specific catenary interface, and matching chargers are installed in many cities, this delimits the design freedom of subsequent generations of electric busses, since they must be adapted to the existing infrastructure if they are not to introduce compatibility problems for their customers. Therefore, guidance should preferably be provided as early as possible in the technology life cycle, even when the aim is to minimize the environmental impact of the technology during its saturation phase.

Two types of change can be distinguished in technology taxonomy – incremental and radical change. The former refers to step-by-step improvements between different product generations through development work based on learning and experience, both in design and manufacturing (Grübler, 1998). Incremental improvements are made continuously with a short time horizon in each step, but with large effect over time. The development of ICE based passenger cars from the introduction of the T-Ford until today, is one example.

The term *radical change* is used both for new innovations, which enable major leaps in productivity within a certain industry, and for large system changes, where one cluster of technologies replaces another cluster with profound impact in society (Grübler, 1998, Sandén and Azar, 2005, Sandén and Karlström, 2007). Radical system change typically takes place when a new technology is allowed to mature in a niche application, often requiring a significant amount of time, and then starts to diffuse rapidly in the growth phase to replace other technologies within many application areas (Sandén and Azar, 2005). An example is the current rapid expansion of wind and solar power (Gosens et al., 2017), with the potential to radically change global electricity production (Sandén and Azar, 2005).

Long term goals and prospective LCA

LCA was originally established with the aim to analyze the environmental burden of existing and reasonably well-defined product systems or services with a short time horizon. If such a conventional study is framed to recommend design changes or find hot spots in manufacturing, it provides support for incremental technology improvements.

However, in the search of a long term sustainable technology path, there must also be long term goals (Sandén, 2004). A key step is to identify technologies which have the potential to solve the environmental problems of current technologies without creating major new impacts (Sandén, 2004), or at least impacts which can be brought to acceptable levels, if given sufficient attention. LCA can be used for assessments of this type, with a long time horizon and to assess different development paths of emerging technologies. The method has been formalized as *prospective LCA* (Arvidsson et al., 2017), and it was identified in paper I as a useful type of study for electric vehicles.

In prospective LCA, study objects identified to undergo the formative or early growth phase, are modeled in a distant future when the technology has reached its full potential to mitigate the environmental impact it was initially intended to address; for example electric vehicles to mitigate climate change. In the future state, the technology will have undergone incremental change in many steps and induced some kind of radical system change when replacing old technology. From the position of the analyst the study is prospective in time, but from the position of the study object it is looking backwards at the causes of future environmental impact (Sandén, 2008).

Guiding technical development with LCA

This thesis explores and discusses the use of LCA to support the development of electrified road vehicles. Little effort was spent on comparing electrified vehicles with conventional ICE vehicles, e.g. whether or not a specific electric vehicle has lower or higher emissions than a conventional vehicle used for the same purpose today. This is in contrast to the setup of LCA studies in the research field at large (paper I), where such comparisons are recommended by expert forums (Jungmeier et al., 2013, 2017). Instead it is acknowledged that fossil based ICE technology is a dead end in the long term and it must be replaced. The appended papers do not use prospective LCA or other methods to establish suitable long-term technology goals, but the goal of a fossil free transportation sector is in itself fundamental to the project.

Electrification has the potential to become a key propulsion technology of the future. The technology development is about to leave the formative phase and enter into the growth phase, with increasing focus on delivering products to consumers and technical improvements. At the same time, there are still opportunities to influence the direction of this development at a relatively early stage. Thus, now is the time to provide support for minimizing all types of environmental impacts, not only greenhouse gas emissions, in a step-by-step approach, but with a long-term awareness. Comparisons with ICE technology are valuable to identify problem shifting, but this has already been addressed by plenty of studies, and there are many other relevant questions which can be addressed by LCA in regard to electric vehicle development.

Furthermore, in order to guide incremental technology improvements towards a long-term goal, actor orientation was identified as crucial. General learning, and explicit advice for design and manufacturing improvements, was judged to be important for stakeholders. In trying to shift the focus of the research field in the same direction, it was found essential to provide methodology recommendations and easily used data tools, as platforms for all types of future studies, with both short and long time horizons.

5.2 Methods used

Literature review

Paper I was set up to investigate the usefulness of different types of LCA studies to provide relevant information to stakeholders in the area of vehicle electrification, and identify robust lessons and learnings from the research field. A structured evaluation of literature was conducted by applying qualitative meta-analysis to all reviewed case studies and quantitative meta-analysis of a number of selected studies, in order to reflect the consequences of certain important methodological choices. Special attention was given to the reporting of goals and the time frame in each study, in comparison with the recommendations provided by the ISO standard (ISO, 2006a, b). Early in the reading process it was noted that other overviewing literature described results as divergent, while case studies of varying scope shared a common denominator in the shape of vague goal descriptions. It was found reasonable for these phenomena to be linked, and a hypothesis was phrased: if comprehensive and detailed goal and scope formulation of individual studies is not sufficiently reported, the results in the research field will appear to be divergent and inconsistent.

The qualitative meta-analysis was conducted by identifying relevant topics, i.e. questions which could be addressed by LCA studies, after which the prevalence of these topics in each reviewed case study could be investigated. A statement about each topic was defined, e.g., that the "supplied electricity for charging is a key factor to results." The coverage of topics and evidence for support or refutation of statements was sought for in tables, figures, and texts coupled to results, discussion of results and conclusions.

Furthermore, all included studies were sorted into categories and presented according to what these covered in terms of vehicle technology and impact. In the final step, it was investigated which selection of scope provided answers to what questions, regardless of how the goal of each study had been stated; clearly, vaguely or not all. This was achieved by asking what we can learn from the different categories, and by qualitatively synthesizing the assessment results and conclusions into lessons and learning for different stakeholders.

LCI models

The two scalable LCI models (papers II-III and V-VI) were developed with the intention of filling existing data gaps and to assist LCA evaluation of electric powertrains through the generation of data for different sized components. The generic structure applied for both models is shown in Figure 5 (next page).

Both LCI model projects were conducted as collaborations between researchers with differing expertise in LCA methodology and component design. Two different types of data (design and production) were combined in each scalable LCI model. The models request the user to enter one or two input parameters that are relatively easily accessible in component or vehicle specifications. By a one button click, the models provide gate-to-gate inventories of the components, together with their mass and subcomponent compositions. Another important feature of both models is that they provide recommendations as to how to link the inventories upstream to the Ecoinvent database (Weidema et al., 2013), to create a complete cradle-to-gate LCIs.

Sections 6.2 and 6.3 elaborate further on the methods used in the LCI model papers.

LCA case study

In paper IV, the LCI model described in papers II-III is brought to use in an LCA study of electric vehicle traction motors. The electric motor model was used to evaluate environmental impact of the PMSM type originally included with Nd(Dy)FeB magnets containing rare-earth elements (REEs). This was also taken as a basis for modifications,

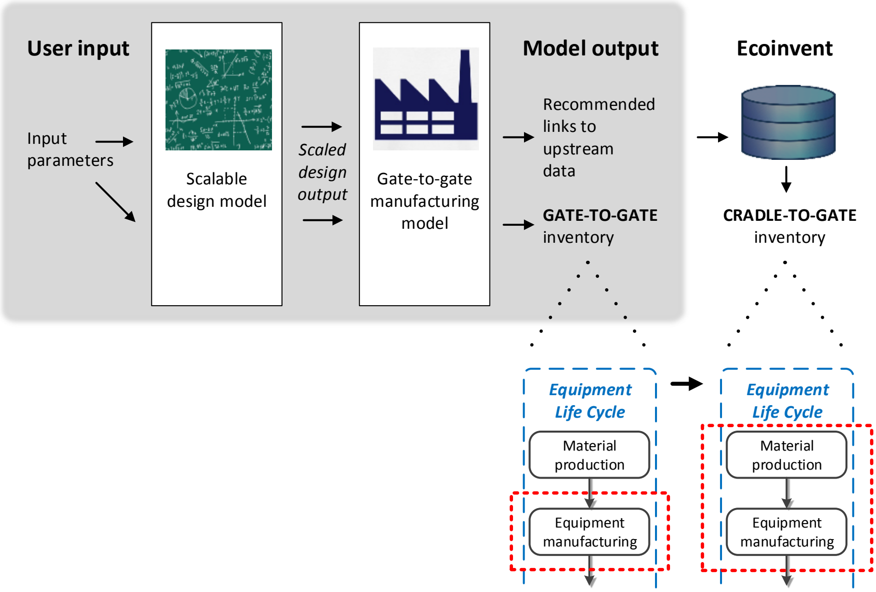


Figure 5: Generic structure of the scalable LCI models and how they are linked to the Ecoinvent database for the generation of cradle-to-gate inventories.

which allowed comparisons with two other permanent magnet motors using different magnets. These were made of another REE (samarium) with cobalt or ceramics (strontium-ferrite). All three options are of high relevance to automotive applications, although the type incorporated in the LCI model is currently the most common (paper II). As for the LCI models, collaboration across disciplines was required to accomplish the technical investigations for the two added design alternatives and for the use phase energy consumption of all motor options. Effort was put into surveying the magnet production chains, including rare-earth oxide production, and to establish new allocation procedures using economic data.

In terms of life cycle stages, the study of paper IV includes production and use of the motors, but not the End-of-life stage, where recycling and disposal of parts take place. It was found that procedures at this stage in the life cycle of electric traction motors are very uncertain and variable, and that there is a lack of representative inventory data (paper IV). Given this uncertainty and variability, a more in-depth investigation of motor End-of-life was left for future studies.

The results were analyzed using the LCIA methods recommended by the International Reference Life Cycle Data System (ILCD) handbook (JRC-IES, 2011). Both endpoint and midpoints methods were applied. In light of this, section 6.5 discusses the challenges of resource related impact assessment.

Chapter 6

Analysis and discussion

Chapter 6 discusses the observations and reflections made during the thesis work, i.e. insights given by combining the content of the six appended papers and the experiences from the overall project. The focus is set on discussing topics of the project not previously explored in depth in the appended papers, to complement their discussion and conclusion sections, and to support the conclusions drawn in Chapter 7 of the thesis (which combines the findings of Chapter 6 with the conclusions made in the appended papers).

As a result, the different sections of this chapter either link to a specific topic brought up in one or more papers (sections 6.1 and 6.5), or synthesize general observations and results from the project (sections 6.2, 6.3 and 6.4). Most comprehensive is section 6.3 where the strategies used for data acquisition and other experiences from the work on papers II-VI are described and systematized, since there is no such overviewing discussion in any of the appended papers. This section also summarizes the empirical contribution made by compiling unit process datasets during the work with papers III-IV and VI.

6.1 Diverging LCA results and future guidelines

Goal and scope formulation is crucial to the interpretation of LCA results, and the key to place them in a larger context. It is the starting point for any critical evaluation of methodological choices and the representativeness of data (ISO, 2006a, b). Even so, paper 1 clearly shows that this important stage in the LCA procedure has received little attention in assessments of electrified road vehicles and that most studies in the research field lack full purpose declarations in line with the ISO standard (ISO, 2006a). In turn, seemingly divergent results become a source of confusion and important principal messages become overshadowed by numerical details and the complexities of the different technical study objects. As touched upon in Chapter 2, this may cause frustration among stakeholders searching for information about the benefits and drawbacks of electric vehicles, especially as to whether existing technology for electrification is better or worse than the currently dominating powertrain solutions, for example as a source of information for policy formulation. One reason is that implicit expectations of all LCA studies of vehicles responding to the same question with the same system boundaries and for a specific group of actors, for example policy makers or car customers, remain unchallenged.

As a response, specific guidelines for LCA of electric vehicles (eLCAr) were developed within the European Green Cars Initiative (Duce et al., 2013), to support LCA practitioners in assessing the potential environmental benefits of electric vehicles and to enhance the comparability of studies. Additionally, other ongoing international collaborations among LCA experts (IEA, 2017) emphasize the importance of a "harmonized LCA methodology" and that the environmental impact of electrification can only be analyzed in comparison to conventional ICE vehicles (Jungmeier, 2017). In essence, making studies comparable implies a pre-defined goal and scope definition. Of course, for some use of LCA a full alignment of methodological choices is necessary, albeit difficult for vehicles of varying size and used for different purposes. This includes any type of environmental product declaration, i.e. when LCAs is used for market communication (Tillman, 2000). However, a detailed standardization of LCA beyond these purposes would contradict the original idea that LCA have numerous application areas with product development and learning at the core (Tillman, 2000). Instead, as shown in paper I, studies are generally different for a reason – they answer different questions. From this perspective, the eLCAr guidelines can be regarded as a valuable educational effort to address the occurrence of inconsistent methodological choices and insufficient reporting of the goal and scope definition.

A much more restricting standardization of LCA is suggested in the framework for Product Environmental Footprints (PEF) which has been launched by the European Commission (EEB, 2016, European Commission, 2016). This is a guideline for product information when making green marketing claims, by ensuring comparability (EEB, 2016). However, the PEF framework also aims to support policy making and "harmonizing scientific analysis" (EEB, 2016). It is looked upon as a game changer for LCA within the research community (Goedkoop, 2015). These ambitions of the PEF framework, pointing partly outside the scope of environmental product declarations, involve a risk that other use of LCA becomes regarded as less legitimate. As a consequence, it is appropriate to question whether a broader use of such specific guidelines actually would contribute to knowledge building in the research field, or hinder it. Paper I indicates that for vehicles, the communication to stakeholders, including policy makers, would appear less divergent if only the existing ISO standard (ISO, 2006a, b) is brought into use as intended.

Lastly, relating to section 5.1, it is important to remember that electric propulsion is an emerging technology with a large remaining improvement potential, and that key benefits of electrifying road vehicles still can be found in fundamental properties. Moreover, it is typical for a technology which is still partly in the formative phase, to have many competing design options under development (Grübler, 1998), e.g. different battery chemistries for electric vehicle applications, as well as production methods. In short, technical variation in the real world partly explains divergent LCA results between electric powertrains and components.

6.2 Making LCI models easy to use

The original motive for initiating and carrying out the two LCI model projects (described in papers II-III and V-VI) was to address the overarching question of by what means LCA of vehicles can advance to better support the development of electrified road vehicles. Data gaps had been identified, as presented in section 4.2. After consultation with colleagues within electric power engineering, it was judged feasible to establish generic models for LCI data based on typical design solutions. The goal was to build support tools for LCA practitioners who conduct studies on electric vehicles or their subsystems, and thereby address research question 1.

The following additional aims were formulated: to make the model easy to use; to make the design scalable in size from easily acquired engineering parameters; and to provide recommendations for upstream links to existing datasets in the Ecoinvent database (Weidema et al., 2013). It was also decided to implement both inventory models as Microsoft Excel spreadsheet files.

Scaling typical design solutions by engineering parameters

Papers II and V explain in detail how the two models represent typical design solutions for the electrical machine and the inverter unit. More specifically, the modeled motor is intended to operate as a single all-electric automotive propulsion source. The inverter unit model represents a stand-alone three phase IGBT inverter unit intended for controlling electric vehicle propulsion motors.

For both models, the masses of the subparts are scaled with common engineering parameters. Torque and power were selected for the motor design, as explained in section 3.2, and power and voltage for the inverter unit model (section 3.3). Torque, power and DC system voltage are all relatively easily accessible parameters for an electric powertrain, as they are a part of marketing information. Thus, the idea is that the models can be used to approximately represent components in a particular vehicle provided the powertrain specification is known in terms of these three parameters. For the motor it is sufficient to use only power as input – when using both torque and power the user implicitly modifies the base speed (explained in section 3.2). In the default setting, the base speed is set to a value typical for passenger cars (4000 rpm), but the model allows for combinations of torque and power, so that the base speed stays within 3000-5000 rpm.

The principal design of the motor was established based on observations of existing electrical traction machine designs, from disassembly of machines and in literature, to become as generic as possible for a PMSM, as judged by the authors. Two detailed publications made by a German power electronics manufacturer, Infineon Technologies AG (2012, 2014), served as the modeling baseline for the inverter unit design.

Ranges defined for each model were set based on engineering judgement with data for two reference components as the basis, established by theoretical calculations for the motor model (20-200 kW and 48-477 Nm) and the baseline data from Infineon for the inverter unit (20-200 kW and 250-700 V). The scaling leads to shifts in the total mass and the material composition of each component, and the mass estimations of both models rely on a combination of theoretical calculations, assumptions and large amounts of quantitative data gathered for all subparts. A key to realizing simple but relatively accurate scaling, is that subparts in each component scale differently based on the input parameters. For example, many parts scale via a recalculation to geometry, i.e. shifts in lengths, areas or volumes are related to the input parameter.

The power values used by the two models are different. The electric motor model uses rated maximum power (corresponding to a temporary thermal overload during operation) as the input parameter, whereas the inverter unit model uses rated nominal power (the highest continuous working point) as the input parameter. In both cases these power values are defined by higher-level powertrain requirements. Nevertheless, the two models are well-adopted to combination since the nominal power requirement of the inverter unit is often chosen to match the maximum power of the electric motor (paper V). Such a matching of power capability between the inverter unit and the electric motor has been confirmed in vehicle benchmarking literature (paper V).

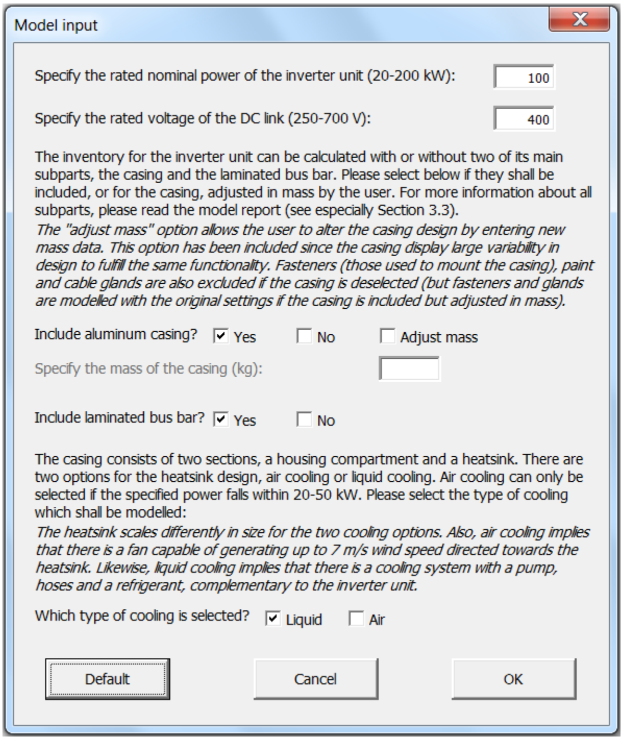
Finally, it was found critical for easy use of the model, that all details and motives for the representation of design and manufacturing in the model, as well as relevant theory, should be compiled in one place. Consequently, each model file is accompanied by a comprehensive model report (Nordelöf et al., 2016, Nordelöf and Alatalo, 2017).

User interface and options

The user interacts with each LCI model via a pop-up window. He or she is requested to enter values for the model parameters, and in response the models calculate complete and scaled manufacturing gate-to-gate inventories, material- and subcomponent compositions plus the total mass of the component. The pop-up window of the inverter unit model is shown in Figure 6, as an example.

As shown in Figure 6, a number of modeling options are included to make the model more flexible for the user. In the inverter unit LCI model, the user can exclude the casing and the laminated bus bar (an integrated structure of conductors) from the calculation. Flexibility was increased even further by allowing the user to enter a substitute value for the mass of the casing. In addition, Figure 6 shows that the inverter unit model includes two different options for cooling: liquid or air. Similarly, in the motor LCI model, two parts can be deselected because they display larger variability in design than other parts: the shaft and the housing (paper II). Bearings are also optional, since they are dependent on whether or not the shaft and housing parts are included

The idea behind all different modeling options is to broaden the applicability of the models. For both components, variability is large as regards packing and cooling solutions, for example due to integration with other powertrain components. The included options



Specify the rated nominal power of the inverter unit (20-200 kW): 100

Specify the rated voltage of the DC link (250-700 V): 400

The inventory for the inverter unit can be calculated with or without two of its main subparts, the casing and the laminated bus bar. Please select below if they shall be included, or for the casing, adjusted in mass by the user. For more information about all subparts, please read the model report (see especially Section 3.3).
The "adjust mass" option allows the user to alter the casing design by entering new mass data. This option has been included since the casing display large variabilty in design to fulfil the same functionality. Fasteners (those used to mount the casing), paint and cable glands are also excluded if the casing is deselected (but fasteners and glands are modelled with the original settings if the casing is included but adjusted in mass).

Include aluminum casing? ☑ Yes ☐ No ☐ Adjust mass

Specify the mass of the casing (kg):

Include laminated bus bar? ☑ Yes ☐ No

The casing consists of two sections, a housing compartment and a heatsink. There are two options for the heatsink design, air cooling or liquid cooling. Air cooling can only be selected if the specified power falls within 20-50 kW. Please select the type of cooling which shall be modelled:
The heatsink scales differently in size for the two cooling options. Also, air cooling implies that there is a fan capable of generating up to 7 m/s wind speed directed towards the heatsink. Likewise, liquid cooling implies that there is a cooling system with a pump, hoses and a refrigerant, complementary to the inverter unit.

Which type of cooling is selected? ☑ Liquid ☐ Air

Figure 6: The inverter unit LCI model input pop-up window.

make it easier for the user to increase the precision of the mass estimation for some specific geometry or cooling designs when data for some subparts is gathered separately.

Linking the models to Ecoinvent

Both LCI models make use of the Ecoinvent database (Weidema et al., 2013) for the representation of certain production activities. In addition, they suggest to the user how to link the models upstream to Ecoinvent to create full cradle-to-grave inventories. As a general principle for establishing the system boundaries of manufacturing processes, production was modeled so that the scaling of the designs could accurately be accounted for, whereafter the system model was expanded towards the cradle to the point where relevant and explicit matching flows were found in Ecoinvent. At that point, the model delivers recommendations on how to link further upstream from the gate-to-gate inventory. In some cases, when the best available data was judged to be already available on a subpart level from Ecoinvent, the number of process steps inside the system boundary are few. In other cases, the model covers a large number of steps between the upper and lower system boundaries. It was also found useful that Ecoinvent offers a set of production activities that reshape and integrate several singular material flows into more aggregated sub-products in a certain type of production effort, or service activity. However, the introduction of these production efforts required an *extended system boundary* to avoid confusion with the actual boundaries of the gate-to-gate model (papers III and VI).

To summarize, in both models the user receives recommendations for how to model upstream flows back to the cradle using Ecoinvent. In addition, a list of Ecoinvent production activities is also provided, so that the recommended upstream flows can be accurately remodeled in terms of material transformation and integration to more aggregated sub-parts in the extended system, and to represent adequate production inputs for the gate-to-gate model.

6.3 Data acquisition

LCA is very data intensive (Baumann and Tillman, 2004, Finnveden et al., 2009). In particular, data acquisition is very time consuming. As a general solution, most LCA studies use data from large open or commercial databases, where data has been compiled over many years from different case studies and inventory projects. The Ecoinvent database is one such example (Weidema et al., 2013). It is a commercial database operated by a non-profit organization, branded as the world's leading LCI database in terms of consistency and transparency (Ecoinvent, 2017). However, there are still many gaps in existing databases, and the use of specific datasets may lead to unrepresentative modeling if they are perceived as broadly applicable, as exemplified for power electronics in paper V. Consequently, more and updated data is often required, especially in the case of electric powertrains, as argued for in papers II-III and V-VI. But strategies on how to go about data collection are rarely presented in LCA literature (Baumann and Tillman, 2004).

As a response, given the large amount of time spent on data acquisition within this project, the ambition of the following section is to provide a description of the strategies used. First, to simplify and clarify terms of discussion, two categories of data can be defined for production and use phase life cycle stages: equipment *design data*, and *manufacturing data*. In both categories, it is necessary to acquire both descriptive and quantitative information. For a full cradle-to-grave LCA study, there is also a need for End-of-life inventory data, but this has not been the focus of this thesis.

Equipment composition and operating data

Papers II and V report how design data was compiled for the electric motor and the inverter unit LCI models. It refers to the equipment as installed in the vehicle. Design data at different levels of aggregation and detail are built into the models, and define their technical relevance. This also describes and quantifies the function of the study objects. As a consequence, there is a close link between design data and operating data. For example, electric motor design data includes operating efficiency, which is a measure of how well the motor functions in terms of different losses. In paper IV, operation efficiency is utilized in calculations of vehicle dynamics and drive cycles to find the data most important for LCA during the use phase: the motor energy consumption. The mass composition of different subparts, which is delivered as an output from each LCI model, is also a type of design data, but on an aggregated level better suited for LCA, since it provides a link to the manufacturing stage.

Working with design data requires considerable in-depth knowledge about component theory, experience in conducting and evaluating calculations, and the ability to make relevant engineering judgements. As a result, interdisciplinary academic collaboration with colleagues conducting technical research on electric powertrain components was a prerequisite for the work of the thesis. Paper II exemplifies how the scalable electric motor model was developed from design tool calculations, and paper IV shows how the drive cycle evaluation was made in collaboration with colleagues.

Information about the design of existing automotive technology can be found in specific *benchmarking literature* published by academia and research institutes, i.e. reports where vehicles and components have been tested in rigs as well as disassembled and photographed (Burress et al., 2011, Burress, 2013, Burress and Campbell, 2013, Olszewski, 2006, Ozpineci, 2016). Equally detailed technical documentation published directly by industry was not found, apart from evaluation equipment application notes from Infineon (2012, 2014), with data for two inverter units referred to as the baseline data sources in paper V. However, once this detailed data was found, containing specific product codes for subcomponents within the inverter unit circuitry, complete material content declarations were available upon request from several suppliers on account of RoHS[4] legislation. Without having encountered this rare chain of open data about electronics, it would have been impossible to establish the inverter unit LCI model as presented in paper V.

In addition, part catalogs, journal articles and datasheets provided specific design details in both LCI models. Textbooks provided important overviews and support for basic assumptions.

Manufacturing data

Papers III and VI report how manufacturing data was compiled for the LCI models. Such data was also collected for the comparative LCA study of motors using different magnet materials, described in paper IV. The manufacturing data of a cradle-to-gate inventory should cover all necessary steps to produce the equipment in accordance with the design, from raw materials to the final product. In the gate-to-gate inventories, inflows generally represent semi-processed materials, but they can also include flows indicating ready-made subparts which are modeled as preassembled larger units.

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[4] RoHS – Restriction of the use of certain Hazardous Substances in Electric and Electronic Equipment, European Union directive (2011/65/EU) (Kemikalieinspektionen, 2016).

For manufacturing data collection, it was considered unrealistic to look for suitable partners for collaboration within all relevant areas of expertise, and so this was not attempted. Instead, factory site visits combined with textbooks on manufacturing served as the most important sources of information for descriptive information. For quantitative data, three different strategies for data collection were used.

The first strategy can be referred to as a conventional approach, because it was carried out in accordance with unreflected expectations on how data collection takes place: straightforward, and from an easily identified *single source*, ready-to-use to for LCA. The acquisition of data for electrical steel production from Surahammars Bruk AB, a Swedish steel mill, represents this type. It is described in paper II. Although combined from several references, the data represents one organization and one facility. The information about emissions and energy use was originally collected for company environmental reports and site permits. There was also one single point of contact, thus making the dialog simple and efficient (Lindenmo, 2012, 2015). However, Surahammars Bruk AB was unwilling to supply information about one important detail, due to business secrecy; the specific blending of silicon steel alloys corresponding to certain grades of electrical steel. This issue was solved by asking for the average composition of all silicon steels used at the steel mill, which in this case was judged to be equally valid and suitable for LCA.

However, access to relevant data for complete process steps suitable for direct use in the modeling work, was rare throughout both LCI model projects. In addition, in most cases, specific process details were needed to make the production datasets applicable and adjustable in accordance with the scaling of the product designs. Open and detailed information had to be sought elsewhere.

The second and third data collection strategies are variants of the same idea – *data building*, i.e. that blocks of data from many different sources were adapted for merging into one dataset. This was found to be the most efficient way to establish useful datasets. Interviews with experts played a key role in this work: in order to provide process descriptions; to provide specific technical details; for quantitative estimations; and to confirm examples of practices or procedural descriptions provided by research articles and textbooks. A more detailed subdivision of data building strategies can be made in those taking a factory site visit as a starting point and those setting out from a textbook description.

The second strategy, data building taking factory site visits as the starting point, was used in both LCI model projects. For the electric motor model, the manufacturing of machines was studied at ELMO Malmköpings Mekaniska Werkstad AB in Flen, Sweden, but for a machine type differing from the PMSM design modeled, i.e. induction machines (paper III). As a consequence, the process flow had to be adjusted in order to become representative for PMSM manufacturing, for example by complementation with information from interviews with experts regarding procedures at other production sites (Hendershot, 2015, Magnusson, 2016) and other equipment (Willard, 2015, Xue, 2015). Machine specifications, process chemicals' data sheets and journal articles were also used in the calculation and compilation of unit process datasets. Additionally, quantitative data was acquired by viewing film clips, for example to measure processing time for specific machining procedures.

A similar setup was used in the inverter unit LCI model project, for data describing surface mounting of printed circuit boards and final assembly of the inverter unit, which was gathered from Aros Electronics AB (paper VI). Adjustments were primarily made for the application of solder paste, but to a far lesser degree compared to in the motor model.

The third strategy, data building taking the starting point from textbook descriptions, was also used in both projects. Datasets for magnets, electrolytic iron, enameled wire and die casted aluminum, were built from various literature sources (paper III). This was also the approach used for modeling the power module production steps in the inverter unit LCI model (paper VI). Textbook descriptions and scientific articles were used as primary data sources, and further in-depth explorations were made in subject-specific technical publications and experts' descriptions.

In total, 25 novel production unit process datasets for LCA were established for the electric motor LCI model, and 16 for the inverter unit model. In addition, four unit processes were established relating to magnet production for the comparative LCA study of paper IV (described in detail in the supplementary information report). Lists of these new datasets are provided in tables 1-3 (on pages 36-37). About a third of the unit processes listed are aggregated datasets, consisting of multiple consecutive productions steps, i.e. using different machining and joining procedures. The making of the Nd(Dy)FeB magnet is a primary example, consisting of twelve advanced processing steps.

The main benefit of the data building approach was that the level of detail could be controlled to make datasets flexible and relevant for design modeling. This was necessary in order to match the scaling of the machine and inverter unit designs in the manufacturing stage, and correctly account for function in each production step. An important aspect was the possibility to keep track of several output parameters when modeling the process outflows, this resulting in multiple reference flows for some of the unit processes (see Table 1 and Table 2).

The contacts established with the ELMO and Aros factories were very important for carrying out both projects. The information gathered included energy consumption charts, purchase summaries, process descriptions and machine inventories. The factory data was also important for data building starting from literature, since specifically selected blocks of data from the two factories were reworked and reused for these datasets. Perhaps most important, general expert explanations with on-site examples about motor (Walter, 2015, 2016) and electronics manufacturing (Edgren, 2014, 2015, 2017) were used for important assumptions based on engineering judgement.

Table 1: The 25 unit processes established for the electric motor LCI model, described in paper III and reported in detail in Nordelöf et al. (2016).

Unit process	Unit of reference flow
Production of electrolytic iron	1 kg of pure iron
Production of Nd(Dy)FeB nickel coated magnets*	1 kg of magnets
Silicon steel alloying	1 ton of silicon steel
Production of electrical steel sheets	1 ton electrical steel
Die casting of aluminum	1 kg of casted product
Enameling magnet wire	1 kg of magnet wire
Assembly of resolver incl. punching of core	100 g of core laminates
Punching of core laminations	1 kg of core laminates
Stacking and welding of the stator core	1 cm of stator core 1 kg of stator core
Winding and phase isolation installation	1 kg of magnet wire
Installation of slot insulation, bandaging and pressing	1 piece of stator package
Impregnation and curing of the stator package	1 cm of stator diameter 1 kg of cured resin 1 kg of stator package
Wire termination	1 stator package (piece)
Machine turning of steel rod (shaft turning)	1 kg of steel shaft
Spline milling (3.5 cm)	1 cm of shaft diameter
Induction surface hardening (3.5 cm)	1 cm of shaft diameter
Stacking of the rotor core, magnet mounting and fixation	1 cm of rotor core 1 kg of rotor core
Punching of stainless steel rotor endplates	1 kg of endplates
Assembling and pressing the rotor package	1 endplate (piece)
Balancing	1 rotor package (piece)
Machining of housing parts	100 g of removed aluminum 1 housing body (piece) 1 endbell (piece)
Cleaning	1 housing (piece)
End assembly	1 motor (piece)
Painting	100 g of dried varnish
Technical building services, motor factory	1 motor (piece)

* The data for the fabrication of the magnet base body originates from one LCA study (Sprecher et al., 2014a, b), but the dataset was substantially reworked and supplemented for the LCI model.

Table 2: The 16 unit processes established for the power electronic inverter unit LCI model, described in paper VI and reported in detail in Nordelöf and Alatalo (2017).

Unit process	Reference unit
Assembly of surface mounted automotive classed PCB	1 m^2 of mounted PCB area
Electroplating of gold	1 kg of gold 1 m^2 of plated surface
Electro-galvanizing (zinc plating of steel)	1 kg of zinc 1 m^2 of plated surface
Machining of casing parts	1 kg of aluminum 1 casing (piece)
Anodizing aluminum surface area	1 m^2 of casing surface
Ceramic substrate fabrication (500 µm thick)	1 m^2 of substrate
Direct copper bonding	1 m^2 of substrate
Patterning of DCB by photo imaging and regenerative etching	1 m^2 of substrate 1 kg of copper removed
Pre-solder cleaning (ultrasonic cleaning and vacuum bake)	1 m^2 of DCB 1 m^2 of baseplate
Stencil printing with cleaning, chip attachment (vacuum vapor-phase diffusion soldering) and system soldering (convection reflow soldering) with lead-free solder	1 kg of solder paste 1 m^2 of DCB 1 m^2 of baseplate
Post-solder solvent cleaning	1 m^2
Plasma cleaning before wire bonding	1 power module (piece)
Wire bonding (ultrasonic welding)	1 cm^2 of chip area
Potting and curing of silicone gel	1 kg of silicone gel 1 power module (piece)
Selective soldering (through-hole) of PCB	1 m^2 of mounted PCB area
Technical building services, electronics assembly factory	1 inverter unit (piece)

Table 3: The four unit processes established for the LCA case study of electric motors, i.e. paper IV, described in detail in the supplementary information of the publication.

Unit process	Reference unit
Production of REOs from bastnäsite concentrate (reworked allocation procedure and new energy data)*	1 kg of rare earth oxides
Production of samarium by metallothermic reduction	1 kg of samarium
Production of samarium-cobalt magnets	1 kg of magnets
Production of wet pressed strontium-ferrite magnets	1 kg of magnets

* This dataset builds on Ecoinvent data (Althaus et al., 2007), but was listed here because it was reworked with updated energy use data (Peiró and Méndez, 2013) and a different economic allocation procedure using new REO price data.

Expert consultations

Interviews with experts were extensively used throughout both LCI model projects. For the data building approach, the role of expert consultation cannot be underestimated, as a method to clarify specific details, to provide general technical information as a basis for assumptions and simplifications, and to confirm examples of practices or procedural descriptions provided by research articles and textbooks. An example of the latter, from paper VI, was when Lenz (2014) confirmed the industrial relevance of a furnace based bonding process between copper and ceramics, very precisely described in a more than 10-year-old journal article (Ning et al., 2003).

As recommended by Baumann and Tillman (2004), it was found very important to do as much "homework" as possible before contacting any expert, in order to be able to ask specific questions and avoid requesting experts to make time for descriptions easily found elsewhere. It was also found to be a good strategy to avoid asking too many questions during one and the same consultation, and instead take careful notes and explore complementary sources in-between interviews. Foremost, it was found very valuable to ask follow-up questions far beyond the information initially asked for, when longer descriptions were offered. Experience showed this was the best way of conveying a clear message of interest and gratitude for the time given. Additionally, on several occasions such descriptions contained information that later proved useful.

In cases when information was scarce in all available written sources, one successful strategy was to prepare a short statement based on engineering judgement before contacting an expert and then asking for a confirmation or a refutation, instead of asking for a general description. Given the right circumstances, almost all experts contacted throughout the two LCI model projects offered their time with great generosity, as exemplified by James R. Hendershot, CEO of Motorsolver LCC, textbook author, and senior electric motor design and manufacturing expert, who responded to several e-mails during his Christmas holidays 2015 (Hendershot, 2015).

Transparency and the level of detail in reporting

The data collection work did not only include raw data collection from primary sources, but also reviewing of other LCI data sources, for example case studies and documentation in databases. It was found essential to report transparent, detailed and disaggregated data records in order to make LCI data possible to criticize, correct and update, and thereby more broadly applicable. A good example is a case study conducted by Sprecher et al. (2014a, 2014b) for the production of neodymium-iron-boron magnets. The comprehensive supplementary information (Sprecher et al., 2014b) made it possible both to detect errors made and still use the data in a corrected version for the electric motor LCI model. The data from Sprecher et al. (2014a, 2014b) was supplemented and corrected after detailed literature studies, and then reworked using patent information for the addition of dysprosium (paper III). This can be contrasted with the use of highly aggregated and nontransparent environmental production declaration data, as discussed in section 4.2, which is very difficult to evaluate in terms of relevance.

For the inventory LCI model, a dataset for nickel plating originally established by Moing et al. (2009) played an important role, since it contained detailed data compiled for both inputs and outputs. It was simplified for the inverter unit LCI model, and it served as a reference when using theory for electrolysis to establish new datasets for gold plating and electro-galvanization.

In summary, reporting of inventory data with sufficient transparency to enable reuse, rework and criticism by other LCA practitioners, was found vital to maintain data usability over time.

6.4 Using LCA to support stepwise improvements

The comparative LCA study described in paper IV comprises three alternative designs of electric motors intended for propulsion of vehicles. More specifically, all motor options have identical stator core cross sections, but differ in the design of the rotors. As mentioned in Chapter 2, each rotor contains different types of permanent magnets – Nd(Dy)FeB, samarium-cobalt and ceramic strontium-ferrite magnets. For the weakest of the magnets, the strontium-ferrite type, the rotor core has differently shaped magnet slots and therefore makes use of another operating principle (the PM-assisted SynRM), as compared to the two motors with stronger magnets (PMSMs). Due to the varying design of the rotor in all three options, they differ in length and operating efficiency.

The LCA study described in paper IV was setup to explore the environmental impact related to the choice of core design and magnet material. The primary target audience aimed for comprises technically skilled design and manufacturing engineers, representing companies that develop and produce electric traction motors for automotive applications. The study also addresses those who make purchase requests for such machines and academic researchers working with automotive technology development or environmental assessment of vehicles. The intention was to guide the work of balancing different design requirements, by providing information about how the current environmental load differs between the motor options for the manufacturing stage and the use phase, by identifying near term trade-offs between impact categories, and by suggesting improvements.

The study excludes the End-of-life life cycle stage (paper IV). One reason was the lack of inventory data and uncertainty around actual End-of-life practices for electric motors (paper IV). Instead, focus was set on the stages in which the primary target group can influence the technical system by means of design choices and actions in manufacturing.

The time horizon is relatively short; the estimated validity of data, results and conclusions falling between 5-7 years. However, the long term goal is to support motor development and by extension, electric vehicle development. It was pointed out in paper I that electric motor manufacturing is still immature and that there is low energy efficiency in comparison with the production of other automotive parts, for example the ICE. Material and energy use can be saved by adapting motor design for manufacturing (paper I). This is important, given the discussion in section 5.1 – significant environmental issues should preferably be addressed as early as possible in a technology diffusion process, when there still is freedom to act (Arvidsson et al., 2017, Collingridge, 1980).

Markedly, the study of paper IV is based on the electric motor LCI model presented in papers II and III. A less accentuated goal was to test how well the technical details of the inventory data model supported an in-depth analysis, and the possibilities of drawing useful conclusions.

6.5 Uncertainties in resource related impact assessment

Paper I shows that electrification of vehicles implies a problem shift from emissions of air borne pollutants to resource related issues. Electric vehicles use more metal resources in the equipment life cycle than ICE vehicles. Most studies reviewed in paper I use ready-made LCIA methods. But few elaborate on the robustness and uncertainties of different LCIA methods or how they relate to each other. Impact categories relating to vehicle tailpipe emissions, such as global warming and acidification, are both well-established (Hauschild et al., 2013) and co-varying (paper I). Resource related impact categories are more complex.

Excavation of ore for metal production as well as energy resources such as fossil fuels, cause environmental impacts, both in terms of depletion and emissions. Consequently, there are two types of impact categories of special importance for LCA of electrified vehicles – resource depletion and toxicity.

Abiotic resource depletion

The indicator for the extraction of non-living resources, such as metals and oil, is often referred to as abiotic resource depletion (Guinée et al., 2002). There are a variety of methods available to characterize the contributions to this impact category, reflecting that there are many different underlying problem definitions made for resource depletion (Finnveden et al., 2009). The stocks of metals present in the Earth lithosphere are estimated from data collected from the prospecting of mines, mining operations and geological surveys, and described in terms of ultimate reserves, reserve bases or economic reserves (Gordon et al., 2006, Guinée et al., 2002, JRC-IES, 2011). The ultimate reserve represents an estimate of the total amount of a metal in the lithosphere, the reserve base is the amount which is currently technically feasible to extract, and the economic reserve is the fraction which is economically viable with current methods (Gordon et al., 2006, Guinée et al., 2002). Economic reserves are also referred to as deposits (JRC-IES, 2011). The data for all types of reserves contain uncertainties, both relating to the precision of measurements, as well as the progress in extraction technology. Gordon et al. (2006) exemplifies how Earth's estimated reserve base for copper span from 548 Tg to 950 Tg between two acknowledged sources. The LCIA methods for resource depletion also take extraction rates into account in the characterization step. These rates vary over time with industrial activity.

In response to the many challenges of LCIA modeling, different expert groups have been set to work on providing guidelines and identifying best practices among available LCIA methods (Hauschild et al., 2013, Jolliet et al., 2014). One such output with significant authority is the recommendation of LCIA methods made within the scope of the International Reference Life Cycle Data System (ILCD) handbook, which is promoted by the expert groups of the Joint Research Centre for the European Commission(JRC-IES, 2011). The ILCD handbook recommends one method for midpoint characterization of resource depletion, the CML method (Guinée et al., 2002), although indicating there is a need for improvement, and another method for endpoint characterization, the ReCiPe method (Goedkoop et al., 2013), as an interim recommendation, this awaiting a more mature version (JRC-IES, 2011, Hauschild et al., 2013). The CML method (Guinée et al., 2002) is based on estimates of Earth's ultimate reserves and current extraction rates of fossil fuels and minerals to indicate scarcity as the long term availability to mankind (Guinée et al., 2002).[5] The ReCiPe method (Goedkoop et al., 2013) builds on existing metal prices and mining data for the depletion of economic reserves over a limited time horizon (Hauschild et al., 2013).

The ILCD handbook also recommends explicit characterization factors (CFs) for each endorsed method (JRC-IES, 2013). For the CML method, this refers to the original CFs, which cover most metals of relevance for electric vehicles, including lithium used in battery cells and REEs used in motor magnets, but these recommendations are now 15 years old (Guinée et al., 2002, JRC-IES, 2013). However, the ReCiPe method (Goedkoop et al., 2013) lack CFs for both lithium and REEs. Such gaps exist also in other easily available LCIA methods (Goedkoop and Spriensma, 2001, Jolliet et al., 2003).

Paper IV examplifies how an unfortunate overestimate of trace metals, i.e. indium and cadmium, in infrastructure datasets of Ecoinvent, combined with high CF for the same metals in the ILCD handbook recommendation (JRC-IES, 2013), brought about a confounding dominance of these trace metals in the resource depletion results, despite none of them being constituents in any of the investigated motors. For this reason, a newer set of CFs (version 4.4) (CML, 2016) was tested for the CML abiotic resource depletion method. It was found that the CF for indium had been downscaled by a factor of 80,000 between the former and latter LCIA versions (paper IV). It was also found that REEs have no CFs in the updated CML method (CML, 2016), and that the CFs of several other elements of importance in the study had undergone major revision between the versions, for example strontium with a factor of 250,000. Clearly, there are fundamental uncertainties coupled to the charactarization methods in LCIA of abiotic resource depletation.

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[5] CML also provides characterization methods in a non-baseline version, building on the reserve base as well as the economic reserve, but these methods are not endorsed by the ILCD handbook.

Toxic emissions from mining

Local emissions of toxic substances from the manufacturing stages of electric powertrains are an environmental aspect brought up by Hawkins et al. (2013). Calculations made in paper I confirm these results and shows that the components specific to the electric powertrain together cause a significant share of the overall human toxicity impact of electric cars, and that these emissions increase in comparison to conventional ICE vehicles. Correspondingly, the results of paper IV show that toxic emissions are among the most important environmental impacts in regard to electric traction motors and that copper production is the main problem, with significant contributions in all toxicity categories.

Mining processes are central for the emissions of toxic substances, coupled both to material processing and electricity production for electric vehicles (paper I and IV). The root cause of most toxic metal emissions is leakage from the waste disposal of mining spoils. High use of copper and nickel, in batteries and electric motors, and copper and gold, in power electronics, increase the disposal of sulfidic tailings of the mining operation (Classen et al., 2009). The extraction of REEs also causes sulfidic waste (paper IV). Mine tailings are often disposed in water, called tailing dams, to avoid toxic dust formation and acid drainage of exposed sulfide rock (Beylot and Villeneuve, 2017). Heavy metals such as arsenic, chromium and copper are emitted from the dams into the local ground water over a long time period. Electricity generated with coal or nuclear power has similar emissions coupled to the extraction of hard coal and uranium ore (R. Dones et al., 2007).

As a solution, improved metal recovery rates from the tailings and upgraded waste handling in the mining industry could clearly decrease the toxic load of electric vehicles (Beylot and Villeneuve, 2017) (paper I and IV). Reducing the use of coal in electricity generation is another key factor (paper I and IV).

However, toxicity impact categories in LCIA (different types of human and ecological toxicity) are complex and have at times been questioned due to gaps both in inventory data and CFs, and because there has been a lack of consensus about the methodology for characterization (Finnveden et al., 2009). Toxicity relates to the inherent toxicity of numerous substances combined with the risk for humans and ecosystems to be exposed in a manner that cause adverse effects (Huijbregts et al., 2000). Toxicological data is limited, both for inherent toxicity and exposure, which couples these impact categories to a high degree of uncertainty (Finnveden et al., 2009). Still, progress has been made in consensus building around the methodological approach and there are now endorsed methods for all toxicity categories in the ILCD handbook (Rosenbaum et al., 2008, Hauschild et al., 2013).

In addition, despite methods being in further need of improvements and that data gaps for CFs call for caution in the analysis of toxic emissions (Hauschild et al., 2013), it is not adequate to ignore LCIA of toxic impacts. On the contrary, the current focus on inventorying climate change related emissions means that emissions from tailing dams are subject to cut-off conventions, and there are indications that current mining emissions are underestimated (Beylot and Villeneuve, 2017).

Chapter 7

Conclusions and contributions

7.1 Empirical contributions

A significant part of this project was spent on empirical work in developing, substantiating and implementing operative tools to support LCA practitioners when conducting studies of electrified vehicles, powertrains or specific components. These model tools, as well as the underlying data, constitute substantial contributions of the project.

Scalable and easy-to-use life cycle inventory models

Two LCI models were developed which estimate the mass and composition of electric vehicle powertrain components, calculate full gate-to-gate manufacturing inventories, and point to existing database records to establish cradle-to-gate data, for one electrical traction motor and one power electronic inverter unit. Both models are scalable from basic engineering requirements, build on typical design solutions and easy-to-use, i.e. the user enters at most two model parameters and receives all results at one click of the button.

Additionally, the LCI models have been thoroughly described in two detailed reports (Nordelöf et al., 2016, Nordelöf and Alatalo, 2017) explaining theory, observations, assumptions, data collection and the principles used for scaling the design in size. The motor model is presented in appended papers II and III, and the inverter unit in papers V and VI. Paper II presents how the motor model scaling relies on electromagnetic calculations from fundamental principles, and paper V how the inverter unit model combines different strategies for scaling depending on the function of subcomponents, into one model. Papers II and V compare real-world component data with the mass estimates calculated by each model in order to validate their function. Both models make proper predictions and qualify as generic inventory generating tools when other, more specific data, is lacking.

The two models simultaneously address three different types of information gaps:

- Design data, i.e. the mass composition of typical powertrain components
- Manufacturing data for typical powertrain components
- The link from easily acquired technical requirements to complete inventories

The main technical features of the electric traction motor model are:

- Synchronous machine operation
- Internal permanent neodymium-dysprosium-iron-boron magnets
- The model parameter range for maximum power is 20-200 kW
- The model parameter range for maximum torque is 48-477 Nm

The main technical features of the power electronic inverter unit model are:

- Stand-alone casing with optionally air- or liquid cooling
- Standard power module design with IGBTs
- The model parameter range for nominal power is 20-200 kW
- The model parameter range for nominal voltage is 250-700 V

The user interacts with the model file via a pop-up interface. This allows entering of the model parameters and provides options for the user to exclude subparts where design variability is most prominent. The same parts can have different designs if the motor or inverter unit are integrated with an adjacent powertrain component, typically the outer protection and cooling structure, i.e. the motor housing and inverter casing. These may be excluded to increase the precision and flexibility of the models. Additionally, to simplify the use of both models, there is a recommendation given to the user for each flow: either to match it with a designated upstream representation in Ecoinvent (Weidema et al., 2013) or to make another attentive selection for the upstream connection. In both cases in order to establish a cradle-to-gate inventory.

Detailed unit process datasets

The detailed manufacturing unit process datasets established for the two LCI models (papers III and IV) and the LCA case study (paper IV) are to a varying extent generic, in terms of describing the manufacturing steps commonly used. Identical or at least similar processing can be used to make other products, for example different types of electrical machines or electronic devices. Tables 1, 2 and 3 summarize all new LCI datasets compiled from factory site visits, factory records, textbooks, expert interviews, machine specifications and engineering judgement.

In total, 45 novel unit process datasets have been compiled and published as a result of the project, and more than a third of these cover multiple process steps. Also, taken one by one, outside the scope of the LCI models, these datasets constitute valuable contributions of the project to the broader LCA research field.

7.2 Methodological findings

This section presents the main methodological findings of the thesis. It is primarily intended for LCA practitioners and specialists conducting LCA of vehicles, subsystems or components.

The purpose declaration

A clear definition of both goal and scope should always be presented in LCA, since it provides the methodological and technical context of the study and a basis for conclusions. Lack of an openly stated goal makes it difficult to criticize the appropriateness of the selected scope and datasets, since there is no underlying motive. In paper I, it is shown that LCA studies covering electrified vehicles generally fail to report the goal and scope definition in accordance with ISO standard (ISO, 2006a, b). It is argued that this is a key explanation for the appearance of the divergence and complexity which follows from varying numerical results.

Concurrently, given the urgency of curbing transported related environmental impacts, activities aiming for standards and recommended practices when conducting LCA on vehicles are increasing. In essence, the failure of compliance with the ISO standard is suggested to be met with additional guidelines on how to scope studies. Comparability of results is indeed necessary in LCA based environmental product declarations. A number of methodologically harmonized studies can also provide support for legislation. But LCA can play a broader role as regards learning and stepwise improvements in design and manufacturing of vehicle subsystems and components. This implies that the goal and scope definition is specific and different between studies. The key to determine if an LCA study contributes with useful information is that the purpose is clearly declared.

Different time horizons and technical scope

Paper I presents that a majority of the reviewed LCA studies do not report a time scope. In addition, most studies focus on current electric vehicle technology used in today's electricity production system, i.e. implicitly the time horizon is short. The lack of a time scope declaration then becomes problematic if, at the same time, the study expresses conclusions as general and time independent.

Again, restricting standards could be a way to ensure harmonization, not only of purpose but also regarding scope and time horizon. However, with reference to section 5.1, it should be remembered that such setups might disregard the long term goal and allot priority to technical solutions that have the least climate impact now, rather that prioritize the reduction of total environmental impact over time.

Two other approaches are discussed in this thesis and the appended papers. The first is to carry out prospective LCA studies using a long time horizon and taking into account that electrification technology has only recently emerged in vehicle development, and is rapidly evolving, as discussed in Section 5.1. Such a setup is suggested in paper I; to use LCA as a learning tool for a strategic assessment of electric vehicle technology, with the goal of identifying both key improvement areas and potential showstoppers that must be avoided in the long term, while aiming for the goal of mitigating climate change. This approach will support development towards a fossil free transportation system, while minimizing other impacts.

The second approach is discussed in section 6.4 and exemplified in paper IV. This study has a short time horizon and a clear technical audience. The study was intentionally delimited in scope to include only the life cycle stages that intended main recipients of the information are able to influence directly, i.e. the End-of-life stage was left out. More generally, this type of study is scoped to answer explicit questions about a part or a technical system in the vehicle, and provide support for a specific stakeholder to take action. It presupposes that both inventory data and analysis have sufficient technical depth to draw useful conclusions. However, it is not the effects of making a design change or adjusting a manufacturing procedure per se that is most interesting, but that it is a step in the right direction. In conclusion, the overarching goal of the second recommended approach is to minimize environmental impact in the long term, while guiding stepwise improvements.

Gathering and reporting inventory data

The data collected during the project can be defined in two categories: equipment design data, and manufacturing data. In both, it is necessary to acquire descriptive as well as quantitative information.

Equipment design data is important for three reasons: it defines the function and relevance of the studied object; it provides operating data for the use phase; and it establishes the mass and material composition of the part or system, which links to upstream manufacturing. For this data type especially, interdisciplinary academic collaboration is recommended, since design questions and energy consumption are the core of applied technical research. Benchmarking literature, displaying dissembled vehicle parts and test statistics are very useful. Detailed technical documentation from industry is harder to find, but not impossible, as exemplified in paper V for the inverter unit where documentation of test objects played a key role. In addition, ROHS compliance means that there are material content declarations available upon request for electronic components. Literature and datasheets provide overviews as well as specific details.

Factory site visits and textbooks are recommended cornerstones for descriptive information about manufacturing. Ready-to-use single source data for LCA from industry is rare, but sometimes possible to acquire, as exemplified for electrical steel in paper III. Different types of data building is the most efficient way to establish datasets which can be made useful, i.e. different blocks of data from many sources are adapted to be merged in one dataset. Interviews with experts play a key role in data building: to provide process descriptions; to provide specific technical details; for quantitative estimations; and to confirm examples of practices or procedural descriptions provided by research articles and textbooks. However, to be successful when establishing contact with a technical expert in a specific field, preparation is required – read up the topic and ask specific questions.

Finally, it can be concluded that reporting of detailed inventories, including descriptions on what the data represents and how it was established, is vital to enable critical review and corrections, and to rework and reuse datasets in such a way that they can remain valid over time and become more broadly applicable.

The reliability of impact assessment methods for resource depletion

Paper I shows that practically all reviewed case studies of electric vehicles use ready-made LCIA methods, and that few reflect on their robustness. For global warming, the key environmental motivation for vehicle electrification, this represents no problem. A robust and well-established characterization method at midpoint has been provided by the IPCC (2007, 2013), including regular updates of the characterization factors. Additionally, the method is recommended by the Joint Research Centre of the European Commission (JRC-IES, 2011).

However, while vehicle electrification has benefits in addressing climate change, there is a risk for a problem shift towards resource related impacts. Consequently, if LCA is used for guidance in minimizing overall impact, there is a need for robust LCIA methods concerning resource depletion, especially in regard to minerals and metals. Indeed, there is a general need for improvement in the LCIA of resource depletion (Hauschild et al., 2013), for example in the underlying data for the characterization factors of many metals.

This was exemplified in paper IV where the CML method (Guinée et al., 2002) for abiotic resource depletion, recommended by JRC-IES (2011), was tested for two different versions of categorization factors (JRC-IES, 2013, CML, 2016). The characterization factors for indium and strontium turned out to be downscaled between the former and latter LCIA versions by factors of 80,000 and 250,000, respectively. Clearly, LCIA of resource depletion lacks stability and must be improved.

7.3 Technology advice for industry and policy makers

In the following, technical recommendations and assessment conclusions are summarized for vehicle electrification stakeholders, i.e. the automotive industry and other related branches, as well as agencies and governments. They are also aimed at a general public audience, this containing potential customers and users of vehicles.

Aim for the full potential

The fundamental motive for a large scale electrification of road vehicles is the decoupling of the majority of all land based transportation from an inherent dependency on fossil fuels, and instead enabling the use of flowing renewable energy. LCA clearly shows that electricity production is currently the dominating factor behind airborne emissions from electric vehicles (paper I). Hence, if, and only if, electricity production becomes free from fossil carbon on a global scale, vehicle electrification will reach its full potential in mitigating global warming (paper I).

In many countries, a shift towards more renewable energy production is in progress. Intermittence is a fundamental feature of flowing renewable energy sources, e.g. wind and solar power. Electric vehicles could become a part solution to the intermittency problem by offering temporary energy storage.

Accordingly, stakeholders in both areas of technology, i.e. both automotive and power industries, and policy makers in agencies and governments, are advised to acknowledge, plan and act with this mutual dependence in mind, along with the long-term goal of fossil free transportation. Clean electricity production is a prerequisite for clean electric vehicles, but the lack of it should not be interpreted as a disqualification of electric propulsion. Instead, it is crucial to transform the energy system in parallel.

Energy efficiency in use

High powertrain efficiency, at both component and system levels, is central to the environmental impact of electric propulsion (paper I). In essence, all well-to-wheel life cycle impact is reduced when less energy is required for vehicle operation. As a consequence, increased efficiency correlates with reduced impact in WTW results. This was exemplified for climate change, land use, human toxicity and respiratory health in the case study of electric traction motors (paper IV).

Moreover, complete LCA studies show that driving is the dominant cause of energy use, counting both the WTW and the equipment life cycles (paper I). Component and system design with low losses address this issue regardless of emissions from the background energy system. Also, it is important to consider efficiency in choosing when and how to apply electric driving. WTW studies show that electric propulsion is most advantageous in city traffic, where the driving behavior and traffic situation are important.

Component suppliers, vehicle manufacturers, policy makers as well as different customers and end users are recommended to prioritize high energy efficiency.

The manufacturing stage becomes increasingly important

The electric powertrain entails a shift in the environmental impact of vehicles between the life cycle stages (paper I). Although vehicle operation remains dominant in terms of total energy use, it can be concluded that with current practices it is more energy demanding to manufacture parts required for electric propulsion, compared to a conventional combustion engine with fuel and exhaust systems. Accordingly, the manufacturing stage increases in importance. In addition, if emissions decrease from the charging electricity WTW life cycle, as in the case with renewables, this effect is further enhanced.

However, a significant share of production related environmental impact is coupled to production energy use. As in the case with the WTW life cycle, reductions of emissions in the background energy system change production emissions. Still, the making of electric powertrain parts necessitates a broader palette of input raw materials and more advanced processing, not only important for energy use, compared to conventional parts. Hence, the manufacturing stage in particular, calls for a broad impact assessment. Another effect is that benefits of electric propulsion increase when vehicles are intensively used with many lifetime kilometers.

Paper IV shows that carefully considered component design and processing can reduce the load of the production stage. For electric motors, the production of base metals, i.e. aluminum, electrical steel and copper, dominates the environmental load. But there is significant room for improvement, for example by minimizing manufacturing scrap and through better recycling.

These conclusions are of importance for directing policy and for continued research and development, both in industry and academia. Technical solutions designed with higher awareness of the challenges of production, and direct improvements of manufacturing processes, could decrease the future environmental load of electric powertrains significantly.

Challenges in resource extraction

Metal production is an important step in the equipment life cycle of vehicle components. Copper, nickel and gold are extracted from sulfide ores for use in electric powertrain components. The waste handling and disposal of sulfidic tailings cause leakage of toxic substances into the ground water, making major contributions to the toxicity load presented in LCA results, at both vehicle and component levels. Paper IV demonstrates that different types of toxicity are important factors behind the overall environmental impact of electric motors and that copper production is the key common denominator. Paper IV also reports that the extraction of magnet materials causes similar problems, although that magnets are not among the main contributors of emissions, since their share of the total mass is relatively low.

Moreover, related to the methodological findings presented earlier, it should be noted that current LCIA methods for the depletion of resources lack both methodological consensus and solid data regarding assessment methods for metals depletion. Essential elements for vehicle electrification, e.g. rare earth metals in motor magnets and lithium in battery cells, are not always covered with characterization factors by the LCIA methods promoted by authoritative expert groups, e.g. the ILCD handbook (JRC-IES, 2011), even when declarations are made to take constraints of currently available mineral deposits into account.

This information is directed to policy makers, the automotive industry and the recycling industry. They should be aware that the environmental burden of primary metal production is extensive. It is also important to note, especially given the status of current LCIA methods, that LCA studies cannot be expected to cover short to medium term supply limitations of rare earth metals or lithium, although they report to include resource depletion.

7.4 Research needs

Two main areas of immediate future work outside the main scope of the thesis were identified during the project, drawing on observations and conclusions made in the appended papers, and from the results of industrial collaborations within the project.

Vehicle End-of-life and circular material loops

The End-of-life stage of electrified vehicles and electric powertrain components is discussed in papers I and IV. However, End-of-life is not included in the scope of the LCA study in paper IV, although design implications for recycling are discussed. A key reason was that the End-of-life stage, if included, would have been based entirely on rough assumptions, with a risk of blurring the results of previous stages where representative data was available.

Paper I concludes that it is common to assume high recycling rates in LCA case studies of electric vehicles, despite vehicle End-of-life generally being poorly mapped. A similar observation was made in the literature reading reported in paper IV, i.e. that the End-of-life stage for electric traction motors is very uncertain and that practices diverge geographically. Electrical steel and aluminum have high recycling rates. However, other key materials are recycled with significant losses, as in the case of copper, and not at all in the case of magnet materials. Effective recycling of materials back to high quality products remains a future challenge rather than being a reality (paper I).

A general observation from reviewing LCA case studies in connection to both papers I and IV, is that full recycling in closed loops back to the same function is described as, or can be misinterpreted as, an existing phenomena. Although the intention in most such case studies is to exemplify the maximum potential benefits of recycling, the message becomes vague because few studies investigate or elaborate on actual recycling rates, or on the challenges of achieving closed material loops. The result can be problematic if existing End-of-life practices appear to create more benefits than actually is the case, since this provides little motive for actions of improvement.

Indeed, circular material flow is undoubtedly an essential part of a sustainable society. In paper I, 100% of the reviewed studies that included recycling found this to be a key factor for final results. Clearly, it can be concluded that efficient recycling will reduce the environmental load of electric vehicles. But much research is needed on how to get there. LCA can play a role in supporting this development. In relation to the work presented in this thesis, and relating to all papers, but foremost papers II-VI, the following questions were identified as a basis for continued research using LCA to support the development of electrified road vehicles:

- How can electric vehicle components be designed to retain or advance their technical performance and also enable reuse and recycling of materials back to their original function?
- How can End-of-life systems be adapted to better reuse parts and recover materials built into electric vehicles?

Trucks and busses

Paper I presents a clear dominance of passenger cars as study objects among reviewed LCA case studies. Other vehicle types, especially trucks and buses, remain to be explored in greater detail. One such effort was made in master thesis collaboration with the Volvo Group, the renowned Swedish manufacturer of heavy vehicles (Inunza Soriano and Laudon, 2012). The study investigated early hybrid and concept plug-in hybrid city trucks for different applications, and established that most environmental benefits in the short term were obtained through hybridization, whereas additional improvements from including all-electric driving ability were indicated, but difficult to ascertain.

City buses, waste collection trucks and distribution trucks are electrified for somewhat other motives than passenger cars. Driving forces include direct cost savings from reduced energy consumption and reduced local environmental impact (Volvo Bus Corporation, 2013). Electric propulsion can give access to city zones where silence or zero emissions are in force owing to public health considerations (Volvo Bus Corporation, 2015a). But effects over the entire life cycle have been addressed by very few studies, and there is a need for further investigation into benefits, drawbacks and how best to utilize electrified heavy vehicles, for example in planning and use in public transportation, including new impact assessment categories such as noise.

Additionally, and also early on in the project, there was master thesis collaboration with Scania, the other well-known Swedish producer of heavy vehicles. This case study evaluated alternatives for electrification of roads and long haul trucks for the transportation of iron ore in northern Sweden (Björkman, 2013). Results indicated clear environmental benefits from using trucks with electric propulsion power provided by overhead catenaries, compared to conventional long-haul trucks and hybrid vehicles. In line with the overall research aim of the project, further efforts were put into evaluating the role of LCA to further support the development of this emerging technology (Nordelöf et al., 2013a). Although not pursued as a main track in the project, this is clearly an area for future research and one where different types of LCA case studies can play an important role by informing actors how to advance the technology, while minimizing environmental impact in the long term.

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