Bachelor's project

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The Carbon Footprint of Electrified City Buses

Case Trondheim

Bachelor's project in Renewable Energy
Supervisor: Kristian Myklebust Lien
May 2020

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Kunnskap for en bedre verden

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Bachelor's Thesis

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Preface

This bachelor's thesis is a product from the course *Bachelor Thesis Renewable Energy* (TFNE3001). The course is a part of the bachelor program in renewable energy engineering, and will account for 20 out of 30 credits in the sixth semester. The report is written in cooperation between two students.

Throughout the work with the thesis, complications and challenges have been met. However, the final outcome, based on the new bus fleet in Trondheim, provide an in depth analysis of the carbon footprint of an electrified bus fleet. The life cycle from material extraction to use phase have been examined and relevant factors discussed.

The group sincerely thanks our internal supervisor, Kristian Lien. His advice, guidance and motivation have been a key factor for the outcome of the thesis. Further, the group wants to extend gratitude to the external supervisors from AtB, Tom Nørbech and Kjell Wilhelm Utvaag, for providing the assignment and helpful information along the way. Finally, the group wants to thank the important help from Jack Frain, Ida Marie Synnevåg and Jostein Johansen Lyngen for proofreading.

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Abstract

As new global and national climate strategies, working towards the Paris Agreement, are implemented, the transportation sector has come into focus. Environmental potential exists in the electrification of the public transportation fleets, and in August 2019, AtB implemented a new bus fleet with 36 electric and 58 hybrid buses in Trondheim, Norway.

This thesis examines the carbon footprint of electrified city buses, by addressing the achieved and potential reduction for the new bus fleet in the Trondheim area. The zero emission assumption is evaluated, as it separates the direct and indirect emissions. Important aspects, such as geographical location of production, charging electricity mix, and impact from production and operation on lifetime emissions, are examined to add comprehensiveness and depth.

A meta-analysis on life cycle assessment studies was completed, to investigate greenhouse gas emissions and energy demand in different parts of bus production, followed by a bus model build up using the findings, and comparing electrified buses with diesel and HVO buses. The models were then used in a case study of the bus fleet in Trondheim, to consider how parameters such as battery production, embodied emissions, electricity mix and carbon intensity affects the carbon footprint from a bus.

The results in this thesis show that the carbon footprint from the bus fleet in the Trondheim area, has been considerably reduced (37%) by implementing biofuel and electrified buses, and that a further reduction of 52% can be achieved by a full electrification. The operation emissions for the fleet were found to be 49 g CO_2-eq/person-km, which is lower than the average city bus and passenger car in Norway. It was also found that embodied emissions constitute 67% of the carbon footprint from an electric city bus, charging with Nordic electricity mix.

The thesis concludes that the embodied emissions in city buses should be considered when electrification increases, and that assuming zero emissions from electric buses are not reasonable, as both embodied emissions and indirect operation emissions are considerable. It is also stated that a framework for the acquisition of new city buses should be defined.

Abstract in Norwegian

Etter som nye globale og nasjonale klimastrategier, som arbeider mot Parisavtalen, blir iverksatt, har transportsektoren blitt satt i større fokus. Et miljøpotensial eksisterer i elektrifiseringen av kollektivflåter, og i august 2019 implementerte AtB en ny bussflåte med 36 elektriske busser og 58 hybridbusser i Trondheim, Norge.

Denne bacheloroppgaven undersøker karbonfotavtrykket til elektrifiserte bybusser, ved å ta for seg oppnådd og potensiell reduksjon for den nye bussflåten i Trondheimsområdet. Antagelsen om nullutslipp vurderes, da den skiller direkte og indirekte utslipp. Viktige aspekter, som geografisk plassering av produksjon, elektrisitetsmiks for lading, og innvirkning fra produksjon og drift på livstidsutslipp, blir undersøkt for å gi helhet og dybde til oppgaven.

Det ble utført en metaanalyse av livssyklusanalyser for å undersøke klimagassutslipp og energibehov i forskjellige deler av bussproduksjon. Deretter ble en bussmodell bygd opp basert på funnene, for å sammenligne elektrifiserte busser mot diesel- og HVO-busser. Modellene ble deretter brukt i en casestudie av bussflåten i Trondheim, for å vurdere hvordan parametre som batteriproduksjon, innebygde utslipp, elektrisitetsmiks og karbonintensitet påvirker karbonfotavtrykket til en buss.

Resultatene viser at karbonfotavtrykket fra bussflåten i Trondheimsområdet ble betydelig redusert (37%) ved å implementere biodrivstoff og elektrifiserte busser, og at en reduksjon på ytterligere 52% kan oppnås ved en full elektrifisering. Driftsutslippene for flåten ble funnet å være 49 g CO_2-ekv/person-km, noe som er lavere enn den gjennomsnittlige bybussen og personbilen i Norge. Det ble også funnet at innebygde utslipp utgjør 67% av karbonfotavtrykket til en elektrisk bybuss som er ladet med nordisk elektrisitetsmiks.

Oppgaven konkluderer med at de innebygde utslippene i bybusser bør vurderes når elektrifiseringen øker, og at det ikke er rimelig å anta elektriske busser som nullutslippsbusser, ettersom både innebygde utslipp og indirekte driftsutslipp er betydelig. Det er også uttalt at det bør defineres et rammeverk for anskaffelse av nye bybusser.

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List of terms

Term	Definition
BAT	Best Available Technologies.
BEV	Battery Electric Vehicle.
BF	Blast Furnace.
BOS	Basic Oxygen Steelmaking.
BTL	Biodiesel to Liquid.
CIS	Commonwealth of Independent States.
CI	Carbon Intensity.
CO_2	Carbon dioxide.
CO_2-eq	Carbon dioxide equivalents.
CPBT	Carbon Payback Time.
EAF	Electric Arc Furnaces.
EAM	European attribute mix.
El-mix	Electricity mix.
EU	European Union.
EU-mix	European production electricity mix.
FAME	Fatty Acid Methyl Esters.
FU	Functional unit.
GHG	Greenhouse Gas.
GO	Guarantee of Origin.
GWP	Global Warming Potential.
HDV	Heavy-duty Vehicle.
HEV	Hybrid Electric Vehicle.
HVO	Hydrotreated Vegetable Oil.
ICE	Internal Combustion Engine.
ICEB	Internal Combustion Engine Buses.

Term	Definition
ICEV	Internal Combustion Engine Vehicle.
IPCC	Intergovernmental Panel on Climate Change.
LCA	Life cycle assessment.
LCI	Life cycle Inventory.
LCIA	Life cycle Inventory Assessment.
LCO	Lithium Cobalt Oxide.
LFP	Lithium Iron Phospate.
LiB	Lithium-ion battery.
LMO	Lithium Manganese Oxide.
NAFTA	North American Free Trade Agreement.
NMC	Lithium Nickel Manganese Cobalt Oxide.
PHEV	Plug-in Hybrid Electric Vehicle.
SS	Stainless Steel.
SSB	Statistisk Sentralbyrå.
TTW	Tank-to-Wheel.
WTT	Well-to-Tank.
WTW	Well-to-Wheel.

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1 Introduction

As new global and national climate strategies were implemented at the start of 2020, the transportation sector has come into huge focus. In Norway, great environmental potential exists in the electrification of the public transportation fleets. Being the technical capital of Norway, Trondheim municipality strive to be a leading example for climate friendly technology. Therefore, AtB, the operator of the public transportation in Trondheim, implemented a new low emission bus fleet in August of 2019, with the purpose to reduce the GHG emissions.

This thesis examines the carbon footprint of electrified city buses. Through a meta-analysis and data from AtB, different bus fleet scenarios are analysed with the help of life cycle thinking and a life cycle methodology. In this chapter the motivation, purpose and problem to be addressed for the thesis is presented.

1.1 Motivation

In the early 1900s the climate change was initially identified from scientists, but it was not until the 1960s the scientist, Guy Stewart Callendar, advocated for the global warming effect on the planet. At that time, the first calculations on the two degree increase of earths temperature were also presented by Callendar. Between the 1960 and 1990, the theory of climate change and global warming was met with tremendous scepticism. However, in 1988, record temperatures were reported in the United States of America, followed by several wildfires throughout the country. After negative environmental events, climate change received more public attention through media, and new informative research studies came to light. One year later, Intergovernmental Panel on Climate Change (IPCC) was established and started their research on climate change. They have been an important organisation on the subject for the last 30 years. Studies IPCC conducted showed predictions on huge environmental disasters, glaciers and poles melting, and a sea level increase by 2100.[1]

Countries and government leaders started to take the reality of climate change on a serious level at the end of the 1900s. State leaders agreed on the Kyoto protocol in 1997, and the Paris agreement in 2015. During the last decade the environmental change has been described as a crisis with leading figures such as Greta Thunberg in Sweden and Licypriya Kangujam in India serving as catalysts for climate demonstrations all around the world. The level of attention is a huge motivation for a low-carbon society where reducing greenhouse gas (GHG) emissions are essential.[1]

In 2014, IPCC reported the global GHG emissions by sectors. The main impact sectors for world average are presented in Figure 1.1. The biggest contributor of GHG emissions is the electricity and heat production sector. This stems from the non-renewable resources in energy production, as well as heat production from electricity. The industry and transportation sectors emit the third and fourth highest GHG numbers according to IPCC. [2]

The GHG emissions in Norway by sectors are presented in Figure 1.2. The sectors with highest significance are different compared to the global sectors. The dominant sector is oil and gas extraction. The energy supply and heating percentage are very low due to renewable hydro power in energy production. Industry and road traffic are the second and third highest impacting sectors, which is similar to the global GHG emissions. [3]

The first steps towards climate change mitigation were through the Kyoto protocol and Paris agreement. The Kyoto protocol was the first agreement to mitigate the GHG emissions in the atmosphere. The protocol was aimed at the

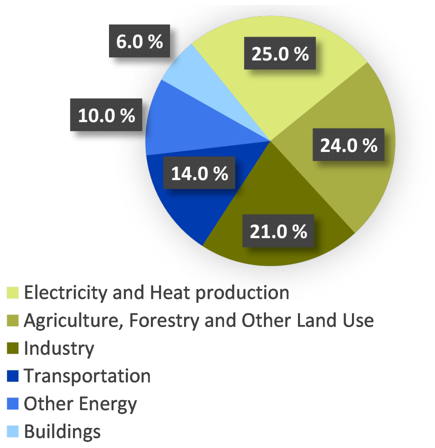

Figure 1.1: *Global greenhouse gas emissions in 2014 illustrated by sectors. Data gathered from [2].*

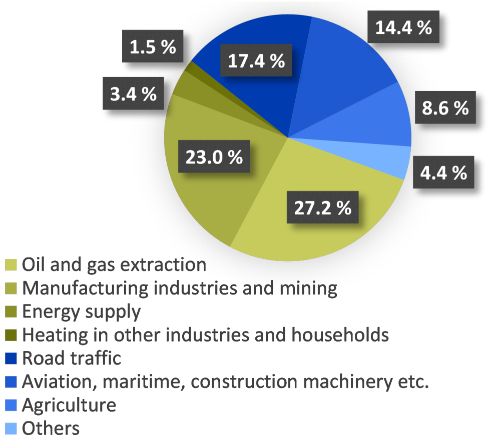

Figure 1.2: *National greenhouse gas emissions in Norway in 2018 illustrated by sectors. Data gathered from [3].*

industrialised nations to reduce their emissions. The more industrialised countries have a bigger responsibility than the less developed countries. The protocol ended in 2012, and many countries did not meet their objectives; two of which were the United States and China, both leading countries of GHG emissions. This led to a 40% rise in GHG emissions from 1990 to 2009. [4]

In 2015, almost every country consented to the Paris agreement, in order to fight the effects of climate change. The main goal of the agreement is to limit the average global temperature growth by the end of the 21st century. It is not to exceed two degrees Celsius from the pre-industrial levels. The agreement also aims to implement steps to prevent the temperature rise to exceed 1.5 degrees Celsius. Out of the Paris agreement, new requirements and standards came forth. The UN have presented seventeen sustainability goals that work to eradicate poverty, fight inequality, and stop climate change by 2030. The green shift and the national goals defined for the next century are motivated with the Paris agreement and UNs sustainability goals. [4, 5]

Norway and the European Union (EU) have analysed the climate potential for the next century. In the beginning of 2020, Norway produced the "Klimakur", evaluating necessary climate cuts by 2030. The "Klimakur" consider the sectors in the Non-Emission-Trading-System (NETS), which include the transport sector. NETS covers the sectors not included in the EU Emission Trading System (EU-ETS). Norway cooperates closely with the EU, and because of this, Norway was presented with a climate budget for the NETS sectors. This means that the emissions every year are regulated, instead of the final emissions in the year 2030. Therefore, regular cuts need to be implemented to achieve these yearly reductions. Norway estimates that transport will have the biggest impact on reduction. Around 11.8 million tonne of GHG emissions is estimated to be reduced by 2030. This reduction is found by moving away from diesel vehicles and implementing biofuel, electric and hydrogen powertrains. In addition to clear electrification goals, the "Klimakur" presents that the transition to a circular economy is an essential process. This establishment is important as new technology in transportation is presented. [6]

The EU and Norway have a clear framework for the circular economy, especially for recycling. In 2015, EU and the Norwegian government increased the standards for vehicle recycling from 85% to 95%. This means that 95% of a car needs to be recycled, while also 85% of the material in a car needs to be recycled. EU has great ambitions up until 2035 where 65% of all generic material are to be recycled. For a circular economy, efficient product recycling is an important element. [7, 8]

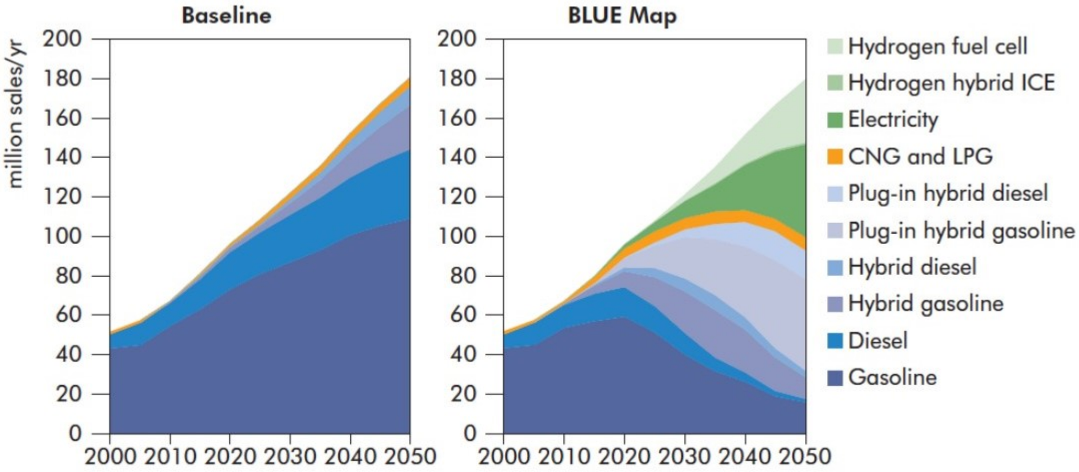

Figure 1.3: *The expected sales in millions per year baseline for powertrains from 2000 until 2050 to the left and the required sales evolution of powertrains from 2000 until 2050 to reach the two degree goal. [9]*

Norway is a part of EUs climate framework for 2030, which shows a clear climate plan. The EU set a goal to reduce GHG emissions from transport with a minimum of 60% by 2050 compared to 1990 levels. They present the estimated evolution of transportation technologies targeting the two degree goal by 2050, displayed in Figure 1.3. It shows a great reduction in diesel, while an increase in hydrogen- and electric powertrains. The electrification of the transport system includes a more energy efficient powertrain system, an increase in renewable electricity production and reduction of fossil fuels as an energy source. [9]

The total emission from transport were 28% above 1990 levels and will need to shrink by two-thirds by 2050 in order to meet EUs goal. The European Commission has therefore initiated a strategy for reducing heavy-duty vehicles (HDVs) fuel consumption and GHG emissions. This includes development of a computer simulation tool for estimation, and a registration of the data acquired from it. The data will be made available to the public starting 2020, and later be used to set mandatory GHG emission limits for newly registered HDVs. [10, 11]

Working towards the Paris agreement, clear climate strategies are essential. The goals of the UN, the EU and the Norwegian "Klimakur" drive the implementation of low emission transportation. Nordic countries are leading the public transportation fleet transformation, as several cities have implemented new bus systems and bus fleets. The technological capital of Norway, Trondheim, is among these, and implemented a low emission fleet in August of 2019 with 36 electric and 58 hybrid buses. [12]

1.2 Purpose

The purpose of this thesis is to give an insight into the environmental consequences pertaining to production and operation of electric buses, by investigating a case study in the Trondheim area. The thesis' authors and AtB will receive a detailed understanding of the bus production emissions; focusing on the battery and other large contributors. As well, the impact operation has on GHG emissions for various powertrains.

The thesis is intended to increase the knowledge on the topic of electric buses and provide attention to complications. The stakeholders for this thesis can be bus companies, bus buyers, bus producers, component producers, environmental advocates, politicians, scientists, recycling companies and others seeking information.

This will expectantly lead to a better understanding of how today's development affects the climate change, and guide the stakeholders. It might give stakeholders motivation to set restrictions and guidelines for the producers of electrified buses, which will in turn reduce the carbon footprint. It might also help to provide information on which electrified options are favourable going forward.

1.3 Problem to be addressed

The GHG emissions from transportation need to be reduced to achieve the climate goals of low emission societies. AtB has therefore taken action by implementing electric buses and replacing fossil fuels with biofuels. The environmental impact of this change are yet to be examined; thus, this thesis will investigate how the electrification impacted AtBs operating emissions, and how embedded emissions need to be considered.

The main problems to be addressed in this thesis are:

- *What is the achieved and potential reduction of the carbon footprint from the new bus fleet in Trondheim?*
- *Is it reasonable to assume that electric buses are zero emission buses?*

To adequately answer the main problems, some sub-questions are presented:

1. What is the geographical locations effect on bus production emissions?
2. What is the impact of the production and operation on the lifetime emissions?
3. How important is the electricity carbon intensity on GHG emissions?

By answering the three questions presented, the problem to be addressed should be covered in detail.

1.4 Structure of thesis

To answer the main problems and sub questions, it is necessary to introduce several technical aspects. This is presented in chapters 2 through 7, while the results, discussion and conclusion are presented in chapters 8 to 10.

Chapter 2 presents the current emissions from the transportation sector in Norway. It focuses on road transport; especially on personal vehicles and city buses. An insight into current public transportation fleets in the Nordic countries and the status of new projects are provided. Lastly, political strategies on a national and local level are presented. Further, **Chapter 3** gives an introduction to circular economy and the methodology of a life cycle assessment. **Chapter 4** explains GHG as well as the global warming potential. The power market is presented with information regarding flow of power and guarantees of origin. Carbon intensity of energy sources and various electricity mixes are also presented.

Chapter 5 provides an introduction to the different types of electric buses and powertrain options. The construction of the bus from individual components is presented with details on the battery usage and prospects. **Chapter**

6 explains the bus production chain from material extraction to vehicle assembly. The chapter provides detailed information regarding steel, aluminium and battery processing.

Chapter 7 is a literature review to investigate the GHG emissions from a bus with a top-down approach. The component, material and total emissions are presented, with a detailed examination of steel, aluminium and battery production. **Chapter 8** is a case study on the emissions from the new bus fleet in the Trondheim area, and presents the results of the thesis. It is built up with a bus model based on chapter 7 and data directly from AtB. **Chapter 9** discusses the results and different factors that impact them. The problem to be addressed is in focus. Finally, **Chapter 10** provides the conclusion of this thesis, based on the results and discussion.

2 Current Status and Future Plans

The transportation sector in Norway is important when working towards the climate goals of 2030 and 2050. The great potential in GHG reduction can be achieved through implementation of low emission vehicles in all aspects of the road transport. This transition is motivated with ambiguous political strategies, both national and local.

This chapter presents emissions from the road transport sector in Norway and the status of public transportation fleets. Political strategies on transportation from the Norwegian government, Trøndelag county and Trondheim municipality are presented.

2.1 Transportation emissions in Norway

Norway emitted 52 million tonne of GHGs in 2018, whereas 17.4% of these were emitted from road transport. From the 9.1 million tonne emitted in the road transport, cars constituted 50%. Public transportation buses do not have their own registered emission category nationally, but are included in the emissions from HDVs. HDVs emit around one third of the emissions, equivalent to 2.9 million tonne of GHGs. An overview of road transport emissions is presented in Figure 2.1 gathered from Statistics Norway (SSB).[3, 13]

The registered national and local emissions only include emissions that are emitted in the registered area, i.e. only local, fossil or direct emissions from combustion. To give an example, if production of the fuel did not occur in the specific area, the emissions from processing are not included. This would be global emissions. It assumes that electric and biofuel have zero emissions. [12]

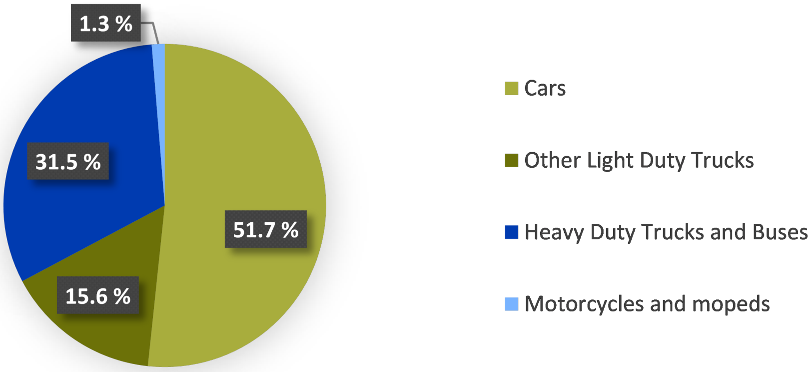

Figure 2.1: *Greenhouse gas emissions in road transportation in Norway divided by sectors. Data gathered from [13].*

The emissions from road transport increased from 7.18 million tonne GHGs in 1990 to 9.1 million tonne GHGs in 2018. In 2015, the emissions reached an all time high with 9.98 million tonne GHGs emitted. The emissions then decreased in the period from 2015 to 2017. In 2018, the emissions in road transport increased again from 8.81 million tonne GHGs in 2017. This increase is related to the reduction of biofuel mixture in diesel because of palm oil[14].[13]

At the start of 2019, SSB presented emissions per person-kilometre [1] in Norway for passenger cars and city buses.

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[1] Person-kilometres is a unit for passenger transport. One person-km equals one passenger transported one kilometre.

SSB presented, even with an increase of kilometres driven from 1990 to 2018, that emissions for both cars and city buses have decreased. This originates from the increased use of low emission energy sources for fuel. The statistics show that in 2018, city buses had higher emissions per person-kilometres than passenger cars. The cars emitted 69.5 gram CO_2-equivalents per person-kilometre, while the city buses emitted 72.5 gram CO_2-eq per person-kilometre. SSB present the development to emerge from the increase of electric passenger cars on the road, and a low magnitude of people utilising the public transportation system. For the public transportation fleets to be competitive in the environmental aspect, new low emission fleets needs to be implemented.[15]

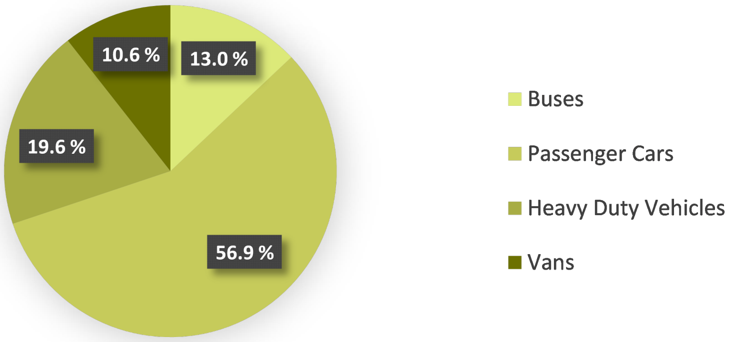

Figure 2.2: *Local emissions from road transport in Trondheim municipality in 2018. Data gathered from [16].*

In the Trondheim Municipality the road transport constituted 34.2% of the total emissions in 2018. This is a total of 156 000 tonne CO_2-eq, an increase with more than 6% from 2017. In Figure 2.2, the emissions from road transport are represented by sectors. Passenger cars shows to emit over half of the emissions in road transport. While buses consist of the 13% of the emissions, resulting in 20 000 tonne CO_2-eq. [16]

2.2 Current public transportation fleets

Public transportation is established in every city and has up until the last few years consisted of internal combustion engine buses (ICEB). In 2017, there were 3 million city buses operating globally, where 385 000 were electric buses. In addition to fully battery electric buses this includes hybrids, trolley and fuel cell buses. But nearly all of these electric buses operate in China, which is the leading country when it comes to implementing electricity in the public transport sector. Beijing planned to operate 10 000 electric buses by 2020. They started slightly above 1 000 in 2018. The last year multiple projects of electrification has been reported all around Europe and America. The electrified bus fleets have become a reality in Netherlands, UK, Germany and the Nordic countries. [17]

There are multiple suppliers of electric buses, and Volvo has become a huge producer in the Nordic countries. The electric Volvo models were first introduced in their home town Gothenburg and branched out to other cities like Stockholm. Furthermore, Volvo have also shipped electric buses to the capital of Norway, Oslo, and in 2019 to Trondheim. Still the investments in Europe are of small scale compared to the investment in China. Figure 2.3 shows the producers that have sold the greatest amount of electric buses in the Nordic countries. BYD auto is a Chinese vehicle producer and has the most buses operating in the north. VDL Group has its origin from the Netherlands and comes second just ahead of Volvo. [17, 18]

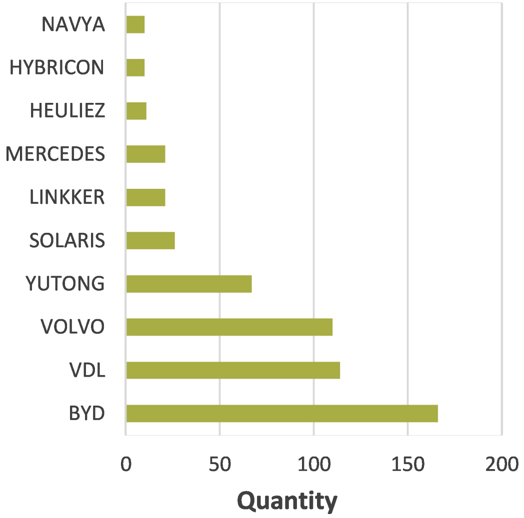

Figure 2.3: *Quantity of electric buses provided to the Nordic countries from producer by the end of 2019. Data gathered from [18].*

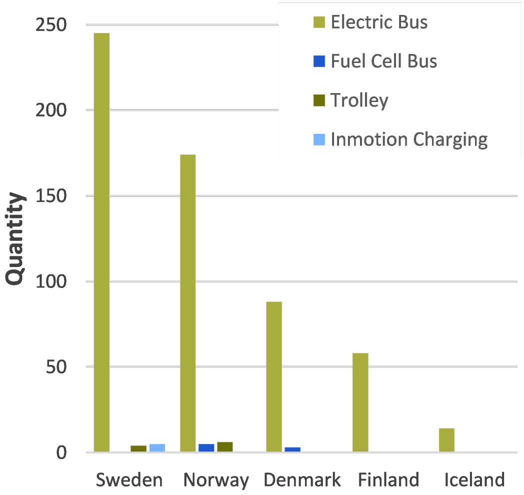

Figure 2.4: *Quantity of electric buses per country by the end of 2019. Data gathered from [18].*

In the Nordic countries, the implementation of electric buses increased drastically at the end of 2019. Several projects were implemented and initiated. In Figure 2.4 the number of electric buses in each Nordic country is presented. In addition to this, during 2019, 913 electric buses were deployed. Currently, the electric buses are the leading powertrain for the low-emission bus fleets. Figure 2.4 shows low amounts of fuel cell buses, trolleys and inmotion charging. In Norway, projects are initiated in Hedmark, Tromsø, Bergen, Drammen, Rogaland and Oslo. After Oslo started the electrification in 2017 the implementation of electric buses in Norway skyrocketed. At the end of 2019, Ruter in Oslo had 115 electric buses, AtB in Trondheim operated 36 and Skyss in Bergen had ordered 88 electric buses.[18, 19]

2.3 Political strategies

Norway published the *Klimakur 2030* in February of 2020 with clear environmental targets for the next century. Many of these goals were already presented before the Klimakur. The measures defined for road transport are divided into activity measures, electrification measures and increased usage of biofuel. [6] The main measures for vehicles and buses are:

- 100% of new personal vehicles are electric from the end of 2025.
- 50% of new trucks are electric or fuel cell trucks from 2030
- 100% of new city buses are electric from the end of 2025
- 75% of long distance buses are electric or fuel cell buses from 2030
- Increased use of advanced liquid biofuel in road transport

The Klimakur also presented the estimated potential for reduced emissions. The total estimated emissions from road transport from 2021 to 2030 are 70.8 million tonne CO_2-eq, while the estimated reduced emissions from the presented measures are 7.47 million tonne CO_2-eq. [6]

Environmental transportation goals are also defined in the various counties within Norway. Among them, Trøndelag county has a goal of a sustainable transport structure and climate neutral shuttle service by 2030. For the public transportation this means a focus on infrastructure for easier utilisation of the collective system. Trøndelag county have implemented the same climate measures as the Norwegian government with a goal that 100% of new city buses are to be electric from 2025 and 75% of new region buses have electric or hydrogen powertrains from 2030.[20]

Before the merging of the North- and South-Trøndelag, South-Trøndelag and AtB had clear goals for emission reduction in the public transportation. After the merger, these goals fell through, and the county has not yet set new goals. It is expected that clear goals will be defined in the near future.

Trondheim is where AtB has it's headquarters and largest operations of city buses. The municipality has established Trondheim to become a leading example and collaborative arena for green value creation and the development of climate-friendly technology and ways of living. The municipality established, in 2017, a climate plan for 2030. They determined some prominent climate goals and used optimistic words throughout the climate plan.[21] Some general goals for 2030 in Trondheim area are:

- By 2020, Trondheim is a role model and a collaborative arena for green value creation and the development of climate-friendly technology and ways of living.
- In 2030, the municipality of Trondheim is a zero emission business.
- By 2030, Trondheim will reduce GHG emissions by 80% compared to 1991 levels.
- In 2030, direct GHG emissions from transport will be 85% lower than in 1991.

Apart from the above mentioned goals, the municipality has not presented clear goals on bus powertrain technology for the coming years. [21]

3 Circular Economy

Circular economy is a model focusing on re-use, re-manufacturing and recycling of material. New products are produced from old products, and aims to replace the current economic model; take, make, dispose. This is an aspect of the society with advantages in regards of resource scarcity, climate change and waste. To achieve a circular economy, an understanding of life cycle thinking is required. An overview of the actual impact of a products life cycle can be analysed with a life cycle assessment model. [22, 23]

3.1 Life cycle thinking

Life cycle thinking is analysing a product beyond the standard production and usage, but throughout the entire life cycle. For each phase of the life cycle the social, environmental and economical impacts of the product are evaluated. A life cycle of a general product is presented in Figure 3.1. The life cycle goes from resource extraction used for production of a product, to end of life where the product is recycled or disposed to landfills. With a better understanding of a product life cycle, specific initiatives can be implemented to improve the three aspects of the life cycle thinking, and eventually a circular economy is achieved. [24]

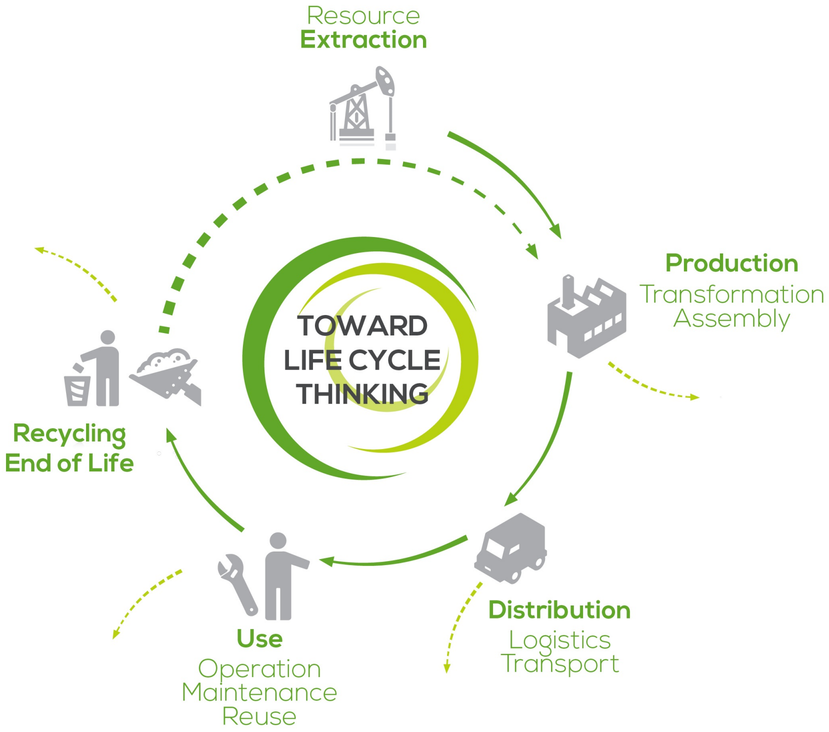

Figure 3.1: *Life cycle of a product from resource extraction through materials processing, manufacture, distribution, use and end of life.[25]*

This thesis focuses on the environmental aspect of the life cycle thinking, and through the life cycle assessment methodology it is possible to analyse the impact a product has on the environment. [24]

3.2 Methodology

The thesis examines several studies that methodically conduct an analysis on products. The products for this thesis are various low or zero emissions buses. This methodical method is a life cycle assessment (LCA). Understanding how this method is conducted is important for a proper analysis of studies that adopt it. Identifying the influential factors and interpreting the results are essential for this thesis.

Life cycle analysis or life cycle assessment is a systematic and methodological method to look at the environmental impact of a product throughout its life cycle. The method is presented in the textbook, Life Cycle Assessment (LCA): A Guide to Best Practice written by Prof. Dr. Walter Klopffer and Prof. Dr. Birgit Grahl. Their definitions and methodology are based on the international standards ISO 14040 and 14044. These standards are used regularly in LCA studies. [26, ch.1]

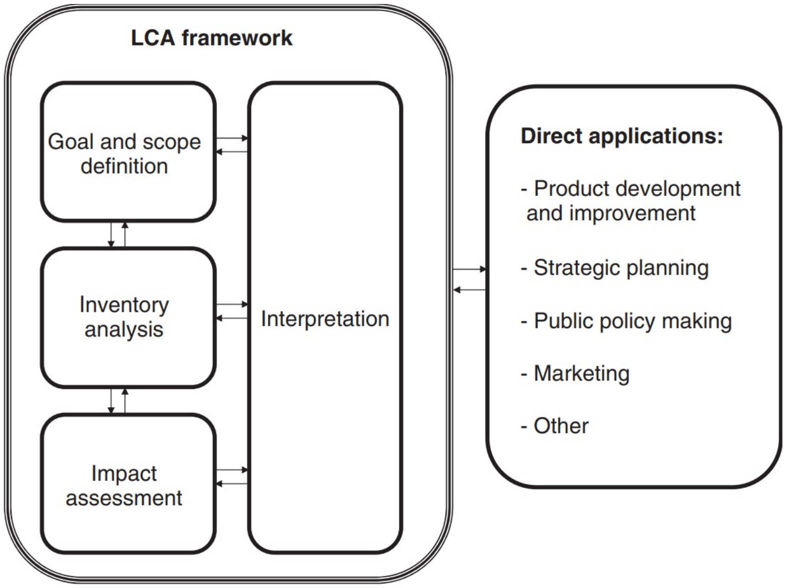

Figure 3.2: *LCA structure based on ISO 14040 and 14044 standard.[26, ch.1]*

Based on these standards, the LCA has a specific structure. This structure is presented in Figure 3.2. It is split into four parts. The Goal and scope, Inventory (LCI), Impact assessment (LCIA) and interpretation. To conduct a successful, comprehensive and detailed LCA report, it’s crucial that the stages are completed correctly.[26, ch.1]

3.2.1 Goal and scope

The first phase of the LCA process is the goal and scope. Both are two important elements that need to be defined. The goal of the study describes the objective; why the study is conducted, who it is conducted for, and if comparative assertions are intended in the study, while the scope is more comprehensive to define. [26, ch.2]

The scope defines the breadth and depth of the study. It determines the system boundaries of the LCA. This can easily be presented in a system flow chart with boundaries, where each unit process and interrelations are presented in boxes. Here one should be as precise as possible. Defining the system boundary is important to get a good comparison of two LCA studies. If LCA studies contradict themselves, it can originate from different methodology and different system boundaries. [26, ch.2]

When defining boundaries for an LCA it is often normal to include the entire life cycle. This is explained as a cradle-to-grave boundary presented as the green line in Figure 3.3. Cradle is the extraction of the resources and grave is the end of life. The boundary of LCAs varies with the intention. Cradle-to-gate is the boundary from raw material extraction to a specific gate. The gate could be a product gate or a mineral processing gate. Gate-to-gate is from one specific entry gate to an exit gate. A frequently used boundary for vehicle LCA is well-to-wheel (WTW) represented as the red line in Figure 3.3. The well represents the extraction of an energy source, example oil, and wheels is when energy is exerted on to the wheels. This boundary includes the processing of the energy source, transportation and use in the vehicle. The WTW can be split into well-to-tank (WTT) and tank-to-wheels (TTW). The WTT is the global processing, while the TTW is the local. If the LCA excludes the WTW, the boundary would be equipment life cycle boundary represented by the blue line. Analysing the use phase, also referred to operation, is represented by the black line in Figure 3.3. [26, ch.2] [27]

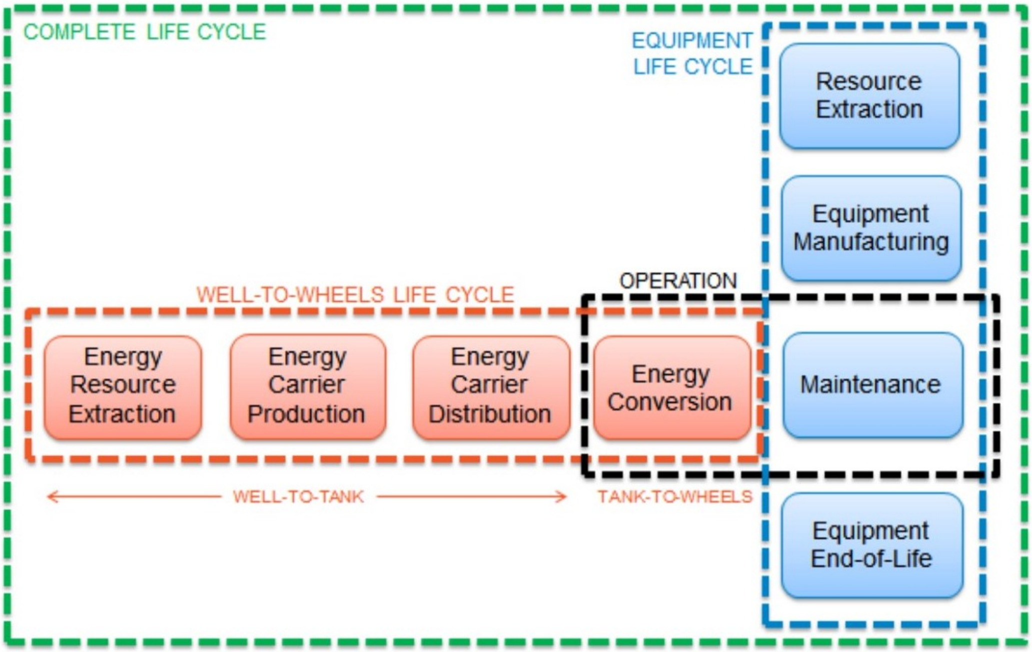

Figure 3.3: *Different boundaries for life cycle assessment. [27]*

In addition, geographical boundary and a temporal system boundary, time horizon, should be defined. How many years will be accounted for in the life cycle is especially important in regards to recycling and new technology which is being developed. Where the material of the product comes from is an important factor. Whether it is from Africa, Asia, Europe, and what country. [26, ch.2]

Apart from the boundary of the scope there are other important factors to define. One of these is the functional unit. The LCA will be based on what the functional unit of the specific product is. This can for example be litres of a beverage, certain length in kilometres a car tire will go, or just a number of specific plastic bags. Apart from this, all specifications of said product need to be defined. [26, ch.2]

3.2.2 Inventory

The life cycle inventory (LCI), is a list and quantification of all the inputs and outputs in the defined boundary system. An LCI has input and output data in all flows and processes, and these data are based on five laws of nature. Conversion of mass, the first and second laws of thermodynamic, conservation of energy and increase of entropy, principle of stoichiometry and Einsteins formula $E = mc^2$. As a result, the LCI have a foundation from thermodynamics, chemistry and the laws of physics to calculate and establish correct data output based on given input. Completing the LCI with an in depth analysis of material and energy flows and providing good data is crucial to achieve a satisfactory LCA. [26, ch.3]

Data are essential for the LCI. Data can be complex and different factors are important for collection of data. Data quality and origin, functional unit, aggregation, documentation and estimations will all affect the resulting LCI and further the LCIA. [26, ch.3]

Providing data with an acceptable quality the origin of these data will be the main factor. Data are split into primary and secondary, also called generic, data. Primary data are provided directly from the producers data on input and outputs of their products. Often these types of data are nearly impossible to obtain, as most of them are classified, thus, an LCI often has to accept secondary data. These are data acquired from literature, often other LCIs on the same subject. Primary data are the data with the highest quality and will provide the best LCI and LCA results. On the other hand, secondary data can be data with great variance or worst case inaccurate. This variance is mostly dependent on the goal and scope of the study from where the data are gathered. The secondary data are generic which means numbers are averaged or rounded to the nearest decimals. By using a correction factor it is possible to take the generic data and apply it to the desired case study. If neither primary or secondary data exist, the data have to be estimated. In Figure 3.4, it shows how an LCA should be assembled based on primary and generic data. Primary should represent the biggest and most important parts of the study while the generic data can supplement and provide data on areas which are hard to document, e.g raw material, energy and transport. [26, ch.3]

Estimating data are preferred over omissions of data despite the uncertainties. This is based on that the less examined systems will always perform better compared to the more examined system. That is at least for data that are not insignificant. Estimation can be based on older data or data with other boundaries, data with chemically similar compounds and materials and data based on information on technical manuals. [26, ch.3]

The materials in the inventory is quantified with units. A unit can be piece, mass, percentage or any other meaningful unit. The unit should be meaningful in the sense that it should be easily converted to the functional unit that the flow system is defined by. This is where secondary data fall into the category inapplicable. The functional unit and boundaries in other studies are dissimilar making the potential data inapplicable to the main case study. [26, ch.3]

Defining the inventory for the study can be comprehensive and understanding what data to include and exclude can be difficult. Some input data can be insignificant, but it is not simple to cut-off data. There are three things that cause inputs to be insignificant. That is mass, energy and environmental relevance. The first criteria is if the mass and energy have percentage fraction below 1% then it can be cut-off. A product that is made out of ten different materials, the material will equivalent a percentage of the product in both mass and energy. If one of these materials have a mass percentage under 1% this material can be cut-off, but just as long as the energy percentage is also under

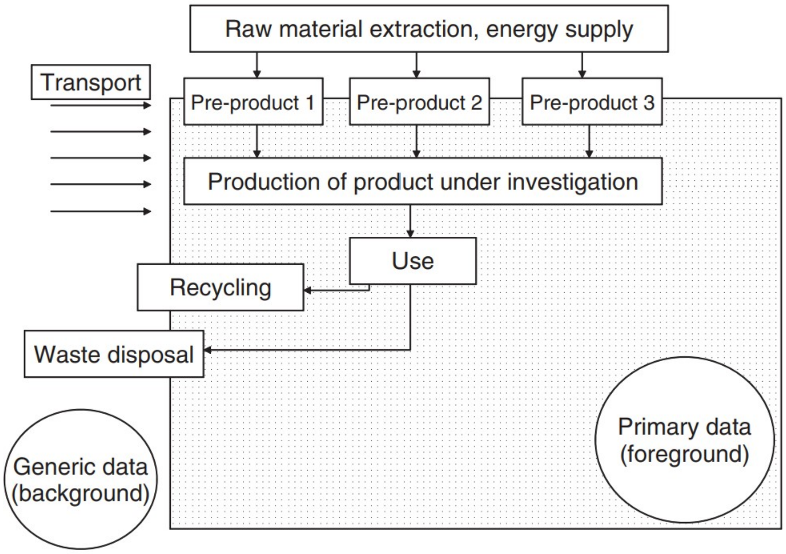

Figure 3.4: *Desirable structure of an LCA with primary and secondary data.[26, ch.3]*

1%. In addition, the rule is often applied that the portion of the mass and energy fraction to be cut off shall not exceed 5% of the total percentage. [26, ch.2]

When presenting the LCI, both transparency and legibility are important to promote. The presented inventory, in a table, must be supplemented with appendices presenting all data, including assumptions and estimations. This has to be directly based on the goal and scope of the study. To provide a good legible inventory, a sensitivity analysis is crucial. The data should also be interpreted and discussed. [26, ch.3]

3.2.3 Impact assessment

The life cycle impact assessment, LCIA, is defined in ISO 14044 as an assessment to understand and evaluate the magnitude and significant of the potential environmental impact for a product system throughout the life cycle of the product. It provides more information, than provided in the LCI, that is easy and simplified, based on input and output data in the product system. [26, ch.4]

The standard from ISO 14044 give the LCIA a structure with both mandatory and optional factors. The LCIA is to define the **impact categories, category indicators and characterisation models**. It is to assign the LCI results to the impact categories and calculate category indicator results. The mandatory steps in the LCIA is presented in Figure 3.5. Other optional elements of the LCIA are **weighting, grouping and calculations of the magnitude of impact category indicators relative to reference information**. [26, ch.4]

An LCIA is a comprehensive project and would require multiple calculations to get the impact results. Fortunately, there are databases and software programmes that can be used to do these vast calculations. Some of these products are the Boustead Model, Ecoinvent, GaBi, SimaPro and Umberto. Some are software programs for flows and processes, while others are databases and some obtain both. [26, ch.3]

The impact categories represent different environmental impacts and are how the results of the LCIA is presented.

The LCI is assigned to different impact categories. There are multiple impact categories that can be used, and which categories that are most relevant to the case study depend on the goal and scope, thus the chosen categories should be presented there. Some of the most used categories are: Climate change, ozone depletion, human toxicity, photochemical ozon formation, acidification, eutrophication, ecotoxicity, resource depletion, water consumption and particulate matter. Choosing only one or a few categories is not a transparent LCA and might give misleading results. [26, ch.4]

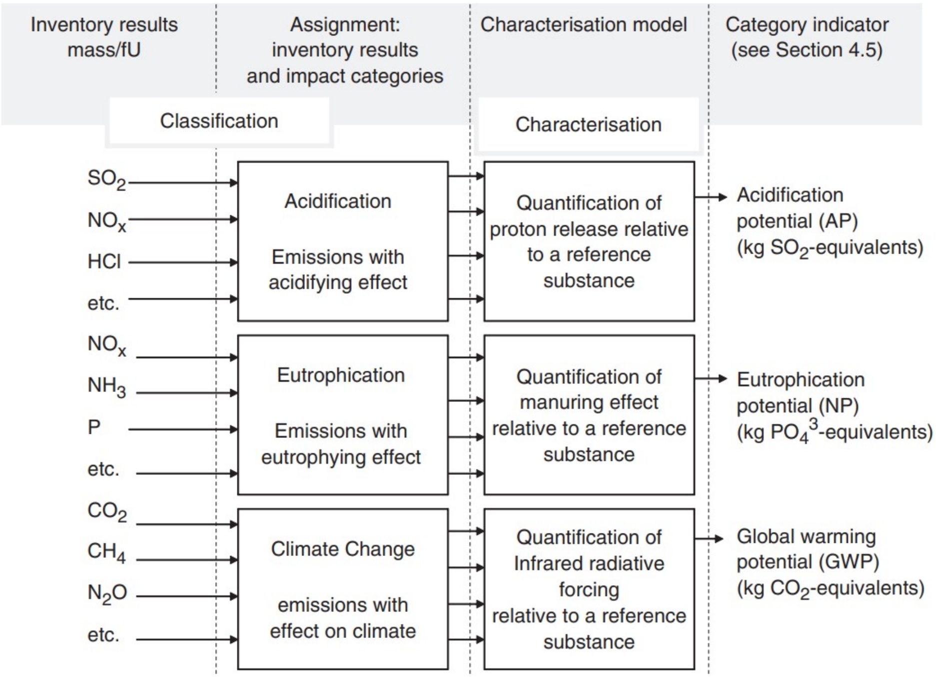

Figure 3.5: *Mandatory method from ISO 14040 and 14044 in LCIA phase of an LCA. [26, ch.4]*

Figure 3.5 presents the process in the LCIA where the results from the LCI are assigned to the impact categories, and these categories are added to a characterisation model, and finally referred to a category indicator. This is normally processed through the software programs that are used for this part of the LCA. Emissions with acidification effect are referred to as SO_2-eq, as emissions with effect on climate change are referred to as CO_2-eq. This is based on what the effect the chemical has on the environment. Methane(CH_4) can be used as an example where realising 1 kg of CH_4 to the atmosphere is the equivalent of 25 kg of CO_2 based on the 100 year global warming potential of each chemical. Both methane and carbon dioxide have an impact on the climate change but with different quantitative effect. [26, ch.4][28]

The defined processes are mandatory steps in an LCIA, also there are optional steps. Normalisation of the indicators is to calculate the magnitude of the indicators with regards to reference information. This reference information can vary, but it will give a simple comparison of the relative magnitudes relevant for the specific study. These results change from numbers that are difficult to grasp to numbers that are understandable and comparative. Software programs have often functions to normalise results. [29][26, ch.4]

Weighting is a controversial step in a LCIA. This step is conducted after classification, characterisation and normalisation. It multiplies the normalised results with a weighting factor that expresses the relative importance of the category. By doing this, it is possible to create a unit the impact categories can be added to, and then obtain a single representation of the environmental impact. There are many different weighting factors and each one will have different impact on the result and conclusion of the LCA. [26, ch.4] [30]

Grouping is another way to present results from the indicators or normalisation. There are two ways to perform this grouping; sort impact categories on a nominal basis or rank the categories in a set hierarchy. There are three different criteria that sort or rank categories in groups. Grouping is a great function for comparing studies. [26, ch.4]

3.2.4 Interpretation and critical analysis

The interpretation and critical analysis is the last step to complete the LCA. The results from the LCIA are analysed and discussed, with recommendations and conclusions. During the interpretation data quality checks are conducted. This can be done with sensitivity, uncertainty and centre of gravity analysis. The result from this final step is to reflect what was presented in the goal of the study. The final part of the LCA can be split into three parts: identification of signification issues, evaluation and conclusion. [31][26, ch.5]

Before writing any conclusions and presenting recommendations there are important processes that need to be conducted. Firstly, it is essential to determine any significant issues in the LCI and LCIA phase relative to the goal and scope of the study. The results of the LCI and LCIA are to meet the demand of the goal and scope of the LCA study. The aim is to avoid misinterpretations. ISO define that inventory data, impact categories and contributions of life cycle sectors can lead to significant issues. When the significant issues are determined and found to meet the goal and scope of the study, an evaluation of the results can be conducted. [26, ch.5]

After confirming any issues or contradictions in the LCA, the results of the LCIA will have to be evaluated. The goal for this evaluation is to ensure the reliability of the results and data. Three techniques can be used to execute this evaluation; **completeness, sensitivity and consistency check**. For a very in depth check of the LCA all these can be completed, but the sensitivity check is the only one that is mandatory by the ISO standard. Without it, the study would not be trustworthy.[26, ch.5]

The completeness check looks at the overview of the report, and how complete it is. The study should not have any gaps, especially regarding significant issues. If there are any gaps the LCI or LCIA should be carried out again. Alternatively, the goal and scope can be altered so that the study would be correct. [26, ch.5]

A sensitivity check looks at uncertainties in the output results based on four input factors; data quality, cut-off criteria, choice of allocation rules and selection of impact categories. The factors the sensitivity check analyses are those that differ in the modelling of the LCA studies. Lastly, the consistency check analyses whether or not the assumptions, data and method are consistent with the goal and scope of the study. [26, ch.5]

The three preceding evaluation methods examine the specific study, while the specific data need a mathematical approach for a proper analysis. There are five methods for mathematical analysis of the data; **contribution, perturbation, uncertainty, comparative and discernibility analysis**. The most used is the uncertainty analysis that evaluates the deviation in the numbers to present the certainty. [26, ch.5]

The contribution analysis evaluates a section's quantitative impact on the total result. The perturbation analysis is similar to sensitivity but with a mathematical methodology. It analyses factors with small alterations. The uncertainty analysis evaluates the propagation of input factors to the output results. This can be deviations in a measuring instrument. The comparative analysis is an important tool to analyse two different product systems that are similar with small alterations. The discernibility analysis is also a helpful tool in comparisons of multiple product systems. [26, ch.5]

Finally the LCA study presents the conclusions of the study, any limitations and further recommendations.

4 Greenhouse Gases and The Power Market

The most popular way of measuring environmental impact is by the use of emissions in the form of greenhouse gases. This chapter will give an insight into greenhouse gases, global warming, power markets and related emissions by introduction of the Guarantee of Origin system. These are all factors which need to be understood to analyse the environmental impact of electric vehicles.

4.1 GHGs and GWP

GHG are gases that trap heat in the atmosphere by absorbing energy and slowing the rate at which energy escapes to space. GHG is a general term that includes several gases. These are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. Methane emissions stem from production and transport of coal, natural gas and oil. Decay of organic waste in municipal solid waste landfills and livestock and other agricultural practices are also a source of methane emissions. Nitrous oxide is emitted from combustion of fossil fuels and solid waste, during agricultural and industrial activities and during treatment of wastewater. Fluorinated gases are a general term for synthetic man-made gases which have four main categories: hydrofluorcarbons (HFCs), perfluorcarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). These have very high global warming potentials relative to the other GHG and can have long atmospheric lifetimes. These are emitted from various industrial processes and are sometimes used as substitutes for stratospheric ozone depleting substances. [32]

The magnitude of the impact on climate change from each gas depends on three main factors. The first is how much is in the atmosphere. Big emissions from GHGs lead to higher concentrations. Secondly, the time they stay in the atmosphere, which can range from a few years to thousands of years. They stay in the atmosphere long enough to become well mixed and therefore the measured amount is roughly the same all over the world. The third main factor are how strongly they impact the atmosphere. How much energy each GHG absorbs is different and therefore has different efficiency in warming the planet. For that reason, it has been calculated a Global Warming Potential (GWP) for each gas to reflect the impact. This makes it possible to compare different gases. It is reported as how much energy it absorbs over a given period of time relative to one metric tonne of carbon dioxide. The time frame of the calculations are often set to 100 years. By shortening this, the GWP will change, as the gases have different lifetimes. A shorter time frame will lead to a higher GWP from gases with shorter lifetime and vice versa. To report the impact on climate change, the GWPs are used to calculate the emissions from the gases in CO_2-equivalents and then summarised to give an overall impact. [33]

4.2 Energy sources

There are different sources of energy in transportation sector that are alternatives for the fossil fuels, petrol and diesel. These are biofuels, electricity and hydrogen. The continuous electrification and implementation of low emission buses lead to an increase in demand for electricity and biofuel production. How these are produced has a great impact on the environment.

WTW analysis is an important tool when evaluating the emissions from various energy sources. The WTW emissions for seven fuel sources are presented in Table 4.1, and are further explained. LNG and LBG are liquid natural gas and liquid biogas. The diesel has a mixture of 12% biofuel. The table shows that diesel emit the highest GHG emission

Table 4.1: *GHG emissions from the WTW cycle of various fuel sources. Data from AtB. [12]*

Fuel	**Emissions**	
	$\left[\frac{tCO_2eq}{tfuel}\right]$	$\left[\frac{gCO_2eq}{kWh}\right]$
Diesel	3.206	-
LNG	2.750	-
Biogas/LBG	0.750	-
Biodiesel	1.740	-
HVO100	1.740	-
Electricity	-	75
Hydrogen	-	75

per tonne fuel. The emission from diesel originates from both production (WTT) and combustion (TTW) of the fuel. Thus, global and local emissions are an important aspect of energy sources emissions. [12]

4.2.1 Biofuels

Biofuel is a common term for biodiesel, bioethanol and biogas. These are fuels produced from biomass, but each has different production chains and resulting carbon intensity. Biomass is the only renewable carbon source because of the carbon cycle. Biological material uses carbon like an energy source to grow. When the material is converted to fuel, the same carbon is emitted, thus, the biomass as an energy source is carbon neutral during combustion, and the extra emissions originate from the production of the fuel, WTT. This is the processing and transportation of the fuel. [34]

Biofuels can be produced from first, second or third generation biomass which represent the feedstock used for production. The first generation is derived from food plants, such as biodiesel from oilseed rape and bioethanol from sugar. This generation presents issues in several areas, such as using food sources for fuel. Thus, more sustainable production chains were created. The second generation is produced from lignocellulose materials derived from whole or parts of plants and trees that are not used for human consumption. The third generation is extracted from aquatic biomass, such as algae. [34]

Bioethanol is an alcohol fuel that is normally mixed into petrol. Normal mix is 10% but Brazil, who are the second biggest producer of bioethanol, have up to 27% bioethanol mixed with petrol. A big problem with bioethanol is that it is mostly produced from first generation biomass, but the product reduces the GHG emissions during combustion of petrol. [35]

Biogas is methane produced from biological material, such as a garbage dump or sewage system. Natural gas is similar to biogas but is a fossil fuel, that mainly consists of methane but also varying amounts of hydrogen sulfide and non-combustible gases such as carbon dioxide, nitrogen and water vapour. Thus, biogas represent a renewable methane source to replace the natural gas. Biogas can be stored in vehicles as liquid biogas(LBG) or as compressed biogas(CBG). [36] LBG is presented in Table 4.1 to emit 0.75 tonne CO_2-eq per tonne fuel.

Biodiesel is often blended with diesel to improve characteristics such as freezing temperature and to reduce the carbon emissions during combustion. An example of this is Fatty Acid Methyl Esters (FAME) biodiesel. This biodiesel cannot fully replace diesel because most combustion engines require alterations, thus, FAME is mixed into diesel, optimally around 7%. Traditional biodiesel to liquid (BTL) is a synthetic diesel which can fully replace diesel. This is similar to hydrogenated Vegetable Oil (HVO), but complications regarding offal as biomass for HVO production has slowed down the commercial use. HVO and BTL have a different production chains compared to FAME, which provide different characteristics. HVO, a synthetic diesel, can completely replace diesel, considering they are very similar. HVO can potentially be mixed with normal diesel at the scale of 30% to 50%. If HVO is produced from secondary and third generation biomass it is possible to reduce the GHG emissions with 90% compared to normal diesel. Normally, FAME and HVO are produced from secondary biomass. [35–37]

In Table 4.1, emissions for both biodiesel and HVO are presented. They emit the same GHG emissions per tonne fuel, but HVO shows to have higher energy content per tonne fuel. This would result in longer range per tonne fuel.

4.2.2 Hydrogen

Hydrogen, similar to biofuel, has the potential to be a zero emission alternative, but most of the produced hydrogen today is from natural gas. The fuel can be used in combustion engines, but is best suited for use in fuel cells. Hydrogen is far from commercialised; with lack of fuel stations it is not made possible for use in passenger cars. Besides, the fuel is also still in the process of being research. But the potential with hydrogen is huge, and as presented in EUs plan for 2050, it is an important part of the future. [36]

4.2.3 Electricity

Electricity is alpha and omega in the electrification of the transportation sector. The production of electricity can vary greatly, and the carbon intensity depends on the energy source. Electricity, like biofuel and hydrogen, has the potential to be a zero emission energy source, but is dependent on the WTW production cycle.

There are various sources used in the production of electricity, and in Table 4.2, carbon intensity in electricity, generated from different sources, are presented. There are many sources for renewable energy production, and the most widespread are hydropower, solar power and wind power. Nuclear energy also contributes to a significant share of the power production. Renewable energy production has low emissions as opposed to fossil fuels. The renewable emission factors are significantly lower than the gas and coal based production sources. There is a 50 fold difference between wind and coal emissions. AtB from Table 4.1 assume a mix of electricity resulting in 75 g CO_2-eq per kWh.

Table 4.2: *GHG emissions from electricity production. Data from NVE [38] and NREL [39]. NG refers to natural gas.*

Resource	**Emissions** $\left[\frac{gCO_2eq}{kWh}\right]$	
	NREL	NVE
Coal	980	-
Gas	-	566
NG	480	-
Biogas	-	176
PV	44	-
Geothermal	40	-
Bio-Power	40	-
Wind	11	20
Nuclear	12	-
Hydro	7	6

Two different sources are provided in Table 4.2, reporting various emissions in electricity production, the National Renewable Energy Laboratory (NREL) and The Norwegian Water Resources and Energy Directorate (NVE). These are expected to provide credible data on the emissions. NREL base their emissions on a comprehensive meta analysis, while NVE use data from the Association of issuing bodies (AIB).

4.3 Power market

The power market is where electricity is transferred between countries by exporting and importing. The power market consists of electricity mixes (el-mixes) produced from different energy sources. Clean energy increasingly becomes part of the power markets, as fossil fuels such as coal and petrol are associated with high emissions and need to be reduced.

To show for the source of the energy in supplied electricity (or heating or cooling), electricity producers are on request issued Guarantees of Origin (GO). It was introduced by EU in 2001 to give consumers a choice between renewable and non-renewable power. [40] The producers can sell their GOs to a power supplier or to a business that wants to make a renewable claim. Thus, the consumer can make a choice to buy renewable energy by including GOs in their subscription. They are handed out by an Issuing Body, usually the national registry, which keeps track of all the commercial transactions. In Norway this is Statnett. One GO represents 1 MWh of produced electricity. The trade of GOs is done in an open market, with certificates traded freely across country borders. The prices of different GOs are determined by supply and demand. [41]

To accurately track the energy source of the delivered electricity to a specific power supply is impossible. GOs are therefore non-tangible commodities which are separated from the actual physical power distribution delivery. [41] This means the physical power delivered to a customer having bought a GO is the same as to a non-GO buying customer. But the GO allows the customer to claim a green source of the energy being used, and therefore sends a market signal showing sustainable intentions. The system can be seen in Figure 4.1. Furthermore, the GO makes sure the renewable power is not accounted for twice. The purpose of the GO system is to give the consumer increased control to choose cleaner energy and increase the incentives to produce renewable energy compared to other types of power production.

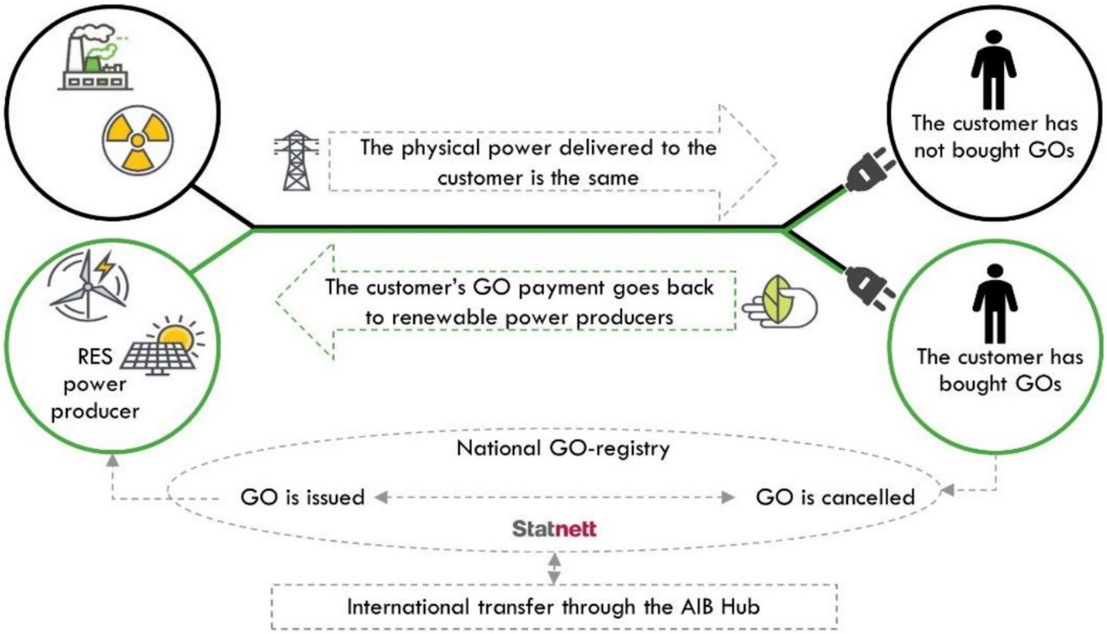

Figure 4.1: *The Guarantee of Origin system. [41]*

A GO specifies the source of electricity; the dates when it was produced; the identity, location, type and capacity of the production facility; whether the GO relates to electricity, heating or cooling; whether and to what extent the installation has benefited from support; the date when the installation became operational; the date and country of issue; and a unique identification number. [42]

Any remaining electricity that is not certified is available on the electricity market as "the residual mix". Different ele-mixes are used to calculate emissions stemming from electricity used from the grid. The origin of these mixes can be based on power production locally and physical flow, or it can be based on GOs. If power suppliers do not purchase GOs they must refer to an electricity disclosure when communicating their production sources. In Norway, this is provided by NVE, The Norwegian Energy Regulatory Authority. Their annual national electricity disclosure is calculated based on European trade with GOs and the European Attribute Mix (EAM), which is calculated by the AIB. The disclosure is based on Norwegian power production, which is mainly renewable (98% in 2018), but only a small part (about 15%) of the GOs sold from this are bought in Norway. Most GOs are sold to other countries and this gives extra incomes to Norwegian producers of renewable energy. To avoid double counting, the GOs are replaced with the EAM. [38, 41]

Table 4.3: *Carbon emission intensity from different el-mixes. Data from NVE [38], AIB [43], the Australian government [44], EEA [45], EPA [46], Climate Transparency [47] and [12]. The values are given in* gCO_2*-eq/kWh.*

Region	Production	Residual	Supplier	Ref
Norway	11	277	234	[43]
Norway	19	520	-	[38]
Sweeden	12	41	8	[43]
Denmark	209	503	415	[43]
Nordic	75	-	-	[12]
Italy	327	483	411	[43]
Poland	846	897	871	[43]
EU	294	486	-	[45]
Australia	800	-	-	[44]
US-avg	432	-	-	[46]
US-high	766	-	-	[46]
US-low	115	-	-	[46]
China	555	-	-	[47]
Japan	506	-	-	[47]

In 2018, the emission factor for Norwegian power production, not accounting for GOs, were 18.9 gCO_2-eq/kWh. If the GO system is used, the factor would be 520 gCO_2-eq/kWh for consumers who have not bought GOs, i.e. the final residual mix from the electricity disclosure [38]. For the total electricity consumption in Norway, the supplier mix, the factor is 234 gCO_2-eq/kWh. These and other relevant el-mixes are presented in Table 4.3.

The production mix accounts for emission from the total on site production in each region. The residual mix is the emission from the amount of attributes[2] from the total production which is not bought GOs for. The supplier mix is the emission from the total electricity consumption in the region, including both the purchased GOs (Tracked consumption) and the final residual mix (untracked consumption). The supplier mix is an average value for emission intensity for the whole region.

The residual mix for Norway presented by NVE, 520 gCO_2/kWh, is the final residual mix, while the rest of the residual mixes are domestic residual mixes. These domestic residual mixes are, in combination with the rest of the regions in EU, used to calculate the EAM. More detailed information on residual mix calculations and methodology can be found in AIBs reports on residual mixes [43, 48]. A new methodology for the calculation is going to be implemented from 2020 [49].

Through the rest of the thesis the final residual mix for Norway (520 gCO_2/kWh) will be abbreviated as NO-GO, the European production mix (294 gCO_2/kWh) as EU-mix and the Norwegian production mix (19 gCO_2/kWh) as NO.

There are three different el-mixes presented for the US (United States of America). This is done to get an intuition of

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[2] power, MWh

the variety of carbon intensity in the country. The power production in regions are different and therefore the US-low represents the region with the lowest carbon intensity, and US-high the opposite. The US-avg is the average carbon intensity for the whole country.

The price market for GOs is intricate, and prices vary with supply and demand for different GO products. The different types of GOs have different demands, and the price is determined by several attributes, e.g. location or technology of the power producer. This creates niche markets with surplus demand and higher prices. Information on the specific prices of GOs is non-transparent, but some approximations are available. The types of GOs with large volumes, such as Nordic Hydro, have low prices, while GOs with smaller volume have higher prices. Average price for Nordic Hydro GOs is about 0.5 Euros/MWh (Oct.2018) and estimated average European price between Oct.2017-Oct.2018 were 0.3-0.6 Euros/MWh. This is the price the producer can sell the GOs for. Because of broker fees, marketing and administrative costs, taxes and profits, the price for the consumer will be significantly higher. In the case of a private consumer price of 2 Euros/MWh, these costs can constitute about 70-80%. The price to the producer in this case is 0.3-0.6 Euros/MWh. This can be the case for low volume markets, while for markets which trades in larger volumes, the share are normally less. By increasing the transparency in the GO prices, the consumer can take more informative choices. [41]

5 Electric Buses

All across Europe, the market for alternative bus technologies are growing at an increasing rate. A report made by Chatrou CME Solutions regarding the buses in Europe, shows that out of a total of 14 392 city buses which were registered in 2019, 39% used an alternative propulsion system. This includes electrical, hybrid, CNG (compressed natural gas) and fuel cell powered buses, with an increase of 11% from 2018. Out of the 39% in 2019, 12% were electric buses. [50]

In order to shift all efforts and energy into electric bus technology, Volvo were the first bus manufacturer to stop production of diesel city buses [51]. Their first generation of electric buses was the Volvo 7900 Electric, a 12 m fully electrical bus with battery capacity of 76 kWh. In 2017 they launched their second generation 7900 Electric, with the possibility to choose between battery packs of 150, 200 or 250 kWh. At Busworld Europe 2019, Volvo 7900 Electric Articulated was introduced, an 18 m or 18.7 m bus with passenger capacity up to 150 and the possibility of a battery pack up to 396 kWh. The Articulated has already been ordered by Transdev for Gothenburg and Nobina for Malmö, with the magnitude of 157 and 60 respectively. These are set to be in operation in late 2020 or early 2021. [52, 53] This showcases the fast development in the electric bus market, and the implementation of new vehicles and technology will help boost it even more.

As we move towards a cleaner future with increasing renewable energy production and electrification, battery electric buses can help reduce the GHG emissions significantly. As advances in technology are made in the fields of batteries, renewable power generation and smart systems; electric buses can be implemented at a larger scale and with an increasing range.

5.1 Powertrain options

Electric vehicle is a general term for vehicles using battery for propulsion purposes. There are mainly three types, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicle (PHEVs) and battery electric vehicles (BEVs).[54]

Both HEVs and PHEVs are driven by a combustion engine and an electric motor, with a fuel tank and a battery. The difference between them is the external charging capability in PHEVs, but not in HEVs. The different electrified powertrains, including the ordinary, Internal Combustion Engine Vehicle (ICEV), is presented in Figure 5.1. The degree of electrification increases to the right in the figure.[54, 55]

HEV has a similar powertrain to ICEV, with small alterations depending on the magnitude of electrification. They are dependent on two energy sources, thus adopting two powertrain systems makes these the most complicated powertrain systems. The mild hybrid is the least electrified type. The combustion engine is always on during operation, thus it is an ICEV with an electric system to improve performance. The mild hybrid can be seen second to left in Figure 5.1.

The full hybrid has a different powertrain system presented in the centre of Figure 5.1. This structure gives the hybrid the possibility to operate in several modes. The two most important are electric only and engine only modes. The battery can be charged from regenerative braking and the engine. The hybrids can convert to be more electric, the PHEV. This is the plug-in hybrid where the battery can charge externally. The battery pack is often much larger than the other normal hybrids, which also results in a greater travelling distance.[55]

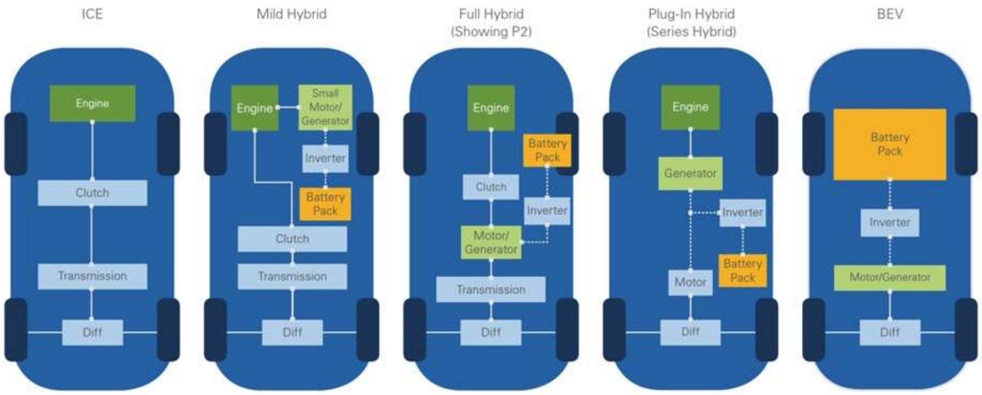

Figure 5.1: *Simple graphical structure of powertrains where the magnitude of electrification increases to the right. [56]*

The biggest advantage of the hybrids is the electric powertrain system which optimises the operation of the combustion engine for greater efficiency. Hybrids uses the battery to power the vehicle and the combustion engine to help when either extra range or power is required. These factors are another reason why BEVs are attractive. The BEV, far right in Figure 5.1, has a simpler configuration. With a larger battery and an electric motor the vehicle is fully electric with no combustion engine.[55]

5.2 Bus construction

A bus is constructed of many different components, which consist of various materials, including the powertrain. Typical method of describing the construction of a bus is by dividing it into two categories; glider and powertrain. Different possible powertrains were presented in section 5.1. The powertrain consists of all the components that provide power from the motor to the wheels. For an electric powertrain that would be the motor, controller, inverter, fluids, differential and battery. The glider consist of the remaining components of the vehicle, i.e Body and doors, brakes, chassis, interior, exterior, tires and wheels. This way, the study is provided with a model such that different powertrain can easily be compared, while the glider of the bus is consistent.[57]

The different powertrains all include different components. The hybrids have the most comprehensive powertrains with two different systems. To provide an overview of the different components, they are presented in Table A.1 in Appendix A, the most important components in the powertrains are presented. The different components in the glider are also presented. This overview is gathered from several sources to present overall the most important parts of the internal combustion engine(ICE) and electric powertrain. [57–60]

To present the construction of a bus, the Volvo 7900 Electric and ICEV models are used as examples. The data obtained on the Volvo 7900 models were gathered from the LCA completed by Nordelöf et al., as they were given data from Volvo. It is however, difficult to obtain detailed data on a specific bus. This is because specification on buses and vehicles are classified, as the industry is highly competitive. [61]

In Figure 5.2 and Figure 5.3, the weight [3] and material distribution of the Volvo 7900 Electric is shown in a per-

---

[3] Weight referred to as the curb weight. This is the weight of the vehicle minus any passengers and cargo.

centage. It shows that the chassis and frame represent the biggest mass on the bus, furthermore, the steel comprises over 50% of the total mass. These are connected with large amounts of steel in the chassis and frame. Plastic and aluminium are also considerably 12% and 9% of the bus construction respectively. [61]

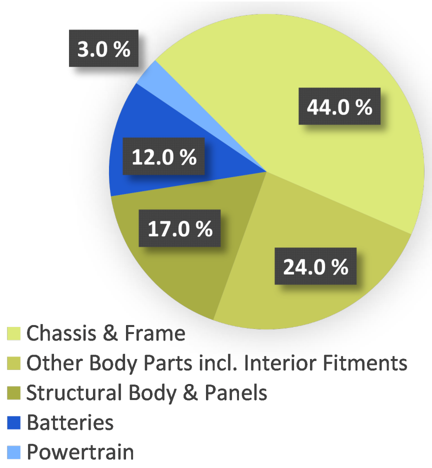

Figure 5.2: *Weight percentage of the different bus components in the Volvo 7900 Electric. Data gathered from Nordelöf et al.[61]*

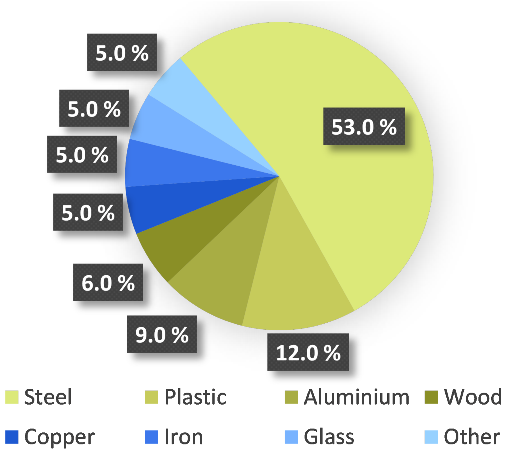

Figure 5.3: *Weight percentage of the different materials in the Volvo 7900 Electric. Data gathered from Nordelöf et al. [61]*

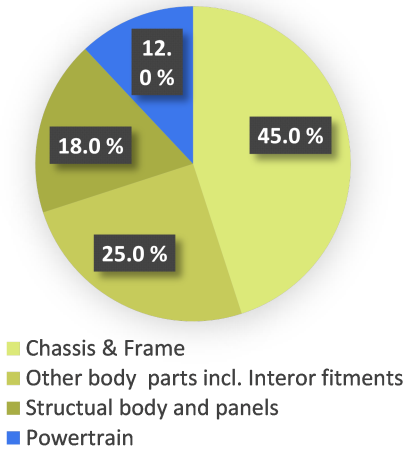

Figure 5.4: *Weight percentage of the different bus components in the Volvo 7900 Conventional. Data gathered from from Nordelöf et al.[61]*

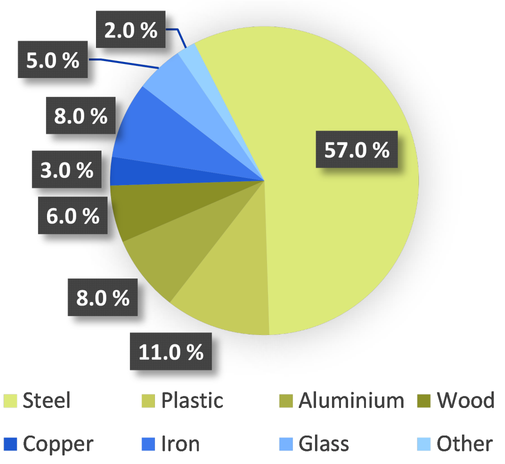

Figure 5.5: *Weight percentage of the different materials in the Volvo 7900 Conventional. Data gathered from Nordelöf et al. [61]*

In Figure 5.4 and Figure 5.5, the specifications for the Volvo 7900 Conventional can be seen. The specs are similar to the electric, with small alterations. The chassis and frame have a greater percentage, together with the steel. Specification regarding the Volvo 7900 Electric, Conventional, HEV and PHEV are presented in Table B.1 and B.2 in Appendix B.[61]

The various buses are constructed of mostly the same material, but with different magnitude. From the material, the components are manufactured, and the majority of components are constructed from a combination of materials. The chassis and frame are constructed mostly from different metals, steel, aluminium and magnesium, to provide both strength and lightweight. The structural body is also constructed of these metals, also including other materials such as plastic. While the interior have the greatest variation of material. The powertrain is mostly constructed of metals and plastic. The battery has the greatest difference in materials, depending on what type of battery. [62–64]

5.3 Battery

For electric buses the battery is an essential part. This technology, by storing energy in the form of electricity in batteries, reduces the need for fossil energy in transportation. The use of batteries is useful for delivering energy to systems where the possibility for power production are restricted. This is especially relevant in the transport sector, for different kinds of vehicles. There are different types of batteries and the technology is growing fast.

Current technology and usage

The most common battery technology used today is the lithium-ion battery (LiB). They are the most suitable energy storage device for powering electric vehicles today. This is because they have high energy and power densities, no memory effect, long life cycle and high energy efficiency. [65] Lithium is lightweight and electropositive, which gives LiBs a fundamental advantage. It is also highly reactive and therefore technologically challenging to build safe batteries with. This has so far been solved by using compounds that are capable of donating lithium ions (Li+), instead of using metallic lithium. When charging, the lithium ions move from the cathode through the electrolyte to the anode. During discharge this happens in reverse. [66]

Even though the battery production in Europe is increasing, most of the production of LiBs today takes place in China. Figure 5.6 shows the battery production in different regions.

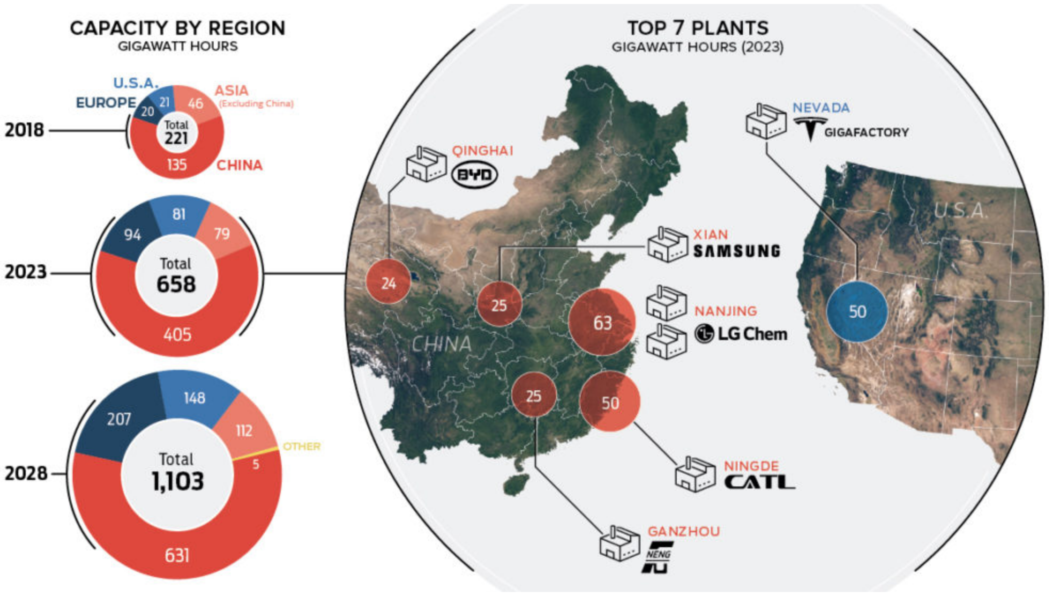

Figure 5.6: *Lithium ion Battery production share in the world, and predicted development. [67]*

The batteries in the Volvo 7900 Electric, HEV and PHEV are 76 kWh, 9 kWh and 19 KWh respectively. [61]

Future prospects

The development of battery technology and production has been significant in the last decade. With the carbon footprint in the spotlight, and an increase in electrification of the transport sector, the demand for battery capacity increases, as does the importance of clean energy for production. This pushes Europe to boost the battery production activity, and several companies will invest heavily in the future.

Northvolt will expand production significantly in the upcoming years. Their mission is to build the greenest battery in the world. The first large scale factory, Northvolt Ett, is being established in northern Sweden, and starts production in 2021 with annual capacity increasing to at least 32 GWh by 2024. They plan to start building a second factory, Northvolt Zwei, in 2021. This will start production in 2024 and have a annual capacity of 16 GWh. The Northvolt factories run on 100% clean energy. They also include most of the battery value chain at site, from active material production to end-of-life treatment. They buy the elementary materials directly from the mines, and wish to be a moving force for development of a Nordic value chain, with material production happening in Sweden, Norway and Finland. [68, 69]

Akasol are the battery supplier for the Volvo 7900 Electric. They are developing new battery technology which will significantly increase the energy density in the battery packs. They are planning a large production capacity increase in a few years' time, and are using renewable energy in the production process. They are expecting that 80% of all new registered city buses will be electrified by 2025. They are currently expanding their battery factory in Langen, Germany, and can from mid-2020 deliver battery systems with 30% extra energy, but with the same weight and installation space. The capacity of the factory is set to be 800 MWh by the end of 2020. Further, they are building a production line in the US which will reach 400 MWh in 2020, and will expand with a second production line in 2022 for additional 1000 MWh. Moreover, they are expanding with another serial production facility in Darmstadt with 2500 MWh by 2021. By 2022, the total battery production capacity of the company will reach 4 GWh. [70]

Akasol's new battery system, AKASystem AKM CYC, is expected to double the battery capacity available for electric buses. The production will start in 2021. This is an NMC battery and Akasol claim that this chemistry will be the prevailing solution going forward. Many of the Chinese producers are using LFP chemistry, but will meet resistance because of limitation in increasing the energy density. The new battery system will reach an energy density of about 221 Wh/kg. This can allow fully electric city and coach buses to have battery systems with capacity between 600-1000 kWh, and achieve a range of up to 850 km. [70, 71]

6 Bus Production

Bus production is a comprehensive process that includes several process chains. The bus production starts from raw material extraction and material processing, continued by material production and component manufacturing. The components include various materials, causing a large number of material chains. Finally the bus is assembled from the glider and powertrain, constructed by components. This long production chain results in multiple inputs and outputs of resources and energy. Transportation is required between every step, and for every needed energy unit, energy production is included. In Figure 6.1 the process chain of a vehicle is presented. [26, ch.1][60]

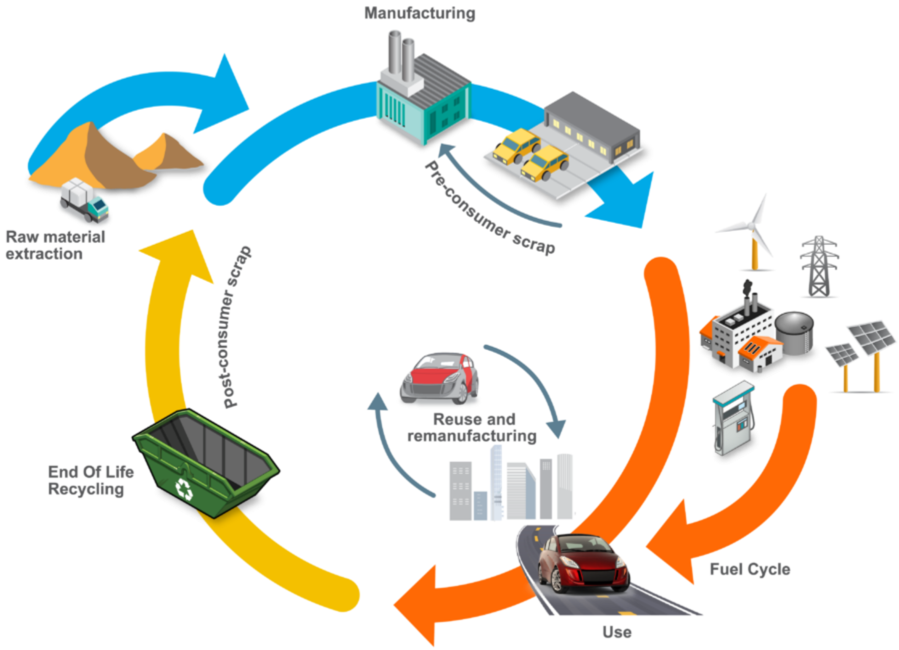

Figure 6.1: *Production chain of a vehicle and energy production up until use phase.[72]*

Another important production chain in Figure 6.1 is the chain for energy production. One example is diesel, where crude oil is recovered from oil drilling, followed by fuel refining, before arriving at a fuel station. Various fuel sources are presented in section 4.2 with their production characteristics.

The energy production chain is straight forward, but the bus production chain includes many processes. The vehicle assembly includes the glider and the powertrain. The glider is produced from chassis, body, wheels etc., while the powertrain is produced from electric motor, inverter etc. These products in themselves are again produced from smaller parts. These smaller components are produced from materials. [60] It is difficult to analyse the entire bus production, therefore this chapter goes further to analyse the material with highest percentage of the mass in a bus. This is steel and aluminium found in 5.3. It also describes the production of a battery in an electric bus.

6.1 Steel production

The steel industry is important in many different aspects of society and it continues to grow. In 2018, the industry produced 1 808 million tonne of crude steel; a 26% since 2008. Steel is an important engineering and construction material with a good ability for re-use as it does not age or decay quickly. Steel also has other advantages that other construction materials do not. The material is light weight, it is cost-efficient as it is widespread. It has long durability and is environmental friendly as it can be re-used. [73, 74]

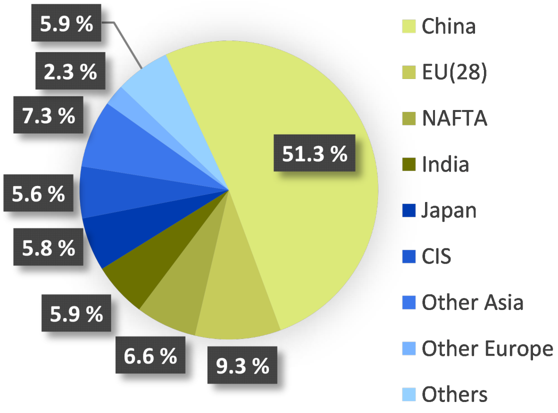

Figure 6.2: *Global steel production by main producers in percentage. Data gathered from [73].*

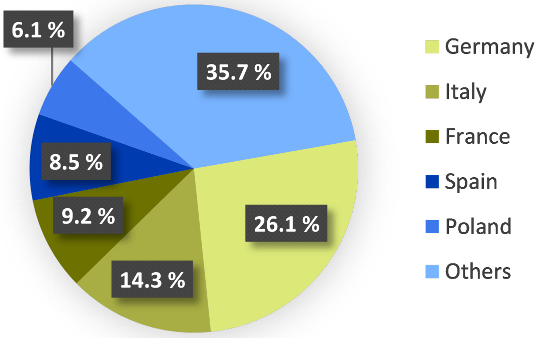

Figure 6.3: *Steel production in Europe by the main producing countries in percentage. Data gathered from [75].*

Crude steel factories are found all around the world. In Figure 6.2, the total crude steel production is presented by country. China processes over half of the worlds crude steel production, followed by India and Japan. Europe has in total 11.6% of the world's crude steel production. This makes Europe the second biggest crude steel producing continent, and out of the 169 million tonne produced in Europe in 2017, Germany processed 26%. Second is Italy with 16.3%, followed by France, Spain and Poland. This is presented in Figure 6.3.[73, 75]

Manufacturing of steel can be processed in one of two ways. Either with a basic oxygen steelmaking (BOS) process or through an electric arc furnace (EAF) process. Both processes are presented in Figure 6.4 where both result in crude steel that would be processed further. BOS have a longer process than EAF, including coke oven process, sintering plant, the blast furnace and finally the basic oxygen furnace. For newer steel production, pelletising the iron ore, to concentrate low grade iron ores, are implemented. The EAF is a direct process from recycled steel. In each step of the processes there are inputs and outputs, products and bi-products. [76, 77]

Extraction is the physical raw material mining. These materials are processed in multiple steps. The main steps for BOF material processing are iron ore pelletising, sintering plant and coke ovens. Pelletising is completed before the sintering, to provide a product that can be used in the sintering plant. Lime, coke and iron ore are added to the sintering in addition to the blast furnace (BF). The sintering plant produces a product that can be used in the blast furnace. Finally, the crude steel is produced from the BOF. This chain process is presented in 6.4. [76]

The EAF process uses recycled steel and melts it to produce crude steel. It is a simple process, but the recycling can be energy intensive. The input metal has to be processed, and frequently used processed metals are the direct reduced iron, hot briquetted iron, pig iron and hot metal. These have been used in varying percentage, successfully by EAF operators. The hot metal is mostly used where there is a shortage of scrap metal and electricity. Hot metal is normally produced through a BF, thus, hot metal is often used when the EAF is in close proximity to a BF. After crude steel is produced from either BOF or EAF, the product can enter a casting plant where it is continuously cast and rolled. The casting house is not included in Figure 6.4. [76, 78]

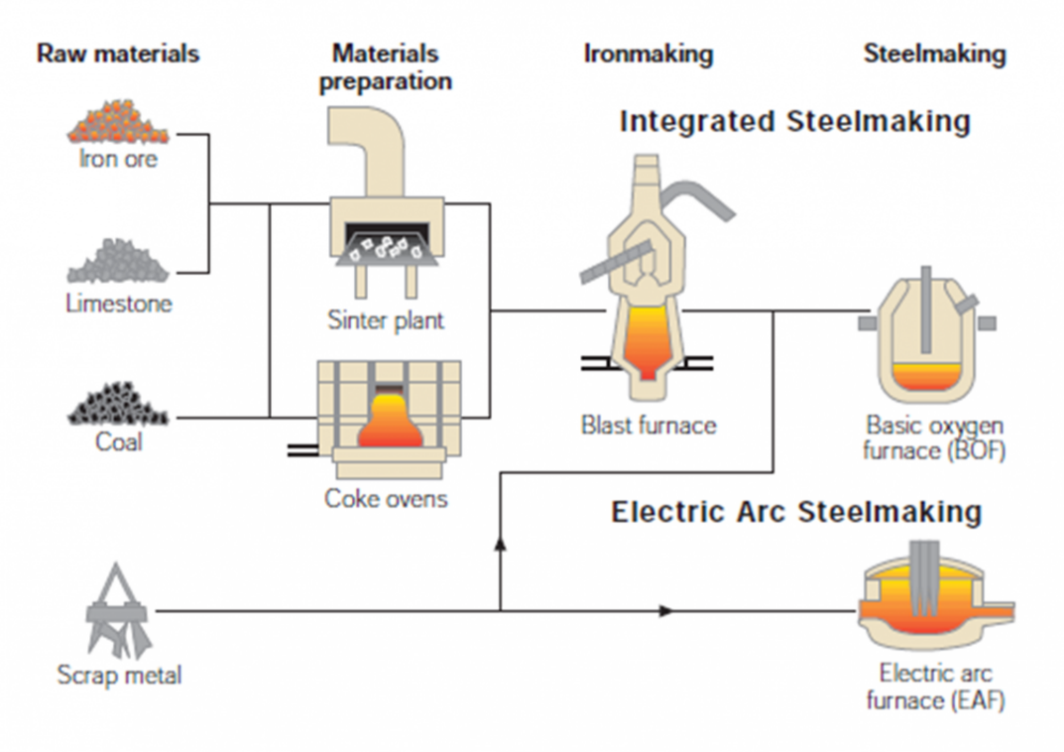

Figure 6.4: *BOF and EAF steel processing with individual steps. [79]*

There are a lot of input and output products during a steel production. Heat is an important input and output product for each process. One unwanted output product is waste, and a major waste product generated during steel production is slag. Because of this, many facilities have slag recovery. This is not an important enough step in the steel production for this thesis, but can have a big impact on the efficiency of the steel system. There are also additional and alternative steps that can be conducted or implemented, such as stainless steel production but this is not analysed in this study. [76–78]

The steel industry is extremely energy intensive. The BOF process requires great amount of heat, while the EAF uses electricity, thus, an environmental friendly energy production is necessary. The heat output in each process can be extracted with regenerative heat exchange, which is quite normal in steel facilities. Local energy production from heat is also normal practice in larger steel facilities.[76, 80]

6.2 Aluminium production

Aluminium, similar to steel, is an important material worldwide. It is versatile, and is used in several applications. Also, similarly to steel, China processes over half of the aluminium production in the world, presented in Figure 6.5. [81, 82]

Aluminium production is a more complex process compared to steel production. Pure aluminium does not occur

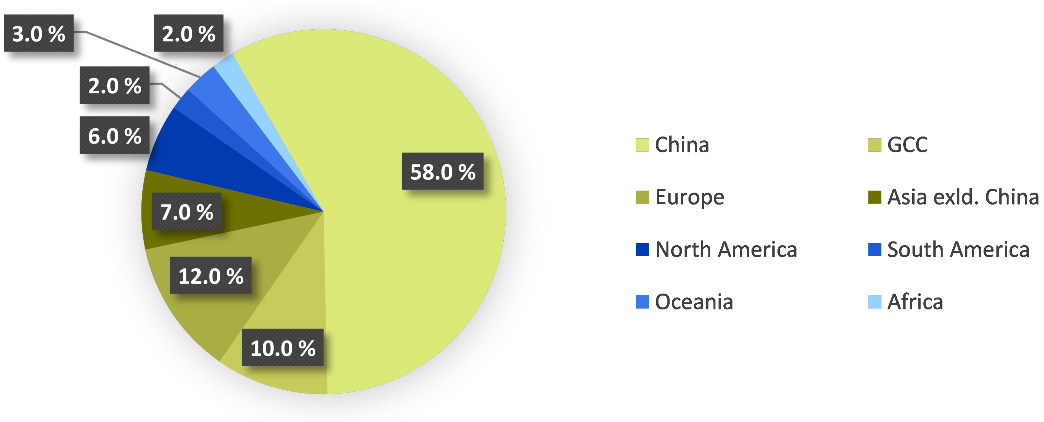

Figure 6.5: *Global aluminium production share by main producers. Data gathered from [82].*

naturally because the atoms bind themselves to other metals. Thus, the aluminium can not easily be separated by melting. The primary aluminium production is a much more energy demanding process, consisting of five main steps; bauxite mining, alumina production, cryolite manufacturing and aluminium production. Additional steps as casthouse processing and scrap recycling. These steps are visualised in Figure 6.6.[83]

The casthouse processing include extruding, rolling and casting to produce finished products. The specific processing of bauxite minerals is often conducted through the Bayer process, also called lime soda bayer process. This process mainly produces aluminium oxide from the bauxite material. The specific aluminium production is conducted with the Hall-Heroult process which is complex, but it is the method of melting the aluminium through different chemical processes. This is energy intensive as one part of the process is an electrolysis. [83–85]

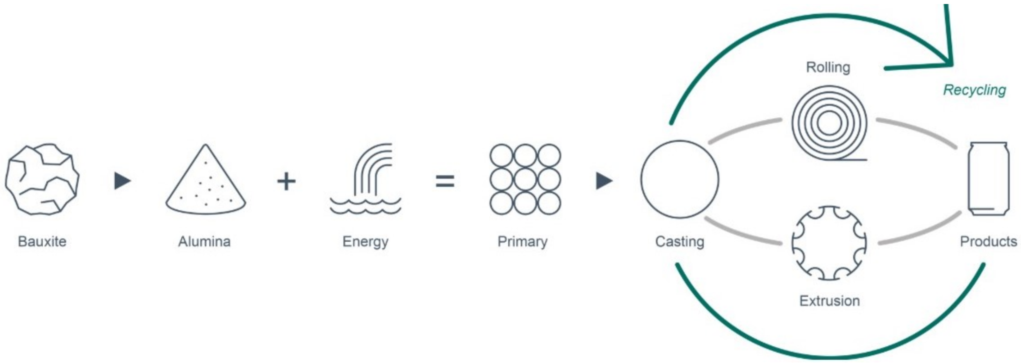

Figure 6.6: *Aluminium production process with individual steps.[85]*

Likewise to steel, there are waste products during aluminium production. The waste product from the primary aluminium production is called dross. This is normally recovered with scrap material in rotary furnaces. From the rotary furnace, there is also a waste called saltcake. For the most efficient aluminium recovery, a thorough integrated recovery system is important. [86]

Presented in Figure 6.6 is also the secondary method of producing aluminium, by using scrap metal. This is completed through recycling and melting down the aluminium to be further processed in the casting plant. This is an energy efficient method, and is more environmental friendly compared to primary production. [87]

A big and leading producer in the aluminium industry is Hydro. The company is established in multiple countries, including Norway. Hydro has a huge focus on sustainability, and environmental friendly aluminium production. They produce both primary and secondary aluminium, and have presented data stating that secondary aluminium production only requires 5% of the energy needed for primary production. This is because Hydro has implemented efficient aluminium production with their own energy supply. [88]

6.3 Battery production

The Li-ion battery is a secondary battery (rechargeable) and there are several different chemistries that can be used. The battery pack consist of many different parts and can be divided into four main components: battery cell, battery management system, cooling system and packaging. These in turn consist of subcomponents.

This chapter will explain how a lithium-ion battery is built up, specific components and the production of the battery pack. The first step is to extract the materials needed and produce the components. Battery cells are then created and put together to form battery modules. Several modules are then combined with other main components into the battery pack. Figure 6.7 represents a simplified flowchart for battery production.

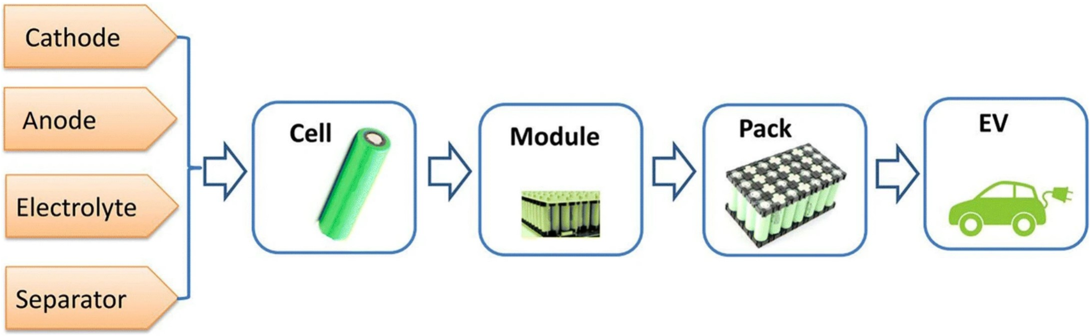

Figure 6.7: *Simplified diagram of battery pack manufacturing process. [65]*

Battery cell

The battery cell consists mainly of four components: electrodes (cathode and anode), separator and electrolyte. Current commercial LiBs are named from the lithium-ion donator in the cathode, because this is the main determinant of cell properties. The most common lithium metal oxides used are: lithium manganese oxide (LMO), lithium cobalt oxide (LCO), lithium iron phospate (LFP), lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). The different chemistries result in different battery characteristics. The anode material currently dominating the market is graphite, but some manufacturers have opted for non-graphite anodes such as lithium titanate (LTO, Li_4, Ti_5O_12). The lithium compounds are crushed into a finely powder and blended with a conductive carbon material in both electrodes. This is done to overcome limitations which are present due to lower conductivities and diffusion coefficients in the compounds, compared to metallic lithium, which leads to a much higher impedance. A solvent and a binder are used to shape the cathode and anode, which is pasted (coated) onto aluminium foil and copper foil respectively. These foils lead to the battery cell terminals. [66] After the cathode and anode are coated, they are dried and pressed into the appropriate thickness.

The electrolyte's function is to pass lithium-ions between cathode and anode. The electrolyte used in LiBs is a mixture of lithium salt (e.g. $LiPF_6$, $LiClO_4$) and organic solvent (e.g. Ethyl methyl carbonate, Dimethyl carbonate) combined to increase mobility of lithium-ions to give higher battery performance. [89]

The separator is a micro-porous membrane. Its function is to prevent contact between the cathode and anode, which would lead to a short circuit, and pass lithium-ions through the pores. It is made of either polyethylene or polypropylene. It also has a safety function called "shutdown" if the cell accidentally reach too high a temperature. The separator will then melt and fill its micro pores to stop lithium-ions flow. The cell also consists of some safety structures, such as tear-away tabs to reduce internal pressure, safety vents for air pressure relief, and thermal interrupters called positive temperature coefficient thermistors, for overcurrent protection. [89]

There are two types of packaging of LiB cells, cylindrical/ prismatic metal cans or stacked laminate films. In the cylindrical configuration the components, i.e cathode, anode, separator, are layered, rolled and sealed in a metal can with electrolyte. The layers in the stacked configuration are enclosed in laminate film and the edges are heat-sealed, which can be seen in Figure 6.8. [89] These can be modified into different sizes customised for its intended use. The cells are then packaged into modules and then put together to form the battery pack.

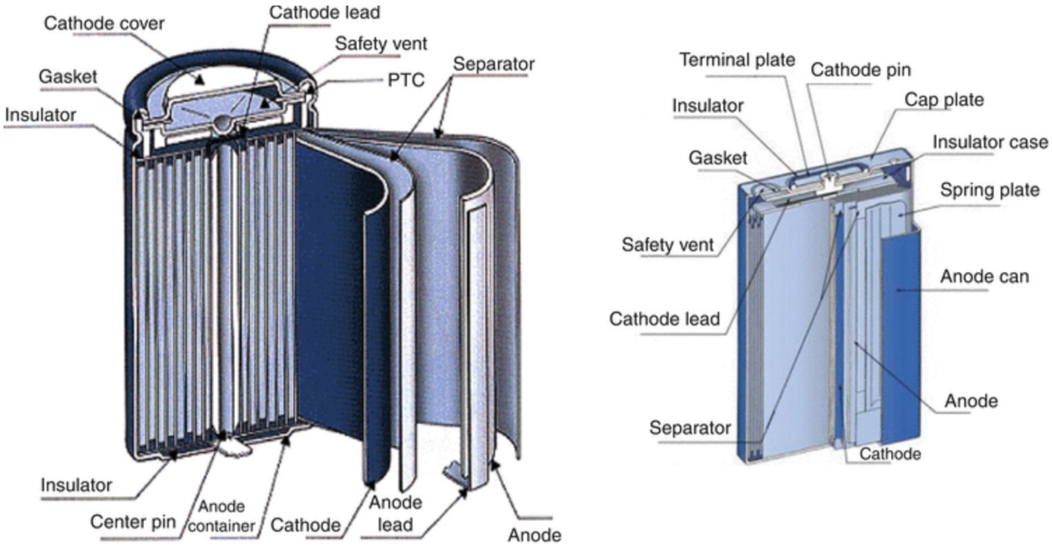

Figure 6.8: *LiB cell configurations and packaging. Cylindrical to the left and stacked to the right. [90]*

Battery management system and cooling system

A battery management system (BMS) is included to make the use of battery cells liable and safe. It tracks and manages key functionalities such as voltage, current, state of charge (SoC), state of health (SoH) and temperature. [66] It includes battery module boards, Integrated Battery Interface system, fasteners, high voltage system and low voltage system.

To keep the temperature in the battery pack under control, a cooling system is required. The main component is an aluminium radiator. It contains a convective heat medium, a glycol coolant contained with aluminium manifolds. Clamps and fasteners are made of steel, and for sealing it is used pipe fittings of plastic and rubber. A thermal gap pad of fiberglass-reinforced filler and polymer are used to ensure the thermal conductivity even more. [91]

Battery assembly

The last part of the battery pack production is the battery assembly. The components are put together to meet the specification demands, i.e battery capacity and operational demands. The assembly process is mainly performed using manual labour, and therefore requires small amounts of energy. [91]

The energy demand for the production of materials in a lithium-ion battery pack can be viewed in Figure 6.9. The energy demand for the battery assembly is not included, since it contributes to a negligible amount of the total.

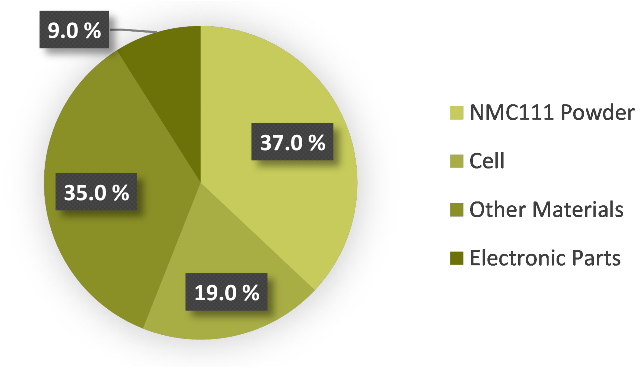

Figure 6.9: *Share of production energy demand for components in a LiB battery pack. Data gathered from [92].*

7 Production Emissions

LCA is a valuable tool for analysing the environmental impact of a product. Many LCA studies have been conducted, some more comprehensive and detailed than others. Some of them can have vague assumptions and wrong use of data causing poor results and misleading conclusions, thus, a thorough analysis is essential. This includes the evaluation of multiple important factors. If the intention is to compare different LCA studies, these factors become more important. Some of these factors are the scope and boundaries, primary and secondary data documentation, FU, software, energy and electricity, sensitivity and uncertainty analysis, direct and indirect emissions and impact categories. Most of these refer to what the study includes and excludes. To be able to properly compare LCA studies they need to include as many of the same factors as possible.

This chapter evaluates studies of GHG emissions for the entire production chain of a bus. This includes the bus as a whole, bus components, materials and battery production. Estimations are conducted for component and battery production. Several LCA studies are analysed and an overview of the studies are presented in Appendix C.

7.1 Bus production emissions

Full life cycle analyses on buses are limited because of the lack of data on bus manufacturing, component composition and upstream material processing. Some studies have been conducted on the matter, and are presented in Table C.1 in Appendix C. The studies vary over an eleven year period, providing results in a larger period span. The lack of newer bus production studies, can result in outdated data and impact results. Prevailing in all the studies are the focus on electrification in the use phase. The LCA studies include the production as a byproduct of their study, where some of the data can be generic. The reviewed studies all analyse twelve meter long buses with comparable mass, with an assumed lifetime of twelve years. They present the data with different FU, but this is calculated to the same unit for presentation. The studies lack results in some areas of production, and do not present production on individual components. Most of the studies present the total emissions of bus production for various powertrain.

7.1.1 Literature analysis

The most comprehensive study is conducted by Nordelöf et al. in 2019, examining the life cycle of four different powertrains; electric, PHEV, HEV and conventional engine. It presents data on material and the manufacturing processing, as well as maintenance emissions. The study applies foreground data from the manufacturing industry for the bus and component manufacturing, while for material processing and extraction they utilise generic background data from ecoinvent version 3.3. The manufacturing of components and bus data are based from facilities in Europe, while the electric motor and battery production, were assumed to take place in Germany and USA respectively. It is assumed that material extraction and processing were executed globally. The emissions from material upstream processing, manufacturing, maintenance and total emissions in production, are presented in Table D.1 in Appendix D. Nordelöf et al. use person-km as the functional unit. The authors estimate an average passenger count of 16 people for a specific bus line, and a yearly driving distance of 65 000 km. With the use of these numbers, the emissions were calculated to tonne CO_2-eq per bus. The study includes a change of battery pack once throughout the bus lifetime.[61]

A study conducted in the United States in 2013 by Cooney et al. compares a conventional bus to an electric bus, throughout the production and use phase. The study uses the EIO-LCA method, ecoinvent- and US LCI database to analyse the production i.e secondary data. These database versions are from 2010 and 2004 respectively. Cooney et al. present the results as vehicle-km. The number of vehicles is one bus and travelling distance is 59 500 km per year, calculated from 37 000 miles.[93]

One of the first detailed studies on bus production was completed by Kärnä in 2012. The study from Finland finds a carbon footprint on the upstream material processing for four different powertrains; diesel, hybrid, electric and converted electric. This is the first in depth analysis of this production process. Nearly all the data are provided from manufacturers, while the reference diesel bus is provided from literature. The manufacturers are Caetanobus, Kabus Ltd, MovekoTech Ltd and Volvo Bus Finland Ltd. However, no information was presented on the geographical area of production and energy, because manufacturers have limited data on the origins of their products. [94]

The two final studies were conducted in the United States by Chester. The studies analyse different transportation means in the United States. The first study was conducted in 2008, and the second a year later. The study in 2009 is a supplementary of the LCA in 2008. The LCA is based on the FTA 2006 database and the EIO-LCA method. The first study examines a diesel bus and an average bus. The yearly travelling distance is 67 600 km calculated from 42 000 US miles. The study by Chester and Horvath from march 2009 focuses more on buses and rails. The study presents results on an electric and an average urban diesel bus. The electric bus has an average of 16 passengers per kilometre, and drives an average of 43 500 km yearly calculated from 27 000 US miles. [95, 96]

7.1.2 Literature results

The total production emissions reported by Nordelöf et al, Cooney et al. and Chester, are visualised in Figure 7.1. The studies have considerable variations in their emission results. A reason for these variations could be the year of the research. Technology has improved greatly in the last decades, explaining the decrease in production emissions, but this does not cohere with the results presented by Cooney et al. The electric and diesel bus have immense emissions in the production phase, even greater than the result by Chester five years earlier.

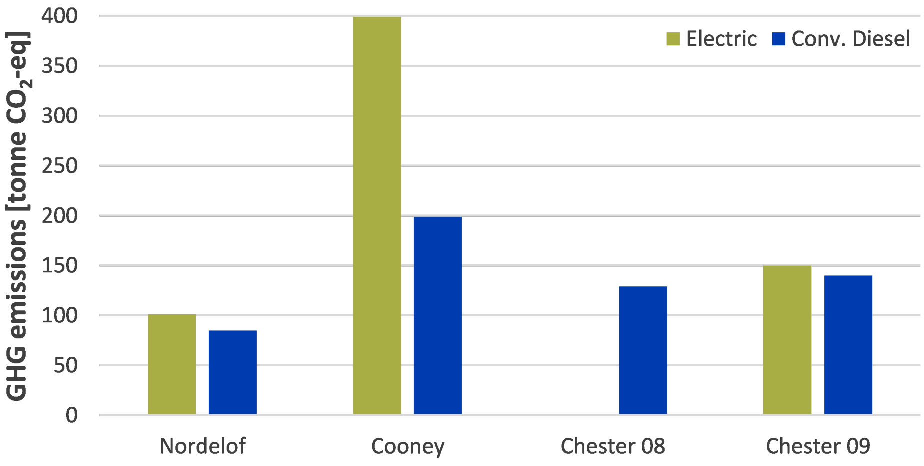

Figure 7.1: *Total bus production emissions of electric and diesel buses from four LCA studies.*

Cooney et al. calculate that a conventional diesel bus emits almost 200 tonne of GHG emissions throughout the production phase. This is 70 tonne more than the diesel bus in Chester 08, and 60 tonne more then the average urban diesel bus from Chester 09. The contrast are even greater compared to Nordelöf et al.'s results, which shows that a conventional diesel bus emits around 85 tonne GHG during production. This is 115 tonne less than the emissions presented in Cooney et al. The electric bus in Conney et al.'s paper emits close to 400 tonne CO_2-eq. This includes 5.5 battery substitutions, hence the immense emissions. However, the electric bus from Cooney et al. emits 300 tonne CO_2-eq more than the one from Nordelöf et al., and Nordelöf et al. change battery only once during the bus's lifetime. The study by Nordelöf et al. is the only study to include maintenance for the buses, new parts and oil, making the results more realistic over the vehicles lifetime.

Cooney et al., Chester, and Nordelöf et al. all analyse a twelve meter bus weighing approximately 12 000 kg, with a 12 year lifetime and driving more or less 60 000 km a year. Therefore, the contrast in the results do not originate from differences in FU, but rather stems from the data quality, geographical area and differences in included processes in their boundaries. The evolved technical advances can give a reason for the evolution of the results from Chester to Nordelöf et al. The data found in the paper by Cooney et al. are based on generic databases years before the study was conducted, which could result in higher emissions. The study from Chester is also based on a database from 2006, FTA. Nordelöf et al.'s study is based on manufacturing data as well as database data in ecoinvent from 2016. These differences in databases can have a huge impact on the results, and in this case could be the justification for the great variations.

In addition to the data quality, the geographic locations will also have an impact through the CI in the electricity. The production in USA will vary greatly based on which state it takes place. Table 4.3 shows the great difference in the CI of the states in USA among other mixes, so even though Chester and Cooney et al. are both based in the USA, the outcome could be very different. Nordelöf et al.'s production is conducted in Europe, and some in the United states. Europe have a lower CI compared to the United States. All three studies are vague when explaining the boundaries of the production of said buses. They do not discuss the production in detail, which makes it difficult to compare the difference in boundaries and processes.

7.2 Component production emissions

For a deeper understanding of the embodied emissions in a bus, it is necessary to analyse the component production. LCAs on bus production are more or less new, and not many studies conduct a detailed analysis on production of bus components. This makes it difficult to get direct data on production of glider and powertrain, specifically chassis, body, battery and other components. An approach to solve this complication is by analysing the component production emissions from personal vehicles, and scale that data to a bus scenario. However, even with personal vehicles, there are a lack of data on component production. One study was found with comprehensive data, and adopting the study was possible with thorough definitions and appropriate assumptions. The scaling from a personal vehicle to a bus needs to be conducted correctly.

7.2.1 Literature analysis and method

During research, two fitting studies were initially found to have satisfactory data on component emissions for hybrid, electric and conventional vehicles. But to be able to estimate the components correctly, without a high deviation on emissions, total weight and weight percentage of all components were necessary. Only the study by Hawkins et al. had the desired data. The two studies researched were Tiago and Hawkins et al. Tiago lacked data on the component weight percentage. An estimate on the weight percentage was used, but after a deeper analysis it could have lead to great deviations on the final results. The emissions are deeply connected to the initial weight of the components, thus small changes in the correct weight would lead to great deviations. Hawkins et al. presented all the necessary data to complete an appropriate estimation. [57, 60]

Hawkins et al. analyse an electric and a conventional vehicle. To be able to estimate the bus component emissions from the vehicle emissions, specifications and results on the vehicles are acquired. Component emissions are given in Table B.4 in Appendix B and component weight with percentage are provided in Table E.1 in Appendix E for the two vehicle models. Comparing the study by Hawkins et al. with the study of Tiago, it shows that the component constructions and what is included and excluded in the glider vary. They also present different components for the emissions. A detailed categorisation of the components in Hawkins' study is vital, to make them comparable with Nordelöf et al.'s categories. These categories are presented in Figure 5.2.[57]

The study by Hawkins et al. uses literature data for the inventory and the vehicle specifications. The glider and ICEV powertrain is based on the GREET 2.7 database, and scaled to be equivalent to a Mercedes A-Class. The ICEV powertrain was modeled after the Volkswagen A4 engine, while the EV powertrain base on the Nissan leaf 2010 version, with supplementary specifications on the batteries from literature. The study analyses two different lithium ion batteries for the EV; NMC and $FePO_4$. Both are 24 kwh and weigh 214 kg and 273 kg respectively. The NMC battery is used for further evaluation. The same glider is used for both powertrains, which makes the curb weight for the two models similar, and easy to compare. Hawkins et al. present their vehicle model compositions down to material detail level in their supplementary.[57]

The study by Tiago is an in depth and detailed study of a hybrid Prius 2013 version. The inventory is provided by the associated university, and other absent data are found through literature. Tiago do not present the weight percentage of the specific components, thus it was not possible to conduct the estimations for this study.

7.2.2 Literature, estimation method and results

The studies by Hawkins et al. and Tiago have great differences in their emissions. The component emissions from the two studies are found in Table E.1 in Appendix E. Tiago's paper presents immense emissions in the powertrain, almost four times higher than the electric from Hawkins et al. and almost seven times higher than the conventional. The high emissions could originate from the additional parts in the hybrid powertrain. The total emissions are also much higher in Tiago. These two studies show that LCA studies on vehicles have great difference in their results, and estimating bus emissions from only one study can end in a misrepresented result.

The component weights provided by Hawkins et al. are divided into the categories presented by Nordelöf et al., as satisfactory as possible. This is presented in Table B.4 in Appendix B. Nordelöf et al. have not defined what is included in each category, thus, the division is completed based on general discretion. Therefore, the data in these categories can have high uncertainty compared to Nordelöf et al.'s division.

The component weight and emissions in Hawkins et al. are weighted for each component based on the Volvo 7900 component weight. Because the component weight for a personal vehicle is different than for a bus, the emissions need to be altered, such that the component emissions constitute the correct percentage in relation to the component weight. Further, the emissions per kg of the components are found, and then scaled to a bus model by multiplying with the weight for the respective bus component. For these calculations the component emissions in Table E.1 in

Appendix E are used with the component weights for Hawkins et al. and Nordelof et al. presented in Table B.4 and B.1 respectively in Appendix B. This method was found to give the best equitable result. The results for the estimation are given in Table D.3 in Appendix D, and visualised in Figure 7.2. The estimated component emissions are compared to the component emissions from the study by Nordelöf et al.

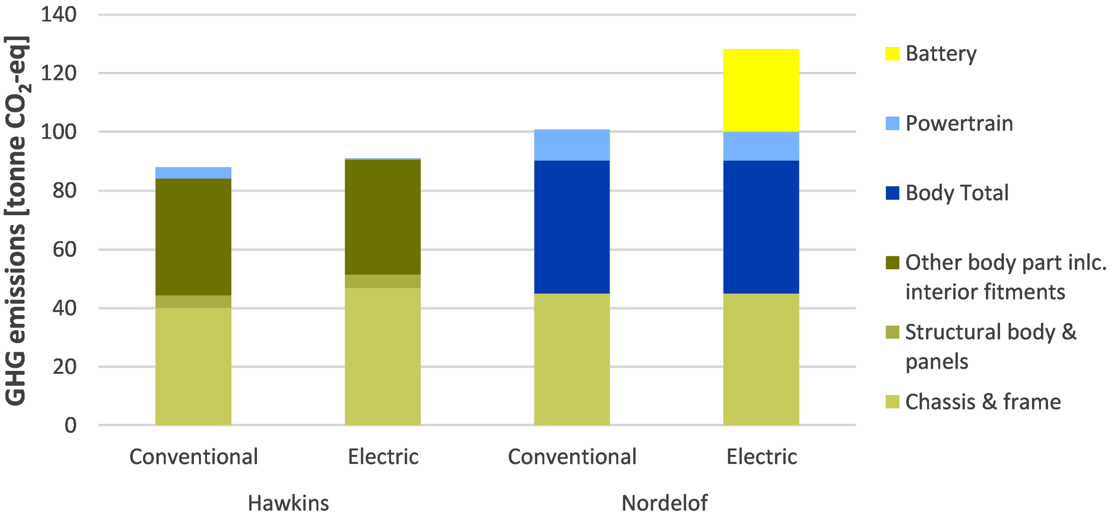

Figure 7.2: *Estimated bus component production emissions from Hawkins et al. compared to component emissions from Nordelöf et al.*

The conventional and electric bus from Hawkins et al. have similar glider emissions, because they both originally were assumed to have the same glider. The powertrains have the greatest difference, but both models have low emissions in this component, where the electric model emit almost zero emissions. Estimating battery emissions based on the weight can be incorrect. This is because the battery has other factors, such as capacity and specific density, that effect the emissions. Because of this the battery is not included in this section. The battery emissions are analysed in section 7.4.

Furthermore, Figure 7.2 shows that the chassis & frame and body constitute the highest emissions from the buses. The total body in Nordelof et al's buses consist of the other body and structural body. The structural body in the estimated buses has low emissions. This originates from the estimations when calculating the emission per kg CO_2-eq per kg component. The structural body of the vehicle in Hawkins et al. weighs 526 kg, while the chassis & frame and other body, weighs 297 kg and 237 kg respectively. The reason for the structural body's high weight is because it consists mainly of steel. If the body was built out of more aluminium, it would have had a lower weight. The other body has almost the same quantity of emissions as the structural body, even though the structural body weighs half as much. This results in low emission per kg of structural body compared to the other body and chassis & frame. Further, the reason that the chassis & frame emits such a considerable amount, is because it constitutes a larger proportion of the bus. The chassis & frame weighs over 5 600 kg, compared to 2 250 kg and 3 100 kg of the body and other body respectively, in the Volvo 7900 from Nordelöf et al. Therefore, the structural body has the lowest emission per kg component, as well as it constitutes the lowest weight proportion of the glider.

The conventional bus from Hawkins et al. has lower emission than the conventional from Nordelöf et al., around

15 tonne CO_2-eq, presented in Figure 7.2. Additionally, the electric bus without the battery, emits around 90 tonne CO_2-eq, 10 tonne less than Nordelöf et al.'s electric. These total emissions mainly stems from the chassis and body production. The powertrain emits almost zero in comparison to Nordelöf et al., where the powertrain shows to have a considerable impact. Generally the conventional and electric bus from Hawkins et al. emit lower emissions than Nordelöf et al. However, the emissions from body and chassis, are relatively similar for all models. The differences in emissions between the studies, could be because of the imperfect estimations, but, the emissions provide a comparison for the validity of Nordelöf et al.'s results. The estimations can embody uncertainty from the original data, as well as in the calculations. The vehicle composition is specific for Hawkins et al's. study, and the results would most likely be different for other vehicle models.

7.3 Material production emissions

The material production will provide an even deeper understanding of the emissions from the bus and component production. The main materials for the Volvo 7900 Electric were presented in Figure 5.3. Steel, aluminium and plastic is the majority of the materials in the bus and the two metals will be further analysed.

The two metals have different production chains resulting in different energy consumption and GHG emissions. To understand their contribution in the bus production chain, LCAs are compared for each material. For a representative comparison, a report from Worldsteel Association compares different metals. They present substantial differences in the global average GHG emissions.Steel has very low GWP compared to aluminium, CFRP and magnesium. Aluminium emits ca. 16 500 kg CO_2-eq per tonne aluminium produced, while steel only emit between 2 000 and 2 500 kg CO_2-eq per tonne steel on average. Additionally, magnesium emit an even greater amount, between 36 000 to 56 000 kg CO_2-eq per tonne magnesium. Thus, the total emissions in a bus, is very dependent on the magnitude of specific materials.[97]

In the studies, some important factors present themselves repeatedly. One factor is especially dominant with regard to the production chain. Included or excluded processes vary throughout the studies. The production of the different materials have many steps in the chain. The studies often include the main steps, but vary when the chain commences and when it ends. Some include the processing of semi-fabricated material, while some finish with the semi-fabricated metal. These boundaries will have a big significance on the outcome. The functional unit and data quality will also influence the result. It is important to calculate flawlessly from per functional unit, to use a common reference unit.

7.3.1 Literature analysis

The fact that steel and aluminium are both huge international industries, which has motivated the research on the environmental impact and implementation of new improved and efficient technology. Several LCA studies have been conducted in numerous countries. Some are case studies on specific steel and aluminium facilities, and some are general studies. A big effort has been made in providing a comprehensive and detailed LCI, so accurate LCIA studies can be conducted. The studies use dissimilar softwares to conduct the LCIA with different climate categories. Describing the scope and boundaries with the functional unit is essential to understand the difference in the studies. Analysed LCA studies are presented in Table C.2 and Table C.3 respectively in Appendix C.

Renzulli et al. analyse only the BOF production, while Norgate et al., Korol and Gao et al. examine both BOF and

EAF. The BOF process is comprehensive because of the multiple processes in the chain. To obtain an overview a table with the included processes, in each study, is presented for the BOF steel processing. This is presented in Table 7.1 and shows great variance in the studies.[80, 98–100]

Table 7.1: *Table presenting BOF LCA boundaries by checking included and excluded processes. Primary data are marked with a ✓mark, while secondary data from databases, is given with an X mark. If the step is not included it is marked with a -. [80, 98–100]*

Study	Extraction	Lime	Coke	Sintering	Pelletising	BF	BOF	Casting	Rolling	Recycling
Renzulli et al.	X	X	✓	✓	X	✓	X	✓	-	-
Norgate et al.	✓	✓	✓	✓	-	✓	✓	-	-	-
Korol	X	✓	X	X	✓	✓	✓	✓	✓	-
Gao et al.	✓	X	✓	✓	✓	✓	✓	✓	✓	✓

Renzulli et al.'s paper has a cradle-to-casting plant gate boundary where the extraction, lime, and pelletising are based on the ecoinvent database version 2 and 3, and do indirectly affect the primary processes. The coke, sintering, BF and BOF have primary data, and are presented as results. The casting is included in the BOF step of the chain. [80]

Korol, in Poland, has a cradle-to-factory gate analysis of the steel production. The flow chart of the processes include the lime plant, sintering, BF, BOF, casting and rolling. The raw material, coke and pelletising are not described but assumed to be indirectly included as input to the processes presented. The study by Gao et al. in China includes most in the scope boundary. It explains in detail the boundary, and present energy and emission results in each of the processes. Limestone processing is included in the extraction of raw material. [98, 100]

Norgate et al. have a comparison analysis between multiple metals, that is different to the other studies which analyse steel only. Two of the metals are steel and stainless steel. The crude steel is processed by the BOF process and stainless steel is processed through the EAF. The study is a cradle-to-crude/stainless steel gate. The process has a step defined as crushing and screening which is assumed to include lime, coke and iron ore processing. The production process is not defined in detail, as the pelletising is not mentioned. The description of the steel production was not thorough, thus, it is challenging to say what is included in the process chain. The steps in Table 7.1 are expected to be included. [99]

Table 7.2: *Table presenting EAF LCA boundaries by checking included and exluded proesses. Primary data are marked with a ✓mark and if the step is not included it is marked with a -. [98, 100]*

Study	Scrap Input	EAF	Casting	Rolling	Final Product	Recycling
Korol	✓	✓	-	-	-	-
Gao et al.	✓	✓	✓	✓	✓	✓

Korol et al. and Gao et al. include EAF processes. Boundaries for these processes are presented in Table 7.2.

The boundaries for EAF are not as comprehensive as BOF, but nevertheless, a table is used to clearly present the differences between Korol et al. and Gao et al. The EAF processing step includes preparation of the furnace, charging, melting and decarburisation. [98, 100]

Table 7.3: *Table presenting aluminium LCA boundaries by checking included and excluded processes. Primary data are marked with a ✓mark and if the step is not included it is marked with a -. [99, 101, 102]*

Study	Bauxit	Alumina	Anode	Electrolysis	Casting	Rolling	Recycling
Yang et al.	✓	✓	✓	✓	✓	-	-
Al Association	✓	✓	-	✓	✓	✓	✓
Norgate et al.	✓	✓	-	✓	-	-	-
Hydro	✓	✓	-	✓	✓	✓	✓

Also, Norgate et al. show results on aluminium production along with 2 other analysed studies and a producer, Yang et al., the Aluminium Association and Hydro. The included processes from each of the studies are demonstrated in Table 7.3. Norgate et al. analyse the aluminium production by the use of the bayer and Hall-Heroult processes. This is a cradle-to-gate study, where it produces semi-fabricated aluminium. Norgate et al. have the fewest steps in it's process following Yang et al. Yang et al. study the production of aluminium through two energy cases: thermal and hydro power. Yang et al.'s study analyses the importance of electricity production in the industry, and is the only study to analyse the anode production for the electrolysis process. [99, 101]

The Aluminium Association conducted a detailed and comprehensive study of the aluminium industry in 2013. They analysed both primary and secondary aluminium production. The study includes all steps in aluminium production excluding the use phase, and provides accurate information about their boundary. Over 70% of their energy mix come from hydropower. Furthermore, they analyse secondary aluminium production with data on each process: scrap collection and processing, scrap melting and casting, dross and saltcake recycling and primary ingot. Primary ingot is the same as casting house. It is the process from finished melting and casting up to finished primary ingot. [102]

Likewise, Hydro published data on their aluminium production. They are producing some of the most environmental friendly aluminium, for both primary and secondary. They operate in the production of primary aluminum, rolled and extruded products and recycling. The company extracts bauxite, refines alumina and produce energy in their product life cycle. Hydro submits clear data on their carbon footprint for various aluminium products.[88, 103]

7.3.2 Literature results on primary production

The resulting primary emissions and energy consumption found from the different LCA studies, can be found in Table F.1 for steel and Table F.3 for aluminium in Appendix F. The results for steel and aluminium are also presented graphically in Figure 7.3 and Figure 7.4 respectively. The emissions from producing one tonne of steel and aluminium are illustrated as green bars, while the energy demand is depicted as a blue line. The results in steel production show slight variations in both emissions and energy. However, for the aluminium, Figure 7.4 shows immense variations for both emissions and energy. The results are shown by a common per unit, one tonne steel and one tonne aluminium, leaving the functional units to have zero significance on the variations in the results.

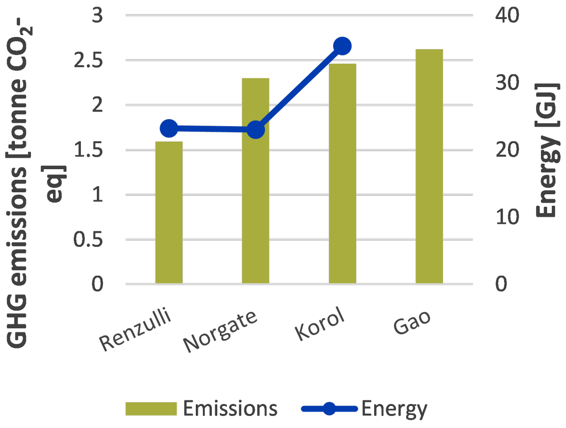

Figure 7.3: *GHG emissions and energy consumption per tonne of steel from four LCA studies for primary steel production.*

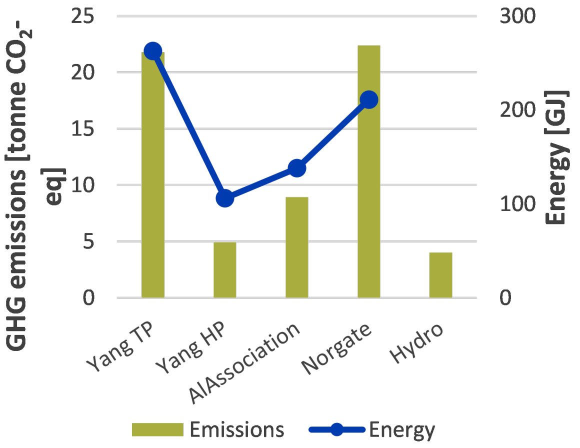

Figure 7.4: *GHG emissions and energy consumption per tonne of aluminium from three LCA studies for primary aluminium production.*

The variations found in steel production, presented in Figure 7.3, are likely to originate from CI in electricity and boundary. The steel processes require a great quantity of energy, mainly from heat, because of the melting processes. Using electricity to create heat in the various processes is both energy inefficient and very carbon intensive. This is the reason larger steel producing facilities, like the factory in Italy described by Renzulli et al., have integrated regenerative heat, where the heat is used for the various processes, but also for local electricity production. The difference in energy demand between Renzulli et al. and Korol comes from, most likely, a energy efficient system by Renzulli et al., where small amounts of heat are lost to the atmosphere, leading to lower emissions.

Renzulli et al. and Norgate et al. both have the same energy demand for producing one tonne steel. However, Norgate et al.'s study shows higher emissions compared to the study published by Renzulli et al. This might be due to the CI in the respective countries' electricity grid. Italy has lower CI in their electricity compared to Norgate et al. in Australia, Korol in Poland and Gao et al. in China. This can also explain the increased emissions in the steel production in the other three studies compared to Renzulli et al. The Worldsteel Association presents data on energy usage in the steel industry and 89% of a BF-BOF's energy input come from coal, 7% from electricity, 3% from natural gas and 1% from other gases and sources [104]. This is of course globally, but it shows that the electricity in the respective country is not a decisive factor. This is because heat is mostly used in the processes, and this is achieved through other energy paths, like coal.

The deviation in both energy demand and emissions, can also originate from the process boundaries. The process boundaries are presented in 7.1. Renzulli et al. have the lowest amount of processes included, after Norgate et al. Gao et al.'s study includes the most steps and is also the study with the highest BOF CO_2-eq emissions. As Norgate et al.'s paper has the lowest included processes, the study could be expected to have the lowest energy demand and GHG emissions. This is not the case, perhaps because of the CI in the consumed energy, and inefficient steel facilities. On the other hand, Gao et al., have both the most included processes and the highest emissions. Gao et al. does not show data on energy demand, but report that the used electricity is provided from coal-fired power generation.

Gao et al. and Renzulli et al. are the only ones who reveal emissions from every single stage of the steel production. Their emissions are displayed in Table F.2 in Appendix F. The table shows the great impact the boundary has on the result. The paper by Gao et al. includes eight main steps, while Renzulli et al.'s includes four. This provides a huge increase in emissions. Also, the emissions in each step vary greatly. Renzulli et al. emit more in each step excluding BF. This might be because Renzulli et al.'s study includes other steps indirectly in the four processes it does include.

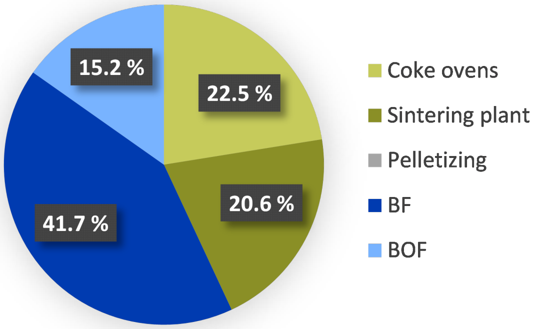

Figure 7.5: *Percentage of emissions from each steel production stage from study by Renzulli et al.*

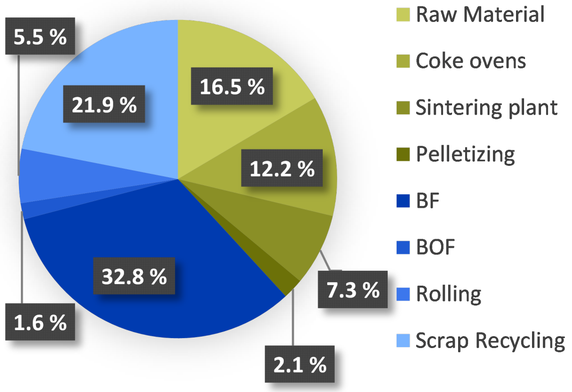

Figure 7.6: *Percentage of emissions from each steel production stage from study by Gao et al.*

Figure 7.5 and Figure 7.6 shows the effect from each process on the total GHG emissions. In both cases the BF process greatly affect the emissions. For Gao et al.'s paper the raw material extraction and scrap recycling are surprisingly high. These processes have the second and third highest emissions in the steel production. While the study from Renzulli et al. has coke ovens and sintering plants as the second and third highest. This shows how the emissions shift in an LCA when processes are included and excluded, or implemented indirectly.

Gao et al.'s study is the only study to include scrap recycling. This is an important aspect of steel life cycle, and excluding this step provides misleading LCA results. The scrap recycling emit 575 kg CO_2-eq, and by discarding this step, the various LCA studies are moreover comparable. The total emission from Gao et al. is reduced to a total of 2 045 kg CO_2-eq, which is the second lowest magnitude of the four studies. The study by Gao et al. corresponds more with the results from Renzulli et al. This also determines the low impact electricity has on the steel production, as Gao et al. utilises the highest CI electricity. By removing the rolling process in Gao et al. the studies are even more comparable, but this would not alter the arguments. If the raw material extraction was removed the studies would be be less analogous, as both include the process, but Renzulli et al.'s has the process indirect in the input and do not present this step directly in the results.

The results from aluminium production presented in Figure 7.4 have huge variations in both emissions and energy consumption. The paper from Worldsteel Association suggested that aluminium has ca. 14 000 tonne CO_2-eq more emissions than steel. By comparing Figure 7.3 and 7.4 this is found to be accurate, but the magnitude varies drastically. Yang et al. TP and Norgate et al. have the highest CO_2-eq emission out of the four studies. Furthermore, Yang et al. hydro power has the lowest followed by the Aluminium Association. In contrast to steel, aluminium production chain depends a lot on electricity, thus, CI will have a massive footprint, as do energy efficiency, on the resulting emissions and energy consumption.

An interesting trend in Figure 7.4 is the emissions and energy being coherent. They drop and increase parallel to each other. Yang et al. TP and Yang et al. HP are the same studies, producing one tonne of aluminium, but the energy demands are very distinct. This is mainly from the efficiency of energy source, and the requirement for resources. Study for Thermal power shows that the energy demand mainly originates from the AC power needed for the electrolysis. This is because of the reduced efficiency in thermal to electric energy, compared to hydro power. In the case of the hydro power, the energy demand for AC power was reduced from 74% till 47%. The energy demand from steam for alumina extraction increased. Also with the reduced energy demand in hydro power, comes clean green energy. Thus, the emissions reduces drastically. The study from Aluminium Association uses 70% hydro power which also leads to low emissions and energy usage.

Hydro produces a product, REDUXA low-carbon aluminium, from primary aluminium production with a carbon footprint of maximum 4 kg CO_2-eq per tonne for aluminium. This low footprint is because of their highly efficient facilities through the entire production chain. Their energy is mostly renewable as they operate mostly in areas with high percentage of renewable power, for example Brazil and Norway. Hydro shows to have clearly the lowest emissions from aluminium production.

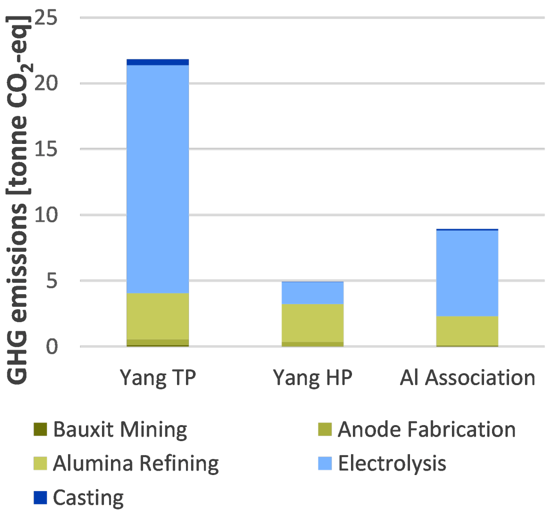

Figure 7.7: *GHG emissions from each process per tonne of aluminium from three LCA studies for primary aluminium production.*

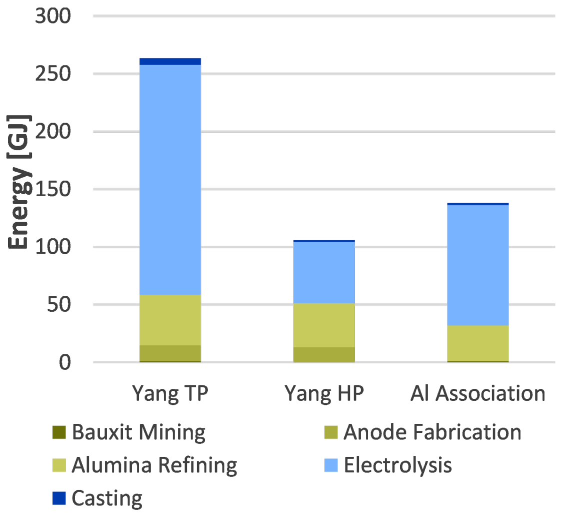

Figure 7.8: *Energy consumption for each process per tonne of aluminium from three LCA studies for primary aluminium production.*

The study by Yang et al. and Aluminium Association are both comprehensive and detailed studies. They both present emissions and energy consumption in each step of the primary aluminium production. The emissions in each individual step is presented for the two studies in Figure 7.7, while the the energy consumption is presented in Figure 7.8. They show that the electrolysis and alumina refining are the steps with highest emissions. This is because these steps are also the most energy intensive. The anode fabrication is presented in Yang et al., showing to have an impact on the results, thus, should not be overlooked while conducting an LCA on aluminium production. The energy shows to have a big impact on the emissions for the various steps. In contrast to steel, the material extraction is not an impacting step for aluminium production, compared to the other processes. Aluminium mainly extract bauxit minerals, while steel require several minerals.

7.3.3 Literature results on secondary production

The increasing volumes of scrap metal in the world will have a bigger importance for the metal production in the future. Because of this, the thesis presents a subsection to analyse the secondary metal production and discuss the challenges that the industry faces.

The main difference between primary and secondary metal processing, is the few energy efficient processes. Due to the fewer steps required, less resources are needed, such as energy. Thus, secondary production methods are resource and energy efficient. The steel is processed through the electric arc furnace, while the aluminium is processed through an electric furnace. The furnaces are electric, hence CI in electricity is an important part of the production. The processes are energy efficient, but for the production to be environmentally friendly, there is a need for green energy production. EAF emissions, and energy results are presented in Figure 7.9 from two LCA studies. While the Aluminium Association and Hydro present results on secondary aluminium production in Figure 7.10.

Norgate et al. reported results on EAF production, but was not included because of the great misrepresentation in the EAF boundaries. Thus, EAF results where presented from Korol and Gao et al. The energy demand in EAF compared to the BOF is considerably reduced. The energy consumption for EAF and secondary aluminium production is not thorough as only one study, for each, provide results on the matter. Also, Korol and Gao et al. vary greatly in emissions. Gao et al. present higher emissions in steel production in the EAF, compared to the BOF emissions in Figure 7.3. Although, Korol report lower emissions on steel production, than the BOF emissions.

An essential phase of secondary metal production is recycling. The study by Korol, does not include the recycling process, which disregards a important factor on the GHG emissions on secondary metal. Gao et al.'s paper do present data on recycling. For the BOF life cycle, the recycling accounted for over 20% of the emissions, presented in Figure 7.6. The boundaries for Korol and Gao et al. are reported in Table 7.2. Gao et al. include four other steps, which Korol does not. This can reason the difference in the emissions in Figure 7.9. Korol does not provide details on the included steps, neither any emissions, making it difficult to analyse further.

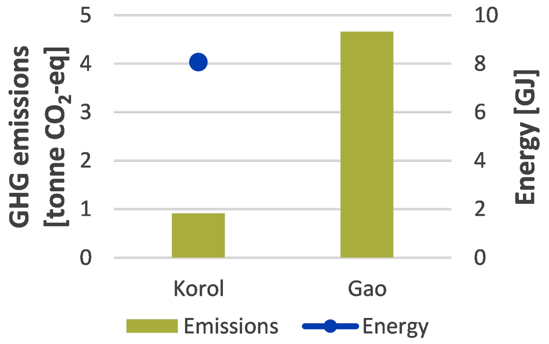

Figure 7.9: *GHG emissions and energy consumption per tonne of steel from three LCA studies for secondary steel production.*

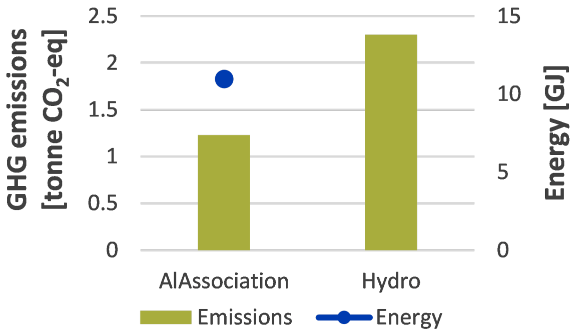

Figure 7.10: *GHG emissions and energy consumption per tonne of aluminium from the Aluminium associations LCA for primary and secondary aluminium production.*

The Aluminium Association report detailed results on the secondary Aluminium production. The energy consumption is immensely reduced in Figure 7.10, compared to the magnitude in Figure 7.4. Lower energy consumption leads to lower emissions in production, reducing the total emissions by 86% Solely analysing the results from Aluminium Association, it shows that secondary production is beneficial. Hydro also present emissions data on their aluminium product CIRCAL, produced from recycled material. The product has slightly more emissions than the aluminum association, but is still very reduced compared to emissions in Figure 7.4.

Also, the Aluminium Association report emissions in each individual step of the secondary production. The processes are presented in sector diagram in Figure 7.12, by emission percentage. The production of the primary ingot has the greatest impact with 46.3% of total emissions. This is the rolling and extruding process. If this step was to be excluded, and only include aluminium ingot after EAF, the secondary production is much more environmental friendly compared to primary production.

For the EAF process, hot metal is used as an input metal. In Figure 7.11, the hot metal has the greatest impact on the emissions during EAF processing, before the electric arc furnace and scrap recycling. Because of the impacting hot metal, alternative input metal should be considered to reduce the emissions from input material processing. The scrap recycling emissions are surprisingly high, compared to aluminium recycling and input metal processing.

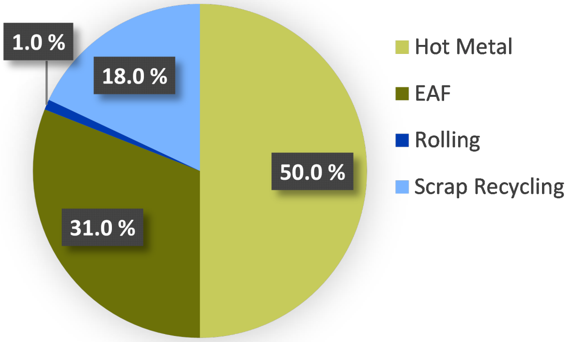

Figure 7.11: *GHG emissions from individual steps in EAF steel production from Gao et al.*

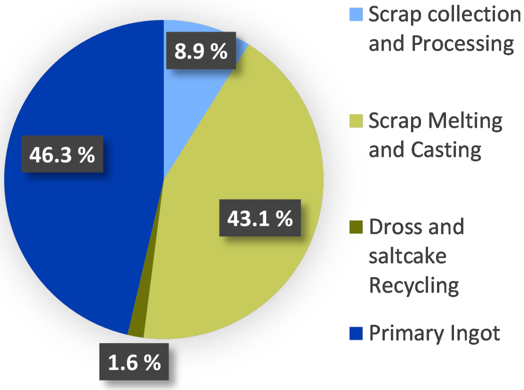

Figure 7.12: *GHG emissions from individually steps in aluminium secondary production from Aluminium Association.*

7.4 Battery production emissions

The battery pack in electric vehicles is the most important component, and the one that differs the most from a conventional vehicle. Several studies have been completed to try to understand the impact from production and operation both in case of energy consumption and GHG emissions. There are big differences in the results, and this can be explained by examining the scope and boundary of the studies. The fast development in battery technology and renewable power generation are important factors to consider when reviewing these.

This sector will present CIs for lithium-ion battery production found in several studies and take a closer look at the assumptions made and methods used. It will also examine the manufacturing energy demand in the production process.

A study by Ellingsen et al. from 2014, investigates the environmental impact from a LiB vehicle pack. It is a process-based attributional LCA on NMC chemistry LiB, based on primary data, and reports the cradle-to-gate impacts. It concludes that the production impact of the battery is mainly caused by the manufacture of battery cells, production of positive electrode paste and the negative current collector. It reports a value of 172 kg CO_2-eq/kWh. It also concludes that it is possible to reduce the GWP impact from production with more than 60%, if the el-mix used in cell manufacture is based on hydroelectric power. The el-mix used in the study had CI similar to natural gas based electricity generation. [91]

Peters 2017 is an LCA review of several studies on lithium-ion battery production. It considers all publications on battery production from 2000-2016, and identifies 113 available LCA studies on LiBs and electric mobility. It examines cumulative energy demand and GWP from different LiB chemistries, and also considers the impact of cycle life and charging. The study finds large variations in results from the reviewed publications, and explains it by differing assumptions regarding key parameters like lifetime, energy density and manufacturing demand. It also finds a big difference in the choice of a top-down or bottom-up approach. The restudy estimates an average value of 1 182 MJ cumulative energy demand and 110 kg CO_2-eq/kWh. [105]

The study by Romare & Dahllöf from 2017 are published by the Swedish energy agency. It examines the life cycle energy consumption and GHG emissions from a lithium-ion battery pack with focus on light vehicles. The study finds an energy demand of 350-650 MJ/kWh and an emission factor of 150-200 kg CO2-eq/kWh. It points at electrodes as the dominant contributor, but also conclude that electronics have a high impact and that emissions and energy use from mining and refining depends on the battery chemistry. The authors states that the data point towards a near-linear scale up of GHG emissions with kWh and weight. Another conclusion is that the el-mix of production location greatly impacts the results. At last, the authors comments that there is not enough transparent data to draw detailed conclusions about battery production emissions. [106]

Dai et al. in 2019 estimates 1 125 MJ energy consumed per kWh battery capacity of a NMC111 battery. The data were obtained in 2017 from a leading Chinese LiB manufacturer. The production of NMC111 powder is the most significant contributor with 36% of the total energy use (39% of GHG emissions). Aluminium and cell production process accounts for respectively 18% and 19% of the total energy. Dai et al. also argues that the energy use in cell production and battery packs assembly is much lower than found in earlier studies, with 216.2 MJ/kWh cell produced. These values differ significantly from the ones found in Ellingsen(2014) where it accounted for 586 MJ/kWh cell produced. However, Ellingsen et al. assumes 50% energy production demand in the report from 2016. This will lead to a 293 MJ/kWh cell produced, which corresponds more with the findings from Dai et al. for cell production. In regards of the NMC111 powder, however, the results are extremely different. Dai et al. includes a much higher heat and electricity consumption. The NMC111 powder and battery are assumed to be produced in the United States with electricity supplied from the national grid mix. [107] [108]

The study by Emilsson and Dahllöf from 2019 is an update from the Swedish Energy Agency on the previous report from 2017. It is heavily based on the new and transparent data presented by Dai et al. in 2019. The authors conclude that the GHG emissions are 61-106 kg CO_2-eq/kWh battery capacity for the NMC chemistry. The range difference mainly depends on the el-mix used in cell production and states that the maximum value would be 146 kg CO_2-eq/kWh if less transparent data were used. The study does not include the emissions from recycling which the

Romare and Dahllöff study does. A value of 15 kg CO_2-eq/kWh is reported in the latter. The range of the Emilsson study of 61-106 kg CO_2-eq/kWh allocate 59 kg CO_2-eq/kWh for the upstream material production and 2-47 kg CO_2-eq/kWh to the cell and battery pack manufacture. The reported value of 59 kg CO_2-eq/kWh is collected from Dai et al. The emissions from cell and pack manufacturing are calculated by using the process energy of 170 MJ/kWh from Dai et al. and include a range of renewable to non-renewable el-mix of 0.05-1 kg CO_2-eq/kWh consumed. The decrease in the high end of the range is mainly due to new production data for cell production. The decrease in the low end of the range is because of the 100 percent renewable energy as a scenario in the cell production. [92]

The emission factor and energy demand for the battery production are given, in addition to the battery chemistry and study model. It can be seen that the data variation for both energy demand and emissions are high. The study model will greatly impact the result of the energy demand and thus, in turn, the emissions. It can therefore be said, that the studies which reviews other publications will be the most accurate for the overall market, but data transparency is still needed for detailed conclusions.

The battery production emissions from the different studies can be seen in Figure 7.13. The production energy demand is also included and the studies are placed chronologically from left to right, showcasing the development in the last five years. It can be seen that the emissions have significantly decreased. From Ellingsen 2014 to Dai et al. 2019 there is a 58% reduction. Opposing to this, the energy demand seems to have increased. This can be explained by the increased transparency in the manufacturing process introduced by Dai et. al in 2019. The reason for the decreasing emissions, in spite of manufacturing energy rising, is the usage of renewable energy for electricity and heat production and the new production data for cell manufacturing.

Table C.4 in Appendix C, presents several studies and respective relevant data. The CI and manufacturing energy in battery production from the studies can be seen in Table G.1 in Appendix G.

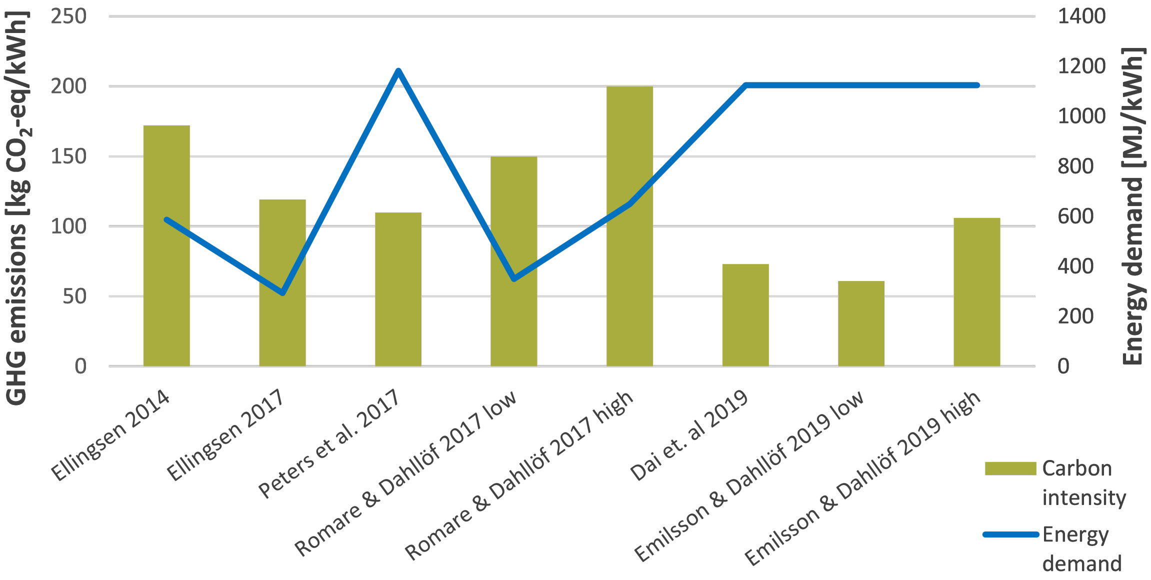

Figure 7.13: *Carbon intensity and manufacturing energy demand from different battery production studies. Battery pack emissions on the left axis and manufacturing energy intensity on the right axis.*

A study by Ellingsen and colleagues from 2016 examines how the size and range of an electric vehicle influences the GHG emissions. In this report, it is shown that production and end-of-life of a 59.9 kWh battery will have an emission of 7.1 tonne CO_2-eq. There are some emissions in the use phase as well, but this is excluded in this thesis to make it more comparable to the other studies. In the study, it is assumed a 50% lower energy demand compared to Ellingsen 2014. The total weight of this battery is given to be 554 kg. This will lead to 119 kg CO_2-eq/kWh for this battery.[108][91]

Summarising and extrapolating the values for the weight of the battery components given in Table G.2 in Appendix G, gives a total weight of a 76 kWh and 200 kWh battery of 700 kg and 1 812 kg respectively. This will give an energy density of 110 Wh/kg. Comparing this to the weight used by Nordelöf [61], which is 1 500 kg and 50 Wh/kg for a 76 kWh battery pack shows a large difference.

8 Case Study - Trondheim

This chapter will investigate the GHG emissions from the bus fleet in the Trondheim area. Firstly, the case study on the Trondheim area is described, together with assumptions. Further, bus models are defined, and embodied and operation emissions, with carbon payback time, on the various bus models are presented. These models are used to examine three fleet scenarios with different el-mixes. Lastly, a sensitivity analysis on CI during production of material and battery are evaluated, along with battery capacity.

8.1 Description

Trondheim is the largest city in Trøndelag county, hence being the center of AtBs operations with the highest share of activity. In August 2019, AtB implemented a new route system to improve the collaboration between the services in Trøndelag, and at the same time implemented a new bus fleet in the Trondheim area working towards a low carbon society. The previous bus fleet was operated by Vy buss AS, Tide Buss and Trønderbilene, while after the transition Vy buss AS and Tide Buss are responsible for the operations. This section is a description of AtBs operations in the Trondheim area. The bus fleets before and after the transition is presented with assumptions and simplifications. [12]

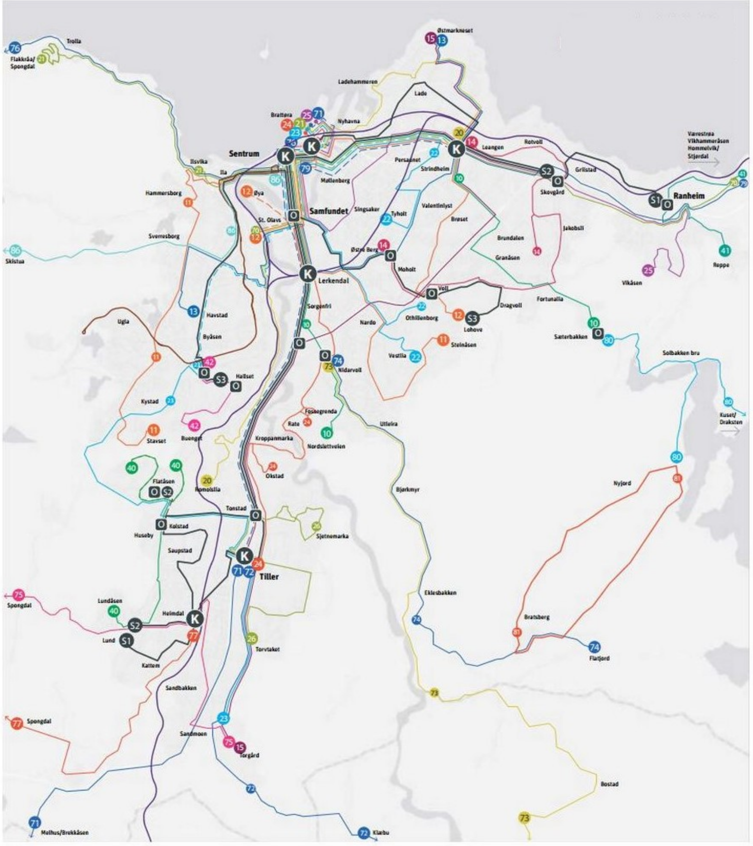

Figure 8.1: *Trondheim area with the affiliated route system.[109]*

The Trondheim area, with the affiliated routes, is depicted in Figure 8.1. The previous bus fleet that operated in this area, consisted of 320 buses, where 3 buses were diesel, 213 gas, 94 biodiesel and 10 of them were hybrids. From

August of 2019, there are zero diesel buses operating in Trondheim, out of the 305 buses in the new bus fleet. Further, 113 are biogas, 98 biodiesel, 58 hybrids and 36 of them are electric. The two fleet compositions are visualised in Figure 8.2 and Figure 8.3. For the previous fleet in 2018, hereby referred to as the 2018 fleet, there were no electric buses, and the biogas buses constituted 66% of the entire fleet. For the new fleet in 2019, hereby referred to as the 2019 fleet, the electric buses make up almost 12%, while biogas buses are reduced to 37%.[12]

The gas buses in the previous fleet used LNG and biogas, while the gas buses in the new fleet use only biogas. The hybrids that are implemented in the new fleet, are the so called "metrobuses" produced by Van Hool, running on biodiesel. The electric buses were produced by two different companies; Volvo provided 12-meter buses and Heuliez delivered 18-meter articulated buses. These have battery capacities of 200 kWh and 106 kWh respectively. In the Trondheim area, the "metrobuses" operate three lines, while four routes are fully electrified with electric buses. [12]

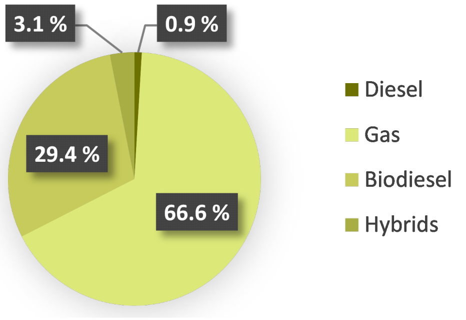

Figure 8.2: *The previous bus fleet composition in the Trondheim area before the transformation.[12]*

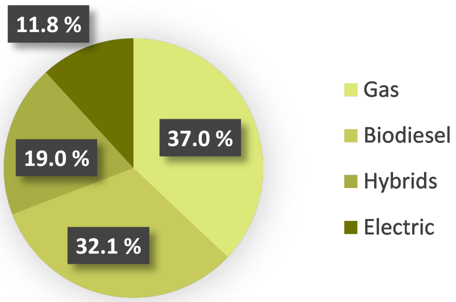

Figure 8.3: *The current bus fleet composition in the Trondheim area after the transformation.[12]*

In addition to the two bus fleets of 2018 and 2019, the case study includes a fully electric scenario, where 305 buses are electric. For this scenario, it is assumed that the fleet only consist of Volvo 7900 Electric buses. The three fleet scenarios are given in Table H.1 in Appendix H, with an overview of their respective bus composition.

The bus fleets of the Trondheim area are complex and many factors are important for the outcome of the results. To be able to conduct the calculations and analyses, it was necessary to define some assumptions and simplifications. The assumptions for the case study are stated in Table 8.1.

The length of the buses operating in the Trondheim area vary. The hybrids from Van Hool are 24 meters, while the eleven electric buses from Heuliez are 18 meters. Also, there are articulated buses with biogas and biodiesel.[12] For simplicity, it is assumed that all the bus lengths are 12 meters.

The batteries in the electric buses are defined to be 200 kwh for the Volvo 7900 Electric, 106 kwh for Heuliez electric and 36 kwh for the hybrids from Van Hool, based on data from AtB. The Volvo HEV and PHEV buses have battery packs of 9 kWh and 19 kWh respectively. It is assumed one battery change for the fully electric buses, two for the Volvo HEV and PHEV options, and no change for the Van Hool HEV. The yearly distance driven and the lifetime for one bus is also based on information from AtB, and is assumed to be 60 000 km yearly over 10 years. [12, 61]

Table 8.1: *Assumptions made for the case study.*

Assumptions	
Bus lengths	12 m
Volvo Electric battery	200 kwh
Heuliez Electric battery	106 kWh
Van Hool HEV Battery	36 kwh
Volvo HEV battery	8.9 kWh
Volvo PHEV Battery	19 kWh
Yearly distance	60 000 km
Lifetime	10 years
Battery Change Electric	1
Battery Change HEV	2
Battery Change PHEV	2

8.2 Bus model - Volvo 7900

This section presents how the subsequent fleet scenarios are estimated. The battery estimations and the new bus constructions for the Volvo 7900 are described. Further, the embodied emissions from four Volvo 7900 bus models are presented, with comparative estimations and studies. Lastly, the operations with a carbon payback time for the bus models are exhibited.

Since most of the electric buses implemented in the Trondheim area are of the Volvo 7900 type, the case study focuses on this bus model. The preceding analyses of bus production, component, material and battery emissions in section 7 is mostly generic, excluding the study by Nordelöf et al. If assuming that Nordelöf et al. presents accurate data and emissions magnitude, with the primary data from Volvo, and ecoinvent as secondary, this can be used as a foundation for further analyses.

The bus models developed in this case study, is based on data presented by Nordelöf et al. in 2019 and estimated batteries. The results analyse the first and second generation Volvo 7900, presented in section 5, to achieve a thorough analysis of both the material and component production. The material analysis is based on the emissions from the first generation analysed by Nordelöf et al. The component analysis is based on the third generation, in which the only assumed alteration is the larger battery pack of 200 kWh.

8.2.1 Battery and bus construction estimations

To provide realistic bus models for the given case study, the weight of the batteries are estimated. This is completed through an extrapolation for the specific capacity. The calculations resulted in 1 812 kg, 102 kg and 188 kg, for the 200 kWh, 9 kWh and 19 kWh batteries respectively. The extrapolation was conducted in the numerical software program MATLAB, based on the data from Ellingsen at al. in Table G.2 in Appendix G.

The estimated batteries are different from Nordelöf et al. This results in a different weight percentage for the bus constructions. With the estimated batteries, the total weight of the Volvo 7900 Electric increases to 13 076 kg. The chassis, body and powertrain are assumed to be the same for the Volvo 7900 bus constructions, while the battery for the electric bus increases from 1 536 kg to 1 812 kg. The specifications for the estimated Volvo 7900 Electric are presented in Figure 8.4.

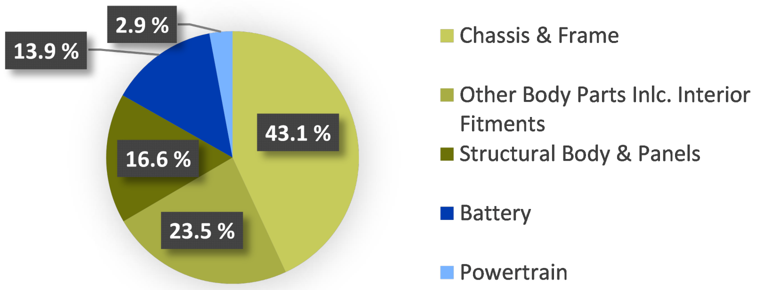

Figure 8.4: *Estimated component configuration for the Volvo 7900 Electric.*

The total weights for the HEV and PHEV, decreases from 12 700 kg to 12 548 kg and from 12 800 kg to 12 604 kg respectively. The overview of the estimated configurations are presented in Table B.3 in Appendix B. The conventional bus from Volvo do not change from the original specifications, because it does not include a traction battery.

8.2.2 Production emissions

Nordelöf et al. provide emissions on both material and components for four Volvo 7900 models. The material emissions are compared to the emissions extracted from the study by Kärnä.

Material

Nordelöf et al. present results on material upstream processing using secondary data from Ecoinvent, while the study conducted by Kärnä analyses upstream processing for different buses with manufacturing data. The results from both studies are presented in Table D.1 in Appendix D, and visualised in Figure 8.5. Nordelöf et al. present data on the electric, conventional, HEV and PHEV, while Kärnä provides emissions for an electric bus, two types of conventional buess and a HEV. The conventional aluminium bus in Kärnä's study is a conventional bus with an aluminium chassis. Steel and aluminium emissions are included for all bus models. Kärnä reports the steel and aluminium emissions in the study, while for the Volvo models, the emissions are estimated.

The total production emissions from the Volvo 7900 models, including material processing, manufacturing and maintenance, are presented in Figure 8.6. The maintenance is expected to include both material processing and manufacturing of oil and any additional parts throughout the use phase.

In Figure 8.6, the conventional bus has the lowest production emissions, while the electric has the highest. This is also reflected in the upstream material emissions in Figure 8.5. The upstream material emissions constitute the largest proportion of the total emissions in the Volvo 7900 models, shown in Figure 8.6. Out of the 62% material emissions in the electric Volvo model, 19% originate from steel and 24% are from aluminium, while from the 69% material emissions in the conventional model 47% originate from the steel and aluminium production. Moreover,

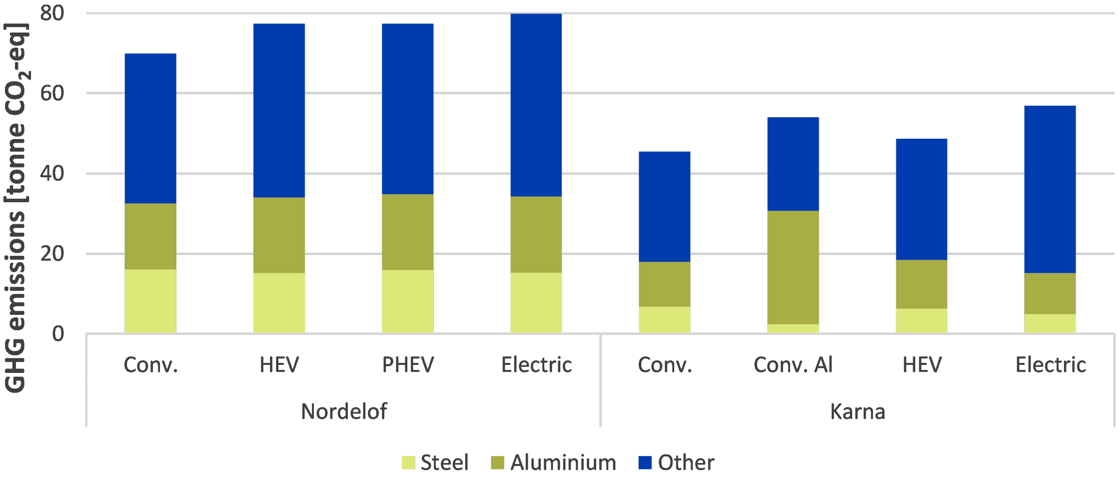

Figure 8.5: *Upstream material production emissions from electric, diesel, PHEV and HEV bus from two LCA studies. Conv. abbreviates to conventional and conv. Al is short for conventional bus with aluminium chassis.*

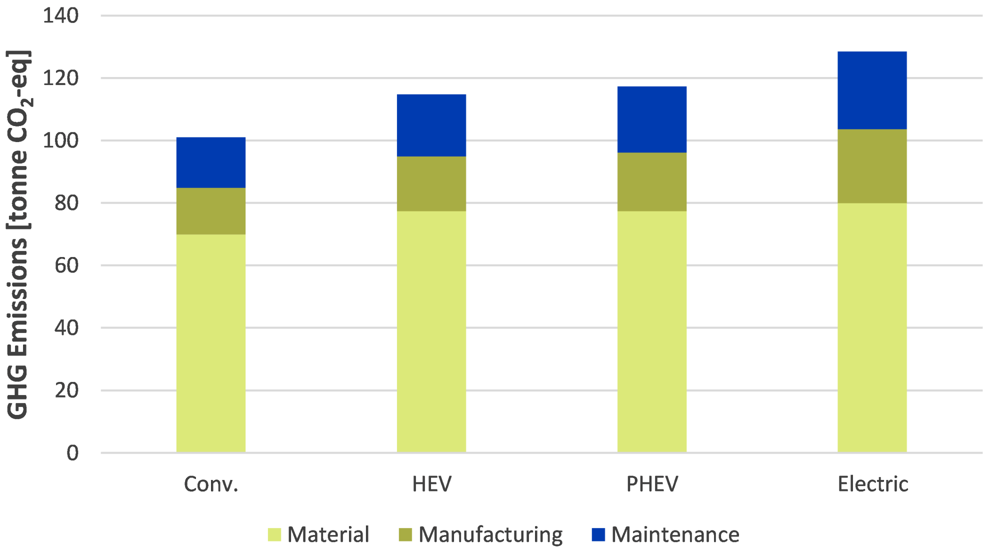

Figure 8.6: *Total GHG emissions from the Volvo bus models presented with material, manufacturing and maintenance emissions. The emissions are extracted from Nordelof et al.[61]*

steel and aluminium account for 27% of the total production emissions in the electric, and 32% in the conventional model. Furthermore, the emissions from steel and aluminium is similar for all four models.

The material emissions from Kärnä has greater variations in emissions compared to the Volvo models in Figure 8.5. The electric bus has the highest emissions, before the conventional aluminium chassis and HEV. Comparing the material emissions to the Volvo models, the emissions are lower. In Kärnä's study, the steel constitute a low proportion of the material emissions, while aluminium constitute a higher percentage. The emissions from the aluminium coincide 52% of the total material emissions in the conventional bus with aluminium chassis.

The reported results are calculated from Volvo 7900 specifications and average emissions on aluminium and steel. The steel emission were calculated from the average 2.24 tonne CO_2-eq per tonne steel. This was extracted from Figure 7.3, as the average emissions of the four studies. Also, the aluminium emissions were calculated with the average 16.5 tonne CO_2-eq per tonne aluminium produced, based on the data from the Worldsteel Association. The Volvo 7900 and Kärnä's emissions are given in Table D.1 and Table D.2 in Appendix D.

Components

Also, Nordelöf et al. report emissions from the components in the Volvo 7900 models, and the results are visualised in Figure 8.7. The batteries in the HEV, PHEV and electric models are estimated emissions from the assumed battery packs, based on literature presented in section 7.4. The body component include the emissions from both the structural body & panels, and other body parts including interior fitments.

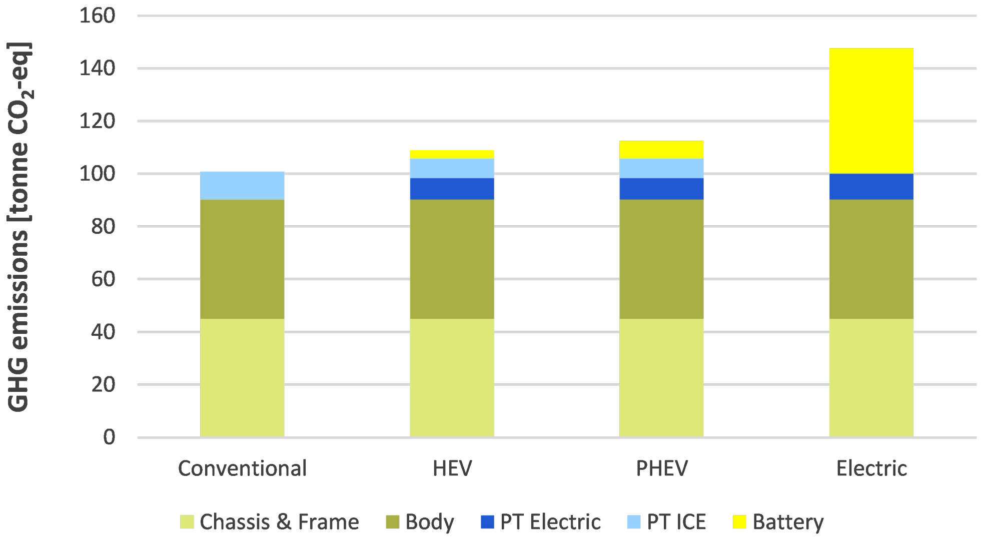

Figure 8.7: *Estimated total GHG emissions from four Volvo bus models. Component emissions in the models are presented with different colours.*

In Figure 8.7, the electric bus model still emit the highest GHG emissions, with an increase to 148 tonne CO_2-eq with the estimated battery emissions. Also, the conventional model still emits the lowest, with the same magnitude as presented in Figure 8.6.

The chassis and body show to constitute the largest share of the emissions for all models, but the magnitude depends on the degree of electrification. The chassis and body emit the same for each of the Volvo models, while the powertrain and battery emissions vary. For the electric, the battery emits 48 tonne CO_2-eq, accounting for 31% of the emissions. The chassis and body account for 90% and 61% of the emissions in the conventional and electric respectively. The body show to account just more than the chassis, around 45% in the conventional and 31% in the electric, while the chassis & frame emit just under 45% of the total emissions in the conventional and 30% in the electric.

The Volvo 7900 component emissions are presented in Table D.3 in Appendix D. The estimated battery emissions in the three electric buses, were calculated based on the assumed CI of 119 kg CO_2-eq/kWh, extracted from Ellingsen et al's study from 2016, and the respective battery sizes presented in Table 8.1.

8.2.3 Carbon payback time

Since the electric bus has embodied emissions that are higher than the other powertrain technologies, it is interesting to take a closer look at these emissions in combination with differences in operations. By investigating the emissions each bus technology has per km during operation, the carbon payback time for the embodied emissions can be estimated. This can be used to get an understanding of which powertrain technology will have the least environmental impact. The el-mixes referred to in this section are: EU-mix (294 gCO_2-eq/kWh), Nordic (75 gCO_2-eq/kWh), NO (19 gCO_2-eq/kWh) and NO-GO (520 gCO_2-eq/kWh). These were presented in section 4.3.

The carbon payback time (CPBT) is defined as the number of kilometres the electric bus has to drive to emit the same amount of GHGs as the compared technology. This is the accumulated emissions from production and operation. The kilometres the electric bus drives after this point, will only lead to an emission reduction in comparison with the other technologies.

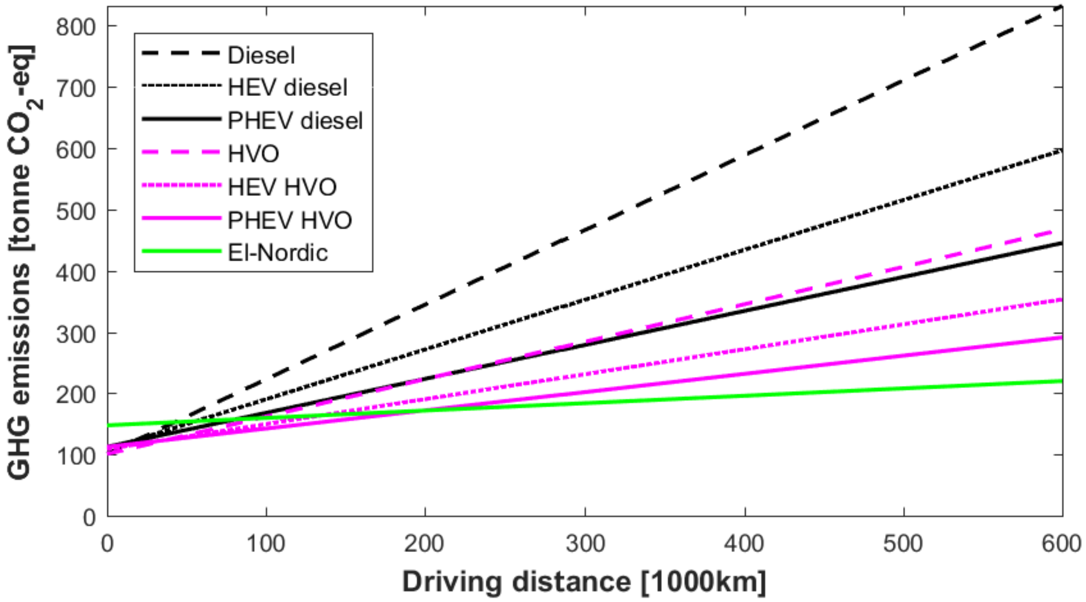

Figure 8.8: *GHG emissions versus driving distance for different fuel technologies. Nordic charging mix is used for the electrified options.*

Figure 8.8 shows the emissions from the operation of different powertrain technologies as a function of distance driven. The el-mix used for charging in the figure is the Nordic el-mix. The slope of the lines represent the emissions per driven kilometre, and the intersection with the y-axis express the embodied emissions reported in Figure 8.7. The kilometre value at which the electric bus intercepts the other bus models, will be the CPBT. The plot is an illustration of the simulations conducted for calculating the CPBT for the various technologies. The slope of the PHEV models vary based on its charging mix. Therefore, comparing a PHEV charging with a given el-mix, to an electric charging with another, will be incompatible. Therefore, to get the CPBT compared to the PHEVs, one simulation were done for each charging mix. These are presented visually in Appendix I and the CPBTs found, are presented in Table 8.2. Each row in the table, represents one simulation. Figure 8.9 shows a compilation of the four simulations, excluding the PHEV options.

Table 8.2: *CPBT for Volvo 7900 Electric using different charging el-mix. Electric compared to three bus models for both diesel and HVO fuel.*

Charging mix	**Diesel** [1000Km]			**HVO** [1000Km]		
Electric ⇓	**Conv**	**HEV**	**PHEV**	**Conv**	**HEV**	**PHEV**
EU-mix	55	86	114	188	846	671
Nordic	43	56	81	95	135	198
NO	40	51	75	85	111	168
NO-GO	77	191	195	63 000	∞	∞

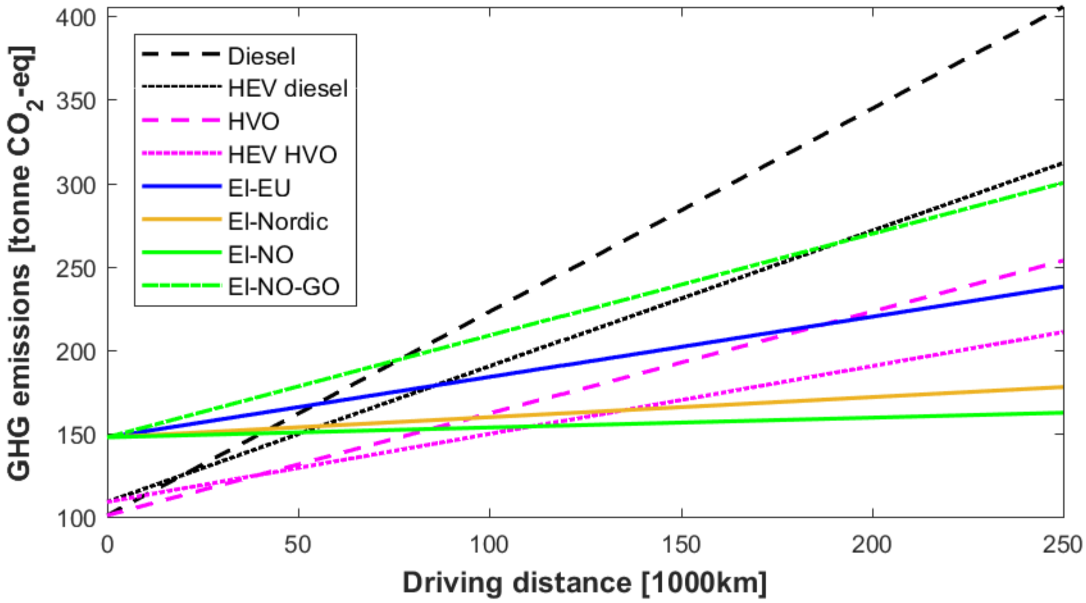

Figure 8.9: *GHG emissions versus driving distance for different bus powertrain technologies, and different charging mixes for the electric option. Segment of 0-250 000 km.*

The electric bus has a short CPBT for the conventional diesel bus, regardless of the charging el-mix. It increases slightly for the HEV diesel, and even more for the PHEV diesel. For the HVO buses, the CPBT will also be longer for the more electrified options, excluding the EU-mix for charging, as the CPBT will be shorter for the PHEV than the HEV in this case. The electric bus charged with the NO-GO el-mix will never get on par with the HVO HEV and HVO PHEV. This means the electric bus has a higher emission intensity per kilometre driven, and will be worse than the HVO buses, no matter how long the lifetime is.

Average fuel and electricity consumption are gathered from [61] for a Volvo 7900. The background data can be viewed in Appendix I.

8.2.4 Lifetime emissions

GHG emissions for the whole lifetime of a bus with different powertrain technologies can be viewed in Figure 8.10. The error bars for the PHEVs represent the difference in emissions for charging with the NO-GO-mix (highest) and the Norwegian production mix (lowest). The production emissions are represented at the bottom of each bar, with the battery production in the middle. These are the emissions presented in Figure 8.7. At the top of the bars are the emissions from the operation of the bus.

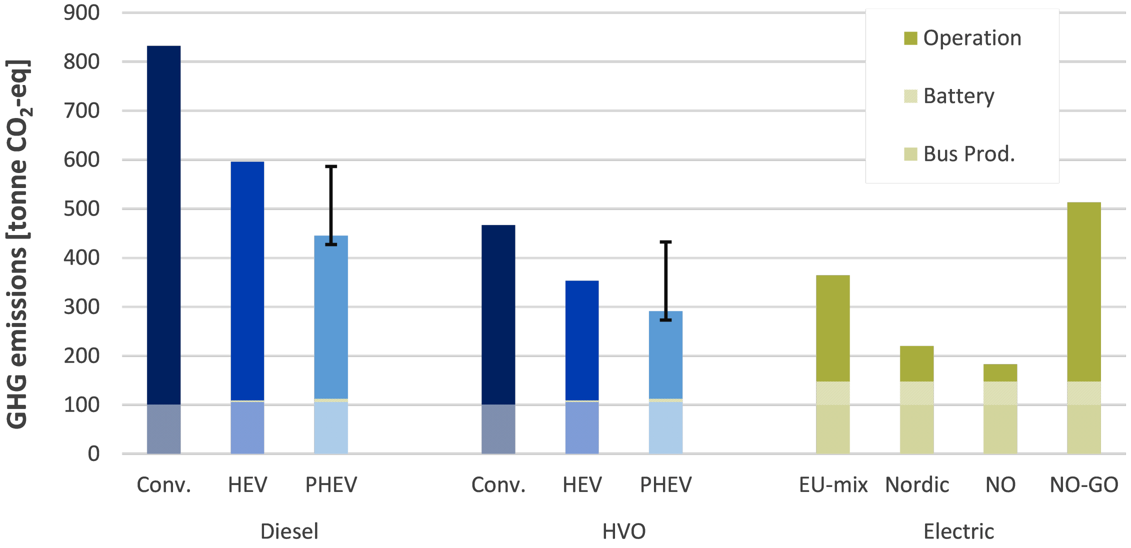

Figure 8.10: *Carbon footprint from a bus with different powertrain and fuel technologies. The distinctly green and different blue colours shows the emissions related to operation. The production emissions are represented at the bottom, and the battery emissions in the middle.*

It can be seen that the emissions for the lifetime of a bus will decrease significantly by electrification. By utilising a diesel HEV and PHEV the GHG emissions can be reduced with one-third and by half respectively.

The production emissions becomes a bigger part of the lifetime emissions as the operation emissions decreases. The embodied emissions contributes to 12-26% of the total lifetime emissions for the diesel options, 22-41% for the HVO options and 40-80% for the electric options. For the electric option with Nordic el-mix, the embodied emissions constitute 67% of the carbon footprint.

The emission reduction compared to conventional diesel bus are 30-49% for the diesel PHEV, 44% for conventional HVO, 58% for HVO HEV, 48-67% for HVO PHEV. For the electric options charging with different el-mixes, the reduction are 56% for the EU-mix, 74% for the Nordic mix, 78% for the Norwegian mix and 38% for the Norwegian without GO. Comparing the electric scenario with NO el-mix to the NO-GO el-mix, there is a reduction of 64% in the carbon footprint.

8.3 Results

In this chapter the results on the case study is presented. The preceding bus models are used to further analyse the bus fleets in the Trondheim area. Fleet emissions are analysed for three scenarios in both production and operations.

8.3.1 Production emissions

Before launching operations, the bus models presented have embodied emissions. This will accumulate to the bus fleets, and the total emissions will depend on the combination of bus types in the fleet. The total emissions for the three bus fleet scenarios are presented in Figure 8.11. The bar to the right represents the electric bus scenario, while the bars to the left and middle, are the previous and current bus fleets respectively. The total production emissions from the fleets are evenly allocated to each kilometre based on their total lifetime distance. This is 60 000 km over 10 years as presented in Table 8.1. Figure 8.11 shows that the production emissions for the current and previous fleet is similar, while the electric fleet has an immense emission in comparison.

The fleet scenarios emit, throughout the lifetime, 0.18, 0.17 and 0.25 kg CO_2-eq per kilometres driven respectively. The emissions are presented as GHG emissions per kilometre driven, to be able to compare the different fleet compositions, because of the differences in the driven kilometre and number of buses. The electric scenario has larger embodied emissions compared to the other scenarios. The difference mainly stems from the battery, which constitute one third of the emissions. The chassis and body comprise the greatest share of each fleet scenarios emissions.

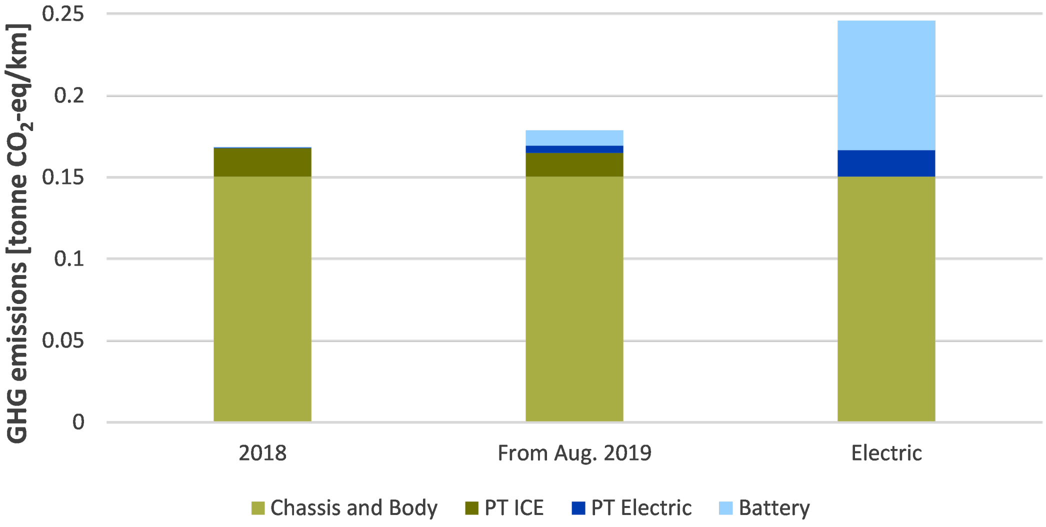

Figure 8.11: *Embodied production emissions from 2018-, 2019- and fully electric bus fleets per km.*

The bus fleet transition from 2018 to 2019 has an increase of embodied emissions of 6%, while a further electrification increases the emissions by 38% from the 2019 fleet. The results for the embodied emissions are reported in Table

K.1 in Appendix K. The calculations are conducted from the bus fleet compositions in Table H.1 in Appendix H and the bus model emissions presented in Figure 8.7.

8.3.2 Lifetime emissions

Figure 8.12 presents emissions from different compositions of the bus park in the Trondheim area. The data from the 2018 and 2019 operations are real life data on GHG emissions provided by AtB, in addition to the electricity consumption for the electric buses in the electric scenarios. The results can also be seen in Table K.2 in Appendix K.

The emissions from August 2019 until the end of the year, are presented to show the impact of the electrification by introducing a new bus fleet, compared to the 2018 fleet. The other bars represent a scenario in which all the buses operated are full electric. The bars in this scenario show the different charging el-mix emissions, from EU-mix, Nordic mix, NO mix and NO-GO mix. The operation in the figure includes both fossil and non-fossil emissions. The production and battery emissions, are extracted from Figure 8.11.

The carbon footprint is reduced by 37% from 2018 to after Aug. 2019. The new current bus fleet also have lower emissions than the electric fleet charged with NO-GO el-mix. Charging an all electric bus fleet with Nordic el-mix or Norwegian production el-mix, will lead to a large reduction of the carbon footprint. In comparison with the current fleet, it will decrease 52% and 61% respectively. Charging the current fleet with NO el-mix will lead to a 10% reduction compared to charging with the NO-GO el-mix, as represented by the error bar.

GOs can be bought to reduce the carbon footprint. Assuming a price range of 5.5-22 NOK/MWh [4], the price of GOs for the yearly consumption in an electric bus is approximately 363-1452 NOK, i.e. 13 000 - 52 000 NOK/year for the current bus fleet[5], or 0.05-0.2 Øre/passenger.

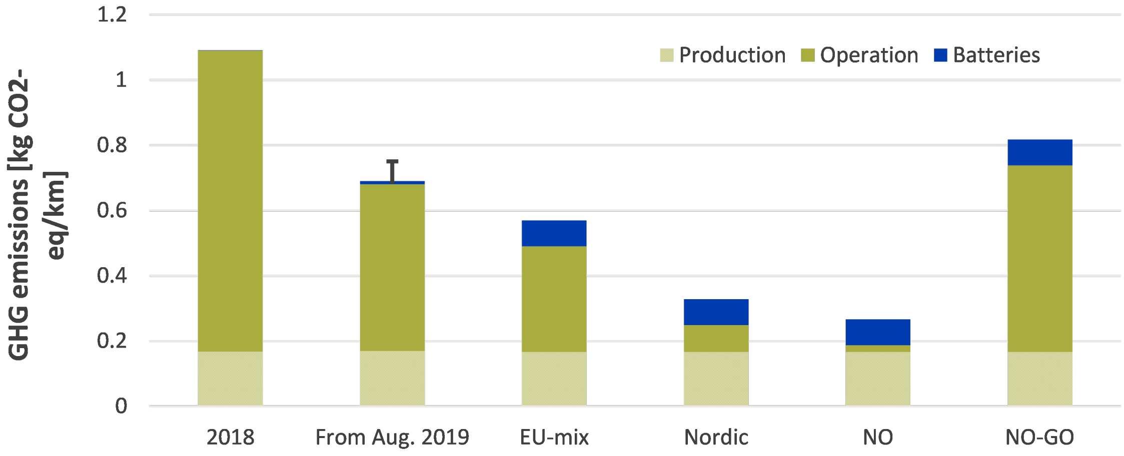

Figure 8.12: *Carbon footprint for different bus fleet compositions per driven distance. The little bar at the top of the 2019 fleet composition shows an uncertainty range in operation emissions caused by the charging mix.*

Figure 8.13 presents the GHG emissions per person-km. The emissions from city buses and passenger cars are averages for 2018, and are presented as a comparison to the emissions from the bus fleets in the Trondheim area.

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[4] 1 Euro = 11 Norwegian Kroner and 1 NOK = 100 Øre

[5] Assuming 1.1kWh/km and yearly driving distance 60 000 km

These averages do not account for the emissions from charging electricity, and all electric vehicles are therefore set to have zero emission. The operation emissions were 89 g CO_2-eq/person-km for the 2018 bus fleet, and it was reduced to 49 g CO_2-eq/person-km by introducing the new fleet. The average values for 2018 in Norway for city buses and passenger cars were 72.5 g CO_2-eq/person-km and 69.5 g CO_2-eq/person-km respectively. For the all electric scenario with Nordic charging el-mix, the GHG emissions from operation will be 8 g CO_2-eq/person-km. This scenario will in addition lead to 8 g CO_2-eq/person-km emissions from battery production. The specific values can be seen in Table K.2 in Appendix K.

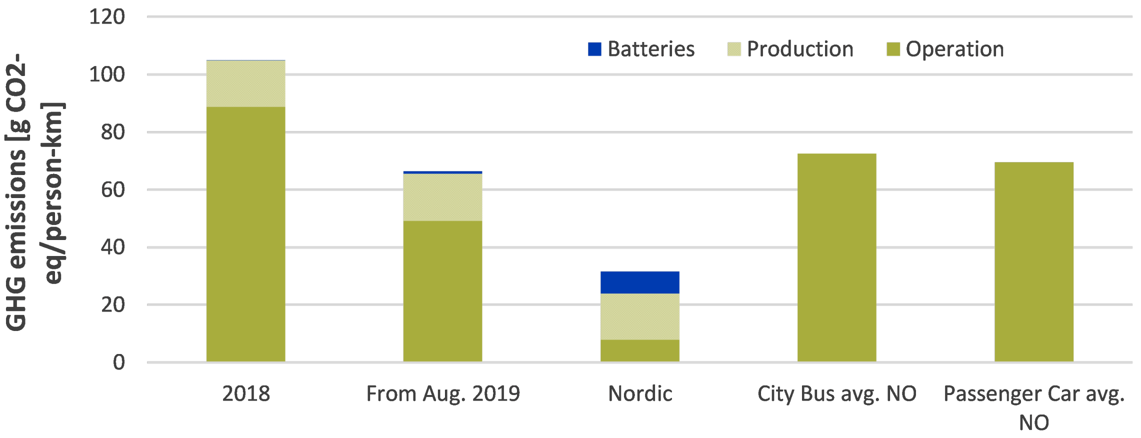


Figure 8.13: *Carbon footprint per person-kilometre for three fleet scenarios. The city bus and passenger car emissions are averages from 2018, providing a comparison. The green shows the emissions related to fuel consumption and the blue emissions from battery production. The production emissions are represented between the operation and battery. The Nordic bar is the electric fleet scenario charging with Nordic el-mix.*

8.4 Sensitivity analysis

Throughout the thesis, several studies are presented and analysed. The results reported from these papers, specifically LCA studies, are established on multiple essential variables. These factors can have a large impact on the results, with only small alterations. Thus, it is essential to conduct a sensitivity analysis. In the production of the material and the battery, the electricity CI can have a decisive impact.

8.4.1 Primary material processing on bus models

An approach to reduce the emissions during the bus production, is by limiting the emissions in the aluminum and steel processing. Analysing the steel and aluminium production with low and high carbon intensive electricity, the impact of the el-mix can be analysed, and the potential reduction can be found. The study from Yang et al. TP and Hydro are used to present sensitivity on aluminium production, while the study by Renzulli and Gao et al. are used to present sensitivity on steel production.

For the electric bus, the steel originally emits 15 tonne CO_2-eq, and by implementing renewable energy source it is reduced to 11 tonne CO_2-eq. Equally, for aluminium, it only emits 5 tonne CO_2-eq, compared to the 19 tonne CO_2-eq originally. For the electric, conventional and HEV bus this reduces the emissions by 15%, 17% and 17% respectively. If the production of the materials were to occur in China with coal and thermal power, similar to Gao and Yang's studies, the emissions would be considerably higher. These emissions are found to be 18 tonne CO_2-eq for steel and 25 tonne CO_2-eq from aluminium for the electric bus. This results in an increase of 7% 8% and 8% for the electric, conventional and HEV bus models respectively.

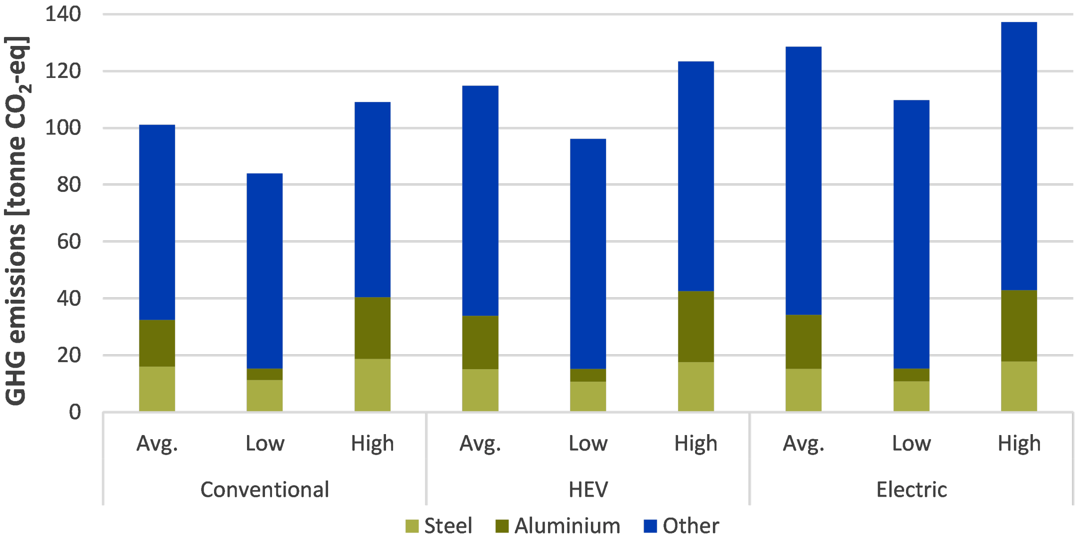


Figure 8.14: *Sensitivity analysis on primary steel and aluminium production. Conducted on three bus models with average, low and high CIs.*

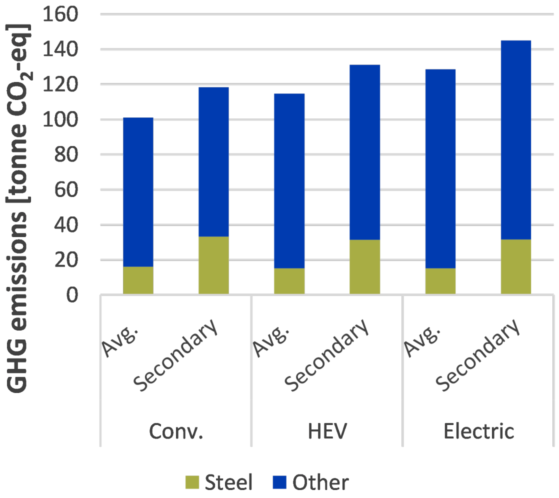
Implementing these low and high emissions for the various bus models, the sensitivity can be visualised. The total emissions, including emissions from steel and aluminium are presented in Figure 8.14 for the electric, conventional and HEV models. The low bars represent efficient and low carbon intensive steel and aluminium production, while the high bars represent material production with fossil fuels. The aluminium has the greatest variations between the high and low. The different models have the same trends between high and low, but vary in magnitude.

The results for the sensitivity are presented in Table J.1 in Appendix J. The CIs used for calculations are 2.6 and 1.6 tonne CO_2-eq per tonne steel for the high and low respectively. For aluminium, 22 and 4.0 tonne CO_2-eq per tonne aluminium are used for high and low CI respectively.

8.4.2 Secondary material processing on 2019 bus fleet

An alternative production path is material processing from recycled scrap. The study by Gao et al. present emissions for secondary processing, and is used to analyse the sensitivity on secondary steel production. For the aluminium, data from the Aluminium Association are applied. The secondary material production for the various bus models are presented in Figure 8.15 and Figure 8.16.

For secondary steel production in Figure 8.15, the emissions increase for each model. However, for secondary aluminium production in Figure 8.16, the emissions decreases. The electric model increases with 13% with secondary steel production, while it decreases by 13% with secondary aluminium production. The results for the secondary material sensitivity are given in Table J.2 in Appendix J. The secondary emissions used for calculating the sensitivity are 4.7 tonne CO_2-eq per tonne steel, and 1.2 tonne CO_2-eq per tonne aluminium.



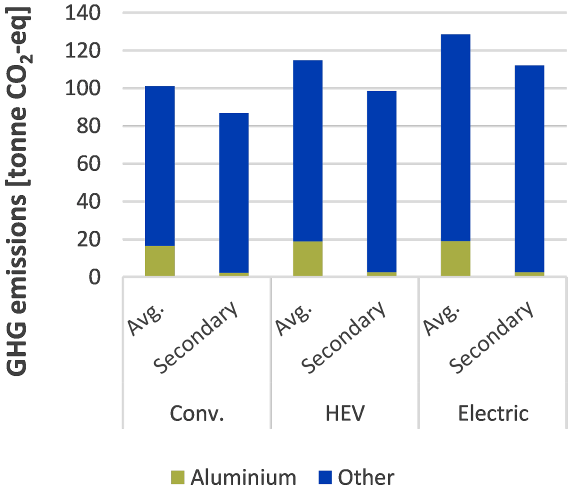


Figure 8.15: *Sensitivity analysis on secondary steel production GHG emissions on total bus production emissions. Conducted on three bus models with two different CI.*

Figure 8.16: *Sensitivity analysis on secondary aluminium production GHG emissions on total bus production emissions. Conducted on three bus models with two different CI.*

8.4.3 Battery

A sensitivity analysis on the battery capacity was completed to get an understanding of how an alteration would affect the GHG emissions. The result can be seen in Figure 8.17. The high scenario is depicted as the dark blue line, and the low scenario is represented by the green line. These use the CI from Emilsson and Dahllöf presented in section 7.4. It can be seen that the emissions, by scale up of the battery capacity, are linear. By reducing the capacity with 50%, from 200 kWh to 100 kWh, the production emissions are reduced with 22 tonne CO_2-eq. When doubling the battery size, to 400 kWh, the emissions increase with 48 tonne CO_2-eq. The differences originating from the CI of the battery production, are 34 tonne CO_2-eq at 200 kWh capacity comparing the high and low scenario. A battery pack with 1 000 kWh capacity will have production emissions of 238 tonne CO_2-eq.

In Figure 8.18, the battery emissions from two bus fleet scenarios are shown. These are based on the three different battery production CIs in Figure 8.17. The relative impact is the same for the two fleets, 2019 and electric only, but the magnitude is larger for the electric only. By calculating the emissions with a CI of 61 kg CO_2-eq/kWh, instead of 119 kg CO_2-eq/kWh, the reduction per kilometre will be 0.037 kg CO_2-eq/km for the electric bus fleet. The difference between the high and low intensities are 0.058 kg CO_2-eq/km. The difference between the high and low for the 2019 bus fleet are only 0.0079 kg CO_2-eq/km. The battery sensitivity analyses are visualised based on Table J.3 and Table J.4 in Appendix J.

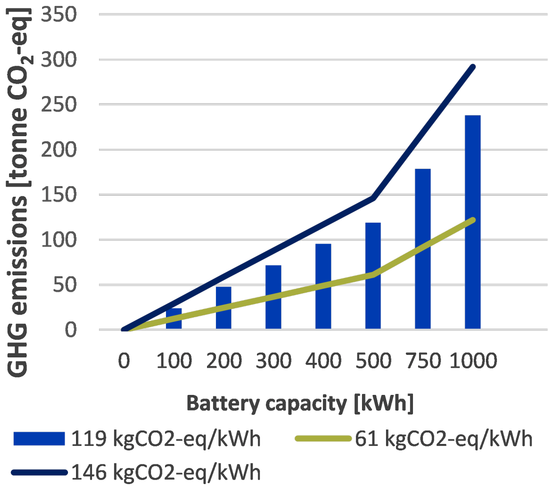


Figure 8.17: *Sensitivity analysis on battery production GHG emissions. Presented as a function of battery capacity and showcases three scenarios for different production CIs. Includes one battery change.*

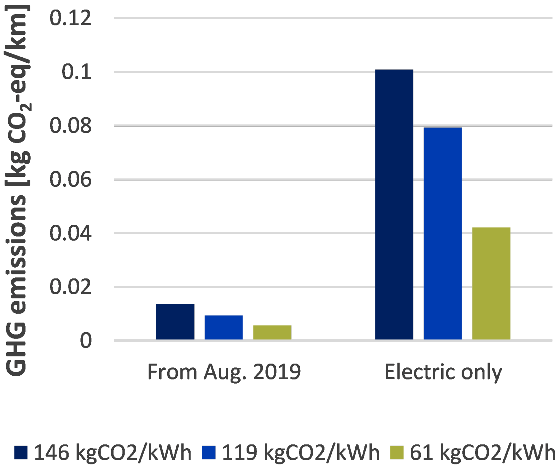


Figure 8.18: *Sensitivity analysis on bus fleet battery production emissions. Impact from different production CIs.*

9 Discussion

Based on the results, this chapter will try to answer the main and sub problems presented in the introduction. The main problems discussed, relate to the **achieved and potential GHG reduction in the current bus fleet**, and an evaluation of the **zero emission assumption**. To examine the main problems, the bus model and assumptions are evaluated to provide credibility, and the sub questions are examined to add completeness and depth.

The first section **evaluates the bus model** by discussing the assumptions and estimations defined. Thereafter, the aspect of **geographical impact on production** ,with focus on data transparency and el-mix, is analysed. The **impact from bus components** is investigated, by evaluating the glider and powertrains, based on the material emissions. Further, a **lifetime powertrain comparison** is conducted to analyse the differences in embodied emissions and the total carbon footprint, of various bus models. Finally, based on the main problems, the **importance of a charging mix** and the case of **problem shifting** is discussed, before further work is presented.

9.1 Bus model evaluation

For the bus models, it was desirable to construct case specific buses for the new and previous bus fleet in the Trondheim area, to achieve realistic results. An LCA were not conducted, thus, it was not possible to present results on each specific bus in the fleet. To complete a precise LCA would have been a too comprehensive task, because of limited data, outdated generic databases and especially time consumption. Thus, a meta-analysis was conducted. To develop the bus models, assumptions were defined and estimations conducted. These propagate uncertainty in both initial data and calculations that could have effected the final results.

The Volvo 7900 Electric was one of the new buses implemented in August of 2019, and detailed specifications and results were presented by Nordelöf et al. This study provide the best and most realistic production results regarding the bus models. The models presented are not ideal and will have uncertainties, but utilising the data from Nordelöf et al. provide representative magnitudes on production emissions, which are realistic for the case study.

9.1.1 Assumptions

Assumptions on the material and battery were determined to be able to present results regarding their emissions. The validity and reasoning of these assumptions is discussed in this section.

Material emissions

Material emissions for specific material, such as steel, were not presented in the Volvo bus models from Nordelöf et al. Thus, to provide depth, the upstream material emissions on steel and aluminium were examined. However, to be able to analyse them in the bus models, their emissions had to be assumed.

The specific steel average is used, because the studies in Figure 7.3 are based on different factors, presenting more or less similar results. Further, Korol, Gao et al. and Norgate analyse facilities with high CI, and the average of all four would represent the best result, as over 50% of steel is produced in China.

The average aluminium emissions are based on the data from the Worldsteel Association. The assumed emission is large compared to studies in Figure 7.4. However, it is assumed because most of the aluminium is produced in

China, and Yang TP and Norgate show immense emissions with high CI. Thus, assuming the average given by the Worldsteel Association is reasonable.

In addition to average emissions, extremities were assumed for the sensitivity analysis. The renewable and energy efficient emission for primary steel, was assumed to be best represented by the data from Renzulli et al. The study analyse an efficient facility with low carbon intensive electricity. For primary aluminium, the product from Hydro represent realistic emissions data, as well as their production is one of the most environmental friendly in the world. The worst case scenario is based on fossil fuel, and assumed to be the studies conducted in China. Gao et al. for steel and Yang et al. with thermal power for Aluminium.

The secondary production was difficult to analyse, because of limited studies. Therefore, for steel, the most comprehensive and detailed study was used; Gao et al. Conducted in China, the study provides a representation for secondary production with coal powered electricity. Aluminium production was extracted from Hydro, as they provide realistic data on low carbon secondary aluminium production.

Battery emissions

The choice of battery production CI was based on a literature analysis of several studies. Since most of the production of LiBs today, and in the future, are happening in China, which have a high CI, it was made a choice to use the 119 kg CO_2-eq/kWh presented by Ellingsen et al. in 2016. This will more likely reflect the CI from battery production on a global scale.

It is assumed one battery change for the electric, and two for the HEV and PHEV. Adding or deducting one battery change would have impacted the emissions. Adding a second battery change for the electric vehicle, the total capacity would correspond to the 300 kWh emissions from Figure 8.17. This leads to an increase in GHG emissions of 24 tonne CO_2-eq. In relation to Figure 8.10, this change will lead to a 11% increase of lifetime emissions for the electric bus charged with Nordic el-mix. The impact of one more or less battery change, will be minimal for the hybrid models. However, since the number of changes were provided directly from the operator, and are assumed the same in almost every study on the topic, the value used for the bus models seems reasonable.

Energy consumption

The data used for energy consumption in the use phase were gathered from Nordelöf et al's study. These data were provided directly from Volvo. These were also confirmed by AtB to be reasonable. Thus, it is assumed that this data is realistic for their operations. However, there could be uncertainty in the WTW factors, as reported values on biofuel emissions and electricity CI can vary. Either way, the assumptions provide an indication of the respective operation emissions.

9.1.2 Data quality

The bus models are based on multiple LCA studies, which utilise different data and inventories, to analyse the desired functional unit. Some of the used data is outdated, generic or not specific for the presented case study. This will have an impact on the accuracy, credibility and how realistic the bus models are.

The study by Nordelöf et al. and Kärnä uses different sets of data. Nordelöf et al. adopt primary data for the manufacturing and assembly, and secondary data from ecoinvent for the material processing. Kärnä applies primary data for the entire study. Nordelöf et al. using secondary data, can impact the authenticity of the bus models. This is because generic database where data are not up-to-date, can give misleading results and conclusions. But, as ecoinvent is a leading inventory for LCA studies, it is expected to provide reasonable data on the subject. Further, outdated data can also be a problem, as the study by Kärnä was conducted in 2012. This can lead to results that are not longer applicable. Nordelöf et al. conducted the study in 2019, implying that the results reported are relevant today.

9.2 The geographical locations effect on bus production emissions

From mineral extraction to a delivered bus product, various materials and individual parts of the bus models, can be expected to have been all around the world. Nordelöf et al. presented manufacturing in Europe and America, and material upstream processing all around the world, which makes the life cycle assessment difficult. The resource inputs in the processes, such as electricity, vary for each location. Therefore, the geographical locations effect on the bus production emissions, are discussed in this section.

Figure 8.6 shows that material processing has larger emissions in comparison to the manufacturing. This can relate to the location of the processing. This could also be the case for the difference in emission between Nordelöf et al. and Kärnä in Figure 8.5. Varying geographical location during production, have different impact on the final GHG emissions. Problematic factors for the geographical location are transportation, data transparency, el-mix and the situation of problem shifting emissions globally.

Transportation, data transparency and problem shifting

Producing a product, with processes all around the world, leads to higher emission in transportation. For increased number of locations, and larger distances between producers, the emissions are further increased. The direct impact of transportation is difficult to examine, but it should be considered.

A further problem with upstream production processes are that manufacturers do not know where the material and parts they acquire is processed. This is stated by Kärnä that uses primary data from manufacturers. The study could not present where the processing was conducted, as the manufacturers did not have that information. With additional processing locations, more companies are involved. Thus, there is a bigger demand for transparency. The lack of information on upstream processing limits the evaluation of geographic impact, but at the same time shows the complications in the industry, and a mindset that has to be altered.

One way to discard of the direct emissions for a location, is by moving industries abroad, to another country or continent. Doing this reduces the direct emissions in a region, but the problem only shifts from one location to another. This is also related to the case of implementing electricity and biofuels. The direct emissions in combustion are removed, but as a consequence, the emissions from the production becomes larger, shifting the problem to another location.

Electricity mix

Analysing the el-mixes presented in Table 4.3, it shows great variation in CI depending on location. Europe has lower carbon intensive electricity compared to Asia and America, while the Nordic countries have one of the lowest carbon intensive el-mixes in the world. The average in the US is 432 g CO2-eq/kWh, which is still 138 g CO2-eq/kWh higher than Europe. China have an even higher CI, with 555 g CO2-eq/kWh. This is concerning as over 50% of both aluminium and steel is processed in China. Additionally, Asia is the biggest producers of battery packs. Thus, implementing lower carbon intensive el-mix should be a focus in Asia and America, while the battery production and material processing should, in a larger scale, be moved to Europe.

Figure 8.14 shows that if bus manufacturers were to import primary aluminium from the Norwegian aluminium producer Hydro, or primary steel from energy efficient facilities in Italy, the emissions could be reduced considerably. By importing these materials, the emissions in the electric, HEV and conventional bus models are reduced by 15%, 17% and 17% respectively. Illustrating the great potential with low CI el-mixes. However, importing aluminium and steel from China, which uses thermal and coal powered energy, the emissions are increased, representing the high bars in Figure 8.14, by 7%, 8% and 8% for electric, HEV and conventional respectively. Notably, coal power has a CI of 980 g CO_2-eq/kWh, which is almost double the intensity in China. Thus, the emissions in reality could be lower, but this provides a representation of a worst case scenario.

When producing the material from secondary metal processing, the el-mix has an even greater impact. This is because the secondary processing, to a greater extent is based on electricity. However, the process is more energy efficient, requiring less energy in general. Steel produced in China with a coal intensive el-mix, results in an increase in emissions from the average, presented in Figure 8.15. Even though the secondary processing is a more energy efficient path, it is more beneficial to produce steel with the BOF steel process. On the other hand, the aluminium is produced in Norway by Hydro, with renewable hydro power. This results in a drastic reduction in aluminium production for the various bus models, presented in Figure 8.16. Based on this, the el-mix in different locations has a decisive impact for sustainable metal production.

Presented in Figure 8.17 the variations on battery emissions dependent on el-mix is presented. With a higher, more carbon intensive el-mix, the emissions can be as high as 146 kg CO_2-eq per kWh. While with renewable battery production the carbon emissions could potentially be reduced to 61 kg CO_2-eq per kWh. By moving the battery production from a country with high electricity CI, e.g. China, to a location with low electricity CI, e.g. the Nordic countries, the emissions can be considerably reduced. As presented in section 5.3, the production capacity in Europe are going to be expanded in the near future, but it is also seen that Asia and China still will be the leading producers of Li-ion batteries.

By introducing production facilities that process every step of the production chain, the problems with geographical location are solved. Reducing the emissions from production is a combination of integrated energy efficiency production chains, with low CI el-mix and reduced transportation. Both Hydro and Northvolt have integrated facilities, processing the entire chain of aluminium and battery products. Both show positive results for lower GHG emissions.

9.3 The components impact on the bus production emissions

The glider and powertrain have different impact on the total GHG emissions in the bus models. The glider, consisting of a body and chassis, generally contributes the biggest emissions, depending on the degree of electrification, presented in Figure 8.7. The powertrain, excluding the battery, generally has a small impact on the total GHG emissions of the bus models, while the battery has a varying impact depending on capacity. The origins of the emissions from chassis & frame, body, powertrain and battery are found from their material composition, the material processing and component manufacturing.

The bus models presented in Figure 8.7 have estimated batteries with a new bus weight distribution, reflecting more realistic bus emission for the case study. The process emissions in Figure 8.6 are based on the initial battery from Nordelöf et al. which makes it not quite comparable with the components. But the material processing and manufacturing will provide a representative comparison, as the ratio of material and manufacturing emissions would be more or less the same. The material emissions could be expected to increase slightly, as the battery has greater emissions in material processing than cell manufacturing and assembly.

Glider

The chassis and body of the buses have the largest contribution to the total GHG emissions. The chassis and body account for 61% and 90% in the electric and conventional bus models. Most of the material in the bus goes to producing the chassis & frame, structural body and other body, as they compose 83% to 88% of the weight in the bus models.

The chassis & frame component emits around 30% of the emissions in the electric model, and around 45% in the conventional model, which are the extremities for the bus models. The emissions originate mainly for steel, as well as other metals such as aluminium. These two metals shows to account for 43% and 47% of the emissions in material processing for the electric and conventional bus model, presented in Figure 8.5. It is important to note that steel accounts for over 50% of the bus weight, but only 19% of the material processing emissions in the electric model. On the other hand, aluminium accounts for only 9% of the bus weight, but at the same time constitute around 24% of the material emissions. This shows the great impact aluminium has on the total GHG emissions. This is also clearly presented by Kärnä in Figure 8.5. The aluminium has a larger impact on the emissions than steel in each of the models, and for the conventional diesel bus with the aluminium chassis, the aluminium accounts for half of the material production. Thus, the chassis & frame is dependent on the amount of high emitting metals, such as aluminium, for the emissions, and less on steel.

From Figure 7.2, the body component emits slightly more than the chassis, around 31% for the electric bus. The emissions from the body stems from the material in the external and internal parts of the bus, as well as the structure. This are materials such as plastics and aluminium. Comparing it to the weight of the total body, it comprises of 40% of the weight, similar to the chassis, but the chassis shows to make up just more, around 43%. Thus, the structural and other body components weigh slightly less than the chassis, but emit slightly more. This can come from that the other materials of the bus, such as plastic and aluminium, have a bigger impact on the emissions compared to the great amount of steel in the chassis. The emissions from the chassis and body is linear when comparing to the composition and weight of the bus. This is because the different material used to produce the bus, is divided very similarly to these components. This also applies for the powertrain.

Powertrain and battery

The powertrain constitutes the lowest GHG emissions from the bus. HEV and PHEV embody the same emissions from both electric and ICE powertrains, but the electric powertrain has slightly higher GHG emissions. This can originate from the extra parts, and a larger steel content in the ICE powertrain. The models with both electric and ICE powertrain installed, have larger emission than the powertrains only operating with either of them. This is reasonable as the hybrid powertrains have components from two different systems.

The battery has a considerable impact on the electric bus model, comprising 31% of the total production emissions. Many studies present different conclusions on processes that impact the production. The cell manufacturing, electrode production and material processing, especially powder production have significant impact. Figure 8.17 shows that the emissions increases linearly with the battery capacity. Producing batteries with high capacity embody large emissions, thus for each specific operation it should be modified. Unnecessary high capacity would have great impact on embodied emissions.

9.4 Powertrain comparison on the carbon footprint

The GHG emissions over the lifetime of a bus will depend on which powertrain is used. An electric bus charged with the Norwegian production el-mix will emit 78% less than the conventional diesel bus over the lifetime, as presented in Figure 8.10. The largest differences are caused by the emissions from operation, but there are also some differences in the production emissions for the different powertrains.

This chapter will discuss differences in emissions from the various powertrains, starting with embodied emissions focusing on the battery, and further, variations in operations are evaluated.

Embodied emissions

The largest difference in embodied emissions is found between the electric and conventional bus models. Analysing Figure 8.7 shows that the electric bus emits 47 tonne CO_2-eq more than the conventional bus. The difference in embodied emissions of the buses, originate mainly from battery production. There are some variations in the powertrains, but the impact is small in comparison to the battery. The HEV and PHEV have slightly higher emissions in the powertrains, as they coincide two different powertrain systems.

The bus models emit the same from chassis and body, while they vary in the powertrain and battery, as presented in Figure 8.7. Emitting the same in chassis and body is not entirely realistic, but they can be assumed to be more or less similar. This is because the buses has the same construction, but some smaller variations for the support of the battery and powertrain is anticipated. Thus, it is expected that the electric buses would have greater emissions in the chassis and body to support the extra weight of the powertrains and battery.

Based on this, the considerable difference in material processing, manufacturing and maintenance, in Figure 8.6, should originate primarily from the batteries. However, analysing Figure 8.5, the electric models show to have small variations in material emissions, even though the battery capacities are significantly different. The HEV and PHEV have a 9 kWh difference in capacity, but emit the same from material processing, and the electric bus use a 76 kWh battery, still only emitting 2.5 tonne CO_2-eq more. This means, in this case, that the material emissions from battery production have a small impact. Furthermore, since the conventional model has notably less material emissions than the electric models, it implies that the electric powertrains have a dominant impact on the difference in material emissions. This further suggest that the difference in manufacturing and maintenance emissions mainly stem from the differences in the battery capacity.

These results imply that the main contributor to the emissions from the battery production is the manufacturing and maintenance, not the material production. This is in line with the earlier studies on battery production emissions, but contradicts the newer findings presented in section 7.4. These pointed at the upstream material production as a significant contributor to the emissions. This means that the difference in the material emissions should be higher than presented in Figure 8.6.

If the battery capacity was to increase in the electric models, the emissions would as well, as discussed in section 9.3. Hence, the batteries could have a greater impact on the difference in embedded emissions. This also applies to the number of battery changes, as it affects the total produced battery capacity. Even tough the HEV and PHEV change battery packs two times, and the electric change once, the difference will still be relatively large, because of the capacity magnitude.

Lifetime emissions

Over the lifetime, a conventional diesel bus will have the largest carbon footprint, while the electric option, charged with electricity from renewable energy, will have the least, as presented in Figure 8.10. For both the diesel and HVO bus models, the conventional has the largest emissions, followed by the HEV and PHEV. It can be seen that the operation emissions decreases with increased electrification.

The amount of GHG emissions from the PHEV options depends on the charging el-mix. Charging with the Nordic el-mix, the diesel PHEV will have 32% less emissions than the diesel HEV, while the HVO PHEV will have 27% less emissions than the HVO HEV in the operation. Charging with a mix corresponding to the final residual mix for Norway (NO-GO), the emissions would almost be the same over the lifetime for the diesel options. However, for the HVO, the PHEV would have a larger carbon footprint. Choosing between the HVO HEV and PHEV will therefore not be a universal decision, but depend on the CI for the charging el-mix.

The reduction of the carbon footprint for the electric bus compared to the other bus models will be heavily dependant on the charging el-mix. An electric bus charging with the EU-mix, will have less emissions than all the diesel options and the conventional HVO, but higher emissions than the HVO HEV and PHEV. This is presented in Figure 8.10. It can more clearly be seen that it will emit more than the HVO PHEV in Table 8.2 as the CPBT for EU-mix are longer than the lifetime driving distance. By taking a wide approach with an European perspective, it seems HEV and PHEV buses running on HVO can be more environmental friendly than the electric buses. This means if all of Europe, with the current el-mix, are going to buy new buses, HEV and PHEV HVO can be the better alternatives to achieve minimal GHG emissions over the lifetime. The results on HVO are indicators, rather than exact, because the WTW of HVO has not been thoroughly examined in this thesis.

An electric bus charging with Nordic el-mix or Norwegian production mix, will have lower carbon footprint than all the diesel and HVO options. This is because of the low CI in the el-mix. By replacing conventional diesel buses with the electric options, the carbon footprint will be reduced by 74% and 78% respectively. This shows a huge potential reduction by electrification of the public transport, using low CI charging el-mix.

The production emissions becomes a larger part of the lifetime emissions as the operation emissions decreases. For the conventional diesel bus, the production emissions constitute 12% of the lifetime emissions, while for the diesel PHEV they are 25%. For the electric bus charged with Nordic el-mix the embodied emissions constitute 67% of the lifetime emissions, and of these, the battery production emissions constitutes 22%. The fact that the embodied emissions becomes a larger part of the lifetime GHG emissions for city buses as the electrification increases, means that the focus of reducing the climate impact must be partly shifted to the production chain.

The carbon footprint from the operation is traditionally the main contributor to lifetime emissions. Reducing this to a minimum, will be a pivotal step to reduce the emissions. This can be done through an electrification, and as the operation emissions decrease, more focus should be put towards reducing the embodied emissions.

9.5 Achieved reduction of the carbon footprint from the new bus fleet in Trondheim

The new bus fleet implemented by AtB in Trondheim area shows a clear reduction in the carbon footprint, presented in Figure 8.12. The emissions were reduced by 37% over the entire lifetime of the bus fleet.

However, analysing Figure 8.11, it can be seen that the production emissions increased. Implementing the 36 electric buses and 48 new hybrids, increased the embodied emissions per kilometre with 6.2%. This increase is mainly from the batteries in the electric buses, but also from the powertrains in the hybrids. Even though the embodied emissions are allocated to each driven kilometre, Figure 8.12 shows that the production emissions has a considerable impact on the carbon footprint. Although, the increase in production emissions in the new fleet is barely visible, there is a a small increase from battery emissions. The slight increase in production in the new fleet is not significant when analysing the lifetime of the fleet.

The reduction in carbon footprint therefore originates from the operations. Removing fossil fuel buses, and implementing higher amount of electric and biofuel buses shows a clear environmental benefit. The bus fleet of 2019 is assumed to operate with the Nordic charging mix. The impact of the charging mix is small because of the low amount of electric buses with charging opportunities in the fleet. This is visualised with the error bar in Figure 8.12.

The fleet emissions are also analysed for person kilometres. This provides the possibility to compare the bus fleet in the Trondheim area to passenger cars and city bus averages. AtB did not acquire the average passenger kilometre, because they had no information on how far each passenger travels. Thus, the average passenger per kilometre was used from SSB. Using their data provides a better comparison for the emissions, as average passenger travelled has no effect. In Figure 8.13, the emissions per person-km are higher from the bus fleet of 2018, than both passenger car and city bus average. The new bus fleet has lower carbon footprint than both the averages, even though the averages only include the operation and assume zero emissions from charging electricity. If only the operation emissions are compared, the new bus fleet shows an even greater reduction per person-km. This implies that travelling with any bus in the Trondheim area will on average be more environmental friendly, than driving an average car or city bus in Norway.

The results for the person-km are found to be in line with other literature results on the topic. [61] The average passenger count per kilometre will influence this result, and a small alteration leads to different results. To compare the results for GHG emissions per person-km to other literature is incompatible and could yield results that could be inconsistent and conflicting. The average passenger per kilometre specific for the Trondheim area will most likely be different than the average value for the entire country, but it will be a reasonable estimation for comparison.

9.6 Potential reduction of the carbon footprint from the new bus fleet in Trondheim

The new bus fleet provides a great reduction of the carbon footprint, but with further implementation of electrified buses, there is possibilities for an even greater reduction. This section will discuss the potential reduction of GHG emissions for the bus fleet in the Trondheim area. This can be done both by reducing the operation emissions and production emissions.

If AtB were to implement a fully electric bus fleet, the emissions would be reduced by over 50%, represented by the Nordic bar in Figure 8.12. Whether or not a fully electric fleet is the best option for further GHG reduction is dependent on the charging mix. For the case of Trondheim area, the Nordic el-mix leads to large reductions. Further, analysing the EU-mix and NO el-mix, they show that both have lower GHG emissions than the current fleet. Implementing any of these fleet scenarios would reduce the emissions further. However, if charging with NO-GO el-mix, the carbon footprint would increase compared to the current fleet.

Depending on the el-mix, a fully electric fleet might not be the superior choice to minimise the emissions. Analysing Figure 8.10 shows that the greatest reduction is found if the charging electricity has either Nordic or Norwegian production mix. On the other hand, if the charging mix is European, it could be better to implement a bus fleet with a combination of HVO buses, as discussed in section 9.4.

Transitioning to a fully electric bus fleet, would lead to a greater magnitude of embodied emissions. Figure 8.11 shows that they would increase with 37.5%. This originated mainly from the battery production, as discussed in section 9.4.

Clearly presented in Figure 8.12, the most efficient way of reducing the carbon footprint is by implementing low emission powertrains. But, as the operation is reduced the embodied emissions becomes crucial. Reducing these could be achieved through energy efficient material- and battery production, with low CI. As discussed in 9.2 implementing integrated facilities with low CI el-mix would provide possibilities of low emissions for material production. The embodied emissions for a fully electric bus fleet could be reduced by 14.7% presented in Figure 8.14. Optionally, implementing secondary aluminium production could reduce the fleet emissions by 12.7% alone, as presented in 8.16. The potential reduction is dependent on the assumed average CI of the material production. Thus, this can in reality be different.

The buses in the electric scenario probably need to have different battery capacities. For the distances which are longer, the capacity may need to be more than 200 kWh, and vice versa for the shorter distances. An increase of the battery capacity for many of the buses will lead to higher embodied emissions based on the sensitivity presented in Figure 8.17. Therefore, the emissions may be different in reality for the electric fleet compositions, than suggested in Figure 8.12.

The choice of CI used for battery production will impact the bus fleet scenarios, visualised in 8.18.A higher intensity will lead to higher emissions per kilometre, and impact from the battery production will become an even more significant part. A lower CI will have an opposite impact. If the battery packs used in the electric buses are produced with renewable energy, the emissions will be reduced by almost 50%, compared to what is assumed in the electric fleet scenario. It becomes evident that the choice of CI becomes an increasingly important factor as battery capacities increases.

9.7 The zero emission assumption

Assuming that electric- and biofuel buses have zero emissions, are questionable. This is assumed in most climate accounts in Norway today and in the "Klimakur 2030". By analysing the current and previous bus fleets in Trondheim area, it can be identified possible misleading emission results.

The 2018 bus fleet in Figure 8.12, had a carbon footprint of 1.1 kg CO_2-eq/km, of which were mostly fossil. This originated mainly from the diesel and LNG usage in operation. The non-fossil fuels only accounted for 16% of the operation emissions. In the current fleet, the fossil emissions are reduced to approximately zero, and the non-fossil emissions have increased to constitute practically 100% of the operation. Thus, the public transportation fleet in Trondheim contribute with approximately zero GHG emissions in the national climate accounts, because of the status that charging el-mix, biofuels and production is assumed to be zero emissions. For the Trondheim municipality this results in a reduction of 64% in the direct emissions, from the 20 000 tonne CO_2-eq emitted from buses in 2018.

However, it is presented in Figure 8.12, that the carbon footprint from the current fleet is considerably larger than zero. Therefore, to assume that non-fossil fuels have zero emissions can be misleading. The fact that electricity can be produced with fossil energy sources, as seen in Table 4.2, can further verify this statement. In addition, Table 4.1 show that the energy sources have a considerable emission magnitude. Although, if it is reasonable to assume HVO and other biofuels as zero emission, is not specifically examined in this thesis.

Figure 8.13 also shows that the results on embodied emissions are too significant to be assumed zero emission. The carbon footprint is expected to be considerably higher for the average city bus and average car. Additionally, adding the emissions from the charging mix, can further increase the total carbon footprint.

9.8 Charging electricity mix's impact on carbon footprint

The importance of the el-mix used for charging an electrified city bus, becomes evident in both Figure 8.12 and Figure 8.10. The electric scenarios represent specific el-mixes, but the span from the NO to the NO-GO provides a range of electricity CI from 19 g CO_2-eq/kWh to 520 g CO_2-eq/kWh. Therefore, these scenario results are indicative for specific regions, rather than exact numbers. Even though the specific data on the CI of the el-mixes in Table 4.3 would be altered, the range of the results provides an intuitive understanding of the carbon footprint.

Buying renewable GOs for the charging electricity, can reduce the carbon footprint by 64% for an electric bus. This is represented as the difference between the NO and NO-GO scenarios. In addition, it gives extra income to the clean energy producers, which in turn means that more capital can be invested in renewable energy production. It also brings incentives to produce power from renewable sources.

Analysing the charging mix used for the current bus fleet, shows that if Nordic Hydro GOs are bought, the carbon footprint will be 10% lower. This is visualised by the error bar in Figure 8.12. The price of the GOs for the yearly consumption in an electric bus is approximately 363-1452 NOK, i.e. 13 000 - 52 000 NOK/year for the current bus fleet, or 0.05-0.2 Øre/passenger. Hence, by investing in GOs, the consumption of charging electricity can be guaranteed renewable, and the operation emissions will be reduced to almost zero for the electric buses. This sends a strong statement that the consumer is doing their utmost to contribute to reducing the GHG emissions.

9.9 Problem shifting from tailpipe emissions to production emissions

A pervasive discussion point throughout the thesis is the problem shifting from tailpipe emissions to production emission. Illuminated on in both section 9.4 and section 9.6, the embodied emissions and energy generation becomes an increasingly decisive part as the bus fleets are electrified. Implementing low emission fuel sources in operation, removes emissions in the use phase, but present new problems in the production phase of the life cycle, including the WTT energy source processing.

When electrifying, the GHG emission from road transport in Figure 1.2, will be reduced, but they will only shift to the energy supply and manufacturing industry sectors. The advances in energy production need to follow the transition, or else, carbon intensive electricity will curb the potential of the electrification. The development shown in Figure 1.3, predicts that there will be a significant increase in power demand in the upcoming years. As electrified buses are rapidly implemented in the Nordic countries, the embodied emissions and energy generation need to be taken into consideration in climate accounts.

Further, the electric transition creates a demand for battery production and new technology. Presented in Figure 5.6, the battery production will grow drastically, requiring a huge demand for materials. This can lead to the problem of material exhaustion. Similarly, for biofuel and material production, requirements for sustainable biomass and secondary processing is beneficial. Therefore, a circular economy with clear recycling requirements, will be essential.

An alternative proposal that could prevent problem shifting, is that the stakeholders set requirements for the electricity used in the production. This can be done by demanding the electricity CI for the companies in the upstream production chain, to be lower than a given value. This means that they have to buy GOs to reduce their carbon footprint. How strict the demands are defined, will put pressure on the companies, by deciding the proportion of the total energy that needs to be declared for. By doing this, it can be assumed that the energy consumers which use clean energy, will get a business advantage when new buses are going to be ordered. The bus operators will therefore choose production companies which are meeting the demands. This use of requirements for GOs will help the development of renewable energy production, and make it more attractive going forward. To incentivise electricity consumers to work towards a lower carbon footprint, will therefore reduce the impact of electric city bus production.

In addition to the measure in "Klimakur 2030", stating that 100% of new city buses are electric from the end of 2025, it should also be defined demands to the carbon footprint of these. This way, a green value chain is advocated. No requirements are set for industry production of the imported products. This problem is prevailing throughout climate goals, both on national and local levels. Further, Trondheim municipality defining the city to be zero emission by 2030, could provide misleading accounts, without a clear requirement for the indirect emissions. A framework for the implementation of new buses should be defined. This can be essential to reduce the carbon footprint.

9.10 Further work

To improve the results on the bus model and the fleet scenarios, some areas should be further investigated. Because of time consumption and data availability, the thesis was restricted to the problem to be addressed. Further work should focus on the economical aspect of implementing electrified buses and extending the life cycle analysis to include maintenance and end of life. For a comprehensive result, biofuels and new battery technology should be investigated in detail. To provide AtB with a deeper understanding of their operation in the regions, the case study should be extended to include Trøndelag county.

Economic assessment

The economical aspect was a decisive factor when implementing the current fleet. It would also, further, be important when considering new fleet scenarios. This would identify unrealistic or beneficial scenarios to further motivate decision making. This is already demonstrated with the economical result of the GO in the power market.

Maintenance and end of life

The thesis has focused on the production and operation phase of the bus fleets. To provide a deeper understanding, the impact from maintenance in use phase and end of life should be evaluated, to a greater extent. The end of life phase becomes a vital part, especially for material exhaustion and secondary material production. This, amongst other things, to meet battery pack demands in the future. Also, maintenance can have a considerable impact, as Figure 8.6 shows, it has a larger impact than the manufacturing. For a longer lifetime, the maintenance can be expected to increase with more repairs and replacement parts. Hence, a meta-analysis evaluating the full life cycle details of the bus fleets should be further studied.

Biofuels

The electric aspect of the low emission fleets has been in focus in the thesis. Thus, discussions on biofuels, and their contribution to a low emission fleet have been limited. To fully analyse the low emission bus models, the biofuel alternatives should be investigated more closely. HVO has great potential as already presented. Biogas has the lowest environmental footprint according to the energy source emissions presented in Table 4.1. Therefore, investigating this further could provide more information regarding potential reduction, and WTW emissions.

New battery technology

Battery technology is fast growing, thus the technology today could be outdated in a few years. New battery technology, which increases the energy density significantly, can give the opportunity to electrify the public transport for further distances, out in the regions. By increasing the battery capacity to 600-1000 kWh, a range of 850 km can be reached. This makes it possible to analyse potential reduction in the regions of Trøndelag, by implementing electrified buses. However, this will have huge impact on embodied emissions from battery production, and could bring complications. Based on this, new battery technology should be investigated further as a part of potential reduction, and embodied emissions.

Opportunity and overnight charging

Norway import energy at night and export during the day, for different reasons, such as being economically viable. This power trading can effect the CI in the charging mix, and should be further investigated to analyse possible impact on the carbon footprint. Analysing the day and night fluctuations in the CI in the el-mix, will be important for a deeper understand of the CI during charging. This might impact the decision on opportunity or overnight charging.

Primary and secondary material production

Recycling and secondary material production leads to metal depletion over time. The effect this has on the material processing and metal quality should be analysed to further understand the material emissions. Also, waste in material production could be analysed to further understand potential reduction in emissions. For example, reducing slag waste in steel could save energy during steel processing.

Trøndelag county

The case study only analyse the Trondheim area. Thus to provide a deeper understanding of the carbon footprint of AtB, the Trøndelag county should be investigated. Additionally, the case study does not analyse specific routes or take into consideration the geographical elevation during operation, as this would have an impact on energy use, as would larger buses. The case study does not look at bus and passenger demand, charging or infrastructure. Infrastructure would increase the total embodied emissions. This would include the charging stations, bus stops and depot.

Component estimations

The estimation model used to estimate the component emissions from Hawkins et al. can be used to further analyse emissions from other components. The estimation model shows to be more or less applicable, comparing with the result from Nordelöf et al. It was not possible to use the model further in this thesis, because of a lack of data.

Impact categories

This thesis only analysed one impact category, climate change. Thus, this is not a comprehensive study on the whole environmental impact. To further analyse the environmental impact of the bus fleet in the Trondheim area, categories such as ozon depletion, human toxicity, photochemical ozon formation; which include NOx, acidification etc. should be investigated.

10 Conclusion

Based on the results, AtB have reduced the carbon footprint from their bus fleet in the Trondheim area with 37%, by implementing biofuel and electrified buses. The fleet is more environmental friendly than an average city bus and passenger car in Norway, with operation emissions of 49 g CO_2-eq/person-km. The slight increase in embodied emissions from the new bus fleet, is insignificant, compared to the achieved reduction of the carbon footprint. A further reduction of 52% can be achieved with a full electrification, because of the Nordic charging electricity mix in Trondheim. In addition, utilising European or Norwegian electricity mix will lead to lower GHG emissions than the current fleet.

The results in this thesis shows that assuming zero emissions from electric buses is not reasonable. The embodied GHG emissions from production, and upstream emissions from both biofuels and charging electricity, need to be accounted for. When the electrification increases, these constitute an increasingly proportion of the carbon footprint, and makes the assumption more influential. Therefore, climate accounts should consider the entire carbon footprint.

The geographical location of the production processes will have a large impact on embodied emissions from bus production, mainly because of the on-site electricity mix. A prevailing factor regarding production, is the lack of information from manufacturers on upstream processing, which limits the evaluation of geographic impact, but at the same time, shows the complications in the industry, and a mindset that has to be altered. Implementing efficient facilities, which includes the entire production chain, with low carbon intensities, are therefore favourable. Both Hydro and Northvolt are leading examples of sustainable product processing and show positive results for lower GHG emissions.

Reducing the operation emissions to a minimum, through low-emission powertrains, will be the pivotal step to reduce the carbon footprint. Based on the findings in this thesis, HVO buses can have a lower carbon footprint than battery electric buses. However, electric buses charging with an electricity mix with low carbon intensity, will be the best option.

As the operation emissions decrease, the embodied emissions will constitute a considerable proportion of the carbon footprint. The embodied emissions constitute 67% of the carbon footprint from an electric bus, charging with Nordic electricity mix. The chassis & frame and body are the dominant components, yet the magnitude is dependent on the material composition. The additional emissions from the increase in battery capacity, as a consequence of electrification, contributes significantly to the carbon footprint. Therefore, problem shifting from tailpipe emissions to production emissions, is a consequence of city bus electrification, and more focus should be put towards reducing the embodied emissions.

The embodied emissions and energy generation emissions need to be taken into consideration in climate accounts. Therefore, a framework for the acquisition of new buses should be defined. This can be essential to reduce the carbon footprint, and demanding that the upstream producers buy guarantees of origin can be beneficial. A 10% reduction of the carbon footprint in the Trondheim area can be achieved by purchasing GOs for the charging electricity.

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A Vehicle components

Table A.1 presents the included components in the powertrain and glider for the four different vehicles: ICEV, HEV, PHEV and BEV. The four types include all the components in the glider, while the components in their respective powertrain vary.

Table A.1: *Overview of included components for powertrain and glider in an ICEV, HEV, PHEV and BEV.*

Powertrain	**ICEV**	**HEV**	**PHEV**	**BEV**
Battery		✓	✓	✓
Charger			✓	✓
Converter		✓	✓	✓
Differentials	✓	✓	✓	✓
Electric Motor		✓	✓	✓
Emission control	✓	✓	✓	
Exhaust	✓	✓	✓	
Fuel tank	✓	✓	✓	
Generator		✓	✓	✓
ICE	✓	✓	✓	
Inverter		✓	✓	✓
12V battery	✓	✓	✓	✓
Suspension	✓	✓	✓	✓
Thermal system	✓	✓	✓	✓
Transmission	✓	✓	✓	✓
Power electronics		✓	✓	✓
Glider				
Chassis	✓	✓	✓	✓
Body & Doors	✓	✓	✓	✓
Brake system	✓	✓	✓	✓
Tires & Wheels	✓	✓	✓	✓
Interior	✓	✓	✓	✓
Exterior	✓	✓	✓	✓

B Bus and vehicle specifications

This appendix provide specifications on the Volvo 7900 bus model. This is both specifications from Volvo provided by Nordelöf et al., and specifications with estimated batteries. Additionally, specifications for Hawkins et al.'s and Tiago's vehicle models are reported.

B.1 Volvo 7900 specifications from Nordelöf et al.

In Table B.1, the specifications for the components in the Volvo 7900 bus models are given. This is for a conventional, electric, HEV and PHEV bus, with data presented in mass and percentage. In Table B.2, the specifications for the materials in the Volvo 7900 buses are provided.

Table B.1: *Volvo 7900 models component specifications from Nordelöf et al. The mass and mass percentage of total weight for four models.*

	Conventional		**Electric**		**HEV**		**PHEV**	
	Mass [kg]	[%]	Mass [kg]	[%]	Mass [kg]	[%]	Mass [kg]	[%]
Chassis & Frame	5 625	45	5 632	44	5 588	44	5 632	44
Other body parts inlc. interior fitments	3 125	25	3 072	24	3 175	25	3 072	24
Structual body and panels	2 250	18	2 176	17	2 159	17	2 176	17
Battery	-	-	1 536	12	254	2	384	3
Powertrain	1 500	12	384	3	1 524	12	1 536	12
Total	12 500	100	12 800	100	12 700	100	12 800	100

Table B.2: *Volvo 7900 models material specifications from Nordelof et al. The mass and mass percentage of total weight for four models.*

	Conventional		**Electric**		**HEV**		**PHEV**	
	Mass [kg]	[%]	Mass [kg]	[%]]	Mass [kg]	[%]	Mass [kg]	[%]
Steel	7 125	57	6 784	53	6 731	53	7 040	55
Plastic	1 375	11	1 536	12	1 524	12	1 408	11
Aluminium	1 000	8	1 152	9	1 143	9	1 152	9
Wood	750	6	768	6	762	6	768	6
Copper	375	3	640	5	635	5	512	4
Iron	1 000	8	640	5	635	5	896	7
Glass	625	5	640	5	635	5	640	5
Other	250	2	640	5	635	5	384	3
Total	12 500	100	12 800	100	12 700	100	12 800	100

B.2 Volvo 7900 estimated specifications

In Table B.3, the estimated specifications for the components in the Volvo 7900 buses are reported. The battery is estiamted for the respective capacity of 9, 19 and 200 kWh for the HEV, PHEV and electric model. The data is presented with mass and percentage.

Table B.3: *Volvo 7900 component specifications with estimated battery weight for three bus models. The mass and mass percentage of total weight for three models.*

	Electric		**HEV**		**PHEV**	
	Mass [kg]	[%]	Mass [kg]	[%]	Mass [kg]	[%]
Chassis & Frame	5 632	43.1	5 588	44.5	5 632	44.7
Other body parts inlc. interior fitments	3 072	23.5	3 175	25.3	3 072	24.3
Structual body and panels	2 176	16.6	2 159	17.2	2 176	17.3
Battery	1 812	2.9	102	0.8	188	1.5
Powertrain	384	2.9	1 524	12.2	1 536	12.2
Total	13 076	100	12 548	100	12 604	100

B.3 Hawkins vehicle specifications

In Table B.4, the component weight for the vehicles in Hawkins et al's and Tiago's study are presented.

Table B.4: *Vehicle component specifications from Hawkins et al.'s conventional and electric model, and Tiago's HEV vehicle. The mass and mass percentage of the total vehicle weight.*

	Conventional		**Electric**		**HEV**	
	Mass [kg]	[%]	Mass [kg]	[%	Mass [kg]	[%]]
Glider	946.2	65.3	946.2	76.68	815.7	57.24
Chassis & Frame	332.0	22.91	332.0	26.90	-	-
Structual body and panels	369.7	25.50	369.7	29.95	-	-
Other body parts inlc. interior fitments	244.5	16.87	244.5	19.81	-	-
Battery	-	-	214.0	17.34	-	-
Powertrain	503.2	34.72	74.17	6.010	403.3	28.30
Miscellaneous	-	-	-	-	203.1	14.25
Total	1449	100	1234	100	1422	100

C LCA study presentation

In this appendix, the various LCA studies that are analysed during the thesis are described.

C.1 Bus production

In Table C.1, the different LCA studies that are analysed for bus production emissions are presented. The table describes the origin of the study, year, functional unit, type of study, the scope of the study and the source of the electricity mix in manufacturing.

Table C.1: *LCA studies on bus manufacturing emissions. The studies are presented with various information.*

Study	Country	Year	FU	Type	Scope	El-Mix Prod.
Nordelof et al.	Sweden	2019	Person-km	LCA	Cradle-to-grave	Ecoinvent
Cooney et al.	USA	2013	vehicle-km	LCA	Grave-to-wheel	Ecoinvent
Kärnä	Finland	2012	Bus	LCA	Grave-to-gate	Ecoinvent
Chester	United States	2008	Bus	LCA	Cradle-to-grave	EIOLCA
Chester	United States	2009	Bus	LCA	Cradle-to-grave	EIOLCA

C.2 Steel production

In Table C.2, the researched studies used for the steel processing are provided. The table presents country of origin, year, functional unit, type of study, scope of study and electricity mixes.

Table C.2: *LCA studies on steel production. The studies are presented with various information.*

Study	Country	Year	FU	Type	Scope	El-Mix
Renzulli et al.	Italy	2016	1 000 000 t	LCA	Cradle-to-gate	Internal/ Italian
Norgate et al.	Australia	2006	1 kg	LCA	Cradle-to-gate	Black coal
Korol	Poland	2012	1 t	LCA	Cradle-to-gate	Assumed Poland
Gao et al.	China	2017	1 t ss	LCA	Gate-to-grave	Coal

C.3 Aluminium production

In Table C.3, the researched studies used for the aluminium processing are presented. The table state the country of origin, year completed, functional unit, type of study, scope of study and electricity mixes.

Table C.3: *LCA studies on aluminium production. The studies are presented with various information.*

Study	Country	Year	FU	Type	Scope	El-Mix	Source
Yang et al.	China	2019	1 t	LCA	Cradle-to-gate	Thermal power & Hydro power	
Al Association	North America	2013	1 t	LCA	Cradle-to-grave	Avg. Grid Mix (Canada & America) Smelting & ingot casting Al industry power mix	
Norgate et al.	Australia	2006	1 kg	LCA	Cradle-to-gate	Black Coal	

C.4 Battery production

In Table C.4, the different LCA studies that are analysed for battery production are specified. The table presents the origin of the study, year, battery chemistry and the study model.

Table C.4: *LCA studies on battery manufacturing. The studies are presented with various information*

Study	Country	Year	Chemistry	Study model
Ellingsen	Norway	2014	NMC	Top-down
Romare & Dahllof	Sweden	2017	NMC	Meta
Emilsson	Sweden	2019	NMC	GREET
Peters et al.	Germany	2017	NMC, LFP, LMO	Meta

D Bus production

This appendix provide an overview over material and component emissions for different bus models. Some of the emissions are reported from studies, and others are estimated.

D.1 Life cycle emissions

In table D.1, the emissions from various bus types are presented. The table presents material upstream processing, manufacturing, maintenance and total bus production emissions. Many of the studies lack results on different processes, as only Nordelof et al.'s study describe emissions on each process.

Table D.1: *Life cycle process emissions from various bus models with the unit tonne CO_2-eq.*

Study	Powertrain	Material Upstream	Manufacturing	Maintenance	Total
Nordelof et al.	Electric	79.9	23.7	25.0	129
	PHEV	77.4	18.7	21.2	117
	HEV	77.4	17.5	20.0	115
	Conv. Diesel	69.9	15.0	16.2	101
Karna	Electric	56.9	-	-	-
	Converted Electric	51.2	-	-	-
	Diesel; Al Chassis	54.0	-	-	-
	Diesel	45.4	-	-	-
	Hybrid	48.6	-	-	-
Cooney et al.	Electric	-	-	-	399
	Conv. Diesel	-	-	-	199
Chester et al. 08	Diesel	-	-	-	129
	Avg. Diesel	-	-	-	160
Chester et al. 09	Electric	-	-	-	150
	Urban Diesel Avg.	-	-	-	140

D.2 Material emissions

Table D.2 present estimated emissions from steel, aluminium and other materials for the Volvo bus models. As well, the material emissions from Kärnä's study are given.

Table D.2: *Estimated material emissions from steel and aluminium based on Nordelof et al.'s Volvo models and reported emissions from Kärnä. Emissions are presented with unit tonne* CO_2*-eq*

	Estimated				Karna			
	Conv.	HEV	PHEV	Electric	Conv.	Conv. Al	HEV	Electric
Steel	16.0	15.1	15.8	15.2	6.70	2.30	6.20	4.90
Aluminium	16.5	18.9	19.0	19.0	11.2	28.3	12.2	10.2
Other	37.4	43.4	42.6	45.7	27.5	23.4	30.2	41.8
Total	69.9	77.4	77.4	79.9	45.4	54.0	48.6	56.9

D.3 Component emissions

In Table D.3, the emissions from the components for Nordelof et al. and Hawkins et al. are given. The battery from Nordelof et al. is represented as "Battery", while estimated batteries are denoted as "Battery est.". The structural body and other body are summed to one body, while the electric and conventional powertrains are summed to one powertrain for the hybrids.

Table D.3: *Component emissions for various bus models, with estimated battery emissions in Nordelof et al. and estimated component emissions in Hawkins et al. Nordelof et al. emissions data are extracted from the study. Emissions are expressed with the unit tonne* CO_2*-eq.*

	Nordelof et al.				Hawkins et al.	
	Conv.	HEV	PHEV	Electric	Conv.	Elecric
Chassis & Frame	44.9	44.9	44.9	44.9	40.0	46.8
Structural body	-	-	-	-	4.20	4.58
Other body	-	-	-	-	39.9	39.2
Body total	45.3	45.3	45.3	45.3	44.1	43.8
Powertrain	10.6	15.5	15.5	9.80	3.80	0.398
Battery	-	8.17	10.21	28.16	-	-
Battery est.	-	1.06	2.26	47.6	-	47.6
Total	101	114	116	128	87.9	91.0
Total est.	101	107	108	148	139	87.9

E Vehicle component emissions

Table E.1 provide component emissions for the study by Hawkins et al. and Tiago. The component emissions from the studies, are categorised to the different components categories from Nordelof et al.

Table E.1: *Vehicle component emissions from Hawkins et al.'s conventional and electric model, and Tiago's HEV model All values are given in kg* CO_2*-eq.*

	Conventional	**Electric**	**HEV**
Chassis & Frame	1 026	1 026	6 488
Structual body and panels	2 090	2 090	-
Other body parts inlc. interior fitments	1 820	1 820	2 141
Battery	-	4 620	312
Powertrain	1 504	2 735	10 123
Total	6 440	13 795	19 064

F Material production

This appendix report emissions and energy consumption for material production found in LCA studies.

F.1 Steel production

In Table F.1, the GHG emissions and energy consumption per tonne steel are presented for primary and secondary steel production. Blast oven furnace (BOF) is primary and electric arc furnace (EAF) is secondary production. The data is extracted from four different LCA studies. In Table F.2, the emission from each processing step is presented from two of the LCA studies.

Table F.1: *GHG emissions and energy consumption for primary and secondary steel production from four LCA studies. Presented with the units tonne CO_2-eq per tonne steel and GJ per tonne steel*

Study	**BOF**		**EAF**	
	Energy Use	GHG emissions	Energy Use	GHG emissions
Renzulli et al.	13.2	1.59	-	-
Norgate et al.	23.0	2.30	75.0	6.80
Korol	15.4	2.46	8.07	0.913
Gao et al.	-	2.62	-	4.66

Table F.2: *GHG emissions from each step in primary steel production from two LCA studies. Presented with the unit tonne CO_2-eq per tonne steel.*

Study	**Renzulli et al.**	**Gao et al.**
Raw Material	-	0.432
Coke oven	0.357	0.320
Sintering Plant	0.327	0.192
Pelletizing	-	0.055
BF	0.663	0.858
BOF	0.242	0.043
Rolling	-	0.144
Scrap Recycling	-	0.574
Total	1.59	2.62

F.2 Aluminium production

Table F.3, provide GHG emissions and energy consumption on primary and secondary aluminium production. This is presented from four studies.

Table F.3: *GHG emissions and energy consumption from primary and secondary aluminium production from four LCA studies. Presented with the units tonne CO_2-eq per tonne aluminium and GJ per tonne aluminium.*

Study	**Primary**		**Secondary**	
	Energy use	GHG emissions	Energy use	GHG emissions
Yang et al. TP	263	21.8	-	-
Yang et al. HP	106	4.90	-	-
Al Association	138	9.00	11.0	1.20
Norgate et al.	211	22.4	-	-
Hydro	-	4.00	-	2.30

G Battery

This appendix provide data on battery production and specific component weight for different capacity.

G.1 Battery production

In Table G.1, the energy consumption and GHG emissions for battery production from several studies are given.

Table G.1: *Reported values for energy consumption and GHG emissions of battery pack production from different studies. Presented with the units MJ/kWh and kg CO_2-eq/kWh.*

Study	Energy	GHG Emissions
Ellingsen	586	172
Romare & Dahllöf	350-650	150-200
Emilsson	1127	61-106
Dai et al.	1125	72.9
Peters et al. NMC	500-2000 (1030 avg.)	40-240
Peters et al. LFP	300-2500 (970 avg.)	30-270 (161 avg.)
Peters et al. LMO	200-1500 (810 avg.)	50-75 (55 avg.)
Peters et al. avg	1182	110

G.2 Battery component weight

Table G.2 provide data regarding the weight for battery components at different capacities. The table is utilised to extrapolate and interpolate the weight for different battery capacities.

Table G.2: *Weight for battery components with respect to the battery capacity. Data extracted directly from Ellingsen et al. 2016*

Component group	17.7 kWh battery	26.6 kWh battery	42.1 kWh battery	59.9 kWh battery
Battery cells [*kg*]	102	152	241	343
Module packaging [*kg*]	32	48	76	108
Battery management system [*kg*]	9.1	9.4	9.9	10.5
Cooling system [*kg*]	8.1	10.5	16.1	23.5
Battery packaging [*kg*]	26	33	50	69

H Case study description

This appendix presents the fleets used in the case study of the thesis. Table H.1 describe the bus compositions of the three fleet scenarios, where the 2018 and from Aug. 2019 are the previous and current bus fleet in the Trondheim area respectively. The electric fleet is the bus fleet scenario which consist of only electric buses.

Table H.1: *Bus compositions for the three bus fleet scenarios used for the case study.*

Bus fleets	**Diesel**	**Biogas**	**Biodiesel**	**Hybrid**	**Electric**	**Total**
2018	3	213	94	10	0	320
From Aug. 2019	0	113	98	58	36	305
Electric	0	0	0	0	305	305

I Carbon Payback Time

This appendix describes the simulations completed for the carbon payback time and information behind the calculations. A model for calculating the carbon payback time and carbon footprint for the different bus models were developed, and from this, simulations done using the numerical software program MATLAB.

Average fuel and electricity consumption for the Volvo 7900 models are presented in Table I.1. The electric and PHEV buses uses fuel heaters which is assumed powered by HVO for the electric, and the same as for propulsion for PHEV. This is gathered from Nordelöf et al.'s study from 2019.

Table I.1: *Fuel and electricity consumption used for the operation in carbon payback time and production emissions from each model, excluding battery.*

Vehicle	Fuel	Electricity	Production emissions
Conventional	0.45 L/km	-	100.82 tonne CO_2-eq
HEV	0.3 L/km	-	105.71 tonne CO_2-eq
PHEV	0.19 L/km	0.53 kWh/km	105.71 tonne CO_2-eq
Electric	0.028 L/km	1.1 kWh/km	100 tonne CO_2-eq

The input parameters on energy density and carbon intensity were gathered from AtB. Emissions intensity used for diesel were 3.206 kg CO_2/kg fuel and 0.845 tonne fuel/m^3. This gives 2.71 kg CO_2/L fuel. HVO emissions intensity parameters were 1.740 kg CO_2/kg fuel and 0.780 tonne fuel/m^3. This gives 1.357 kg CO_2/L fuel. The GHG emission for a given number of driven kilometres for a bus, is calculated from equation (I.1).

$$GHG_{production,vehicle} + GHG_{battery,vehicle} + d * (FC_{vehicle} * CI_{fuel} + CI_{el-mix} * EC_{vehicle}) \tag{I.1}$$

The denoted "vehicle" is the bus type, i.e. conventional, HEV, PHEV or Electric. Fuel is the fuel type used (diesel or HVO) and el-mix is the electricity mix used for charging. The GHG production does not include the battery production, as this is a separate parameter in this case. The rest of the parameters are presented in Table I.2. Figure I.1, Figure I.2 and Figure I.3 showcases the simulated emissions from the model, for EU-mix, NO el-mix and NO-GO el-mix respectively. Figure I.4 shows the simulated values for the range of 600 000 km for several alternatives. The carbon payback time is found where the electric options intersects the other powertrain options.

Table I.2: *Parameters used for the carbon payback time calculations in* (I.1).

Parameter	Symbol	Unit
Fuel consumption	FC	L/km
Electricity consumption	EC	kWh/km
Greenhouse gas emissions	GHG	kg CO_2-eq
Carbon intensity	CI	kg CO_2-eq/kwh
Driven kilometres	d	km

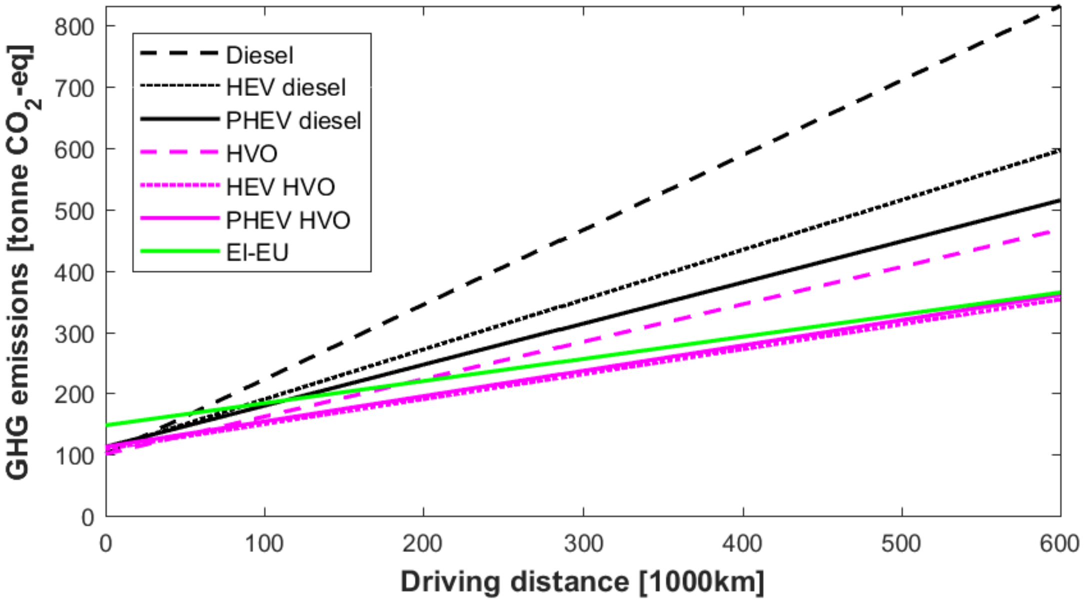

Figure I.1: *GHG emissions versus driving distance for different bus powertrain technologies, charging with European electricity mix.*

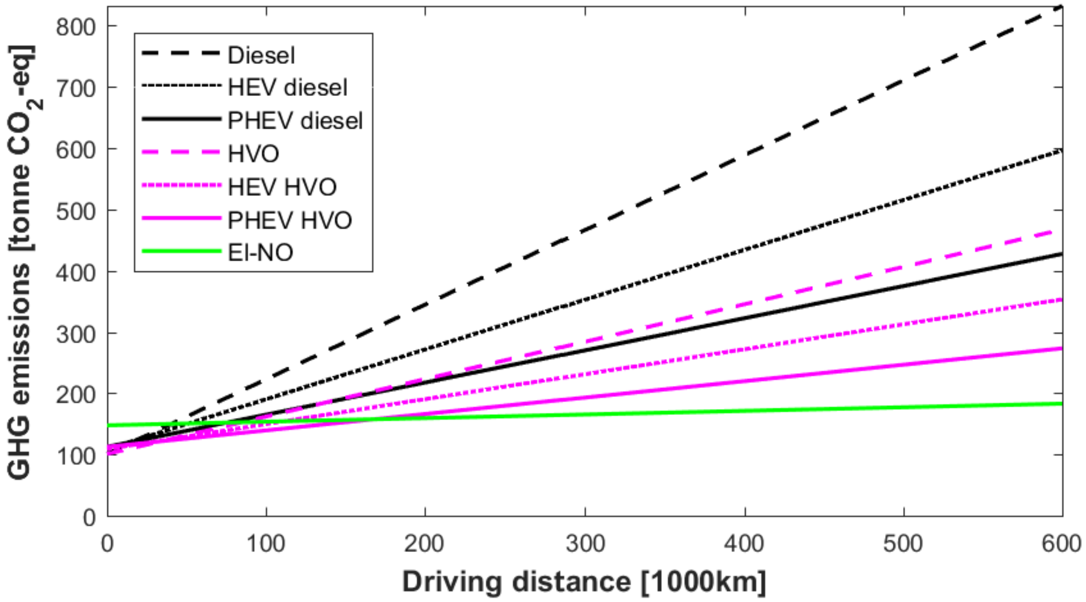

Figure I.2: *Emissions versus driving distance for different bus powertrain technologies, charging with Norwegian production electricity mix.*

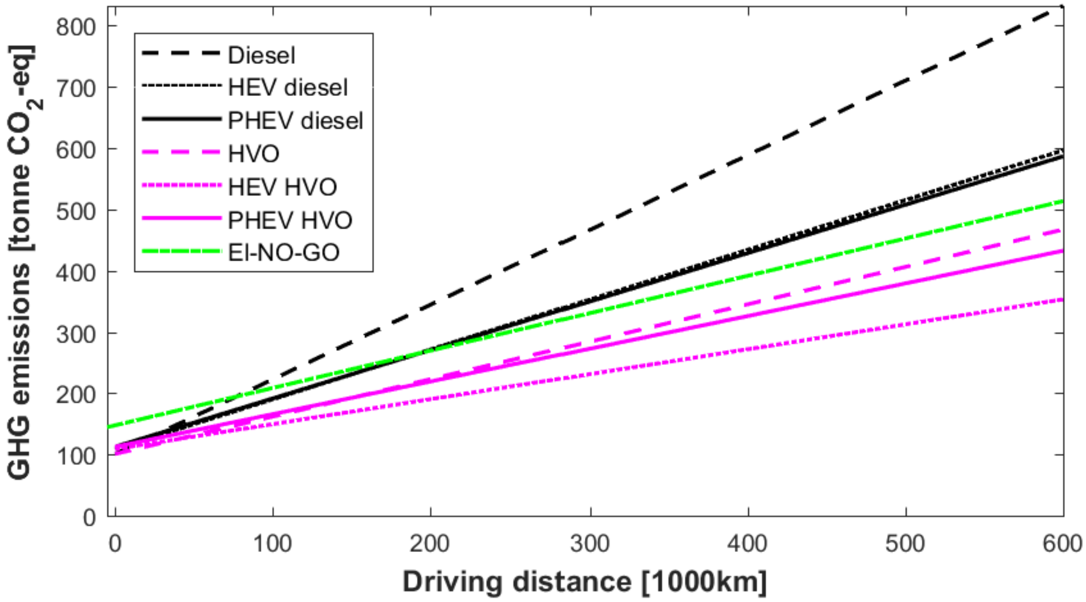

Figure I.3: *GHG emissions versus driving distance for different bus powertrain technologies, charging with Norwegian electricity mix which is not bought guarantees of origin for.*

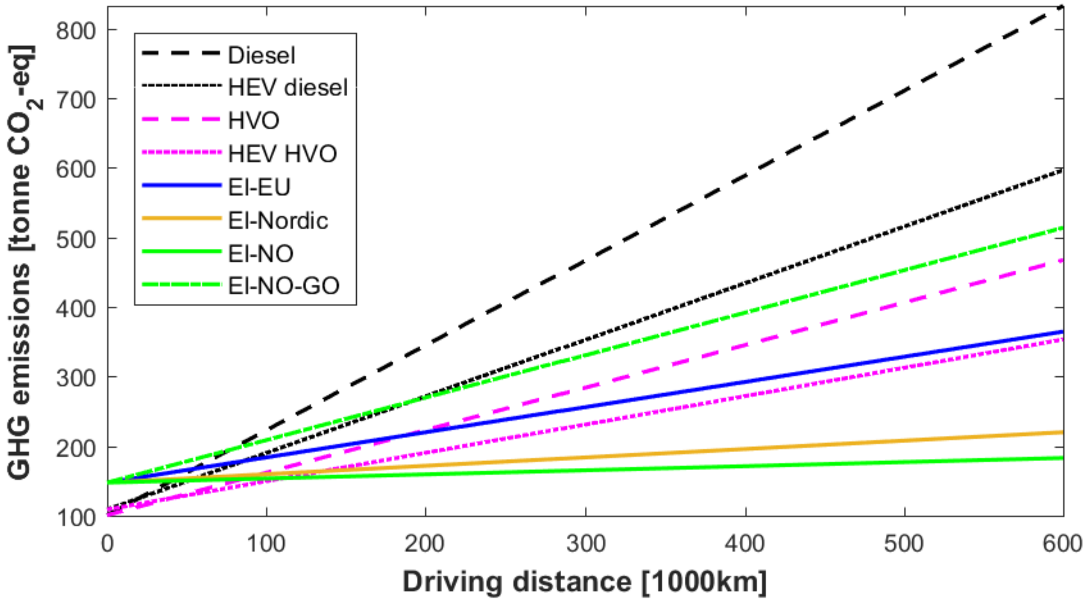

Figure I.4: *GHG emissions versus driving distance for different bus powertrain technologies and electricity mixes.*

J Sensitivty analysis

In this appendix the sensitivity analysis results for the materials steel and aluminium, and battery are presented.

J.1 Primary material sensitivity

Table J.1 presents the results for the sensitivity analysis on primary material production for conventional, HEV and electric bus model. The average, best and worst case scenario are presented.

Table J.1: *Sensitivity analysis results for primary steel and aluminium production for three bus models. Average, low and high emissions for the various bus models. Presented with the unit tonne* CO_2*-eq.*

Powertrain		Average	Low	High
Conventional	Steel	16.0	11.3	18.7
	Aluminium	16.5	4.00	21.8
	Bus	101	83.9	109
HEV	Steel	15.1	10.7	17.6
	Aluminium	18.9	4.57	24.9
	Bus	115	96.1	123
Electric	Steel	15.2	10.8	17.8
	Aluminium	19.01	4.610	25.1
	Bus	129	110	137

J.2 Secondary material sensitivity

Table J.2 presents the results for the sensitivity analysis on secondary material production for conventional, HEV and electric bus model.

Table J.2: *Sensitivity analysis results for secondary steel and aluminium production for three bus models. Presented with the unit tonne* CO_2*-eq.*

Bus model	Secondary steel		Secondary aluminium	
	Steel	Other	Aluminium	Other
Conventional	33.2	85.1	2.30	84.6
HEV	31.37	99.7	2.56	96.0
Electric	31.6	113	2.65	110

J.3 Battery sensitivity

A sensitivity analysis on battery pack capacity's impact on GHG emission, can be seen in Table J.3. It is assumed one battery change. The emissions are also presented for three different battery production carbon intensities.

Table J.3: *Sensitivity analysis for GHG emission from different battery capacity's. Using three different CI and one battery change assumed.*

Battery Capacity	GHG emissions [tonne CO_2-eq]		
[kWh]	61 kg CO_2-eq/kWh	119 kg CO_2-eq/kWh	119 kg CO_2-eq/kWh
50	6.1	11.9	14.6
100	12.2	23.8	29.2
200	24.4	47.6	58.4
300	36.6	71.4	87.6
400	48.8	95.2	116.8
500	61	119	146
750	91.5	178.5	219
1000	122	238	292

The results from a sensitivity analysis on the battery production CI's impact on bus fleet battery emissions, are presented in Table J.4.

Table J.4: *Sensitivity analysis on battery production CI impact on bus fleet battery emissions. Unit g CO_2-eq/kWh*

CI [kg CO_2-eq/kWh]	2018	Aug. 2019	Electric
61	0.134	5.70	42.2
119	0.223	9.37	79.3
146	0.320	13.6	101

K Bus fleet emissions

This appendix presents the embodied GHG emissions and carbon footprint of the different bus fleet scenarios. 2018 refer to the bus fleet before the new bus fleet was implemented. Aug. 2019 is the new bus fleet in the Trondheim area, and EU-mix, Nordic, NO and NO-GO are full electric bus fleet scenarios charging with different el-mixes.

K.1 Embodied fleet results

Table K.1 presents the results for the embodied emissions in the three bus fleets: 2018, from August 2019 and the electric. The results are presented with emissions from each component, and calculated to average kilometre each fleet has driven.

Table K.1: *Embodied fleet emissions with components, for the three bus fleet scenarios in the Trondheim area. Presented with the unit tonne CO_2-eq/km.*

Components	2018	From Aug. 2019	Electric
Chassis and Body	0.1503	0.1503	0.1503
PT ICE	0.01752	0.01457	0
PT Electric	0.0004252	0.004514	0.01633
Battery	0.0002231	0.009373	0.07933
Total	0.1685	0.1788	0.2460

K.2 Fleet lifetime results

The GHG emissions from the operation, production and batteries from the different bus fleet scenarios, can be viewed in K.2. Both values per kilometre and person-km are represented.

Table K.2: *GHG emissions for the different bus fleet scenarios in the Trondheim area. Presented embodied emissions per km and per person-km.*

		2018	Aug. 2019	EU-mix	Nordic	NO	NO-GO
Per km	Operation	0.9219	0.5115	0.32340	0.08250	0.02090	0.5720
[kg CO_2-eq/km]	Batteries	0.0002231	0.009373	0.07933	0.07933	0.07933	0.07933
	Production	0.1683	0.1694	0.1667	0.1667	0.1667	0.1667
	Total	1.090	0.6903	0.5694	0.3285	0.2669	0.8180
Per person-km	Operation	88.73	49.23	31.13	7.940	2.012	55.05
[kg CO_2-eq/person-km]	Batteries	0.02147	0.9021	7.636	7.636	7.636	7.636
	Production	16.20	16.31	16.04	16.04	16.04	16.04
	Total	104.9	66.44	54.80	31.62	25.69	78.73

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The Carbon Footprint of Electrified City Buses

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Kunnskap for en bedre verden