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Comparing Apples and Pears

How will regional differences affect the environmental outcome when comparing electric and conventional vehicles?

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Abstract

In recent years a number of studies have assessed the life cycle emissions of electric vehicles, with differing focus areas. In this study we sought to further broaden the comparison of electric vehicles and conventional vehicles by taking into account the generation of electricity in various countries. This research combine recent existing life cycle assessments and statistics into a complete analysis of the life cycle CO_2 emissions of an electric vehicle, including emissions at point of use in China, Germany, India, Japan, Norway and the United States. These results were compared to a conventional vehicle of similar characteristics, using gasoline or diesel as fuel.

By assuming a vehicle lifetime of 150,000 km, we found that electric vehicles powered with electricity from either China or India contributes to minor or no environmental savings relative to conventional vehicles. As 96 % of electricity generation in Norway is derived from renewable energy sources, driving an electric vehicle offer by far the highest environmental savings, up to 64 %. When utilizing the electric vehicle in the remaining countries one achieves CO_2 savings of 14 to 27 %, depending on battery applied and fuel of comparison.

The countries selected in our study accounts for approximately 75 % of the worldwide electric vehicle fleet. Our results express that 68 % of the fleet suits as an environmentally friendlier alternative relative to conventional vehicles, while the remaining 25 % remains to be considered.

Preface

The choice of topic is based on personal curiosity regarding the subject combined with recent development of mass-produced electric vehicles, and our mutual interest concerning the many aspects of environmental initiatives. As the environmental impact of electric vehicles across countries has received minor consideration in previous studies, we found it rewarding to contribute with further findings.

First and foremost, we would like to thank our supervisor Roar Os Ådland, for seeing the potential in our unconventional thesis for students of economics, in addition to providing valuable input along the way. Our major subjects at NHH include Energy, Natural Resources and the Environment, and Financial Economics. Hence, knowledge about the technical aspects of the thesis was to some extent limited. However, our educational background helped us a lot when writing this thesis, as we have captured a greater understanding of the mechanics of the economy, which in turn enabled us to look at various aspects from different angles relative to prior studies. In the same way as elements in finance and economy are affected by multiple factors, as is the field of life cycle assessment. Our natural curiosity, and embedded search for causes of events learned from the field of economics, has in turn enabled us to adequately assess the theme in the thesis.

In retrospect, we feel fortunate to be provided the opportunity to conduct an extensive research on an exiting theme of current relevance, and we have learned a great deal during the process. Writing the thesis has been a challenging and enjoyable experience, and we have gained valuable knowledge concerning the many aspects affecting the electric vehicles environmental impact.

We would like to express appreciation to our fellow students for contributing to an academic and supportive environment. At last, we thank Anders Hammer Strømman for pointing out interesting readings and providing us with their latest research on a short notice.

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List of Abbreviations

Abbreviations in order of appearance in the thesis:

CO_2	Carbon dioxide
GHG	Greenhouse gases
EU	European Union
LDV	Light-duty vehicle
ICEV	Internal combustion engine vehicle
EV	Electric vehicle
LCA	Life cycle assessment
ISO	The International Organization for Standardization
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
GWP	Global warming potential
NEDC	New European Driving Cycle
$LiFePO_4$	Lithium iron phosphate
LiNCM	Lithium nickel cobalt manganese
$LiMnO_2$	Lithium manganese oxide
$LiMn_2O_4$	Lithium manganese oxide
WTW	Well-to-wheels
WTT	Well-to-tank
TTW	Tank-to-wheels
GCV	Gross calorific value
EROI	Energy return on investment
PV	Photovoltaic
FCEV	Fuel cell electric vehicle
MEF	Marginal emissions factor

In this thesis we use the term CO_2 when expressing the global warming potential (GWP). When mentioning CO_2, we refer to CO_2 equivalents, which may also include other gasses. See section 2.2 for a description of GWP. When referring to emissions or pollution, we are referring specifically to the CO_2 equivalent emissions/pollution.

1. Introduction

As a result of the industrial revolution the environment has been exposed to increased threats, primarily caused by emissions related to combustion of fossil fuels. The World Meteorological Organization (2012) has stated that the amount of carbon dioxide (CO_2) in the atmosphere reached 140 % of the pre-industrial level in 2011. High values of greenhouse gases (GHG) affect the environment in multiple ways, the most prominent being rising sea- and air temperature, more intense storms, and changes in precipitation patterns. Among the most prominent climate changes, the global average temperature has risen with 0.8 degrees since the industrial revolution (MDep 2012).

IEA (2012a) reported that electricity and heat production were responsible for 41 % of global CO_2 emissions in 2010. At current conditions the electricity and heat sector relies heavily on coal and other fossil fuels, a crucial factor causing high emissions. Taking the United States as an example, 42 % of the electricity is generated from coal production, while measured in CO_2, coal represents about 80 % of total CO_2 emissions from the sector (EPA 2012). A contribution to further concerns in that sense is the projections provided in the World Energy Outlook (IEA 2012b), which states that the demand for electricity by 2035 will be more than 70 % above current levels. In addition, IEA (2009) states that 19 % of global energy use and 23 % of energy-related CO_2 emissions are attributable to transport. Combined with the electricity and heat sector, this makes up nearly two-thirds of global CO_2 emissions. Of the total transport energy use, 47 % are attributable to Light-duty vehicles (including automobiles, light trucks, SUVs and mini-vans).

Use of vehicles for transportation is steadily rising, and according to UNEP (2013), the global vehicle fleet will grow from less than one billion to 2.5 billion or more by 2050. One of the main concerns is that 90 % of the growth is occurring in non-OECD countries where the average vehicle efficiency is getting worse, in contrast to vehicles in OECD countries. Given current trends, emissions related to transport are estimated to rise approximately 50 % by 2030, and more than 80 % by 2050 (IEA 2009). This points to the need to adopt effective solutions with the purpose of reducing emissions from road transport, in order to secure a sustainable future.

1.1 The Need for Alternative Vehicles

To avoid the most severe impacts of climate change the Intergovernmental Panel on Climate Change (IPCC) suggest that global CO_2 emissions must be reduced by at least 50 % by 2050 (2007). To achieve this, reducing emissions from the transport sector is essential even if effective actions are put to place in the remaining sectors. In 2009, the leaders of the European Union (EU) and the G8 set an even more aggressive target in response to the environmental threats; the object is to reduce GHG emissions by at least 80 % below 1990 levels within 2050. An intermediate target to accomplish this involves reducing the CO_2 emissions from the road transport sector with 95 % by 2050 (ECF 2010). A well-known target by the EU called "20-20-20", sets three key objectives for 2020 which involves reducing GHG emissions by 20 % from 1990 levels, achieve a 20 % improvement in the EUs energy efficiency, and raising the share of energy consumption from renewable recourses to 20 % (EC 2013).

The road transport sector is dependent on several improvements in order to achieve the aforementioned goals. To cut CO_2 emissions from light-duty vehicles (LDV) this will include solutions to improve the internal combustion engine vehicle (ICEV) efficiency, vehicle hybridisation and improving efficiency of electric and fuel cell vehicles (IEA 2009). Alternative vehicles can potentially play a major role in order to achieve decarbonisation of the road transport sector in the future. Along with being recognized as more environmentally friendly, there are other important criteria to consider before alternative vehicles can achieve an appreciable share of the vehicle market. Such criteria include affordable prices, infrastructure (access to fuel) and vehicle performance such as driving range etc. Actions directed towards efficiency includes among others reducing tailpipe emissions from ICEVs and emissions associated with manufacturing of vehicles. Connected to reducing emissions in the manufacturing phase is the need to achieve a more efficient electricity sector and increase the use of renewable energy sources, which are also crucial factors for the environmental impact of vehicles with electric engines.

In this research we have decided to exclude Hybrid Electrical Vehicles, Plugin Hybrid Electrical Vehicles and Fuel Cell Electric Vehicles, looking at a fully Electrical Vehicle (EV), and comparing it with an ICEV. The LDV fleet is almost unconditionally ICEVs. In 2005, more than 80 % of the worldwide stock was fuelled by gasoline, while the remaining was mostly diesel (IEA 2009). The current global EV stock consists of approximately 180,000 vehicles, with a goal of achieving 20 million EVs on the road by 2020 (IEA 2013b).

When examining CO_2 emissions during the life cycle of different vehicle types, it is important to understand the main differences, and the various factors causing the emissions. The main difference between a modern EV and an ICEV are predominantly that the EV lack the internal combustion engine and related parts such as a fuel tank, fuel lines, fuel injection systems, cooling system, and exhaust systems. In contrast, the EV contains an electric motor, a rechargeable battery pack, a controller that feeds electricity to the motor from the driver's accelerator pedal, and a charging system (J.D. Power 2012). Considering emissions from production, EVs are often built with more lightweight materials such as aluminium rather than significantly less CO_2-intensive steel. Producing the battery is also a CO_2-intensive process, and there seems to be consensus among scientists that production of an EV emits significantly more CO_2 than an ICEV. During the use-phase of an ICEV, emissions at point of use are related to the amount of gasoline burned in the engine. The fuel efficiency of the engine is therefore what determines the amount of CO_2 any given ICEV will emit per km.

1.2 Goals of the Study

EVs has been highlighted as an important initiative to reduce global CO_2 emissions, as current mass-produced EVs to a greater extent offers the same abilities as the conventional vehicle, combined with zero tailpipe emissions. Before one can conclude that EVs are more environmental friendly than ICEVs, there are several aspects to take into account. It is important to consider that even though the EV offers zero tailpipe emissions, actual CO_2 emissions arise when generating electricity, as well as emissions when producing and recycling the vehicle (applicable to both EV and ICEV). To provide a more complete basis for comparison of EVs and ICEVs, we consider it appropriate to include a full life cycle assessment (LCA).

CO_2 emissions from electricity generation may vary considerably, mainly dependent on the energy source used. As a consequence, the environmental benefit of the EV will be greatly influenced by the country where it is utilized. A key underlying theme of our study is to consider how the environmental comparison of EVs versus ICEVs varies when taking into account regional differences in electricity generation, transmission and distribution.

The objectives of this study are:

- To give an environmental comparison of EVs and ICEVs by estimating total life cycle CO_2 emissions.
- To assess how total life cycle CO_2 emissions of EVs varies across different countries and its implications regarding the comparison with ICEVs.

To develop an appropriate LCA, the model has been constructed to assess the environmental aspects of the different stages that occur over the entire lifetime. The scope of the study includes vehicle production, use-phase, and end-of-life treatment combined with relevant supply chains. To estimate the aforementioned objectives, the model is based on secondary data from esteemed studies and recent statistics covering the various life stages.

When selecting countries for our analysis, our main approach was to choose countries that have initiated introduction of EVs. Thereby providing us with two natural choices, the United States and Japan, as their stock of EVs represents more than 60 % of the worldwide EV fleet[1]. Norway was a natural choice to include due to their excellent example of a renewable energy grid, combined with the fact that Norway achieved the highest share of EV sales globally by the end of 2012. In order to broaden the perspective we wanted to include emerging economies with a known CO_2-intensive electricity generation and possibly a less evolved electricity grid. The choice naturally fell on India and China, where the vehicle fleet is expected to grow rapidly, along with being the two most populous countries in the world. In addition, India and China are the only emerging countries that possess significant shares of the worldwide EV fleet, 0.8 % and 6.2 % respectively (IEA 2013b). Germany was selected as a representative for the European countries, as Germany is considered to be the major economic and political power in Europe. Germany has also formulated clear objectives concerning EVs, namely a goal of achieving one million EVs on German roads within 2020 (BMU 2009). Combined, our six countries constitute approximately 75 % of the entire world fleet of EVs. The selected countries were compared towards a list of governmental incentives promoting EVs, and we found that there are governmental incentives of varying degree present for each country. This includes financial incentives, incentives for infrastructure, as well as for research and development. The incentives differ

[1] A map showing shares of the worldwide EV stock in 2012 by IEA (2013b) can be seen in appendix 1.

in magnitude, among other, exclusion of almost all taxes in Norway, no road taxes in Germany and purchase subsidies in China, Japan, India and United States. For a list of countries and incentives see appendix 2 (IEA 2013b).

Parts of our report leans on the work of Hawkins et al. (2012). With respect to prior studies, they profess to offer significantly more resolution regarding the manufacture of vehicle components, as well as full transparency. In our opinion, this is to date the most complete, comprehensive and transparent inventory for comparing the EV with an ICEV, the study appears as a natural choice to use as the vehicle framework in our study. Nevertheless, we seek to improve the understanding of how use-phase CO_2 emissions for EVs will differ across countries as electricity generation is conducted in a variety of ways. Consequently, including regional differences will provide an indication as to where it may be environmentally sensible to promote the EV. Hawkins et al. (2012) focused on the European electricity mix, which means the result may be less applicable for consumers in other parts of the world. Although our report includes only six countries, the variation between them allows the results to be applicable for countries with similar characteristics and thereby extending the geographical scope of the study.

Compared to the work of Wilson (2013), our study offers more transparency and reasoning regarding the different use-phase processes for the various vehicles. Our study also displays a more detailed overview of the miscellaneous life cycle components associated with vehicle manufacturing and recycling, along with providing comprehensive interpretation connected to their corresponding environmental impact. In our opinion, we present a more suitable basis for comparison of EVs and ICEVs, as their study operate with differing vehicle lifetime assumptions. Though the work of Wilson has a similar goal as us, we find their report to be insufficient both in terms of transparency and lack of sources. To our knowledge the report is not peer-reviewed or acknowledged by scientists.

Our contribution to the literature involves providing a transparent analysis of the complete life cycle based on well-esteemed and peer-reviewed LCAs from the various life stages of a vehicle. Our study is based on the latest research and statistics available. The main contribution being the assessment of the use-phase, where we provide a more broadened approach relative to previous literature. Our study takes into to account how the EVs environmental impact vary across countries, thus achieving a unique comparison of EVs and ICEVs for each of the countries considered in this study. This enlarges our geographical relevance compared to others, as we have not come across any scientific, peer-reviewed studies looking at how EVs perform in different electricity mixes and infrastructures. Our study also contributes with a comparison of previous well-esteemed research on batteries, which we have implemented in the full life cycle. In this regard, one can get a better comparison of how the battery production impact will vary on a complete life cycle basis. Relative to both aforementioned reports, our study also offers a differing approach regarding vehicle lifetime assumptions, as it provides an environmental break-even analysis. Both studies are described in detail in section 2.3.

This thesis is divided into seven sections, starting with this introduction. We then move on to the theoretical background where we present the basics of LCAs, how to calculate the global warming potential and a describtion of related research. The final part of the theoretical background includes a presentation of the lithium-ion battery system and its application in the electric vehicle. The third section is a review of our data, describing how and where it is collected, as well as a discussion of their validity. Thereafter we present the methods applied, explaining how the model has been constructed, how the data is implemented and the assumptions made. We then go on to presenting our results, followed by a discussion related to the topics and assumptions made in our research. Finally, the main conclusions of the study are presented.

2. Theoretical Background

2.1 Life Cycle Assessment - a “cradle-to -grave” analysis

The task of assessing and quantifying the environmental impact associated with a product, process or activity throughout the supply chain is known as a Life Cycle Assessment. This “cradle-to-grave” approach includes impacts of a product from the extraction of raw materials used, trough processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling. (ISO 2006a)

The roots of LCA goes back to the late nineteen sixties, and focused on issues such as energy efficiency, consumption of raw materials and to some extent waste disposal (EEA 1998). LCA has evolved a great deal since then and the first official international standard was introduced in 1997/98. This standard was revised in 2006, resulting in the standards applied today. The purpose of the standard was to make it easier to compare results of different LCA studies. The standard contains several requirements and recommendations in order to improve equivalence in assumptions, provide contexts to each study and ensure transparency (ISO 2006a).

A standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose. The International Organization for Standardization (ISO) does not decide when to develop a new standard, it rather responds to a request from an industry or other stakeholders such as consumer groups. A panel of experts from all over the world, within a technical committee, develops the ISO standard. Once the need for a standard has been established, these experts meet to discuss and negotiate a draft standard, including scope, key definitions and content. As soon as a draft has been developed, the document is shared with ISO’s members, who in turn are inquired to offer comments and to provide a final vote. If a consensus is reached the draft becomes an ISO standard, if not it goes back to the technical committee for further edits. These ISO standards are reviewed every five years (ISO 2013).

The principles and framework of LCAs are described in ISO 14040. These should be used as guidance for decisions relating to both the planning and the conducting of an LCA.

Four main phases of LCA studies are described: (see Figure 1)

- The goal and scope definition
    - A definition of the goal and scope must be explicitly stated in an LCA. The goal contains background information on the study, while the scope definition describes the methodological framework in detail. The depth and the breadth of an LCA can differ considerably depending on the goal of a particular LCA.
- Life cycle inventory analysis (LCI)
    - This phase involves collection of the data necessary to meet the goals of the defined study. It includes an inventory of input/output data with regards to the system that is being studied. The inputs and outputs are compiled, quantified and normalised to the functional unit[2].
- Life cycle impact assessment (LCIA)
    - The purpose of the LCIA is to provide additional information to help assess a product system's LCI results, in order to better understand and evaluate the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
- Interpretation
    - This is the final phase of the LCA procedure, where the results of the LCI and LCIA are summarized and discussed as a basis for conclusions and recommendations in accordance with the goal and scope definition.

[2] A functional unit is the quantified performance of a product system for use as a reference unit, for instance CO_2 per km driven or CO_2 per kWh of electricity.

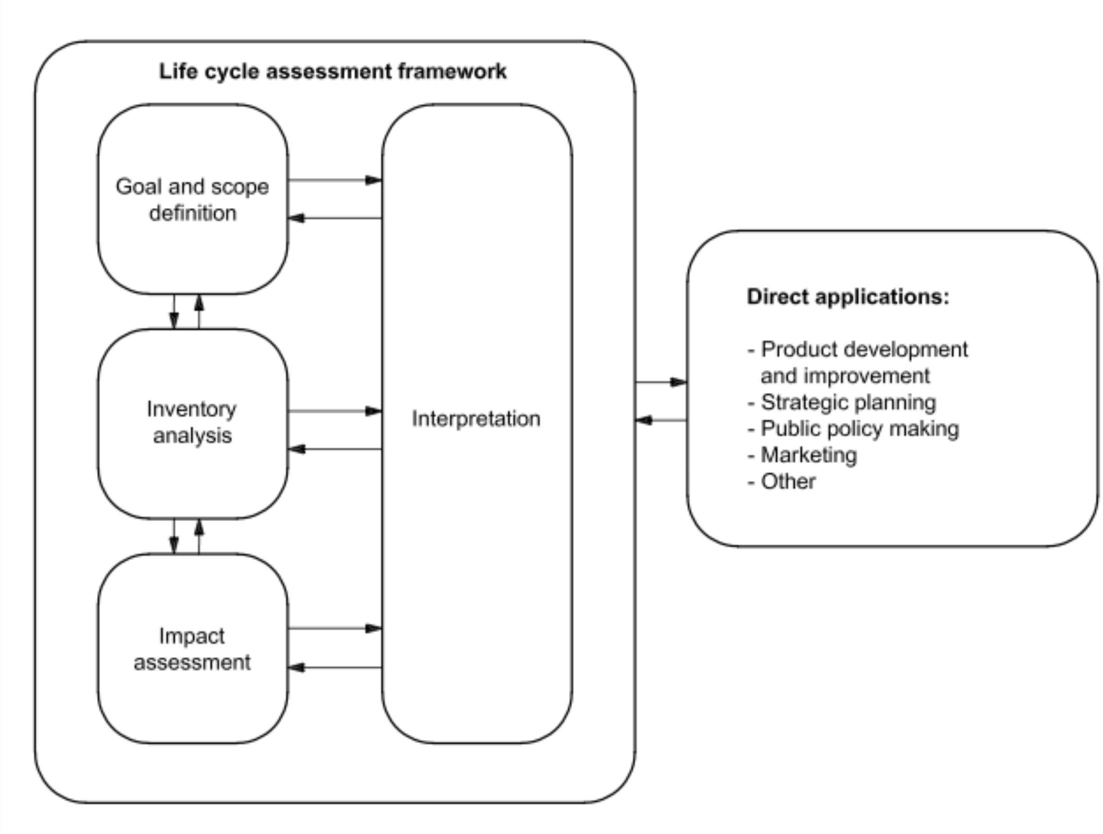

Figure 1: Life Cycle Assessment Framework (ISO 2006a)

The comprehensive requirements are mainly guidelines for how to conduct and document an LCA. In this regard, the analyst has a great deal of freedom to make individual decisions that can have a substantial effect on the final result, as long as the decisions are documented and discussed. The purpose is to facilitate comparison of LCA results with similar goal/scope, by evaluating the assumptions that causes differences in the outcome. A concrete example can be seen in our analysis when the different battery LCAs are compared and where the various results are analysed and traced back to different assumptions or inputs (ISO 2006b).

The ISO standards of LCA states that the approach to what should be included may differ, as certain life stages can constitute varying degree of impact. For instance, it is not always necessary to include the construction of a fossil fuel plant, as this stage is often seen to be negligible, while for a renewable energy plant this will contribute a significant proportion of the total CO_2 life cycle emissions (ISO 2006a).

The uptake of CO_2 by plants is proposed to be noted as a “negative emission”, and may be useful in the case of assessing long lived products (eg. from wood) which sequester CO_2 from the atmosphere for a long time (Guinée 2002). Another perspective that is relevant for our application would be the recycling dilemma; certain materials from vehicle recycling can lead to a reduced environmental effect on the succeeding item. This would suggest that recycling of certain parts of the product, such as aluminium, could be regarded as a “negative emission” factor, as recycling scrap aluminium only requires 5 % of the energy used to make new aluminium (Hydro 2013). Some reports use “negative emissions” as they base their calculations on expected future recycling technologies, which include a significant level of recyclability. In the data we use from Hawkins et al. (2012), potential “negative emission” effects are not considered. If one does not take the “negative emission” into account, the recycling process usually represents a small part of total CO_2 emissions.

2.2 Global Warming Potential (GWP)

Chemicals released into the atmosphere may contribute to the “greenhouse effect” of rising temperature and climate change by trapping the Earths heat. GWP refers to the warming relative to CO_2 and the impact scores are calculated using the mass of a gas released to air, modified by a GWP equivalency factor. The factor is an estimate of the atmospheric lifetime and radiative forcing that may contribute to global climate change, compared to the reference chemical, CO_2. (Usually 100-year timeframe) (EPA 2013).

Example of Species	GWP (100 years time horizon)
CO_2	1
Methane	21
Nitrous Oxide	310
HFC-23	11,700

Table 1: Global Warming Potential (UNFCCC 2013)

The equation to calculate the impact score for an individual chemical is as follows:

$$IS_{GW} = EF_{GWP} \cdot Amt_{GG}$$

Where:

IS_{GW} is the global warming impact score for the greenhouse gas (kg CO_2 – equivalents) per functional unit.

EF_{GWP} is the GWP equivalency factor for the greenhouse gas (CO_2 – equivalents, 100 – year time horizon)

Amt_{GG} is the inventory amount of the greenhouse gas released to air (kg) per functional unit.

2.3 Related research

In this study all inputs to our calculations are based on secondary data. Vehicle specific data applied in our research is derived from the work of Hawkins et al. (2012), while the remaining life stages are composed on an independent basis. Hawkins et al. conducted an environmental comparison of ICEVs versus EVs over the entire life cycle, and one of their objectives was to provide a transparent comparison overview to pave the way for further examination regarding the topic. The research is based on the assumption that the EV is powered by the European electricity mix, where they found the EV to reduce CO_2 emissions by 26 to 30 % relative to the gasoline ICEV and 17 to 21 % relative to the diesel ICEV, assuming lifetimes of 150,000 km. One of the most important highlights from the report is that producing an EV is almost twice as CO_2 pollutant as the ICEV, making the final result particularly sensitive to assumptions regarding electricity source, use-phase energy consumption, vehicle lifetime, and battery replacement schedules. The battery emissions associated with the production of the EV accounts for 43 to 48 % of total production emissions, depending on the battery applied.

Notter et al. (2010) performed a similar study as Hawkins et al., with a detailed life cycle inventory of the battery, though only a rough LCA of the EV. EPA (2013) has also conducted a comprehensive research on batteries in EVs during their entire life cycle, including the battery impact in the use stage. Parts of their research are based on secondary data from esteemed studies such as Notter et al. (2010), Majeau-Bettez et al. (2011) and Hawkins et al. (2012). However, the study does not include emissions from production of the vehicles.

Daimler AG (2012) presents a comparison of CO_2 emissions from an electric- and conventional version of the same vehicle, and the comparison reveals that the EV emitted over twice as much CO_2 as the ICEV in the production phase. With a driving distance of 120,000 km the study presents that the two vehicles emitted approximately the same amount of CO_2 based on power from the European electricity mix. Nevertheless, when the EV is powered with renewably electricity it releases almost 60 % less CO_2 over the entire life cycle, highlighting the importance of the electricity source.

Another complete LCA regarding EVs were presented by Volkswagen (2012), the results presented in the study are duplex; one concern the current state of the EV while the second reflects expected improvements for the future. The lifetime mileage applied in the study was assumed to be 150,000 km. They estimated battery production to emit 33 grams of CO_2 per km, while the base vehicle and electric components emit 41 grams of CO_2 per km during production. This adds to a total of 74 grams of CO_2 per km from the production-phase. With their green factory concept they are aiming to reduce these production emissions to a total of 55 grams of CO_2 per km. When it comes to vehicle recycling, Volkswagen assumes energy requirements equivalent to 1 gram of CO_2 per km, in addition they account for a recycling credit of 10 grams of CO_2 per km. Current estimates for the use-phase are based on the European electricity mix, resulting in 88 grams of CO_2 per km, with a goal for the future of 1 gram of CO_2 per km, which is based on their assumptions of electricity powered entirely from renewable sources (wind power).

The current metric for comparing the environmental status of European vehicles is based on observing tailpipe CO_2 emissions using the New European Driving Cycle (NEDC). Ricardo (2011) highlights that this is an insufficient approach, as it ignores CO_2 emissions resulting from production of the fuel/electricity and emissions attached to vehicle production. Emissions associated with vehicle production and disposal is becoming a greater part of the vehicles life cycle, due to increased access to zero emissions vehicles and more efficient ICEVs. Among others, Ricardo's results show that a mid-size EV emitted 8.8 tonnes of CO_2 in production (46 % of total life cycle emissions), while a mid-size gasoline vehicle emitted 5.6 tonnes of CO_2 (23 % of total life cycle emissions).

Wilson (2013) compares total life cycle CO_2 emissions of EVs in twenty of the worlds leading countries. The report points out that EVs are not a standalone initiative to reduce CO_2 emissions, as the electricity sources applied across countries need to be included in the assessment. The result range from 70 to 370 grams of CO_2 per km for Paraguay and India respectively, based on a vehicle lifetime of 150,000 km. A general finding is that EVs in coal-dominated countries emits four times greater than in countries with low carbon power, and that EVs provide no or minor reductions in overall emissions compared to the ICEV in these countries. One of the concerns with the report is the assumption of different vehicle lifetimes, 150,000 km for the EV and 200,000 km for the ICEV. The reasons for operating with a shorter lifetime for the EV is due to assumptions regarding the battery lifetime, which is a debated topic where simply time, will provide the answers. Many emphasize that in order to provide a correct comparison, it is essential to assume equal expected lifetime. Other concerns include that the research by Wilson (2013) is an independent study conducted by one researcher running a private research group. The study is by our knowledge not peer-reviewed, and deficient in terms of transparency. If we compare the results of the study with those of Hawkins et al. (2012) we can see that due to the assumptions made by Wilson of higher use-phase energy requirements and the emissions from electricity generation, the results end up well above those of Hawkins. Hawkins et al. achieves approximately 300 grams of CO_2 emission per km when utilizing only lignite (brown coal) as the source for electricity, which is one of the most polluting sources of energy, while Wilson gets emissions of 370 grams of CO_2 per km when powered with electricity in India. Due to the lack of transparency, we find it difficult to gain adequate insight as to why they achieve such high estimates in the case of India.

PE International (2013) performed an estimation of how total life cycle CO_2 emissions will change in the future for different vehicle technologies. The report is the outcome of the study commissioned by Ricardo (2011). Different scenarios for the years of 2020 and 2030 are categorized as either a “Typical case” or a “Best case”. The “Typical case” represents the lower limits of predictions, while the “Best case” represents the upper limits of potential future improvements.

- For the ICEV, the “Typical case” for 2020 and 2030 involves a prediction of reducing total lifetime CO_2 emissions by 7 and 18 % respectively. The “Best case” for 2020 and 2030 involves a predicted reduction of 10 and 70 %.
- For the EV, the “Typical case” for 2020 and 2030 involves a predicted reduction of 12 and 36 %, respectively. The “Best case” for 2020 and 2030 involves a predicted reduction of 24 and 55 %.
- For all scenarios the EV offers lower total lifetime CO_2 emissions than the ICEV, with exception of the “Best case” scenario in 2030.
- The future savings is mainly a result of expected CO_2 savings in the grid mixes, more efficient fuel/electricity consumption from vehicles, increased share of bioethanol, and improved automobile and battery technology.

Previous studies shows that life cycle emissions of EVs are especially sensitive to assumptions regarding electricity source. This is something we want to investigate further by evaluating the selected countries way of generating electricity. By doing so we can get an overview of the countries that have an environmental profile adapted to EVs, and where it may be counterproductive to promote the EV given current conditions.

The primary reason for the differences in CO_2 emissions in the production phase of the vehicles can be contributed to the battery production for the EV. In order to gain insight about this effect it is important to get a more comprehensive understanding regarding battery technologies.

2.4 Lithium-ion Battery System

In 1991, the Sony Corporation commercialized the first lithium-ion battery. Today lithium-ion is the fastest growing and most promising battery chemistry, and holds the position as the primary choice for most EV producers. We will not explicitly explain the chemistry or physics of the battery system; nevertheless, we try to provide an image of the range of differences that exist within the battery species containing lithium-ion.

The battery core of a lithium-ion battery cell is composed of a cathode, an anode and electrolyte as conductor. The cathode is a metal oxide and the anode consists of porous carbon. The casual battery user might think there is only one lithium-ion battery. In fact there are many species and the difference lies mainly in the cathode materials, however innovative materials are also appearing in the anode. Manufacturers are constantly improving the lithium-ion technology, with new and enhanced chemical combinations being introduced regularly.

Both the manufacturing process and the difference in raw materials used in batteries play a part in the CO_2 account of the entire battery. In retrospect, one has to look at the specific chemistry, produced in a specific way, in order to calculate the impact of any given EV battery. A list of the most popular lithium-ion batteries and their typical applications can be found in appendix 3.

Another important aspect when comparing different batteries is the uncertainty related to aging. First of all, many of the battery technologies are relatively young or have evolved a lot in recent years, and how these batteries age is yet to be determined. Second, the different chemical compositions of the batteries have different impact on the battery attributes when it comes to such issues as life span, cost, specific energy, specific power, performance and safety (See appendix 4). The content described regarding batteries are obtained from Buchman (2013), an educational website on batteries sponsored by Cadex Electronics Inc.

The complete battery pack for an EV consists of many different elements such as multiple separate battery cells, thermal unit control, wiring, and an electronic card as a part of a battery management system (EPA 2013).

3. Data Review

In our research, we have collected secondary data related to the different stages of a vehicles life cycle. These data are combined into a transparent and complete analysis.

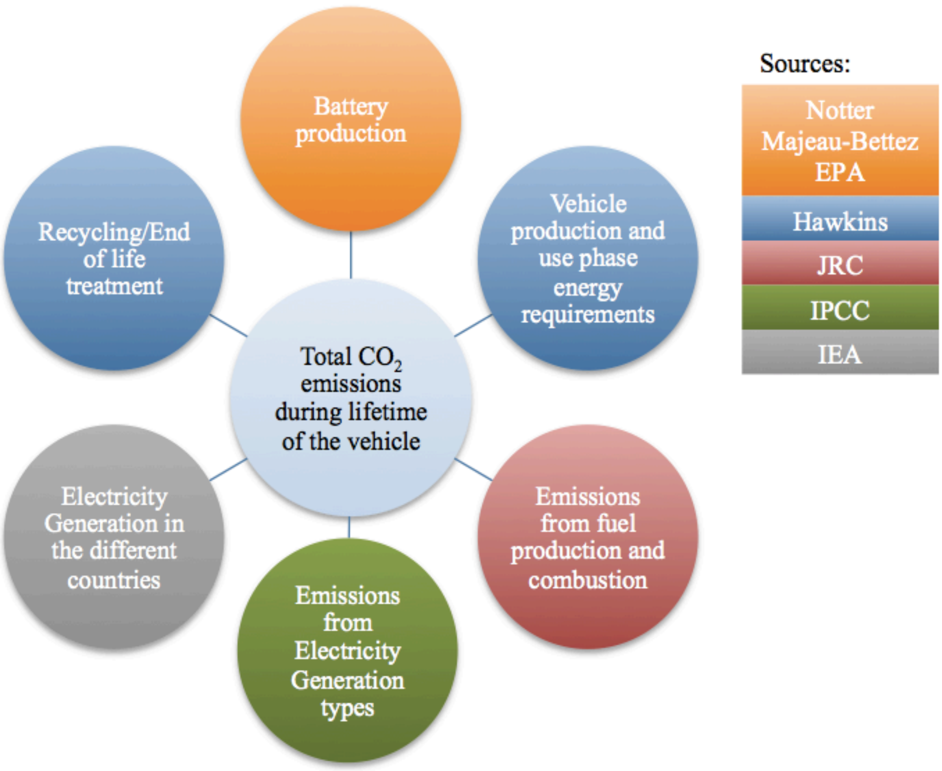

Figure 2: Overview of sources used in the various parts of the life cycle

The figure above is a map providing a brief illustration of which sources that has been used in the different parts of the vehicles life cycle. A detailed description of the data collected follows below.

3.1 Production and End-of-life

The total CO_2 emissions associated with the production process and end-of-life treatment of the different vehicles are obtained from the study "Comparative Environmental Life-Cycle Assessment of Conventional and Electric Vehicles" by Hawkins et al. (2012). The EV model is based on the Nissan Leaf and the ICEV model is adopted to match the Mercedes A-Class. These vehicles are comparable with respect to performance characteristics, masses and size.

In the production phase they included 16 different vehicle components, which in turn consisted of 140 subcomponents. The study assumed that the various vehicles had a common generic glider (vehicle without powertrain). Furthermore, they customized each vehicles powertrain with regards to their fuel specifications. In order to model the common glider and the ICEVs powertrain they used the GREET 2.7 vehicle cycle model as a starting point and thereby adjusted it to the characteristics of the Mercedes A-Class. The GREET 2.7 vehicle cycle model takes into account the emission effects linked to vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal/recycling (Burnham et al. 2006). The engine composition used in the report is based on the Volkswagen Golf A4, while the powertrain of the EV is modelled after the configurations of the Nissan Leaf.

The entire end-of-life treatment assumes to be set in motion after a vehicle lifetime of 150,000 km. The end-of-life vehicle treatment is based on Ecoinvent v2.2, a database containing approximately 4,000 datasets concerning products, services and processes commonly used in LCAs (Ecoinvent 2010). The battery treatment consists of dismantling and a cryogenic shattering process. Material recovery and disposal processes are also included in the end-of-life treatment. For further details on the specifications of the various vehicles see appendix 5.

3.2 Batteries

As mentioned, we have used data associated with the production phase from Hawkins et al. (2012). In the production phase, they take into account that the EV can be constructed with two different battery types, thus resulting in two final results for the EV. The two battery types the report has included are lithium iron phosphate ($LiFePO_4$) and lithium nickel cobalt manganese (LiNCM). The battery data is collected from Majeau-Bettez et al. (2011), which is a transparent inventory assessment related to the production of LiNCM and $LiFePO_4$ batteries, designed to be adapted into LCA studies of EVs. Our base case calculation follows the same battery assumptions as used in Hawkins et al. (2012). Assumptions regarding batteries made by the researchers may have a large impact on the final result. As a way to test the sensitivity of our final life cycle results with regards to battery assumptions, we have thus chosen to replace the original batteries applied in our base case with batteries presented in two additional LCAs. Effectively providing a sensitivity analysis containing six different estimates of total life cycle emissions of the EV, in each of the selected countries[3]. This will in turn provide a more nuanced picture, as well as underline the difficulties of comparing LCAs and the uncertainty regarding battery production. The two studies we have chosen to include battery data from is Notter et al. (2010) and EPA (2013), as these studies have similar objectives as Majeau-Bettez et al. (2011).

The study of EPA (2013) examined three different battery types, both $LiFePO_4$ and LiNCM, as well as lithium manganese oxide ($LiMnO_2$). In terms of Notter et al. (2011), the study investigated one battery type, namely lithium manganese oxide ($LiMn_2O_4$). Although $LiMnO_2$ and $LiMn_2O_4$ are referred to with the same title, there are certain differences in composition and content that sets them apart. EPA (2013) operates with emissions per kWh battery capacity as a functional unit, while Notter et al. (2010) uses emissions per kg battery produced.

Comparing the results of Notter et al. with Majeau-Bettez et al., the results of the latter is significantly higher, even though the battery chemistries in question differ, mainly due to estimates of manufacturing energy requirements. Majeau-Bettez et al. stated that the estimates of electricity and heat requirements for battery and subcomponent manufacturing used by Notter et al. are about 40 times smaller than the estimates by Rydh and Sanden (2005), which the former based their estimates upon.

Regarding the EPA (2013) study, their research shows that energy use differed among battery manufacturing methods, and whether or not they used solvent for electrode production. The solvent-less method appeared to use much less energy compared to estimates provided in prior studies of cell and pack manufacture (e.g., Majeau-Bettez et al. 2011). This was also supported by Zackrisson et al. (2010), who concluded that it is environmentally preferable to use water as a solvent. This translated into low manufacturing-stage impacts in categories driven by energy consumption, such as GWP. Compared with Majeau-Bettez et al., GWP results from EPA are lower, where the difference is attributed primarily to the difference in the energy needed during upstream production of the anode and cathode materials, as well as the lithium salts. The calculations for the $LiMnO_2$ battery is based on a solvent-less manufacturing process which is very mechanistically different from

[3] One estimate for each of the different battery types implemented in the EV.

the solvent-based process, and less energy intensive. The absolute impact values are significantly higher for the LiNCM and $LiFePO_4$ batteries, due to higher energy use in the production of the cathode, electrolyte and battery pack. The use of a solvent-less process by the manufacturer contributes to the fact that $LiMnO_2$ battery chemistry uses less energy and has a smaller global warming impact.

Utilizing different types of batteries have certain complications, such as the uncertainty with respect to the actual lifetime of the batteries. Though the assumed lifetime in general for lithium-ion batteries are 10 years, there may also be differences in lifetime across chemistries. According to Majeau-Bettez et al. and EPA, $LiFePO_4$ batteries may have a longer useful lifetime due to its ability to weather a greater number of charge-discharge cycles[4]. When comparing the results from the studies of Majeau-Bettez et al. and Hawkins et al. we can see that the $LiFePO_4$ battery is found to have the lowest GWP in the former, while when implemented in the EV with equal lifetime in the latter, the LiNCM end up with the lowest impact. This is a direct consequence of Hawkins et al. disregarding the expected difference in charge-discharge cycles for the different batteries.

The battery data for each of the various batteries were adapted to match the characteristics of the Nissan Leaf[5], and the calculated total CO_2 emissions from the production of each battery were thus added to total emissions from the remaining life stages.

3.3 Use-phase Energy Requirements

The vehicles specific use-phase energy requirements are based on estimates provided in Hawkins et al. (2012). The requirements were developed using the industry performance test with the NEDC, following the UNECE 101 regulation (2005). The test is designed to assess the fuel economy of light-duty vehicles, and involves combining four elementary urban driving cycles and one extra-urban driving cycle. For the EV it also includes regenerative charging and energy losses during overnight charging. The use-phase energy requirements were thus calculated to be 0.173 kWh per km for the EVs, 0.0535 litres per km for the diesel ICEV, and 0.0685 litres per km for the gasoline ICEV.

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[4] Expected charge-discharge cycles of 6000 compared to 3000 for LiNCM. (Majeau-Bettez et al. 2011)

[5] The calculation and implementation process is further explained in section 4.1.

Besides the use-phase energy requirements we have also obtained CO_2 emissions associated with maintenance and parts replacements that occur during the vehicles lifetime, such as tire wear etc. These emissions are given on a per km basis; for the ICEVs the estimate is 8.9 grams of CO_2 per km and for the EVs the estimate is 7.2 grams of CO_2 per km. The estimates are based upon available reports and the writers' own assumptions.

3.4 Gasoline and Diesel

In order to calculate CO_2 emissions associated with consumption of gasoline and diesel we have based our calculations on data from a well-to-wheel (WTW) analysis made be the Joint Research Centre of the European Commission. In the well-to-tank (WTT) approach, the study (JRC 2013a) has included the following steps: production and conditioning at source, transformation to market, transformation near market, as well as conditioning and distribution.

- Production and conditioning at source involves all actions required to extract, capture and cultivate the primary energy source.
- Transportation to market takes into account emissions associated with transporting the primary energy source to processing.
- Transformation near the market includes the processing and transformation process in order to produce the final fuel.
- Conditioning and distribution involves all final steps to distribute the finished fuel to the various refuelling stations.

The research is conducted in order to find the average European WTT emissions for different fuels. The actual WTT emission of a specific litre of fuel might have a higher or lower CO_2 emission, depending on factors such as the source of extraction (oil sand, deep sea, conventional etc.), refinery specifications and the distance to market, as described further below. We have chosen to use this average in all of our scenarios, due to the complexity of finding specific information regarding the origin of the fuel for each country. Including LCAs from each specific area could also result in a higher uncertainty due to a possible lack of consistency amongst the researchers.

In the tank-to-wheels (TTW) approach, the study (JRC 2013b) measures the amount of CO_2 emissions released when the fuel is combusted. The figures are expressed in grams of CO_2 per mega joule (MJ) of the final fuel. In order to convert the amount to grams of CO_2 per litre we have used conversion factors given in a "units and conversions fact sheet" made by MIT (2007).

It is estimated that nearly 17 % of the worlds potential resources of recoverable shale oil are concentrated in the United States (EIA 2013a), and the extraction of shale oil in the United States has increased from 111,000 barrels per day in 2004 to 553,000 in 2011, this accounts for more than 0.5 % of worldwide oil production (PWC 2013). Production from Canadian oil sands reached more than 1,700,000 barrels per day in 2011, equivalent to about 2 % of worldwide oil production (AE 2013).

As the surging global demand for oil continues, the share of unconventional oil sources such as oil sands in Canada, heavy oil in Venezuela and shale oil from the United States is increasing. With a higher energy input per unit of oil extracted, these sources emit more CO_2 during the upstream/production phase than most conventional oil sources.

In our research, we have based all gasoline and diesel ICEV emissions from average European WTT estimates by JRC (2013a). Running a vehicle on fuel from different oil sources will have the same tailpipe emissions, while the upstream/production has a large span of emissions depending mainly on the source of extraction. A meta-analysis conducted by CERA (2010) shows that deviations in WTT estimates range from 47 % below U.S. average to 70 % above, depending on source of extraction. The report finds that West Texas Intermediate crude is the cleanest source, while certain heavy oil and oil sands are categorized as the dirtiest. Due to the large deviations in WTT estimates, the report concludes that WTW emissions range from 10 % below to 15 % above the average.

Brandt (2011) stated in a meta-analysis that there are large ranges in emissions from current conventional oil streams into the EU, with low and high ranges (Norway and Nigeria) and low and high ranges of the different oil sand projects and processes. To get comparability, Brandt has used EU-specific values from certain process stages such as refining and processing, and transport and distribution derived from JRC (2013), the same report as we based our estimates upon. Comparing Brandt's research to the estimates used in our study, the WTT impacts of the best to worst cases range from 28 % below to 259 % above. In a

WTW perspective this can affect the gasoline emissions from a decrease of 4 % (Norway) to an increase of 41 % (worst oil sand project). The most likely case of oil sand extraction constitutes a 23 % increase in WTW emissions for gasoline.

Brandt et al. has also conducted two studies regarding GHG emissions of oil shales, findings from these studies shows that life cycle CO_2 emissions from oil shale liquid fuels are likely to be 21 to 47 % (Brandt 2008) and 25 to 75 % (Brandt et al. 2010) higher than those from conventional oil, depending on the details of the process used.

3.5 Electricity Generation Technology

In the model we have used CO_2 emissions per unit of electricity (kWh) generated by a specific energy source, the data were collected from a special report on renewable energy sources and climate change mitigation conducted by IPCC (2011). The data is the result of a comprehensive review of published LCAs of electricity generation technologies. In order to find potentially relevant literature on the subject a numerous of mechanisms where put to place, such as; searching through major databases by using search algorithms and combinations of key words, looking for relevant literature at specific reference lists, and searching through certain websites and familiar LCA literature databases. As a result of the aforementioned process, 2,165 references where collected and the literature was subsequently categorized by content and submitted to a database.

The next step in the comprehensive review was to perform a literature screening made by several experts in order to select data that approved certain standards of quality and relevance. The literature screening consisted of a three-folded process. The first screen took into account that the references contained peer-reviewed journal articles, scientifically detailed conference proceedings, PhD theses, and special reports published after 1980 in English. Another criteria in the first screen were that references had to include two or more life cycle phases.

After passing the first screen the references were evaluated based on more straighten quality and relevance standards. This included employing an acceptable accounting method regarding LCA and GHG. This was followed by reviewing reported inputs, scenario/technology features, assumptions and results in order to evaluate their reliability, and to make sure the technology was of modern or future relevance. The last screen involved testing for transcription, such as reviewing whether the emissions estimates were duplicated, as well as being presented numerically and easily convertible to grams of CO_2 per kWh. Of the 2,165 references initially included, only 296 references passed all three screenings.

In order to analyse the results, the estimates were categorized with regards to technology within the energy sources considered in the report. Secondly the estimates were converted to grams of CO_2 per kWh, and the estimates were excluded if the conversion required exogenous assumptions. At last, emissions that included contribution from either heat production or land use change were also excluded. In our analysis we use the median of all estimates as a basis for calculations, the report also includes: minimum-, 25th percentile-, 75th percentile and maximum values.

Technology	**Coal**	**Oil**	**Natural Gas**	**Solar PV**	**Geothermal**	**Solar Thermal**	**Biopower**	**Nuclear**	**Wind**	**Ocean**	**Hydro**	**Other Sources**
g CO_2 per kWh	***1001***	***840***	***469***	***46***	***45***	***22***	***18***	***16***	***12***	***8***	***4***	***226***

Table 2: Emissions from electricity generation by source, median of estimates (IPCC 2011)

As we can see from Table 2, coal is the most carbonintensive energy source, 250 times more pollutant than hydropower. There is also a very clear distinction between CO_2 emissions from fossil fuels to renewable energy sources.

When using this data material, we do not consider the specific CO_2 emissions for a single plant in a specific country. The data reflects the median life cycle emission for each electricity generation technology. Deviations could stem from issues such as types of coal used for generation, longer or shorter distances of raw material freight, efficiency of the given plant, construction method and materials, age of the facility etc. These factors could be significant in the different geographic areas in our scenarios, however, detailed LCA data for each country are not available, and might not be suitable for comparison.

When looking at the coal power generation, being the largest contributor of CO_2 emissions, we consider the IPCC median estimate as applicable to all countries in our selection. As previously stated, this approach is uncertain. Many aspects will have an impact on the life cycle emissions; and some of these aspects will be further discussed below.

One could make assumptions that more research has been conducted in developed countries, and that this could be a potential bias regarding emissions in for instance India and China. A research paper on coal production in China written by Song et al. (2012) suggest that the average life cycle CO_2 emissions from coal-fired electricity generation amounts to 1020 grams per kWh, which is in line with our assumptions. One can also assume that recent developed coal plants tend to be more efficient, which translates directly into lower CO_2 emissions per kWh generated (Rai et al. 2013). This argument might favour countries such as India and especially China; according to IEA Statistics (2013a) both attained a tremendous growth in total electricity generation over the last two decades (See Figure 3). This may indicate that there is a greater share of newer coal plants in these countries compared to for instance the US.

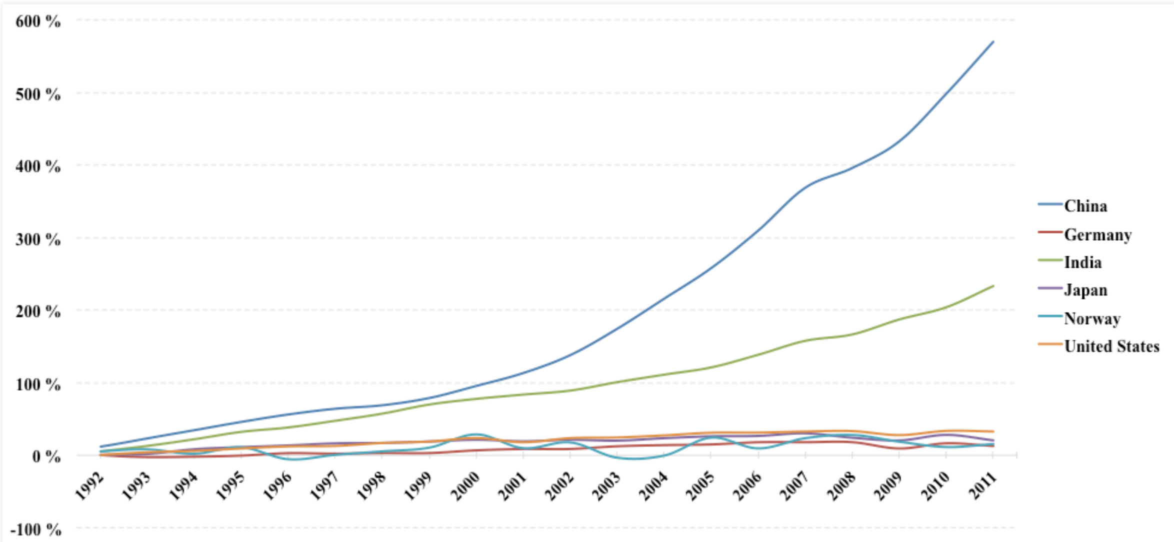

Figure 3: Growth in Electricity Production in absolute terms since 1991

In the total life cycle of a coal-fired power plant, the power plant operation is the major emitter with 96 %, while transportation, mining and constructions accounts for 2, 1, and 1 %, respectively (Spath et al. 1999) (See Figure 4)[6]. In addition, a study on Chinese power plants by Liang et al. (2013) estimates that 90 % of emissions comes from power plant operation, 8.3 % from mining, while transport constitute a mere 1.7 %. Taking this into account, different transport distances across countries will not pose any significant impact on the final CO_2 estimates.

[6] This study is based on an average plant from 1995 in the United States

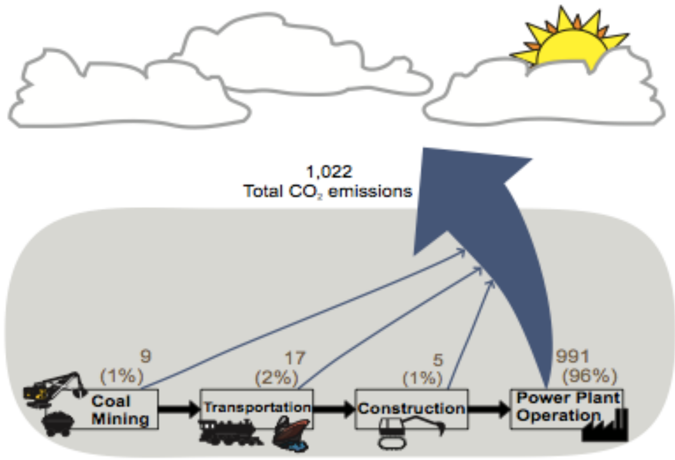

Figure 4: US coal-fired power plant, emissions in grams of CO_2 per kWh (Spath et al. 1999)

In the power plant operation, CO_2 emission output is mainly explained by CO_2 emission per Btu of the coal type used, and the efficiency of the plant. Different types of coal have different emission factors per kWh. In most cases lower gross calorific value (GCV) results in higher CO_2 emissions. In India, the domestic coal is typically sub-bituminous with a GCV of 4,200 kcal/kg, while imported coal is typically bituminous with GCV of approximately 6,665 kcal/kg. It is estimated that India imports one third of total coal used in power plants (Rai et al. 2013). India's Central Electricity Authority (2013) reports a coal power generation of 60.8 % and additional coal power generation from lignite of 2.9 %, with average direct emissions of 1050 and 1420 grams of CO_2 per kWh, which adds to an average of 1067 grams of CO_2 per kWh, before accounting for additional life cycle emissions and grid loss. This suggests that India might have higher emissions from coal than expressed by our estimates. When comparing our calculations regarding CO_2 per kWh in each country with the estimates conducted by IEA (2012a), we find that our estimates is in line with what could be expected, with the exception of Japan. Our calculations for India is well-below what is presented by IEA, while the calculations for the remaining countries are above, which is naturally to assume as our calculations contains several life cycle stages. In terms of Japan we find that our calculations is well above, indicating that Japan may have a cleaner electricity generation than applied in our metrics.

3.6 Electricity Generation

In order to calculate grams of CO_2 emissions per kWh generated by each of the selected countries electricity grid, we have based our calculations on observed gross electricity production by energy source, found at IEA Statistics online (2013b). The data we have included is from 2011, as it is the latest data available. Data specifications are explained in IEAs report on Electricity Information 2013. Gross electricity production is measured as the total energy produced at the different plants in each country. Which includes the plants own use of energy, energy sent out to the electricity grid, energy to keep the back-up systems maintained, and any losses in transformation at the plants. The unit of electricity is given in gigawatt-hours (GWh).

Technology	Coal	Oil	Natural Gas	Biopower	Nuclear	Wind	Hydropower
China	79 %	0 %	2 %	1 %	2 %	1 %	15 %
Germany	45 %	1 %	14 %	5 %	18 %	8 %	4 %
India	68 %	1 %	10 %	3 %	3 %	2 %	12 %
Japan	27 %	15 %	36 %	3 %	10 %	0 %	9 %
Norway	0 %	0 %	3 %	0 %	0 %	1 %	95 %
United States	43 %	1 %	24 %	1 %	19 %	3 %	8 %

Table 3: Major sources of electricity generation, largest share for each country is highlighted in blue. (IEA 2013)

Table 3 displays the seven dominant energy sources of the selected countries. Coal is the major source of electricity generation for four out of the six selected countries, where China is the country with the highest share of coal generation. There is also a clear distinction between Norway and the other countries when it comes to utilization of renewable energy sources, where as much as 95 % of all electricity is generated from Hydropower plants.

We have chosen to look at total production figures, disregarding the actual consumption. A country might consume more electricity than they produce, or vice versa. To locate the origination of the actual electricity consumed is, due to the nature of electricity, not feasible. For instance if India produces 20 % less than they consume, and you could in fact trace the 20 % back to imports of renewable energy, this could have a certain impact on our results. In our sense the focus should be on what the specific countries could do with their own electricity generation, in order to create a cleaner grid.

When calculating the energy use of the EVs we also take into consideration the specific grid loss in the selected countries. The grid loss includes losses in transmission between sources of supply and points of distribution and in the distribution to consumers, including pilferage. The size of the grid loss depends on the physical characteristics of the system, and how it is operated. Losses can vary from year to year; consequently we have chosen to use an average over the last five years of data (2006-2010) to correct any possible spikes. The grid loss data is collected from IEA Statistics (2011), and is given as a percentage of the total number of GWh generated by the total electricity plants in each country.

Grid Loss	
China	6.2 %
Germany	4.4 %
India	22.6 %
Japan	4.6 %
Norway	7.1 %
United States	6.1 %

Table 4: Share of grid losses (IEA Statistics 2011)

As Table 4 shows, India is the country with the highest grid loss, as much as 22.6 % of the electricity generated is lost before it is consumed. This implies that in India one must actually produce 1.3 kWh in order to distribute 1 kWh to the consumer.

4. Methods

This section describes the steps taken to conduct the LCA model for this study, and points out the assumptions made during the process. As mentioned earlier, the scope of this study includes vehicle production, use-phase, and end-of-life treatment combined with all applicable supply chains. The results of this thesis are presented as total life cycle emissions, namely as tonnes of CO_2. In line with assumptions made in the majority of related research as well as estimates from the vehicle industry, both vehicle and battery lifetimes are assumed to be 150,000 km. As a supplement, EPA (2013) reports that the expected lifetime of a battery is close to 10 years. Taking into account the driving behaviour in Norway, where the average annual mileage of light duty vehicles the first ten years of use is close to 15,000 km (SSB 2013), this supports our vehicle lifetime assumption.

4.1 Vehicle Production

The study of Hawkins et al. (2012) has divided the production-phase into four different life cycle components; base vehicle, engine, other powertrain, and battery. The results of the study are given in a per km basis, which we have scaled to total production results using the vehicle lifetime assumed by the authors. Regarding the battery sensitivity analysis, the functional unit of the battery data from Notter et al. (2010) and EPA (2013) were given as respectively CO_2 emissions per kg battery and per kWh battery capacity. In the study of Hawkins et al. the battery masses were 214 and 273 kg for respectively LiNCM and $LiFePO_4$, both with a battery capacity of 24 kWh. The functional unit results presented by EPA were multiplied with 24 kWh in order to implement the battery data in the LCA model. Due to the functional unit and battery type employed in Notter et al., certain challenges manifest themselves in the implementation of the battery data. The main challenge was to select an appropriate battery mass that can satisfy the vehicle use-phase energy requirement of 0.173 kWh per km. Notter et al. evaluated a battery with mass of 300 kg. Since the original Nissan Leaf battery is stated to weigh approximately 300 kg and is of similar chemistry[7], we have used 300 kg as a basis for calculation.

[7] Nissan Leaf utilizes a Lithium Manganese battery ($LiMn_2O_4$), for a list of battery chemistries used in different EVs, see appendix 6.

4.2 Emissions from Electricity Generation

For the selected countries, production figures published by IEA Statistics (2013b) were used to calculate the share of electricity generation by energy source. CO_2 emissions per kWh generated were calculated as illustrated in the formula below.

$$CO_2e_{gen} = \sum_{i=1}^{N} CO_2e_i \cdot X_i + X_{N+1} \cdot \frac{1}{N}\sum_{i=1}^{N} CO_2e_i$$

Where:

CO_2e_{gen} is the CO_2 emissions per kWh generated

CO_2e_i is the CO_2 emissions per kWh generated by energy source i

X_i is the share of total electricity generation from energy source i

X_{N+1} is the share of total electricity generation from other energy sources

For each country, the CO_2 emissions related to generating one unit (kWh) of electricity by energy source were multiplied by its corresponding share. The last expression in the above formula corresponds to the treatment of other energy sources, which consists of the two specified sections “other” and “waste” obtained in IEA Statistics (2013b). The share of electricity generation by other energy sources was thus multiplied with the average CO_2 emissions of the reported energy sources in IPCC (2011). The assumptions put to place regarding other energy sources will not pose any significant impact on the final estimate, as this share constitute a small part of total generation for all of the selected countries, at most 2.3 %.

At last, in order to calculate CO_2 emissions per kWh consumed from each country’s electricity mix we had to include the corresponding share of grid loss as follows.

$$CO_2e_{con} = \frac{CO_2e_{gen}}{1 - GL}$$

Where:

GL is the share of grid loss

CO_2e_{con} is the CO_2 emissions per kWh consumed

As the formula illustrates, an increased share of grid loss will contribute to higher levels of CO_2 emissions per kWh consumed.

4.3 Use-phase Emissions EV

After calculating the selected countries specific CO_2 emissions per kWh consumed, these projections were multiplied with the EVs corresponding use-phase energy requirement. Thus providing an estimate of the CO_2 emissions that occur when driving the EV in the different countries. As a final step, the emissions connected to maintenance of 7.2 grams of CO_2 per km were incorporated. The calculation process is illustrated in the formula below.

$$CO_2e_{km-EV} = CO_2e_{con} \cdot UPER_{EV} + CO_2e_{main-EV}$$

Where:

CO_2e_{km-EV} is the CO_2 emissions per km for the EV

$CO_2e_{main-EV}$ is the CO_2 emissions per km related to maintenance for the EV

$UPER_{EV}$ is the use-phase energy requirement applicable to the EV

The calculations resulted in the following CO_2 emissions per km, including maintenance emissions:

	China	**Germany**	**India**	**Japan**	**Norway**	**United States**
CO_2/kWh	854.9	556.9	956.2	588.9	22.1	593.3
CO_2/km	155.1	103.5	172.6	109.1	11.0	109.8

Table 5: Use-phase CO_2 emissions per kWh and km in the respective countries

4.4 Emissions from Fuel

In the WTT- and TTW report, the estimates were provided as grams of CO_2 per MJ for both gasoline and diesel. Thus we used the conversion factors of 32.1 and 35.8 MJ per litre for, respectively, gasoline and diesel as a way to convert the estimates to grams of CO_2 per litre.

$$CO_2e_{L-i} = \left[CO_2e_{MJ-i}^{TTW} + CO_2e_{MJ-i}^{WTT}\right] \cdot MJ/L_i \quad i = gasoline\ or\ diesel$$

Where:

CO_2e_{L-i} is the CO_2 emissions per litre of i

$CO_2e^{TTW}_{MJ-i}$ is the TTW CO_2 emissions per MJ of i

$CO_2e^{WTT}_{MJ-i}$ is the WTT CO_2 emissions per MJ of i

MJ/L_i is the amount of MJ per litre of i

Using the formulas illustrated above, we found that the estimated grams of CO_2-equivalents emitted per litre related to WTT are 551 and 443 for diesel and gasoline respectively. During combustion, diesel emits 2621 grams of CO_2 per litre, while gasoline emits 2356.

4.5 Use-phase Emissions ICEV

In order to calculate diesel and gasoline CO_2 emissions during the fuel combustion process, and the related upstream emissions in a per km basis, we need to take into account the specific use-phase energy requirements of the two vehicles. The estimates for the fuel requirement of the diesel engine is 0.0535 litre per km, while 0.0685 for the gasoline. To calculate total emissions per km, we have used the following formula.

$$CO_2e_{km-i} = CO_2e_{L-i} \cdot UPER_i + CO_2e_{main-ICEV}$$

Where:

CO_2e_{km-i} is the CO_2 emissions per km ICEV i

$CO_2e_{main-ICEV}$ is the CO_2 emissions per km related to maintenance for the ICEV

$UPER_i$ is the use-phase energy requirement applicable to the ICEV i

Taking into account the specific use-phase energy requirements, emissions were calculated to be 191.7 grams of CO_2 per km for the gasoline ICEV and 169.7 for the diesel ICEV. We can see that the emission from gasoline is higher, even though the upstream and combustion of a litre of gasoline emits less than diesel. This can be explained by the inferior fuel efficiency of the gasoline engine compared to the diesel. Finally, maintenance emissions occurring during the use-phase were also included as a per km impact, which is projected to be 8.9 grams of CO_2. When including maintenance, the results were calculated to be 200.6 and 178.6 grams of CO_2 emissions per km for, respectively, the gasoline- and diesel ICEV. As we can see, CO_2 emissions per km for both the gasoline and diesel ICEV are higher than the EVs CO_2 emissions per km within all of the selected countries.

4.6 End-of-life Emissions

As a final step in the LCA approach we included recycling emissions that occur when achieving the vehicle lifetime of 150,000 km. These emissions were originally provided on a per km basis, similar to the production figures, and the data were consequently scaled to total emissions figures using the vehicle lifetime assumption in the corresponding study. The emissions regarding the end-of-life treatment were added to the previous discussed emissions, thus providing the final LCA emission result for the various vehicles.

4.7 Sensitivity Analyses

The vehicle lifetime assumption allows for uncertainty as EVs are still in an early life stage and further knowledge concerning battery technology is needed. The average ICEV is also known to run further than 150,000 km. If one looks at the average scrapping age in Norway of 19 years and the total average driving distance per vehicle of approximately 12,900 km each year, one could argue that the total lifetime distance of the ICEV should be closer to 250,000 km. To account for some of the uncertainty regarding battery lifetime and driving distance expectations, a sensitivity analysis were performed by varying the vehicle lifetime from 100,000 to 250,000 km. In addition, we performed a break-even analysis, which were performed using solver in excel and follows the principles in the formula below.

$$CO_2e_{prod}^{ICEV} + CO_2e_{use}^{ICEV} \cdot X_{km} + CO_2e_{rec}^{ICEV} = CO_2e_{prod}^{EV} + CO_2e_{use}^{EV} \cdot X_{km} + CO_2e_{rec}^{EV}$$

Where:

X_{km} is the break-even distance

$CO_2e^i_{prod}$ is the CO_2 emissions occurring in the production-phase

$CO_2e^i_{rec}$ is the CO_2 emissions occurring in the recycling-phase

$CO_2e^i_{use}$ is the CO_2 emissions per km, including maintenance

The break-even distance states the total mileage to when the ICEV (gasoline or diesel) has emitted the same level of CO_2 as the EV ($LiFePO_4$ or LiNCM). At mileage beyond the break-even distance the EV emits lower total life cycle CO_2 emissions than the ICEV[8], the break-even analysis effectively provides a basis for comparison regardless of the assumed vehicle lifetime. We have also included a "Taxi case" with the assumption of an increased vehicle lifetime, to a total of 300,000 km, involving one battery change for the EV when using the LiNCM battery. The "Taxi case" accounts for the fact that a vehicle is usually not recycled after 150,000 km, and we expect that EVs will in turn change the battery pack rather than being dismantled prematurely.

[8] Applies only if EVs CO_2 emissions per km are at lower level than of ICEVs

5. Results

In our base case analysis, the vehicle lifetime assumption applicable for the various vehicles and the battery types are based on a 150,000 km estimate. The results for the EV illustrates a distinct difference between countries, ranging from total CO_2 emissions of 13.2 to 14.5 tonnes in Norway, while 37.5 to 38.7 in India, where the $LiFePO_4$ battery constitutes the highest level of emissions in each country. Compared to the emissions applicable to the ICEVs, we see that for both battery types, when utilized in India one will achieve slightly higher life cycle CO_2 emissions than the gasoline ICEV, while 11-14 % beyond the levels of the diesel ICEV. In China, CO_2 emissions from the EV are higher than the diesel ICEV, however lower than that of the gasoline. Driving the EV in the United States, Japan and Germany will in turn emit 21-27 % less CO_2 than the gasoline ICEV, and 14-20 % below the levels of the diesel. Norway, being the ideal country for implementing EVs shows a total reduction of 57-64 % depending on the different battery types and fuel of choice. A detailed illustration of the different life cycle stages are shown in Figure 5.

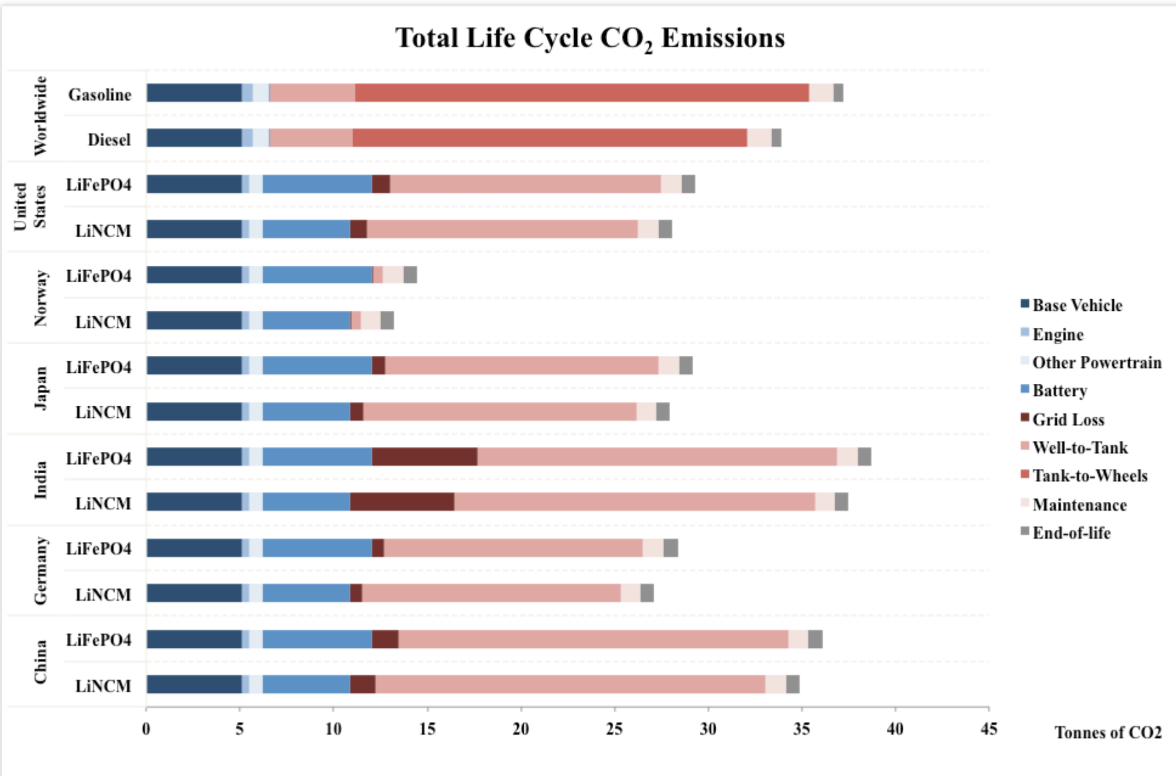

Figure 5: Life cycle emissions in tonnes of CO_2-equivalents, based on 150,000 km lifetime. Blue tones are production related, while the red tones relates to the use-phase.

In the production phase, the EVs emitted 64-83 % more CO_2 than the ICEVs. Where the battery constitutes most of the large difference in emissions, accounting for 43-48 % of the EVs total emissions from manufacturing. Comparing production and use-phase CO_2 emissions, we see that ICEV emissions from production make up 18-19 % of the total, while EVs range from 29 to 83 % for India and Norway respectively. Current metrics for environmental comparison of vehicles commonly focus simply on tailpipe emissions. However, our results express the importance of examining use-phase processes beyond tailpipe emissions, as this also constitutes a significant part for the ICEVs, 16 and 17 % of total CO_2 emissions for the gasoline and diesel ICEV. As use-phase energy requirements constantly becomes more efficient, total life cycle emissions is to an increasingly extent affected by the production phase, fuel/electricity production and end-of-life treatment. These emissions obviously constitute 100 % of EVs environmental impact, while for the gasoline and diesel ICEVs they account for 35 and 38 %. Regarding end-of-life treatment, our assessment displays that emissions attached to recycling amounted to merely 2-3 % for the majority of the metrics, thereby expressing the importance of reducing emissions in the remaining life stages as the most vital. However, certain studies emphasize environmental savings in the future as a result of improved recycling technologies. Possibilities of ”negative emissions” from reuse of materials in the future may increase the importance of end-of-life treatment.

When looking at India and China’s generation of electricity we can categorize them as coal-dominated countries, as respectively 68 and 79 % of total electricity is obtained using coal as energy source. Common for these countries is that deployment of EVs has limited or negative environmental benefit, well aligned with the results presented by Wilson (2013). As mentioned previously, the largest share of the expected vehicle fleet growth stems from non-OECD countries, where the average vehicle efficiency has a negative trend. Given current conditions, gradual deployment of EVs will according to our metrics be unable to prevent the aforementioned hazards. When comparing the results of India and China versus Norway, we clearly observe the importance of energy source used in electricity generation. The EVs total life cycle CO_2 emissions in India are 267 to 283 % higher than in Norway, expressing the range of emissions an EV could potentially emit.

CO_2 emissions related to the use-phase of EVs are the only life stage that provides any differences when comparing the EVs environmental impact across countries. As Figure 5 shows, driving an EV in Norwegian conditions constitute by far the greatest environmental savings relative to the gasoline and diesel ICEV. As 96 % of total electricity generation in Norway is derived from renewable energy sources, our results is aligned with the results of Daimler AG (2012), where the report states that EVs powered with renewable electricity offers CO_2 savings of almost 60 % over the entire life cycle relative to an comparable ICEV. With only 22.1 grams of CO_2 emitted per kWh consumed, Norwegian conditions express the importance of renewable energy sources in order to really benefit from deployment of EVs, thereby illustrating EVs environmental potential worldwide. An interesting note is that our results in the case of Germany is quite similar to the results of Hawkins et al. (2012), where they assume that the EV is powered by the European electricity mix. This indicates that Germany serves as an appropriate representative for the current electricity mix in Europe. When assessing the environmental impact of utilizing the EV in Germany, Japan and USA, we observe that the results to a great extent feature the same characteristics and emissions levels. Commonly, they all offer environmental savings relative to the ICEV, our results thereby supports that the majority of the current EV fleet satisfies its purpose as an environmentally friendlier alternative.

Although electricity generation in China is more polluting than in India, driving an EV in the latter performs worse in our environmental comparison, thereby expressing the sensitivity of total life cycle CO_2 emissions when taking into account grid losses. As CO_2 emissions caused directly from grid losses in India reached as high as 14 and 15 % of total emissions, an important step towards more EV friendly conditions also entails effective actions aimed at improving the grid infrastructure.

5.1 Break-even Analysis

We now disregard the 150,000 km assumption, and look at the number of km driven before the EV become beneficial in terms of total life cycle CO_2 emissions. Using the $LiFePO_4$ battery as a basis, results vary from merely 30,000 km in Norway, or 2 years based on average yearly driving distance of 15,000, to 950,000 km and 63 years in India when evaluated against the diesel ICEV. Germany, USA and Japan achieve a break-even distance well below 100,000 km, when compared to both the diesel and gasoline ICEV. Compared to the gasoline ICEV, the EV becomes CO_2 beneficial in India at about 200,000 km. The results of the break-even analysis for the EV with a LiNCM battery pack and the sensitivity analysis including vehicle lifetimes of 100,000 and 250,000 km can be found in appendix 7 and 8.

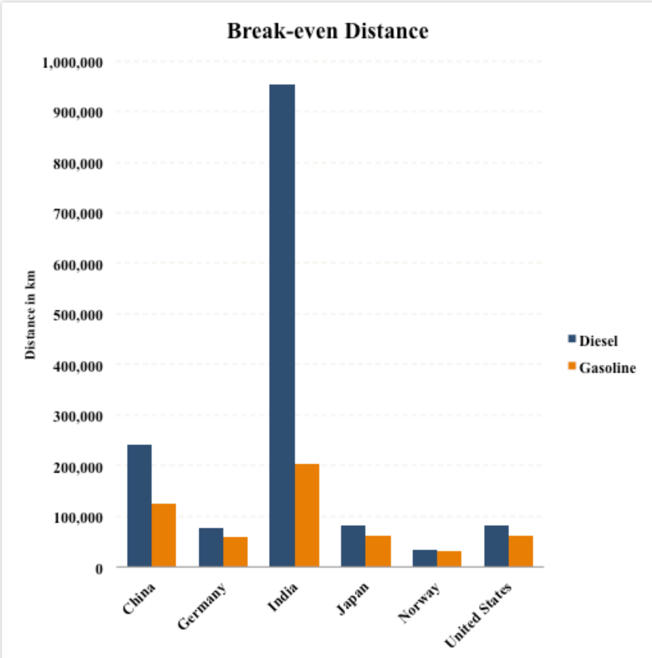

Figure 6: Break-even analysis in km, when using the LiFePO$_4$ battery, relative to gasoline and diesel ICEVs in the respective countries

Taking India as an example, the EV will provide savings of 6 grams of CO_2 per km relative to the diesel ICEV, while compared to the gasoline ICEV the savings amounts to 28 grams of CO_2. This will in turn require the EV to drive substantially longer when evaluated against the diesel ICEV in order to equalize the higher emissions from the production- and recycling-phase.

5.2 Battery Replacement

In parts of the analysis, we decided to include additional research and perform certain sensitivity analyses to further examine critical elements in our model when changing assumptions. As a way to test the total life cycle CO_2 emissions sensitivity towards battery data assumptions, the original batteries were thus replaced. All batteries were compared, and the figure below shows the various total life cycle emissions of the EV when applying different battery assumptions.

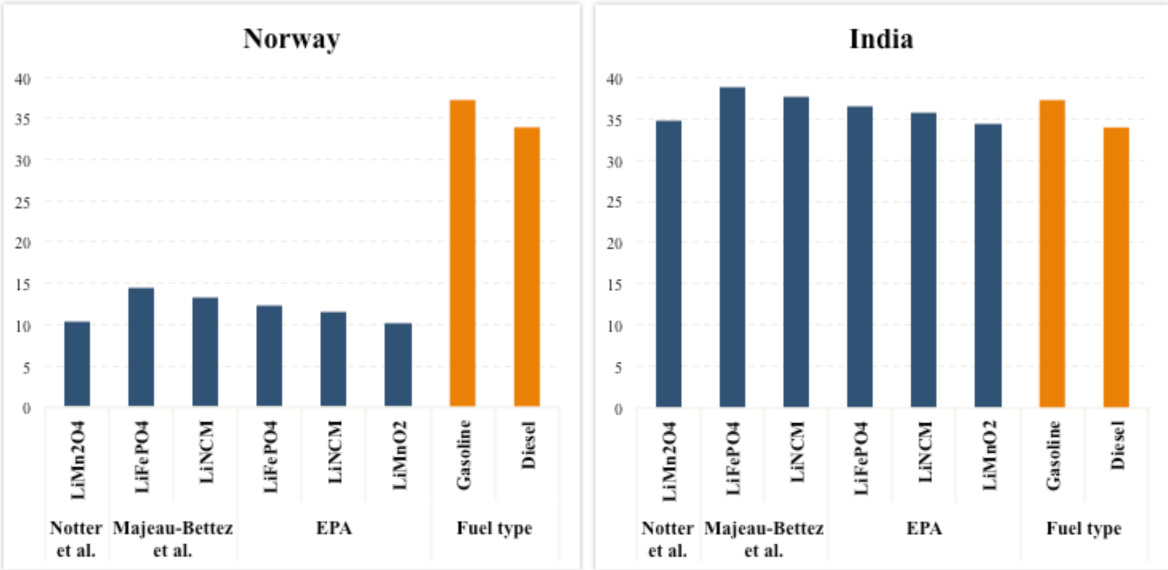

Figure 7: Total life cycle emissions in tonnes when using different battery assumptions

Figure 7 illustrates that using batteries with lower emission levels than that of Hawkins et al. (2012), EVs in India ends up being slightly less polluting than the gasoline ICEV, but still emitting more CO_2 than the diesel ICEV.

To extract total emissions during the production phase of the various batteries implemented in our analysis, we had to convert the estimates from Notter et al. (2010) and EPA (2013) to fit our battery capacity requirements. When calculating the emissions from the $LiMn_2O_4$ battery by Notter et al., which is of similar character as the batteries used in the Nissan Leaf, we get a total of 1.8 tonnes of CO_2, which is 61 % less than the LiNCM battery used in our base case. EPA conducted a study of the two same battery types used in our thesis, and the calculations show a total emission of 3.6 tonnes for the $LiFePO_4$ and 2.9 tonnes for the LiNCM, which both constitute a reduction of 38 % compared to our base case battery estimates. In addition, they examined a battery using water as solvent ($LiMnO_2$), which apparently emits significantly less CO_2 during production. This battery has a mere 1.5 tonnes of emissions, 74 % less than the $LiFePO_4$ battery estimate from our base case. In terms of total vehicle production emissions, estimates regarding batteries have a substantial effect. Using EPAs estimates instead of our base case estimates for the $LiFePO_4$ and LiNCM batteries, emissions are reduced by 18 and 16 % in the vehicle production phase. Replacing the $LiFePO_4$ battery from our base case with the $LiMnO_2$ battery constitutes a reduction of 36 %. In terms of total emissions during the full life cycle, the effect of battery emission estimates differs greatly depending on the countries electricity grid emission levels. If we look at the extremes in our thesis, namely Norway and India, we see that switching from the original $LiFePO_4$ estimate to EPAs estimate of the water solvent based $LiMnO_2$ battery, full life cycle emissions[9] are reduced by 30 and 11 %, respectively. This informs us that LCAs of EVs are very sensitive to assumptions regarding battery production, especially when utilizing an electricity grid based on renewable energy. It also indicates that reducing emissions from battery production should be a prominent focus area for producers of EVs if their overall goal is to reduce CO_2 emissions globally. A large part of the battery production emissions are due to the utilization of energy, often in the form of electricity from a coal-based grid. Some possible steps towards reducing battery emissions may be to use water as solvent, and introducing more renewable energy to the electricity grids.

5.3 The "Taxi case"

In this case, we have made assumptions of expanded vehicle lifetime expectancy, namely 300,000 km. Although batteries have an expected lifetime of 10 years, in this case we expect the vehicle to drive twice the length of an average vehicle in a given year, hence the "Taxi case". As we also include the assumption of twice the expected charge-discharge cycles for the $LiFePO_4$ relative to the LiNCM, driving 300,000 km involves one battery change when using the latter. The error bars in figure 8 demonstrate the results sensitivity towards fuel and electricity assumptions. These are included to illustrate the possible differences in assumptions regarding where the fuel stems from, and the possibility of a country's average electricity grid emission deviating from the median[10]. Regarding fuel production, the error bars illustrates the best-case Norwegian conventional oil, and "most likely oil sand estimate" as the worst[11]. Concerning electricity generation, the error bars display the 25. and 75. percentile CO_2 estimates from the meta-analysis conducted by IPCC (2012).

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[9] Assumed lifetime of 150,000 km for the EV.

[10] One may assume Japan and India to be in the lower and higher range of the error bars.

[11] Norwegian conventional oil constitute a WTW emission reduction of 4 %, while the "most likely oil sand estimate" involves an increase of 23 %. (Brandt 2011)

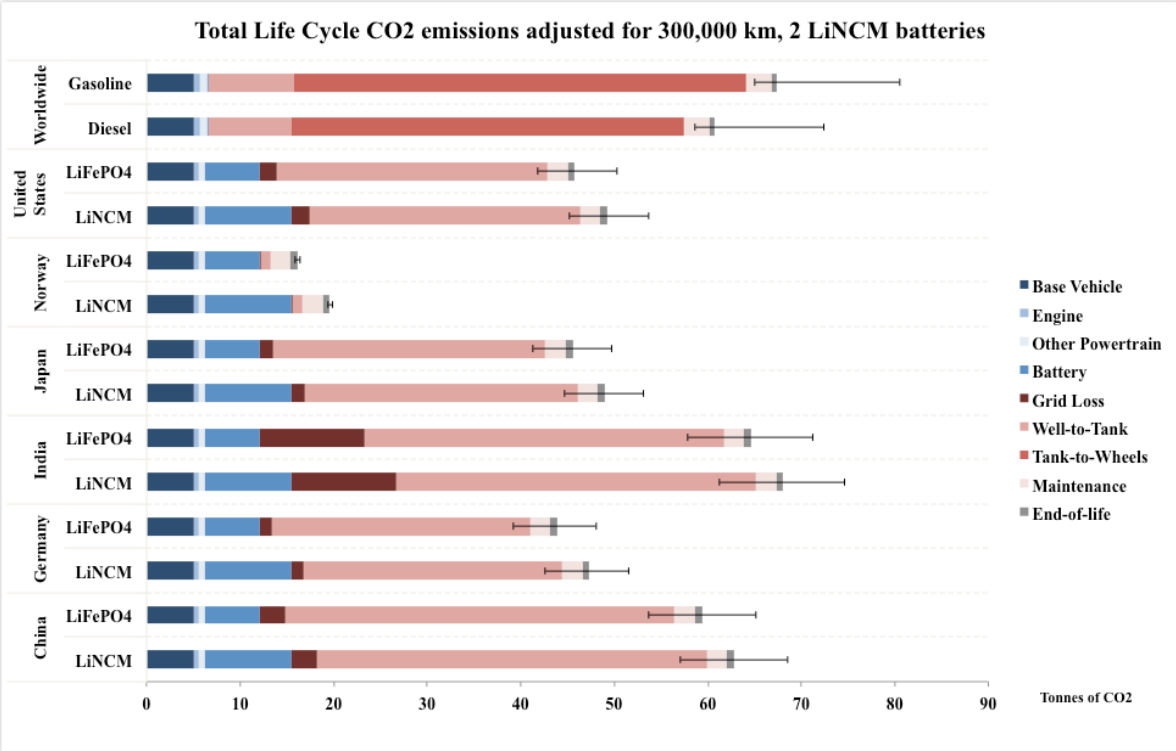

Figure 8: Total CO2 emissions in tonnes, error bars showing sensitivity analysis for fuel and electricity based on research described.

In this case we can see that the EV in India still performs slightly worse than the gasoline ICEV, in the scenario with two LiNCM batteries. While using $LiFePO_4$, the EV now emits less than the gasoline vehicle. In both cases, the diesel ICEV still emits less CO_2 during the lifetime. The results shows that compared to the base case, the EV results from the "Taxi case" will in all scenarios except the EV using two LiNCM batteries in China and India, offer greater environmental savings relative to the ICEVs. In Norway as much as 16 percentage points lower than the base case for the EV using one $LiFePO_4$ battery, and 7 percentage points when using two LiNCM batteries. This suggests that in the case of driving an EV in Norway with a vehicle lifetime of 300,000 km will emit between 68 and 76 % less CO_2 than that of the ICEVs. Studying the error bars suggests that driving a gasoline ICEV with oil sand as the primary energy source emits significantly more CO_2 than the EVs in any of the selected countries.

6. Discussion

The scope of this thesis includes total CO_2 emissions attached to various life cycles of EVs and ICEVs, which in turn creates the basis of our final comparison. At the same time we recognize that it could be sensible to include additional aspects in an environmental comparison beyond our scope, some of them are discussed below.

As we have emphasized previously, CO_2 emissions also occur in the use-phase of EVs. However, these emissions are not emitted at the point of use, merely at the point of electricity generation. Consequently, EVs may be an effective initiative in order to reduce air pollution in areas of dense population, thereby contributing to a healthier environment in large cities. Kampa and Castanas (2008) presented that human health effects of air pollution include among others; premature mortality, and various lung- and heart diseases. One of the highlights of this thesis is that the EV contributes to limited- or no environmental benefits in both India and China. A common feature for these countries are extremely population dense cities, as China contains the largest population by a single country followed by India on second place. Bearing this in mind, one can argue that EVs obtains an additional environmental advantage beyond the scope of this thesis, thereby affecting the perspective and ranking of our initial results. We would like to emphasize that if one were to focus merely on local pollution with the use of EVs in coal-dominated countries, emissions will be reduced in the cities, however not globally. Furthermore, EVs can serve as a measure directed towards more comfortable surroundings when taking into account its reduced noise level compared to ICEVs.

In regards to the recycling and reuse of materials, we have not put a lot of focus on this in our thesis. As mentioned, in some cases LCAs operate with “negative emissions”. With optimistic assumptions for the future, one can expect that reusing batteries, or some of their content will reduce future emissions. This is also applicable to other parts of both the EVs and the ICEVs. A study by Volkswagen (2012) operates with these “negative emissions”, and has an expected future re-use credit of 1.5 tonnes of CO_2, which accounts for a reduction in their total production emissions of 13.5 %. Bearing this in mind, one could argue that if sufficiently effective technologies for reusing materials are put into place, this will have a significant impact on the total environmental impact of the vehicles.

The energy output per input for each barrel of oil is referred to as energy return on investment (EROI). Guilford et al. (2011) conducted a research in the United States and found that the EROI of oil and gas has fluctuated over time. There also exists an overall negative trend in EROI, as finding and producing oil is steadily decreasing while energy investments are increasing. The average EROI for oil discovery has decreased from 1200:1 in 1919 to 5:1 in 2007. The EROI for production of oil was on average 17:1 from 1986 to 2002 and has declined to about 11:1 in the late 2000s.

Methods to derive EROI for oil and gas discovery:

$$EROI = \frac{Mean\ quantity\ of\ energy\ discovered\ from\ oil\ and\ gas\ activities}{Quantity\ of\ energy\ used\ in\ corresponding\ activities}$$

Methods to derive EROI for oil and gas production:

$$EROI = \frac{Quantity\ of\ energy\ supplied\ from\ oil\ and\ gas\ produced}{Quantity\ of\ energy\ used\ in\ corresponding\ activities}$$

Hall et al. (2013) performed a meta-analysis, summarizing the results of existing studies of EROI. The report presents declining EROI in petroleum production for all sites with available data, reaching a similar conclusion as Guilford et al. (2011). They also presented that the mean EROI for tar sands and oil shales are approximately 4:1 and 7:1. While Hydro and Wind are relatively favourable to Solar Photovoltaic (PV) viewed in an EROI perspective, with 84:1, 18:1, and 10:1, respectively. Many informal reports suggests that Solar PV is reaching "price parity" with fossil fuels, and that the future of Solar PV is expected to be bright. Raguei et al. (2012) concluded their report on EROI of Solar PV, stating that improvements in technologies over the last decade has brought notable increases in the EROI of Solar PV, ranges from 6:1 to 12:1 makes it directly comparable to conventional thermal electricity.

A lower EROI is often regarded as a critical source to higher emission levels, and reduced profits due to the higher input per output of energy. While the EROI of oil is expected to decrease with the increased extraction of unconventional sources, we expect the EROI of renewable energy sources to increase with the development of new and better technologies.

Electrification of the vehicle fleet may contribute to substantial macroeconomic effects, as the current vehicle fleet is highly dependent on worldwide oil supply, with more than 40 %

of oil being used for light-vehicle transportation (McKinsey 2009). Peak oil is commonly referred to as the point in time when the maximum rate of oil extraction is reached, effectively causing future supply of oil to decrease. There are large disagreements whether or not we have reached this point in time. However, assuming peak oil[12] has been or will soon be reached, large economical impacts may manifest if the projected growth of the vehicle fleet is entirely covered by ICEVs. Increased demand combined with scarcity of oil will in turn boost the price of oil, contributing to financial inequalities worldwide. Out of the six selected countries in this thesis, five of them are among the top six net importers of oil, the exception being Norway (EIA 2013b). Deployment of EVs will reduce the transportation sector's need of petroleum-based fuels and thereby to some extent diminish the countries challenges connected with oil dependency, at the same time putting downward pressure on world oil prices. However, without domestic battery production and domestic electricity generation, the reduced trade deficit associated with oil will to some extent be offset by increased battery and electricity costs (Becker 2009). In this context, sectors connected to electricity generation and grid infrastructure will require large investment in order to accommodate growth in EVs. As a supplement, we have performed an estimation of increased electricity generation requirements given that one achieves a full electrification of the current non-commercial vehicle fleet in the respective countries. The results vary to a great extent, from a requirement of 18 and 14 % increase in Germany and Japan, to a mere 2 and 3 % in China and India. While in Norway and USA the increase is approximately 5 and 10 %. Gradually introducing EVs will in that respect not involve a drastic expansion of the electricity generation, given our assumptions (see appendix 9).

Simultaneously, deployment of EVs will create increased demand for lithium-ion batteries, and detecting sufficient supply of lithium as a raw material is a major challenge for the mining industry. Nearly 70 % of the world's lithium is derived from salt lakes, while the residual comes from hard rock. Given current conditions, the supply of lithium is abundant and concerns regarding scarcity are only speculations. However, electrification of the vehicle fleet would in turn escalate the demand for lithium and currently there are no materials offering the same performance at a comparable price. The anode material, graphite, also offers concerns connected to shortage of supply, in addition to the expensive process of

[12] Applicable for both peak oil and the assumption of peak conventional or "cheap" oil.

constructing the material and the high amount of waste stemming from production (Buchman, 2013). As there might occur scarcity in certain inputs used in EVs, the future vehicle fleet may rely on additional alternative vehicles as a way to reduce CO_2 emissions. An alternative that has been highlighted is the fuel cell electric vehicle (FCEV); and many believe that the FCEV can provide the same characteristics as the ICEV over the long run. Similar to EVs, FCEVs are in an early life stage and are expected to commence mass production between 2015 and 2020. One of the main challenges in order to achieve commercialization of FCEVs has been its dependence of platinum, which is a necessary material in the fuel cell. The industry has so far managed to reduce the amount of platinum in one fuel cell from several hundreds grams to approximately 40 grams, while the long-term target involves reducing the amount towards the levels of diesel ICEVs, i.e. 2-4 grams. Due to the scarcity of platinum, it may be necessary to achieve the aforementioned long-term target in order to compete with EVs and ICEVs (NHF 2013).

As this thesis highlights, the environmental conditions adapted for EVs varies to a great extent across countries. Implementing incentives to promote electrification of the vehicle fleet will in certain countries be environmentally counterproductive given current electricity infrastructure. Polluting electricity infrastructure may act as an obstacle towards deployment of EVs, likewise, low levels of EVs will reduce the environmental incentives linked to improving the infrastructure. All countries should have obvious environmental reasons to decrease their emissions from electricity generation; nevertheless, we would like to emphasize that electrification of the vehicle fleet will further strengthen these. Developing a noticeable EV share of the total vehicle fleet will in all cases be be a long-term objective, promotion of EVs should therefor be examined along with future dedication to improve the electricity infrastructure. Actions aimed at increasing the share of renewable energy sources are equivalent to reducing CO_2 emission levels from electricity generation. As our results underline, it is essential that countries dominated by fossil fuels intend to restructure their use of energy sources in order to really benefit from deployment of EVs. Environmental goals such as the “20-20-20” target, explained in the introduction of this thesis, will contribute to create a more EV adapted environment. In fact, achieving higher volumes of EVs can facilitate more favourable conditions concerning exploitation of renewable energy sources, as it may reduce the volatility of electricity consumption. Storing a large volume of electricity is non-feasible, consequently serving as an obstacle for generation of electricity that cannot easily be adjusted, which is often the case for electricity from renewable sources, e.g. wind technology. EV users charging during off-peak hours will to some extent lead to a more uniform demand for electricity, hence the need to adjust electricity generation might be reduced.

In order to extract accurate marginal CO_2 emission by the use of EVs, we focus on the average grid mix as a basis for calculation. Hereby, we presume that the EVs are already incorporated into the current electricity consumption in the respective countries. To calculate the actual emissions from adding a new consumption source to a grid in near-term is often referred to as the "marginal emissions factor" (MEF) (Hawkes 2010). The marginal generator is the last power plant that is brought online to supply demand in a given hour. MEF represents emissions from the set of last power plants that is put to place in order to encounter additional electricity demand. This definition assumes that deployment of EVs require additional electricity and represent the last demand supplied in a given hour. Characterizing these upstream emissions requires detailed modelling of the electricity sector to correctly identify the MEF, which depends on quantity, timing and location of the demand (McCarthy and Yang 2009). Another approach is the long term marginal supply, often called the "build-marginal", where one assess the emissions from the average mix of the technologies to be installed next. These three different approaches can differ greatly in emissions levels, with the MEF usually being considered as more pollutant than the average grid mix since hydro, nuclear and renewable power plants with low operating costs are usually not a part of marginal electricity generation. The "build-marginal" depends on expected future instalments of generation capacity, which is bound to be uncertain. In our research, we find it appropriate to use the average generation mix in each country to represent the CO_2 emissions from an EV being used today. It would also be interesting to look at the "build-marginal", as a large EV-fleet rollout will require large increased capacity in some of our selected countries (see appendix 9)

Our study presents how the EVs life cycle CO_2 emissions vary across countries by taking into account differences in electricity generation and distribution. However, our study does not include how the emissions from the production-phase might vary with regards to point of production. Ellingsen et al. (2013) has recently conducted a research on the cradle-to-gate impacts of a LiNCM battery pack of similar capacity[13] used in our thesis. This new analysis

[13] 26.6 kWh used, while in Hawkins et al. the batteries has a capacity of 24 kWh.

is based mainly on primary data, in contrast to many preceding studies, which are based mostly on secondary data due to limited accessibility to battery industry data. The analysis shows that the battery emits 4.6 tonnes of CO_2 during production. Another important aspect this study points out is the impact of the electricity grid mix during production. Moving from the present expected mix[14] during production to electricity generated by hydropower (ex. Norway), one can expect to achieve emission reductions of 60 %. In other terms one would end up with a total CO_2 emission from production below 2 tonnes. A battery plant purely electrified by coal will have expected CO_2 emissions of well above 6 tonnes, 40% above their base case result. The analysis also assess the aspects of powertrain efficiency, concluding that it directly influences the usable lifetime of the battery in the vehicle, which translates to a change in emission impact on a per km basis. In this regard EV producers may improve battery lifetime by improving the powertrain efficiency. As a concluding remark, Ellingsen et al. advocates decreasing manufacturing energy requirements or using cleaner electricity sources, closing the material loop by recycling, and increasing the battery lifetime, as key aspects towards increasing the EVs environmental advantages relative to ICEVs.

Through mass production and technology improvements, EVs has steadily acquired a lot of the same vehicle performance as the ICEV, enabling EVs to come forward as a practical alternative for a broader range of vehicle consumers. This thesis has focused on the environmental impacts of deploying EVs versus sustaining ICEVs across countries. In order to capture a great extent of the total vehicle fleet, the EV is dependent on further factors than simply being the most environmental friendly option. One of the primary customer necessities applicable for the average vehicle owner is affordability. As the batteries of EVs are required to hold substantial amounts of power, they are composed of high quality materials and the production process is extensive. This can be regarded as important reasons as to why EVs are initially more expensive than ICEVs of similar characteristics, granted no political involvement such as subsidies, etc. Without political involvement, the higher cost associated with EVs may cause reluctance among consumers, thereby providing a hurdle towards economics of scale. This provides the famous chicken or the egg dilemma; consumers will refrain from purchasing EVs due to higher costs, while higher cost remains as consumers prevent further mass production. The dilemma can also be transmitted to

[14] Which is based on a medium voltage electricity mix, assuming the following allocation: 46 % coal, 33 % nuclear, 15 % gas, 4.4 % oil, 1.4 % hydro, 0.12 % solar photovoltaic, and 0.044 % waste incineration.

charging infrastructure, commercial companies may be reluctant to set up charging stations due to insufficient client base, while potential consumers may be unwilling to buy EVs due to lack of charging stations. These factors imply that governmental assistance can be beneficial in order to effectively deploy EVs in their early life stage. However, governmental assistance and thereby deployment of EVs should not take place prior to measures towards suitable environmental conditions.

7. Conclusion

The environmental impact from the current vehicle fleet constitutes a significant share of worldwide CO_2 emissions, which combined with a projected vast growth in the road transport sector, will lead to an amplification of global emissions. The lingering threats of global warming thereby indicate a distinct need to reduce CO_2 emissions from the road transport. In addition, depletion of oil reserves, assumptions of peak oil production and diminishing EROI from finding and extracting oil are all scenarios that requires actions towards reducing the transport sectors dependency on crude oil. Promotion of EVs has gained a great deal of focus in recent years as a possible measure towards reducing CO_2 emissions and the dependency on crude oil. In this thesis we have conducted a comparison of CO_2 emissions from the entire life span of EVs and ICEVs. All data applied were based on secondary data from LCAs in the different branches of the life cycle chain. The goal was to achieve a complete estimation of CO_2 emissions throughout the entire life of a vehicle across countries, from the point of resource extraction to disposal/recycling.

In the study of Hawkins et al. (2012), it emerges that the production phase applicable to EVs offers almost twice the carbon footprint as the ICEV. In consequence, the EV must achieve lower emission levels during the use-phase in order to come forward as a more environmental friendly alternative. Our results reflect a great variability of CO_2 emissions occurring in this life stage, as the allocation of energy sources used for electricity generation are distributed in several ways. Hence, utilizing EVs in different countries shows a broad spectre of total life cycle CO_2 emissions. In our base case, EVs powered with electricity in India are expected to emit 283 % more relative to Norwegian electricity, and up to 14 % more than a diesel ICEV. With Norway's extensive use of renewable energy sources, they contain suitable conditions in order to bring forward the EVs environmental potential, with CO_2 savings up to 64 %.

When examining the end-of-life treatment associated with EVs, our results reveals that recycling in general constitute a small fraction of total life cycle CO_2 emissions. This indicates the importance of reducing emissions in the remaining life stages as most essential. However, the possible "negative emissions" from re-use could alter this perception, and a multitude of researchers regard future technology associated with recycling as promising.

Our metrics illustrates the wide range of total life cycle emissions an EV may potentially emit; the most vital step in order to shrink the differences includes a more extensive use of renewable energy sources worldwide. However, the results applicable to EVs powered with Indian electricity also express the drawback of an inefficient grid infrastructure, as 14-15 % of total CO_2 emissions are explained by grid losses.

Vehicle lifetime assumptions constitute an essential factor in the final comparison, due to the prominent CO_2 emissions levels in the production phase of the EVs. Bearing this in mind, we decided to include a break-even analysis, which, in turn expresses the millage as to when the ICEV has emitted the same amount of CO_2 as the EV. Of the most profound results, an EV in India will only become environmental beneficial at mileages beyond 953,817 km, while in Norway, merely 34,032 km is required[15]. This basically means that according to our metrics the EV will not be environmentally friendlier than the diesel ICEV regardless of the lifetime expectancy of the vehicles, given current conditions in India.

When introducing different assumptions for the batteries, implementing the batteries with the lowest carbon footprint in our model leads to reductions in total life cycle emissions ranging from 11 to 30 %[16], emphasizing the importance of battery production emissions.

We have examined approximately 75 % of the worldwide EV fleet. By reviewing the six countries, our results indicates that about 68 % of the fleet is located in countries where the EV is estimated to emit less CO_2 than the ICEV, the remaining 25 % remains to be considered. Even though our conclusion reveals that EVs are preferable to ICEVs in countries where most of the current EV fleet is active, thereby suggesting that incentives in general are beneficial in order to reduce global CO_2 emissions. We would still like to point out the need for further improvement, as stated by many studies before us. To reduce the global warming potential of the EVs, we have encountered a number of important aspects and measures when examining earlier research on the subject. Among the most prominent involves reducing emission from battery production- and electricity generation, diminish grid losses, improving the powertrain, and recycling/reuse of materials.

[15] Under the assumption of an EV with $LiFePO_4$ battery pack when evaluated against the diesel ICEV.

[16] $LiMn_2O_4$ by EPA (2013), using water as solvent. This estimate is not far from what Ellingsen et al. estimated a LiNCM battery produced in an electricity mix based entirely on hydropower to emit.

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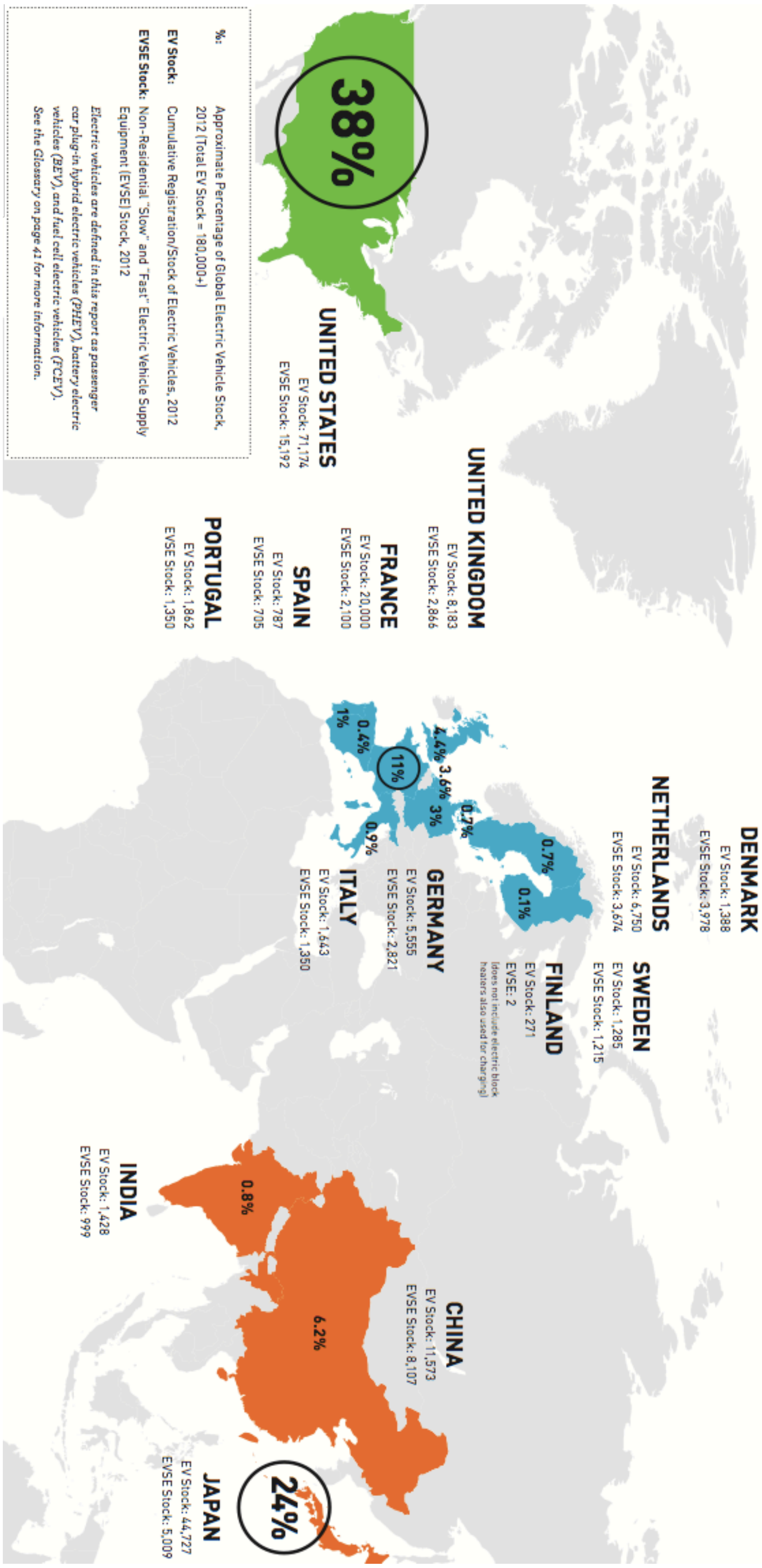
Appendix 1: Allocation of the worldwide EV fleet



Source: (IEA 2013b)

Appendix 2: List of countries and incentives

	Incentives	Infrastructure	R&D
China	Purchase subsidies for vehicles of up to RMB 60,000.	---	RMB 6.95 billion for demonstration projects.
Germany	Exemption from road taxes.	Four regions nominated as showcase regions for BEVs and PHEVs.	Financial support granted for R&D for electric drivetrains, creation and optimization of value chain, information and communications technology (ICT), and battery research.
India	INR 100,000 or 20% of cost of vehicle, whichever is less. Reduced excise duties on BEV/PHEVs.	The National Mission for Electric Mobility will facilitate installation of charging infrastructure.	Building R&D capability through joint efforts across government, industry, and academia. Focus on battery cells and management systems.
Japan	Support to pay for 1/2 of the price gap between EV and corresponding ICE vehicles, up to YEN 1 million per vehicle.	Support to pay for 1/2 of the price of EVSE (up to YEN 1.5 million per charger).	Major focus on infrastructure RD&D.
Norway	No import taxes, reduced yearly car tax, allowed to drive in bus lane, free parking and charging in cities, avoiding congestion charges (road tolls). (MDep 2012, elbil.no)	Highly developed, 3500 charging posts and 100 fast-charging stations.	
United States	Up to USD 7,500 tax credit for vehicles, based on battery capacity. Phased out after 200,000 vehicles from qualified manufacturers.	A tax credit of 30% of the cost, not to exceed USD 30,000, for commercial EVSE installation; a tax credit of up to USD 1,000 for consumers who purchase qualified residential EVSE. USD 360 million for infrastructure demonstration projects.	2012 budget of USD 268 million for battery, fuel cell, vehicle systems and infrastructure R&D.

Source: (IEA 2013b)

Appendix 3: List of most popular Lithium-ion batteries and typical applications

The table offers clarity by listing these batteries by their full name, chemical definition, abbreviations and short form. To complete the list of popular Li-ion batteries, the table also includes NCA and Li-titanate, two lesser-known members of the Li-ion family.

Chemical name	Material	Abbreviation	Short form	Notes
Lithium Cobalt Oxide[1] Also Lithium Cobalate or lithium-ion-cobalt)	$LiCoO_2$ (60% Co)	LCO	Li-cobalt	High capacity; for cell phone laptop, camera
Lithium Manganese Oxide[1] Also Lithium Manganate or lithium-ion-manganese	$LiMn_2O_4$	LMO	Li-manganese, or spinel	Most safe; lower capacity than Li-cobalt but high specific power and long life. Power tools, e-bikes, EV, medical, hobbyist.
Lithium Iron Phosphate[1]	$LiFePO_4$	LFP	Li-phosphate	
Lithium Nickel Manganese Cobalt Oxide[1], also lithium-manganese-cobalt-oxide	$LiNiMnCoO_2$ (10–20% Co)	NMC	NMC	
Lithium Nickel Cobalt Aluminum Oxide[1]	$LiNiCoAlO_2$ (9% Co)	NCA	NCA	Gaining importance in electric powertrain and grid storage
Lithium Titanate[2]	$Li_4Ti_5O_{12}$	LTO	Li-titanate	

[1] Cathode material [2] Anode material

Source: (Buchman 2013)

Appendix 4: Battery attributes

Specification on different batteries and their different characteristics

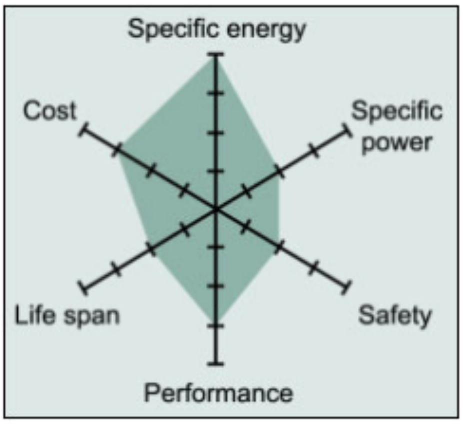


Figure 3: **Snapshot of an average Li-cobalt battery**

Li-cobalt excels on high specific energy but offers only moderate performance specific power, safety and life span.

Courtesy of Cadex

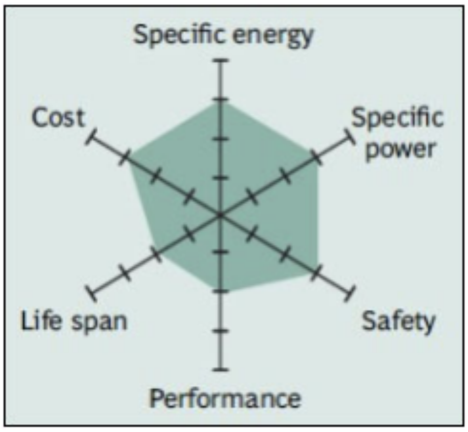


Figure 5: Snapshot of a typical Li-manganese battery

Although moderate in overall performance, newer designs of Li-manganese offer improvements in specific power, safety and life span.

Courtesy of BCG research

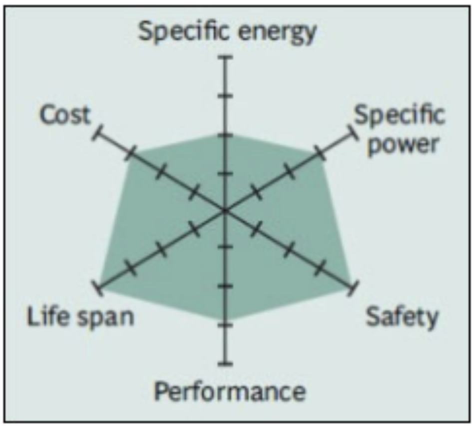


Figure 6: Snapshot of a typical Li-phosphate battery

Li-phosphate has excellent safety and long life span but moderate specific energy and and a lower voltage than other lithium-based batteries.

Courtesy of BCG research

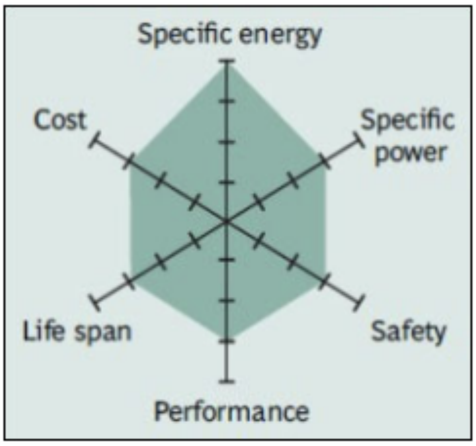


Figure 7: Snapshot of NMC

NMC has good overall performance and excels on specific energy. This battery is the preferred candidate for the electric vehicle and has the lowest self-heating rate.

Courtesy of BCG research

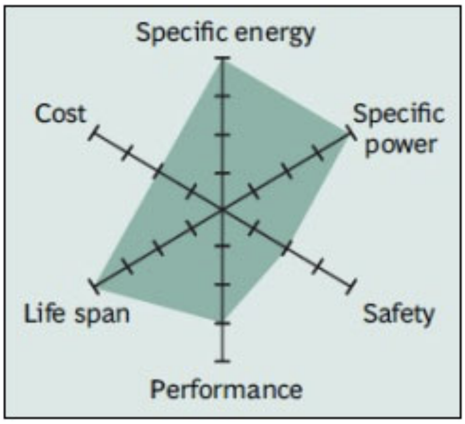


Figure 8: Snapshot of NCA

High energy and power densities, as well as good life span, make the NCA
a candidate for EV powertrains. High cost and marginal safety are negatives.

Courtesy of BCG research

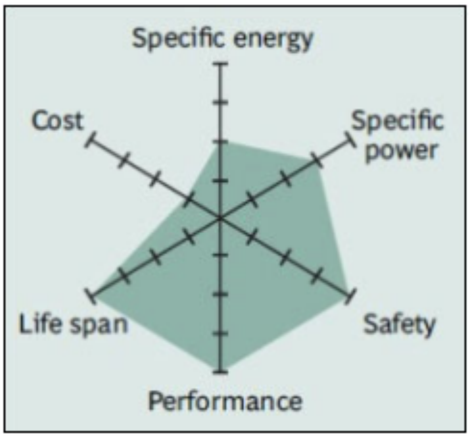


Figure 9: Snapshot of Li-titanate

Li-titanate excels in safety, low-temperature performance and life span. Efforts are being made to improve the specific energy and lower cost.

Courtesy of BCG research

Source: (Buchman 2013)

Appendix 5: Specification of the various vehicles

Electrical vehicles:

Model: Nissan Leaf

- Battery: Lithium iron phosphate ($LiFePO_4$)
- Electric engine: 80 kW
- Battery capacity: 24 kWh
- Battery weight: 273 kg
- Weight: 1521 kg
- Use-phase energy requirements: 0.173 kWh/km

Model: Nissan Leaf

- Battery: Lithium nickel cobalt manganese (LiNCM)
- Electric engine: 80 kW
- Battery capacity: 24 kWh
- Battery weight: 214 kg
- Weight: 1462 kg
- Use-phase energy requirements: 0.173 kWh/km

Conventional vehicles

Model: Mercedes A-170

- Fuel: Gasoline
- Weight: 1225-1365 kg
- Use-phase energy requirements: 0.0685 L/km

Model: Average of Mercedes A-160 and A-180

- Fuel: Diesel
- Weight: 1225-1365 kg
- Use-phase energy requirements: 0.0535 L/km

Appendix 6: Lithium-Ion battery chemistries in passenger cars, some major Lithium-based technologies in the United States.

Types of Cathodes	Developers	Vehicle Application
Nickel, cobalt, and aluminum (NCA)	Johnson Controls, Panasonic	Mercedes Benz S400 Hybrid, Tesla Model S
Manganese	LG Chem, NEC	Chevrolet Volt, Nissan Leaf
Iron-nano-phosphate	A123 Systems[a]	Fisker Karma,[b] Chevrolet Spark
Nickel, manganese, and cobalt (NMC)	EnerDel	THINK City electric vehicle [c]

Notes: Each technology is paired with lithium.

a. A123 Systems filed for bankruptcy in 2012 and changed its name to B456 Systems on March 22, 2013.
b. Fisker suspended production of the Karma in July 2011. Mark Loveday, "Fisker Karma Production Restart Still a 'Couple of Months' Away," Inside EVs, March 6, 2013.
c. THINK City vehicles were initially sold for fleet use by the state of Indiana. The company declared bankruptcy in 2011.

Source: (Canis 2013)

Appendix 7: Break-even analysis

Break-even Distance in km

	$LiFePO_4$		LiNCM	
Country	**Diesel**	**Gasoline**	**Diesel**	**Gasoline**
China	242,626	125,204	189,659	97,872
Germany	75,993	58,739	59,403	45,916
India	953,817	203,509	745,593	159,082
Japan	82,036	62,285	64,127	48,688
Norway	34,032	30,076	26,602	23,510
United States	82,957	62,815	64,847	49,102

The mileage shown in the table expresses the distance as to when the EV become environmentally beneficial compared to the ICEV.

Appendix 8: Vehicle lifetime sensitivity

Vehicle Lifetime (km):		**100,000**		**150,000**		**250,000**	
CO_2 Emissions Relative to:		**Diesel**	**Gasoline**	**Diesel**	**Gasoline**	**Diesel**	**Gasoline**
China	**LiNCM**	8 %	0 %	3 %	-6 %	-3 %	-12 %
	$LiFePO_4$	13 %	4 %	6 %	-3 %	0 %	-10 %
Germany	**LiNCM**	-12 %	-19 %	-20 %	-27 %	-28 %	-35 %
	$LiFePO_4$	-7 %	-15 %	-16 %	-24 %	-25 %	-32 %
India	**LiNCM**	15 %	6 %	11 %	1 %	6 %	-4 %
	$LiFePO_4$	20 %	11 %	14 %	4 %	8 %	-2 %
Japan	**LiNCM**	-10 %	-17 %	-18 %	-25 %	-25 %	-32 %
	$LiFePO_4$	-5 %	-13 %	-14 %	-22 %	-23 %	-30 %
Norway	**LiNCM**	-49 %	-53 %	-61 %	-64 %	-72 %	-75 %
	$LiFePO_4$	-44 %	-49 %	-57 %	-61 %	-70 %	-73 %
United States	**LiNCM**	-10 %	-17 %	-17 %	-25 %	-25 %	-32 %
	$LiFePO_4$	-5 %	-12 %	-14 %	-21 %	-22 %	-30 %

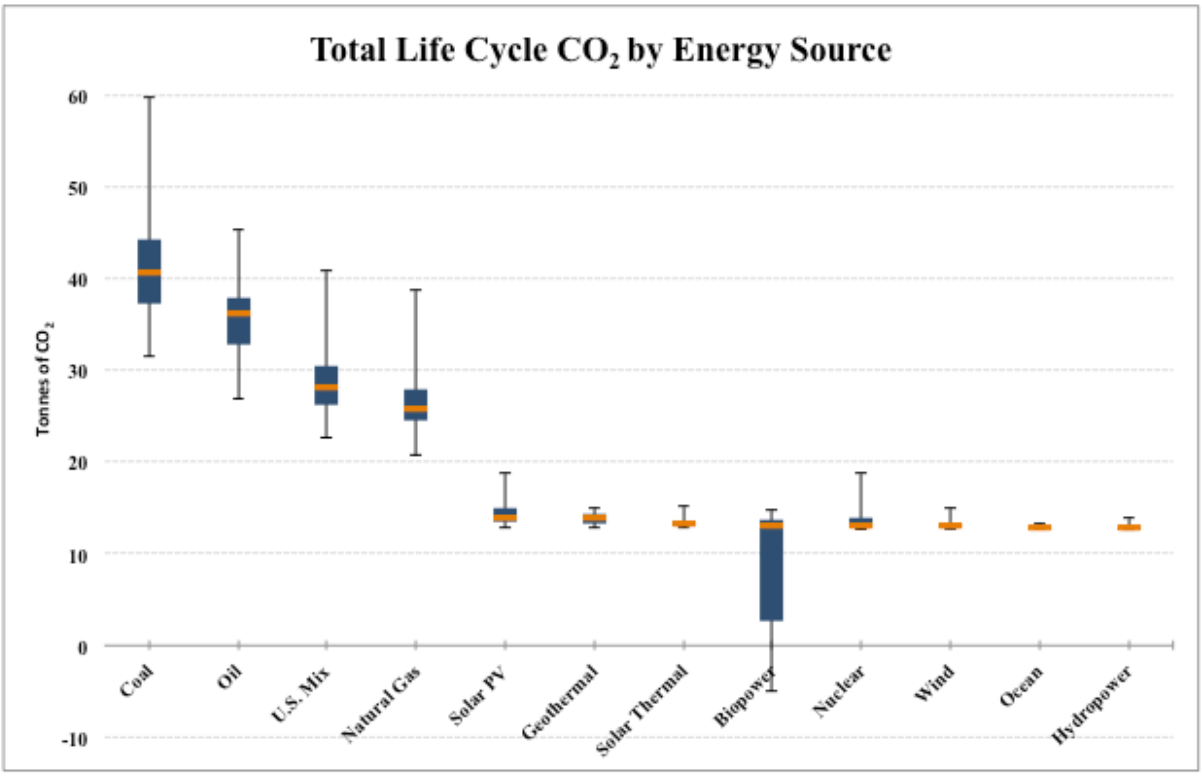
An analysis showing the sensitivity of assumptions regarding vehicle lifetime.

Appendix 9: EV Impact analysis – increased capacity requirement

Impact in % of Total Electricity Generation			
Country	**100 %**	**50 %**	**25 %**
China	2 %	1 %	0 %
Germany	18 %	9 %	5 %
India	3 %	2 %	1 %
Japan	14 %	7 %	4 %
Norway	5 %	2 %	1 %
United States	7 %	4 %	2 %

This is an analysis showing the increase in electricity generation capacity required in each country when switching 100, 50 and 25 % of the total non commercial vehicle fleet. (Percentage increase needed compared to generation estimates by IEA Statistics, based on our assumptions of electricity use from an EV.)

Appendix 10: Total EV emissions depending on energy source



An analysis showing the total life cycle emissions from utilizing 100 % of a specific electricity source for an EV with the LiNCM battery. An average grid loss of 7 % is assumed and a vehicle lifetime expectancy of 150,000 km. The orange line showing the median estimates, the blue square shows 25. and 75. percentile, while the error bars display the maximum and minimum values from the LCA conducted by IPCC on emissions of electricity sources.

Appendix 11: Sensitivity analysis regarding use-phase energy requirements

Use-phase Energy Requirement:		20 % Decrease		Base Case		20 % Increase	
CO_2 Emissions Relative to:		Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline
China	LiNCM	-10 %	-18 %	3 %	-6 %	16 %	6 %
	$LiFePO_4$	-7 %	-15 %	6 %	-3 %	20 %	9 %
Germany	LiNCM	-29 %	-35 %	-20 %	-27 %	-12 %	-19 %
	$LiFePO_4$	-25 %	-32 %	-16 %	-24 %	-8 %	-16 %
India	LiNCM	-4 %	-13 %	11 %	1 %	25 %	14 %
	$LiFePO_4$	0 %	-9 %	14 %	4 %	29 %	17 %
Japan	LiNCM	-27 %	-33 %	-18 %	-25 %	-9 %	-17 %
	$LiFePO_4$	-23 %	-30 %	-14 %	-22 %	-5 %	-13 %
Norway	LiNCM	-61 %	-65 %	-61 %	-64 %	-61 %	-64 %
	$LiFePO_4$	-58 %	-61 %	-57 %	-61 %	-57 %	-61 %
United States	LiNCM	-26 %	-33 %	-17 %	-25 %	-8 %	-16 %
	$LiFePO_4$	-23 %	-30 %	-14 %	-21 %	-5 %	-13 %

Base Case	0.173
20% Increase	0.208
20% Decrease	0.138

An analysis showing how sensitive the model is to changing assumptions regarding the energy requirements of the specific vehicle.

Appendix 12: Battery replacement calculations

	Total CO_2 Emitted depending on Battery Estimate								
	Production	Maintenance	CO_2 from	Notter et al.	Majeau-Bettez et al.		EPA		
Country	excl. battery	+ End of Life	Electricity use	$LiMn_2O_4$	$LiFePO_4$	LiNCM	$LiFePO_4$	LiNCM	$LiMnO_2$
China	6.2	1.8	22.2	32.0	36.1	34.9	33.8	33.1	31.7
Germany	6.2	1.8	14.5	24.3	28.4	27.2	26.1	25.4	24.0
India	6.2	1.8	24.8	34.6	38.7	37.5	36.5	35.7	34.4
Japan	6.2	1.8	15.3	25.1	29.2	28.0	26.9	26.2	24.8
Norway	6.2	1.8	0.6	10.4	14.5	13.3	12.2	11.5	10.1
United States	6.2	1.8	15.4	25.2	29.3	28.1	27.1	26.3	25.0

Measured in tonnes of CO_2

Data for the graph with battery replacement, presented in the results, section 5.2.

Appendix 13: Rough estimate of total CO_2 emission reductions per country

Emission reduction impacts (switching the entire LDV fleet, yearly reduction in CO_2 emissions)

	China	Germany	India	Japan	Norway	United States
Gasoline	192	192	192	192	192	192
EV (LiNCM)	148	96	165	102	4	103
Reduction per Vehicle	44	95	26	90	188	89
LDV fleet yearly reduction*	22,646	60,528	5,251	78,648	6,493	158,955
Reduction in % of total emissions	**0.3 %**	**6.6 %**	**0.3 %**	**6.0 %**	**12.2 %**	**2.4 %**

* in thousand tonnes

This rough analysis shows how large the reduction in emissions per year will be in the selected countries, in percentage of total CO2 emissions. This involves switching the entire non commercial vehicle fleet to EVs with LiNCM battery. (Given assumptions that the entire vehicle fleet today is comparable to our estimate of the gasoline ICEV).

Appendix 14: CO_2 emissions applicable to the different life cycle stages

Production:

Life Cycle Component	Tonnes of CO_2, Total Production							
	Electric Vehicles				Conventional Vehicles			
	LiNCM		$LiFePO_4$		Diesel		Gasoline	
Base Vehicle	5.1	*47 %*	5.1	*42 %*	5.1	*77 %*	5.1	*77 %*
Engine	0.4	*4 %*	0.4	*3 %*	0.6	*9 %*	0.6	*9 %*
Other Powertrain	0.7	*7 %*	0.7	*6 %*	0.8	*12 %*	0.8	*12 %*
Battery	4.7	*43 %*	5.9	*48 %*	0.1	*1 %*	0.1	*1 %*
Total Production	10.9		12.1		6.6		6.6	

Life Cycle Component	Grams of CO_2 per km, Production							
	Electric Vehicles				Conventional Vehicles			
	LiNCM		$LiFePO_4$		Diesel		Gasoline	
Base Vehicle	34.0	*47 %*	34.0	*42 %*	34.0	*77 %*	34.0	*77 %*
Engine	2.7	*4 %*	2.7	*3 %*	4.0	*9 %*	4.0	*9 %*
Other Powertrain	4.8	*7 %*	4.8	*6 %*	5.5	*12 %*	5.5	*12 %*
Battery	31.0	*43 %*	39.0	*48 %*	0.6	*1 %*	0.6	*1 %*
Sum, Production	72.5		80.5		44.1		44.1	

Use-phase:

Unit of measure	Use-phase Energy Requirement			
	Electric Vehicles		Conventional Vehicle	
	LiNCM	$LiFePO_4$	Diesel	Gasoline
MJ/km or mL/km	0.623	0.623	53.5	68.5
kWh/km or L/km	0.173	0.173	0.0535	0.0685

Life Cycle Stages	g CO_2 per MJ			
	Diesel		Gasoline	
Production & Conditioning at source	4.7	*31 %*	4.6	*33 %*
Transportation to Market	1.0	*6 %*	1.0	*7 %*
Transformation near Market	8.6	*56 %*	7.0	*51 %*
Conditioning & Distribution	1.1	*7 %*	1.2	*9 %*
WTT	**15.4**	***17 %***	**13.8**	***16 %***
TTW (Total combustion)	**73.2**	***83 %***	**73.4**	***84 %***
WTW	**88.6**		**87.2**	

Conversion Factors		
MJ per	Diesel	Gasoline
Litre	35.8	32.1

Life Cycle Stages	g CO_2 per Litre			
WTT	**551**	***17 %***	**443**	***16 %***
TTW (Total combustion)	**2621**	***83 %***	**2356**	***84 %***
WTW	**3172**		**2799**	

Sections	g CO_2 per km	
	Diesel	Gasoline
WTT	29.5	30.3
TTW	140.2	161.4
WTW	169.7	191.7

Technology	Coal	Oil	Natural Gas	Solar PV	Geothermal	Solar Thermal	Biopower	Nuclear	Wind	Ocean	Hydropower	Other Sources
g CO2/kWh	1001	840	469	46	45	22	18	16	12	8	4	226

Technology	Coal	Oil	Natural Gas	Solar PV	Geothermal	Solar Thermal	Biopower	Nuclear	Wind	Ocean	Hydropower	Other Sources
China	*79 %*	*0 %*	*2 %*	*0 %*	*0 %*	*0 %*	*1 %*	*2 %*	*1 %*	*0 %*	*15 %*	*0 %*
Germany	*45 %*	*1 %*	*14 %*	*3 %*	*0 %*	*0 %*	*5 %*	*18 %*	*8 %*	*0 %*	*4 %*	*2 %*
India	*68 %*	*1 %*	*10 %*	*0 %*	*0 %*	*0 %*	*3 %*	*3 %*	*2 %*	*0 %*	*12 %*	*0 %*
Japan	*27 %*	*15 %*	*36 %*	*0 %*	*0 %*	*0 %*	*3 %*	*10 %*	*0 %*	*0 %*	*9 %*	*1 %*
Norway	*0 %*	*0 %*	*3 %*	*0 %*	*0 %*	*0 %*	*0 %*	*0 %*	*1 %*	*0 %*	*95 %*	*0 %*
United States	*43 %*	*1 %*	*24 %*	*0 %*	*0 %*	*0 %*	*1 %*	*19 %*	*3 %*	*0 %*	*8 %*	*1 %*

	China	Germany	India	Japan	Norway	United States	Diesel	Gasoline
CO_2/kWh	854.9	556.9	956.2	588.9	22.1	593.3	-	-
CO_2/km	155.1	103.5	172.6	109.1	11.0	109.8	178.6	200.6

**Including maintenance*

End-of-life:

Life Cycle Component	Grams of CO_2 per km, Maintenance/End-of-life			
	Electric Vehicles		Conventional Vehicles	
	LiNCM	$LiFePO_4$	Diesel	Gasoline
Use-phase, maintenance	7.2	7.2	8.9	8.9
End-of-life treatment	4.7	5.0	3.4	3.4

Life Cycle Component	Tonnes of CO_2, Total Maintenance/End-of-life			
	Electric Vehicles		Conventional Vehicles	
	LiNCM	$LiFePO_4$	Diesel	Gasoline
Use-phase, maintenance	1.1	1.1	1.3	1.3
End-of-life treatment	0.7	0.8	0.5	0.5

Appendix 15: Base case results

Life Cycle Components		Base Vehicle	Engine	Other Powertrain	Battery	Grid Loss	Well-to-Tank*	Tank-to-Wheels	Maintenance	End-of-life	Total
China	LiNCM	5.1	0.4	0.7	4.7	1.4	20.8	0.0	1.1	0.7	**34.8**
		15 %	*1 %*	*2 %*	*13 %*	*4 %*	*60 %*	*0 %*	*3 %*	*2 %*	
	$LiFePO_4$	5.1	0.4	0.7	5.9	1.4	20.8	0.0	1.1	0.8	**36.1**
		14 %	*1 %*	*2 %*	*16 %*	*4 %*	*58 %*	*0 %*	*3 %*	*2 %*	
Germany	LiNCM	5.1	0.4	0.7	4.7	0.6	13.8	0.0	1.1	0.7	**27.1**
		19 %	*1 %*	*3 %*	*17 %*	*2 %*	*51 %*	*0 %*	*4 %*	*3 %*	
	$LiFePO_4$	5.1	0.4	0.7	5.9	0.6	13.8	0.0	1.1	0.8	**28.4**
		18 %	*1 %*	*3 %*	*21 %*	*2 %*	*49 %*	*0 %*	*4 %*	*3 %*	
India	LiNCM	5.1	0.4	0.7	4.7	5.6	19.2	0.0	1.1	0.7	**37.5**
		14 %	*1 %*	*2 %*	*12 %*	*15 %*	*51 %*	*0 %*	*3 %*	*2 %*	
	$LiFePO_4$	5.1	0.4	0.7	5.9	5.6	19.2	0.0	1.1	0.8	**38.7**
		13 %	*1 %*	*2 %*	*15 %*	*14 %*	*50 %*	*0 %*	*3 %*	*2 %*	
Japan	LiNCM	5.1	0.4	0.7	4.7	0.7	14.6	0.0	1.1	0.7	**27.9**
		18 %	*1 %*	*3 %*	*17 %*	*3 %*	*52 %*	*0 %*	*4 %*	*3 %*	
	$LiFePO_4$	5.1	0.4	0.7	5.9	0.7	14.6	0.0	1.1	0.8	**29.2**
		17 %	*1 %*	*2 %*	*20 %*	*2 %*	*50 %*	*0 %*	*4 %*	*3 %*	
Norway	LiNCM	5.1	0.4	0.7	4.7	0.0	0.5	0.0	1.1	0.7	**13.2**
		39 %	*3 %*	*5 %*	*35 %*	*0 %*	*4 %*	*0 %*	*8 %*	*5 %*	
	$LiFePO_4$	5.1	0.4	0.7	5.9	0.0	0.5	0.0	1.1	0.8	**14.5**
		35 %	*3 %*	*5 %*	*40 %*	*0 %*	*4 %*	*0 %*	*7 %*	*5 %*	
United States	LiNCM	5.1	0.4	0.7	4.7	0.9	14.5	0.0	1.1	0.7	**28.1**
		18 %	*1 %*	*3 %*	*17 %*	*3 %*	*52 %*	*0 %*	*4 %*	*3 %*	
	$LiFePO_4$	5.1	0.4	0.7	5.9	0.9	14.5	0.0	1.1	0.8	**29.3**
		17 %	*1 %*	*2 %*	*20 %*	*3 %*	*49 %*	*0 %*	*4 %*	*3 %*	
Worldwide	Diesel	5.1	0.6	0.8	0.1	0.0	4.4	21.0	1.3	0.5	**33.9**
		15 %	*2 %*	*2 %*	*0 %*	*0 %*	*13 %*	*62 %*	*4 %*	*2 %*	
	Gasoline	5.1	0.6	0.8	0.1	0.0	4.6	24.2	1.3	0.5	**37.2**
		14 %	*2 %*	*2 %*	*0 %*	*0 %*	*12 %*	*65 %*	*4 %*	*1 %*	

The results above are measured in total tonnes of CO_2, vehicle lifetime of 150,000 km.

Life Cycle Components		Base Vehicle	Engine	Other Powertrain	Battery	Grid loss	Well-to-Tank*	Tank-to-Wheels	Maintenance	End-of-life	Total
China	LiNCM	34.0	2.7	4.8	31.0	9.2	138.7	0.0	7.2	4.7	**232.3**
		15 %	*1 %*	*2 %*	*13 %*	*4 %*	*60 %*	*0 %*	*3 %*	*2 %*	
	$LiFePO_4$	34.0	2.7	4.8	39.0	9.2	138.7	0.0	7.2	5.0	**240.6**
		14 %	*1 %*	*2 %*	*16 %*	*4 %*	*58 %*	*0 %*	*3 %*	*2 %*	
Germany	LiNCM	34.0	2.7	4.8	31.0	4.3	92.1	0.0	7.2	4.7	**180.7**
		19 %	*1 %*	*3 %*	*17 %*	*2 %*	*51 %*	*0 %*	*4 %*	*3 %*	
	$LiFePO_4$	34.0	2.7	4.8	39.0	4.3	92.1	0.0	7.2	5.0	**189.0**
		18 %	*1 %*	*3 %*	*21 %*	*2 %*	*49 %*	*0 %*	*4 %*	*3 %*	
India	LiNCM	34.0	2.7	4.8	31.0	37.4	128.0	0.0	7.2	4.7	**249.8**
		14 %	*1 %*	*2 %*	*12 %*	*15 %*	*51 %*	*0 %*	*3 %*	*2 %*	
	$LiFePO_4$	34.0	2.7	4.8	39.0	37.4	128.0	0.0	7.2	5.0	**258.1**
		13 %	*1 %*	*2 %*	*15 %*	*14 %*	*50 %*	*0 %*	*3 %*	*2 %*	
Japan	LiNCM	34.0	2.7	4.8	31.0	4.7	97.2	0.0	7.2	4.7	**186.3**
		18 %	*1 %*	*3 %*	*17 %*	*3 %*	*52 %*	*0 %*	*4 %*	*3 %*	
	$LiFePO_4$	34.0	2.7	4.8	39.0	4.7	97.2	0.0	7.2	5.0	**194.6**
		17 %	*1 %*	*2 %*	*20 %*	*2 %*	*50 %*	*0 %*	*4 %*	*3 %*	
Norway	LiNCM	34.0	2.7	4.8	31.0	0.3	3.5	0.0	7.2	4.7	**88.2**
		39 %	*3 %*	*5 %*	*35 %*	*0 %*	*4 %*	*0 %*	*8 %*	*5 %*	
	$LiFePO_4$	34.0	2.7	4.8	39.0	0.3	3.5	0.0	7.2	5.0	**96.5**
		35 %	*3 %*	*5 %*	*40 %*	*0 %*	*4 %*	*0 %*	*7 %*	*5 %*	
United States	LiNCM	34.0	2.7	4.8	31.0	6.2	96.4	0.0	7.2	4.7	**187.0**
		18 %	*1 %*	*3 %*	*17 %*	*3 %*	*52 %*	*0 %*	*4 %*	*3 %*	
	$LiFePO_4$	34.0	2.7	4.8	39.0	6.2	96.4	0.0	7.2	5.0	**195.3**
		17 %	*1 %*	*2 %*	*20 %*	*3 %*	*49 %*	*0 %*	*4 %*	*3 %*	
Worldwide	Diesel	34.0	4.0	5.5	0.6	0.0	29.5	140.2	8.9	3.4	**226.1**
		15 %	*2 %*	*2 %*	*0 %*	*0 %*	*13 %*	*62 %*	*4 %*	*2 %*	
	Gasoline	34.0	4.0	5.5	0.6	0.0	30.3	161.4	8.9	3.4	**248.1**
		14 %	*2 %*	*2 %*	*0 %*	*0 %*	*12 %*	*65 %*	*4 %*	*1 %*	

The results above are measured in grams of CO_2 per km driven, vehicle lifetime of 150,000 km.