NTNU – Trondheim
Norwegian University of
Science and Technology

Environmental Assessment of Bus Transport in the Trondheim Region

Evaluation of Relevant Bus and Fuel Technologies and their Potential for Mitigating Emissions from Passenger Transportation

Tonje Buø

Master in Industrial Ecology
Submission date: June 2015
Supervisor: Edgar Hertwich, EPT
Co-supervisor: Kjartan Steen-Olsen, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2015-11

MASTER THESIS

for

Student Tonje Buø

Spring 2015

Environmental assessment of bus transport in the Trondheim region

Miljøanalyse av busstransport i Trondheimsregionen

Background and objective

The Industrial Ecology Programme's ongoing project "The People's Climate Research" aims to quantify the carbon footprint (CF) of Norwegian households and assess how it can be reduced through voluntary household actions. As one of the most important contributing domains of household carbon footprint, transport will be a core focus area of the project. Public transport by bus is a mode of travel which has received fairly limited attention in the scientific literature compared to private car and air travel. The task of the student will hence be to rectify this, by undertaking an overall assessment of the environmental impacts of transport by bus, taking the city of Trondheim and surrounding regions as the case study. The main environmental focus of the assessment should be put on climate impacts. The student should use a life-cycle assessment type of framework to conduct the analysis, drawing on existing life cycle data for buses to be modified for the case at hand, in combination with case-specific data on key parameters such as driving patterns and occupancy rates, etc.

The following tasks are to be considered:

1. Review the literature of environmental assessments of bus transport, including scientific articles as well as industry reports
2. Construct a life cycle inventory to analyse bus transport in the Trondheim region
3. Assess the carbon footprint of passenger transport by bus in the Trondheim region, differentiating as far as possible between different bus routes, time of day, etc.
4. Draw on existing studies to evaluate net climate costs/benefits of bus transport compared to alternative modes in various scenarios/situations, and discuss the considerations that must be made in such evaluations

-- " --

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

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

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

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

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

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

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

Department of Energy and Process Engineering, 14. January 2015

Olav Bolland
Department Head

Edgar G. Hertwich
Academic Supervisor

Research Advisor: Kjartan Steen-Olsen

Preface

This thesis ends my master studies in Industrial Ecology at department of Energy and Process Engeneering at the Norwegian University of Science and Technology (NTNU). The work has been carried out in collaboration with the transportation agency AtB and Sør-Trøndelag County Council. In addition to providing insight into the environmental impacts of bus transport to the collaborators, this work also contributes to extending the knowledge base on bus transport in the ongoing project "The People's Climate Research".

The scope of the project and the objectives are based on the attached project description. However, the bus routes could not be differentiated in terms of fuel consumption that arises from different driving patterns. As this data was not available from AtB, route specific fuel consumption would require on board measurements, which would be too time consuming for this thesis. The limited access to data from bus producers imposed some challenges for the data compilation. While there are several initiatives to provide transparent inventories of the production of private vehicles, production of transit vehicles is less transparent today.

Overall, this thesis has been a good experience and given me valuable insight in the challenges associated with sustainable mobility.

Trondheim, June 24, 2015

Tonje Buø

Acknowledgment

Several persons have contributed to this work and helped me along the way. First, I want to thank my supervisors Edgar Hertwich and Kjartan Steen Olsen for their academic support and useful discussions. Their inputs have been important for my progress throughout the semester. I also want to thank my contact persons at AtB and Sør-Trøndelag County Council, Frode Einar Krokstad and Lars Fabricius, for answering all my emails and contributing with valuable data input. A special gratitude goes to to all the people in Miljøpakken, the bus companies and service garages for their expert advises. They are too many to be listed here, but their contributions were significant to the work.

My friends and family have provided me with moral support throughout the semester. A special thanks to my parents for always supporting me and giving good advice along the way. My final gratitude goes to my classmates in the Industrial Ecology Programme. These two last years wold not have been the same experience without you.

T.B.

Abstract

The overall aim of this thesis is to assess the carbon footprint of transport by bus in the Trondheim region. Bus transportation is promoted as a strategy both to combat local pollution problems in urban areas and to mitigate global greenhouse gas emissions from passenger transport. Still, the environmental impacts of bus transport have received fairly limited attention in research.

The environmental impacts of bus transport are calculated through life cycle assessment. A model is developed for the bus and fuel technologies included in the bus fleet in Trondheim. The analysis is limited to city buses, which in Trondheim comprise hybrid, natural gas and biodiesel buses. All life cycle phases of bus transport are included. The environmental impacts are measured by the impact categories climate change, fossil depletion, eutrophication, acidification, particulate matter formation and land occupation. The thesis draws on previous LCA studies of cars to compare GHG emissions per passenger kilometer between different bus routes. A comparison is also made for work travels in Trondheim to investigate the effect of climate mitigation measures implemented the later years.

The results shows that the hybrid bus performs best in terms of greenhouse gas emissions and fossil depletion per vehicle kilometer, while the natural gas bus had lower emissions in the remaining five impact categories. By switching to biogas, it is found that this bus technology achieved similar impacts to the hybrid bus also in the two former categories.

Looking at specific bus routes, it is found that buses with 5-10 passengers had lower GHG emissions than a car with 1-2 persons, depending on the bus technology. Both technology advancements and modal shifts are promoted by national authorities as ways to reduce the overall emissions from passenger transportation. Comparing the carbon footprint of work travels between 2009 and 2014 shows that the modal shift had the largest mitigation effect.

The largest reduction potential per vehicle kilometer is identified in the operation phase of the buses. With the use of biofuels, these emissions can be reduced significantly. The mitigation potential is however dependent on the type of biofuels, thus policy makers should be aware of problem shifting.

Sammendrag

Det overordnede målet for denne masteroppgaven er å beregne karbonfotavtrykket av busstransport i Trondheimsregionen. Både nasjonalt og internasjonalt inngår busstransport som et viktig tiltak for å redusere de negative miljøpåvirkningene fra passasjertransport. På tross av dette er miljøkonsekvensene fra busstransport lite dokumentert i forskning.

Miljøpåvirkningene fra busstransport beregnes ved hjelp av en livssyklusanalyse. En modell utvikles for buss- og drivstoffteknologiene som inngår i bussparken i Trondheim. Analysen begrenser seg til bybusser, og inkluderer dermed hybrid, naturgass og biodiesel busser. Alle livssyklusfaser inkluderes i analysen. I tillegg til klimapåvirkning beregnes også dannelse av svevestøv, eutrofiering, forsuring, forbruk av fossile ressurser og arealforbruk for å måle total miljøpåvirkning. Tidligere livssyklusanalyser av biler tas i bruk for å sammenligne karbonfotavtrykket per personkilometer fra buss- og biltransport. Til slutt beregnes karbonfotavtrykket til arbeidsreiser for å undersøke effekten av ulike tiltak passasjertransport i Trondheim.

Resultatene fra sammenligningen av de ulike bussteknologiene viser at hybridbussene genererer lavest utslipp av drivhusgasser og lavest forbruk av fossile ressurser per kjøretøykilometer. Naturgassbussene har imidlertid lavest miljøpåvirkning i de fem andre inkluderte kategoriene. Ved innblanding av biogass oppnår gassbussene de samme utslippene som hybridbussene også i de ovennevnte kategoriene.

Analysen av ulike bussruter viser at man i gjennomsnitt trenger 5-10 passasjerer på en buss, avhengig av bussteknologi, for å oppnå samme karbonfotavtrykk som en bil med 1-2 passasjerer. Både ny teknologi og overgang til mer effektive transportformer er strategier som bidrar til å redusere utslipp fra passasjertransport. Resultatene for det totale karbonfotavtrykket for arbeidsreiser viser at den største reduksjonen kommer fra overgangen til mer effektive transportformer.

Det største forbedringspotensialet for busstransport blir funnet i operasjonsfasen. Gjennom bruk av biodrivstoff kan utslippene fra denne reduseres signifikant. Forbedringspotensialet er imidlertid avhengig av type biodrivstoff, og politikere bør være oppmerksom på miljøkonsekvenser som kan oppstå i produksjonen av biodrivstoff.

Contents

List of Tables

List of Figures

1. Introduction

1.1. Background

The transportation sector accounts for around 25% of global carbon dioxide (CO_2) emissions (EEA, 2008). The share is likely to rise in the future with increasing growth in population and increased affluence in developing countries. Deep cuts are needed in this sector to reach the emission targets set by the Intergovernmental Panel on Climate Change (IPCC). IPCC states that a 50% reduction in greenhouse gas (GHG) emissions by 2050 is required to limit global warming to below 2°C.

Norway has adopted ambitious environmental goals in line with the recommendations from IPCC, and aim to be carbon-neutral by 2050 (Miljøverndepartementet, 2008). The transport sector is currently the second largest GHG emitting sector within the country, which means that there is a strong focus directed towards transport as a mean to achieve the emission targets (MD2012). This is further elaborated in the National Transport plan for the period 2014 until 2023, which states that transportation policy should contribute to reducing GHG emissions and hazardous effects from transport, as well as contributing to reach national targets (Brunvoll and Monsrud, 2013).

The majority of the emissions from transport stems from road traffic, and the use of private cars is the main source of emissions.The relative share of private cars has increased significantly the past ten years, which can be explained by a growth in both population and affluence. The expansion in car travels must be reversed if Norway is to achieve the deep emission cuts needed to achieve carbon-neutrality by 2050.

The key to achieve deep emission cuts lies in finding the appropriate combination of measures (Hermansen, 2011). While individual measures may cause conflicts between goals and achieve little public acceptance, a combination of measures is more likely to succeed. National authorities emphasizes both measures that trigger modal shifts, as well as measures that initiate investments in more fuel efficient and environmentally friendly vehicles (Miljødirektoratet, 2015b). A special emphasis is put on urban areas, because of the large reduction potential(Nenseth and Nielsen, 2009). Two out of three Norwegians live in cities, and cities are expected to grow both in size and population until 2050. At the same time, half of GHG emissions in urban areas stem from road transport. The traffic congestion also causes local pollution problems, deteriorating air quality and generating noise. In order to develop a sustainable transport system, the national authorities have targeted a zero-growth in private car travels in order to ease pressure on infrastructure and develop sustainable transport systems (Avinor et al., 2015). The shorter car travels should be shifted towards cycling and walking, while longer travels should see a shift to public transport. As a consequence of this strategy, the transportation agencies have estimated that the share of public transport must increase by 60% until 2030 and more than double until 2050.

1.2. Gap in research

Public transportation is included in both national and local strategies to reduce urban environmental impacts form passenger transportation. Even so, bus transport has received fairly limited attention in research compared to private cars and air travels (**?**). Public bodies also tend to focus on direct emissions in their assessments, ignoring the upstream impacts from production of vehicles and fuel (Chester et al., 2012). In order to quantify the environmental benefits of a modal shift and document distance to emission targets, the whole value chain of bus transport should be considered. Internationally, a few LCA studies of bus transport have been conducted, but in Norway there are few complete LCA studies. There is thus a need for an LCA adapted to Norwegian conditions, especially for key parameters such as driving patterns and occupancy rates.

1.3. Problem Description

The overall aim of this thesis is to assess the carbon footprint of transport by bus in the Trondheim region. Within this overarching goal, the thesis will aim at answering the following research questions:

1. What are the life cycle environmental impacts generated by bus transport in Trondheim?
    - Which life cycle phases are responsible for the majority of emissions?
    - How are the results influenced by changes in bus and fuel technology?
2. How is the environmental performance per passenger kilometer influenced by different occupancy rates and time of travel?
3. What are the net environmental costs/benefits of bus transportation compared to alternative modes of transport?
4. How can this analysis contribute to further decision support in planning of bus transport in Trondheim?

1.4. Scope

In order to assess the environmental impacts resulting from bus transport in Trondheim, a quantitative model based on life cycle methodology has been developed. The model will cover life cycle impacts resulting from the production, use and end of life (EOL) treatment of the buses. Three bus types are included, in line with the characteristics of the AtB bus fleet: natural gas (CNG) buses, hybrid buses and diesel buses running on a blend of biodiesel and fossil diesel. The assessment is limited to city buses and the driving pattern thus reflects the conditions within a city. City buses usually have a higher energy use per kilometer, due to frequent starts and stops. The results are intended to be used for support in planning of the future bus service and to build up the knowledge base of bus transportation. The assessment is carried out in line with the ISO 14040 and 14044 standards.

1.5. Structure of the Report

The thesis is divided in six chapters. The following chapter includes a literature review, presenting the theoretical framework of LCA, the Norwegian context of this study and the included bus and fuel technologies. In the end of the chapter, previous LCA studies are presented. The third chapter presents the case study and how the life cycle methodology is applied to this study. The chapter also gives a comprehensive presentation of the important assumptions and modeling choices. The results are presented in chapter five, and are discussed in more detail in the following chapter. Chapter six is the final chapter which presents the conclusions drawn from the previous chapter and final remarks.

2. Literature

This chapter describes the literature that will be used to answer the research questions in section 1.3. The aim is to provide a theoretical framework for the LCA conducted in this thesis. First, the theoretical basis of life cycle methodology will be described, followed by a presentation of the most important emissions from the operation phase of buses. Furthermoe, the relevant bus and fuel technologies are discussed in terms of environmental benefits and drawbacks. Finally, previous LCA studies are reviewed to serve as a state-of-the-art of LCA studies in passenger transport. It has been chosen to conduct a detailed literature review since there was no previous project work related to this thesis.

2.1. Life Cycle Assessment

Life cycle assessment (LCA) is a tool used to evaluate the environmental performance of a system throughout the whole life cycle, from raw material extraction through material production and manufacturing, use and finally, end of life (EOL) treatment and disposal(Baumann and Tillman, 2004). Taking a life cycle perspective can be useful both to identify the most significant phases of a production process, but also to avoid potential shifting of environmental burden between the different life cycle stages (ISO, 2006b). LCA has a number of applications: it can be used to compare different alternatives that fulfills the same function,to improve a production system, or as support for policy decisions (Baumann and Tillman, 2004). The LCA procedure consists of four different phases, which are closely linked to each other. The different phases can be seen in figure 2.1 and will be presented more in depth in the following chapters. The methodology has been in use since the 1970s, but was not coined until 1991. A standardized LCA methodology was developed and published by the International Organization for Standardization (ISO) in 1997. Today there are two standards

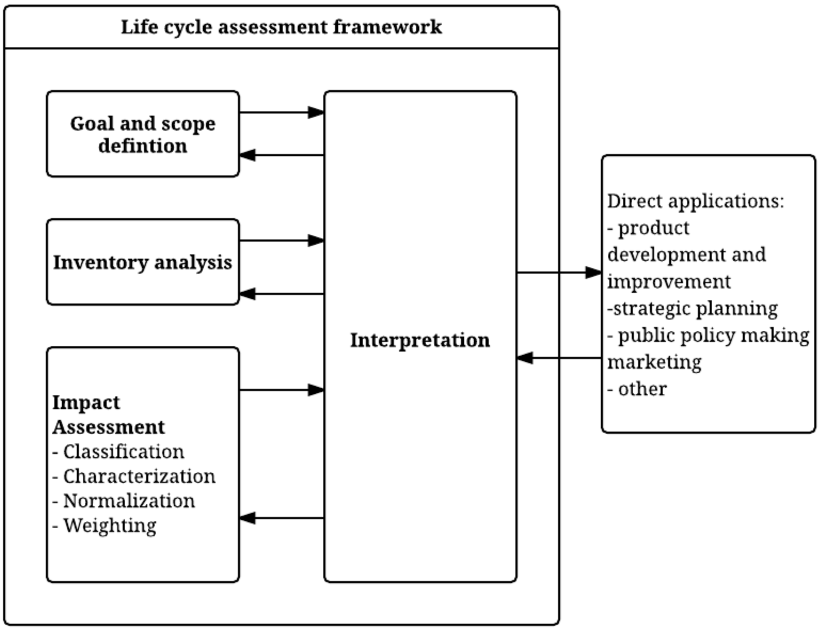

Figure 2.1.: LCA framework according to ISO14040. Copied from ISO 14040 (ISO, 2006b)

available serving as guidance to perform a standardized LCA: ISO 14040 and ISO 14044 (ISO, 2006b,a).

2.1.1. Goal and Scope Definition

The goal states the motivation behind the study and should clearly inform the readers about the intended application. In order to define the scope of the study, a number of modeling choices have to be made. The modeling choices include deciding on a functional unit, choosing impact categories to consider, and defining system boundaries.

After the goal is stated and the products of the system are decided, the next step is to determine the functional unit (FU) (Baumann and Tillman, 2004). The functional unit reflects the function of the product or the system and serves as a reference flow to which all other modeled flows of the system are related to. An example of a functional unit is one person kilometer traveled. This functional unit makes it possible to the environmental impacts of different transportation modes that all fulfill the function of transporting a person from A to B.

System boundaries are defined after the determination of the FU. The system boundaries determine which unit processes to be included in the study, and needs to be defined in several dimensions: boundaries in relation to natural systems, geographical boundaries, time boundaries and boundaries within the technical systems. Which processes to include depends on the goal and scope of the system, but in general several life cycle stages should be considered, from materials production to end of life treatment. While setting the system boundaries it is important to document the assumptions made, as well as the limitations resulting from these assumptions. The last part of the goal and scope definition is to select the impact categories that will be investigated, which together with the system boundaries is guiding the data collection.

2.1.2. Inventory Analysis

In the inventory analysis, the life cycle inventory (LCI) of the system is created through data collection and calculations. The aim is to quantify the inputs and outputs of the system in relation to the functional unit. The inventory analysis is an iterative process, and adjustments in the data collection processes are often needed after gaining more insight into the study. Inputs to the system are materials, energy or other physical requirements. Outputs, on the other hand, can be classified as by-products, co-products or waste. They also include environmental aspects caused by the system, such as emissions to air and discharges to water. Baumann and Tillman (2004) emphasizes that only the environmentally relevant flows should be included. At this life cycle stage, the need for allocation is also decided upon (ISO, 2006b). Allocation is needed if we are dealing with a system producing multiple outputs. An allocation procedure can then be used to distribute the environmental burdens between the products. ISO (2006a) states that allocation can be avoided by dividing the unit processes into smaller sub processes and collecting the inputs and outputs associated with these. Another alternative is systems expansion where the system boundaries are expanded to include additional functions of the co-products. If allocation cannot be avoided, partitioning based on the physical characteristics of the products should be used.

2.1.3. Impact Assessment

The goal of the life cycle impact assessment phase is to convert the inventory data (emissions and resource use) to environmental impacts, often presented as category indicators (Baumann and Tillman, 2004). This is done in order to present more understandable results.

The impact assessment phase of LCA consists of four steps: Classification, characterization, normalization and weighting, whereby the two latter are optional and will not be described here (ISO, 2006b). In classification the LCI results are sorted according to the type of environmental impact they contribute to. CO_2 and CH_4 emissions, for instance, contribute to global warming potential. After the results have been classified, they can be merged into one common indicator for each impact category. The characterization factors of the emissions or resource use are based on scientific models from chemistry, toxicology etc. The indicator for global warming is CO_2 equivalents (CO_2-eq), which means that all emissions contributing to global warming must be converted to this unit.

A widely used impact assessment method is ReCiPe, developed by Goedkoop et al. (2009). ReCiPe offers quantification methods for both midpoint and endpoint LCA indicators. These are described as two separate environmental mechanisms: The first mechanism describes the midpoint level, where LCI results are converted into category indicators, and the second mechanism quantifies their effect on the three endpoint indicators: damage to human health, damage to ecosystems and resource loss. Goedkoop et al. (2009)emphasize that the first step has a relatively low uncertainty because it is based on scientific models and data published by IPCC. The second step, however, involves more uncertainty, as it is based on their own models and data from WHO.

2.1.4. Interpretation

In the last step of LCA, the results are interpreted in order to make conclusions. The interpretation part of an LCA should also include an evaluation of the methodology used, i.e. the limitations posed by choosing the system boundaries and impact assessment methods in the study, or those resulting from potential gaps in data. Recommendations for future work should also be mentioned here (ISO, 2006b).

2.1.5. LCA tools used in the analysis

Arda

Arda is a LCA software developed by the Industrial Ecology research group at NTNU. It is used for both educational and professional purposes. Arda allows the user to construct their own foreground matrix, and couples this with the background database ecoinvent v.2.2. The software is also integrated with the ReCiPE impact assessment methodology, as discussed in chapter 2.1.3.

ecoinvent v. 2.2

LCA is a very data intensive framework (Strømman, 2010). In order to construct a complete life cycle inventory, it is therefore necessary to build on accumulated knowledge from previous LCA studies. This can be done by linking the foreground system with a commercially available LCA database comprising all the relevant background processes. There are five commercially available LCA databases today, where the ecoinvent database is considered the most comprehensive and best quality general LCA database for European purposes.

The ecoinvent database builds on over 20 years of experience of compiling LCI data and performing LCA studies (Ecoinvent Centre, 2015). The ecoinvent Centre states on their websites that their aim is to provide transparent international LCA data to their users, whether it is consultancies or research institutions. The only drawback of the database is the construction that can appear somewhat fragmented (Strømman, 2010). This is because the emissions and requirements matrices can be split across several different sub-processes, making it difficult to assess the input/output tables.

2.2. Direct Emissions from Vehicle Operation

The direct emissions from vehicle operation are well documented in the literature. In order to reduce emissions from vehicle operation,it is important to know which pollutants are generated and their respecitve source. This section will focus on the direct emissions from vehicle operation, what environmental impacts they cause and how they are regulated.

Direct emissions can be split into exhaust emissions from combustion of fuel in the engine (tailpipe), and non-exhaust emissions from tire, brake and road wear, caused by the vehicle's motion (Sundvor, 2013). Exhaust emissions constitute the major part of direct emissions. The exception is for particulate matter, where the share of non-exhaust emissions can be as high as 50% (Cooper et al., 2012). Some of the non-exhaust emissions are not airborne, but their heavy metal content is accounted for as emissions to water and soil (Spielmann et al., 2007).

Vehicle operation cause both global and local environmental impacts (Cooper et al., 2012). Emissions of (CO_2 contributes to global warming, while pollutants such as particulate matter (PM), dinotrogen oxides (N_2O), sulfur dioxides (SO_2) and ozone (O_3) cause local air pollution problems and affect human health. Norway monitors emissions of the latter pollutants in urban areas and have imposed targets for their concentration levels (Luftkvalitet.info, 2015). The Norwegian government have also introduced taxes on fossil fuels as a mean to to reduce the emissions of CO_2 (Miljødirektoratet, 2015a).

2.2.1. Euro Standards

The Euro standards are implemented emission regulations for heavy-duty and light vehicles in the European Union. The standards are an important measure to regulate emissions of harmful substances from road transportation. Pollutants included in the Euro standards are well tested for their health and environmental impact (Cooper et al., 2012). The first Euro standards regulating emissions from heavy-duty vehicles came in 1988 (Lindqvist, 2012). The first three standards applied only to diesel engines, but as positive ignition engines (gas and petrol) have been introduced to the market, they have been included in the latest standards. The new Euro Standard, Euro VI, introduces stricter regulations for nitrogen oxides (NO_x) and particulate matter (PM) emissions. As can be seen in table 2.1, NO_x emissions are reduced by 2,88grams per km and PM emissions have been halved. The regulated emissions for heavy-duty engines can be seen in table 2.1. CO, THC, NMHC and CH_4 are abbreviations for carbon monoxide, total hydrocarbons, non-methane hydrocarbons and methane.

Emissions of CO_2 have just recently been included in EU regulations (Lindqvist, 2012). However, the binding limits for CO_2 emissions from road vehicles covers only passenger cars and vans. No current technology can help reduce tailpipe CO_2 emissions, which means that re-

Table 2.1.: Euro Emission Standards for Transit Vehicles (g/km) (Cooper et al. (2012)Lindqvist (2012), Dieselnet (2012))

Emission Standards	Date	CO	THC*	NMHC**	NO_x	PM	CH_4**
Euro I	1992	8,1	1,98	14,4	0,648		
Euro II	1998	7,2	1,98		12,6	0,27	
Euro III	2000	3,78	1,188	1,404	9	0,18	2,88
Euro IV	2005	2,7	0,828	0,99	6,3	0,036	1,98
Euro V	2008	2,7	0,828	0,99	3,6	0,036	1,98
Euro VI	2013	2,7	0,234	0,288	0,72	0,018	0,9

**Only diesel engines **Only gas engines*

duction in these emissions can only be obtained by improved fuel economy. Factors that have proven to affect the fuel consumption in vehicles will be discussed in the next section.

2.2.2. Factors affecting fuel consumption

The driving cycle has been identified as the most important factor for the fuel consumption and thus emissions of the vehicle (Cooper et al., 2012; Barth and Boriboonsomsin, 2010; Pelkmans et al., 2001). Research has also found a correlation between a low average speed and fuel consumption (Barth and Boriboonsomsin, 2010). Low average speed is usually linked to traffic congestion, which causes more frequent starts and stops and a net negative impact on CO_2 emissions because the vehicles spend longer time on the road. A driving cycle with frequent starts and stops is characteristic for urban traffic (Cooper et al., 2012). When comparing urban and more rural driving cycles, there is a significant difference in fuel consumption. Urban drive cycles can have as much as 30% higher fuel consumption compared to steady-state cycles.

A real-world driving cycle from Belgium showed that a bus in real-city operation had a driving cycle consisting of 40% acceleration, 21% standstill, 33% deceleration and 7% cruising (Pelkmans et al., 2001). Even though the time-share of acceleration was only 33%, it is responsible for 70% of the fuel consumption. Pelkmans et al. (2001) also found that an increase of standstill would increase total fuel consumption, due to the additional need for acceleration.

The mileage of buses can also affect the exhaust emissions significantly (Cooper et al., 2012).

With increased mileage, there is an increase in emission values for NO_x and CO_2.

2.3. Bus and Fuel Technologies

The development of a more environmentally-friendly passenger transport in Norway must also aim to reduce the emissions from each individual vehicle (Miljødirektoratet, 2015b). This can be achieved by technology advancements. The following section will describe the fuel and bus technologies that are included in the LCA modeling, in terms of technological characteristics, and their environmental benefits and drawbacks.

2.3.1. Hybrid Electric Buses

Any vehicle with two or more different energy sources can in principal be defined as a hybrid vehicle (TCRP, 2009). The most common hybrid vehicle for transit purposes is an electric propulsion system combined with a conventional internal combustion engine (ICE) (FTA, 2005). The engine can be fuelled by diesel, gasoline, propane or natural gas.

The main components of an electric hybrid vehicle are a conventional ICE coupled to an electric generator (the power unit), electric motor, and battery package for energy storage. Most hybrid buses in use today have either lead-acid or nickel metal hydride batteries, which are recharged during driving or by the electrical grid. The recharging during driving is either provided by the ICE or by regenerative breaking. Regenerative breaking stores the energy from deceleration of the vehicle in the battery and can be used for additional propulsion power in acceleration phases. The electric motor provides extra power for acceleration and hill climbing, which allows for a smaller and more efficient ICE. This leads to decreased energy use, both due to the reduced weight of the vehicle, and the more balanced and efficient use of the engine.

Hybrid vehicles can be classified according to the division of power between the two energy sources. The two sources can either operate in parallel to provide motive power, or they can be coupled in a series. In a parallel hybrid vehicle, both the electric drive system and the ICE is coupled to the drivetrain. With this configuration the vehicle may be powered by both electricity and fuel combustion combined, or either source separately (FTA, 2005). Usually,

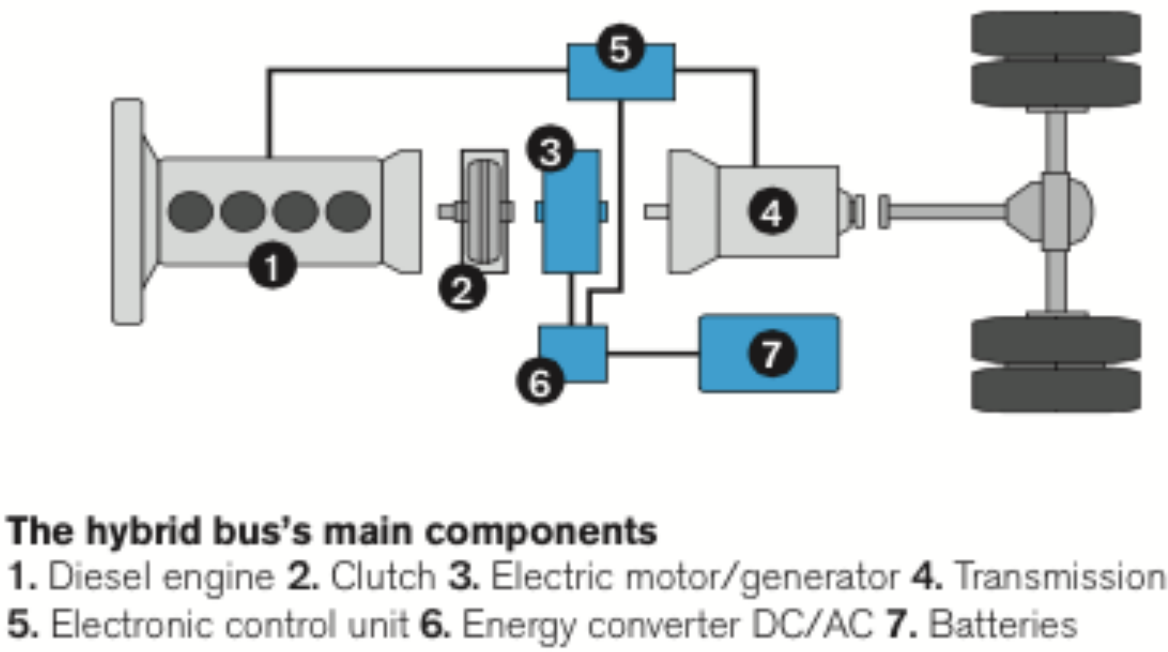

Figure 2.2.: Driveline of the VOLVO 7000 hybrid parallel bus (Volvo Bus Corporation, 2008)

the ICE provides power at high, constant speeds, while the electric motor provides power during stops and at low speeds. For acceleration of the vehicle, the motive power comes from a combination of the two sources.

When the ICE and electric drive system are coupled in series, the ICE is completely mechanically decoupled from the drive wheels. All energy needed for operating is electrical power generated by the ICE. This configuration allows the ICE to be switched off for exclusively electric operation. Series hybrid can also be configured for recharging of the batteries through the electric grid, allowing for an extension of the electric driving range.

Most of the hybrid buses in operation in Norway today are parallel hybrid buses, running on diesel in addition to electricity. They are continuously recharged during driving and do not require recharging. Plug-in hybrid buses have however been considered for city transportation, as they would offer further reductions in emissions and noise, in addition to reduced dependency on fossil fuels. The drawback of these buses is of course the need for construction of new infrastructure for charging.

Environmental considerations

The composition of the exhaust emissions is the same as from diesel buses, but the amount may be lower due to reduced fuel consumption obtained by regenerative braking and an improved power system (Cooper et al., 2012). Improvements in emissions is therefore mainly in the form of reduced CO_2 emissions (TransLink, 2006). Significant reductions in regulated emissions have also been reported, especially in CO and NO_x (FTA, 2005). The PM emissions are comparable to a diesel bus with particulate filter.

The electric drive components can however increase the emissions associated with the production phase, compared to a conventional diesel bus (TransLink, 2006). The hybrid buses also comes at a higher purchase costs.

2.3.2. Natural Gas Buses

Buses running on natural gas are similar to conventional diesel buses in construction. The engine is composed of 90% of the same materials as a diesel engine, as most natural gas buses have diesel engines converted to gas operation (Nylund et al., 2004; Sundvor, 2013). There are two types of natural gas engines in the marked today: spark-ignited engines with stoichiometric combustion or lean-burn combustion. The stoichiometric combustion engines can be efficient to reduce local air pollution problems because they allow for use of 3-way catalysators. These catalysators are known to remove pollutants from exhaust gas efficiently, in some cases an efficiency of 99% is documented(Hagman, 2002). A lean-burn combustion engine is however more fuel efficient. This engine also reduces emissions of NO_x, due to a higher air volume and lower temperatures in the combustion chamber.

The fuel-air ratio is decisive for complete combustion of natural gas. Incomplete combustion generates emissions of methane (CH_4), a GHG which has a global warming potential about 20 times larger than CO_2. This is usually not a problem in modern natural gas buses because of newly developed electronically controlled fuel injection systems (Nylund et al., 2004).

The natural gas is stored and distributed in containers on top of the bus. The compression tanks used to store the natural gas require 4-5 times more space than the same volume of diesel fuel (Hagman, 2002). Natural gas engines are configured for operation on both compressed natural gas (CNG), and liquefied natural gas (LNG). According to Selfors et al. (2004), the Norwegian natural gas consists of 90% methane. Natural gas can be transformed to either compressed natural gas (CNG) or liquefied natural gas (LNG) for transportation purposes. CNG is natural gas stored under a pressure of minimum 150 bars. LNG is liquefied, cooled natural gas. The gas is usually cooled down to -163°C to keep liquid at normal pressure.

Environmental considerations

The combustion of methane emits 25% less CO_2 than equivalent energy use from diesel in engines with the same coefficient of performance (Hagman, 2002). In addition, vehicles running on natural gas reduce emissions of particles because of soot-free combustion. Using natural gas is also beneficial due to the abundance in natural gas reserves compared to oil.

The main drawbacks of natural gas buses is the higher energy use and the higher purchase cost compared to conventional diesel buses. The higher energy use is a result of higher temperature in combustion, in addition to the required energy for regulation of air volumes in the engine (by throttling). An empirical study of natural gas buses in Bergen showed a 30% higher energy use than diesel buses of similar size. As a result, CO_2 emissions are the same, or even higher than conventional diesel buses.

Including CNG buses in the bus fleet is beneficial to reduce local air pollution in urban areas. Compared to a diesel bus complying to a Euro 3 emission standard, PM emission are reduced by 90% (Nylund et al., 2004). There is a significant increase in CH_4 emissions due to unburned fuel in the exhaust, but studies have shown that the increase is not sufficient to increase total GHGs compared to a diesel bus (Cooper et al., 2012; Nylund et al., 2004). There is a large variation in NO_x emissions, depending on the exhaust treatment technology applied. Improvements ranges from 20 to 80%. CO emissions follows the same pattern.

2.3.3. Biodiesel

Biodiesel refers to fatty acid methyl esters prepared from biological feedstock (Verhé et al., 2004). The biological feedstock can be vegetable oil, animal fat, single cells oil or waste material. Today, there is an extensive use of rape crops, also called rapeseed oil methyl esters (RME). We often distinguish between first generation biodiesel, produced from food crops, and second generation biodiesel produced from biomass, biomass residuals or other waste materials.

First generation biodiesel can be produced from different types of vegetable oil. The fuel has similar properties as mineral diesel oil, and can therefore be used in conventional diesel engines. Similar properties also means that biodiesel and conventional diesel can be blended together in any ratio. Biodiesel has a lower calorific value than mineral fuel, which means that the fuel consumption is slightly higher. Verhé et al. (2004) estimates the difference to 5-6%.

The vegetable oil undergoes a trans-esterification process in order to be used as fuel in conventional diesel vehicles. In this process, the vegetable oil is reacted with an alcohol, usually methanol, in order to produce glycerol and ester (Luján et al., 2009).The trans-esterification process generates a number of co-products, mainly residue after pressing, which can be used as animal feed, or in biogas production.

Environmental considerations

The use of biodiesel in transportation is beneficial for two reasons (Luján et al., 2009). First of all, the production of fuels from crops help reducing the dependency on fossil fuels in the transportation sector. SenterNovem (2008) found that the biodiesel fuel chain results in a 57% improvement of fossil depletion compared to mineral diesel oil. The other advantage of introducing biodiesel is reduction in tailpipe emissions, especially in CO_2. Combustion of biodiesel is considered carbon-neutral because the growing of new biomass captures CO_2 emissions resulting from combustion of fuel in the engine (SenterNovem, 2008).

The reduction in fossil depletion does however not translate directly into reduced CO_2 emissions for first generation biodiesel, becuase of the indirect emissions from production of the fuel (SenterNovem, 2008). Food crops used in biodiesel are produced by intensive farming, which emits considerable amounts of dinotrogen oxides (N_2O). N_2O is a greenhouse gas with a global warming potential around 300 times larger than CO_2. In total, the production and cultivation of rape seeds and conversion to biofuel generates GHGs four times higher than the production of fossil diesel.

Other tailpipe emissions have proved to be reduced to a varying degree, depending on the quality of the fuel, type of engine and exhaust treatment technology (Verhé et al., 2004). Significant reductions have been observed in CO and HC emissions, which can be explained by a more complete combustion due to a higher oxygen content in the fuel. For PM, reductions up to 70% have been observed. Emissions of sulfur oxides are also completely eliminated due to the low sulfur content (Camobreco et al., 1998). Studies have however documented an increase in NO_x emissions (Verhé et al., 2004). In some vehicles an increase of 20% have been observed. The reason for the increase mightbe a higher combustion temperature in the engine when biodiesel is used.

2.4. Previous LCA studies

There have been conducted numerous LCA studies of car transportation, which means that there are detailed inventories available different types of cars. There are however very few LCA studies of bus transport, at least with transparent life cycle inventories for the production phase of the bus. This literature review aims to compile scientific articles and non-scientific reports to provide context and give a starting point for this LCA study. The studies have been selected due to their relevance for this thesis. Since the overall goal is to quantify the carbon footprint of bus transport, the literature review mostly focuses on GHG emissions.

The objectives of the literature review can be more explicitly stated as follows:

- Identify previous LCA studies on bus transport.
  - Which bus and fuel technologies are covered?
  - Which life cycle phases are the main contributors to emissions?
  - What does the literature say about the environmental performance of buses, compared to other transport forms?
- Provide specific data for the modeling of the LCI.
- Compile results that can serve as comparison for this study.

2.4.1. LCA of bus transport

Life-cycle environmental inventory of passenger transportation modes in the US is a doctoral thesis conducted by Mikhal V.Chester at the University of California (Chester, 2008). The thesis includes a comprehensive life cycle inventory for passenger transportation by bus, air, rail, ferry, automobile and metro. Both operational and non-operational components were included in the analysis. To construct the life cycle inventory, a hybrid LCA approach was used. The non-operational components were mostly modeled by the use of environmental input-output LCA (EIO-LCA) based on purchases of fuel, vehicle components etc. in the US economy. Both energy use and emissions were considered.

Several journal articles are published based on Chester's doctoral thesis. Two of them have been reviewed here to compile specific data for bus transport. When evaluating the literature in the next chapter, it will be referred to the doctoral thesis by Chester (2008).

The article *Environmental assessment of passenger transportation should include infrastructure and supply chains*(Chester and Horvath, 2009) presents the results for life cycle energy use and emissions from different transport modes in urban areas. Chester and Horvath (2009) found that including the whole life cycle of different transport modes changes the energy use and emissions significantly. For on road transport modes, the contribution amount to 63% over vehicle tailpipe operation. The authors also found that the relative performance of modes is sensitive to passenger occupancy. For an urban diesel bus the difference in in energy use between the peak and off-peak times was 4,6 MJ per passenger km (pkm). Correspondingly for GHG emissions, the difference was estimated to 370g CO_2- equivalents (CO_2-eq).

The thesis also included a case study of three metropolitan regions in the US (Chester et al., 2010). The distribution of passengers between the different transport modes was obtained by the use of travel surveys, containing the travel characteristics of each region. They found that the operation phase is the largest contributor to GHG emissions for on road modes (bus and automobile). For the other emission categories, however, the non-operational components constitute the highest share. Private vehicles were found to dominate both energy use and emissions in the total regional performance. Automobiles accounted for as much as 86-96% of energy use and emissions. New York performed best of the three regions due to a larger share of transit ridership.

Sundvor (2013)assessed the environmental impacts of three bus types commonly used in the Trondheim region. Over the lifetime of the vehicles, he found that the transit vehicles by far exceeded the private vehicles in CO_2- eq. When the results were normalized to passenger kilometers traveled, the transit vehicles however proved to have a better performance than the private vehicles. Comparing different passenger loads, the emission break-even points between private and public transportation were found. With a passenger load higher than 23 passengers, the transit vehicles outperformed the private vehicles regardless of bus technology.

The scientific report *Bus* is a comprehensive study of life-cycle energy use and emissions associated with bus transport in Norway, published by the Western Norway Research Institute (Simonsen, 2012a). The author draws on existing literature and historical figures in order to quantify and compare environmental performance of different bus technologies. The report includes both diesel, biodiesel, hydrogen and natural gas buses, and is thus the most comprehensive study in terms of technologies. The carbon footprint (CF) per vkm and pkm was found to be lowest for the hybrid bus modeled in the study, while the estimate for hydrogen city buses showed the highest CO_2 emissions and energy use. Passenger loads were based on historical figures for average passenger occupancy in Norwegian city and express buses.

2.4.2. LCA of different bus and fuel technologies

In his master thesis, Cooney applied life cycle assessment to compare a conventional diesel bus to an electric powered bus (Cooney, 2011). The results from the study showed that the use phase dominates most of the impact categories for both buses. For the electric powered bus, however, the battery production generated significant emissions in several impact categories. Cooney emphasized that the performance of the electric bus depends on the power generation technology. With electricity mixes on the state level, the electric bus outperformed the diesel bus in only eight states.

Ally and Pryor (2007) applied life cycle assessment to compare the environmental performance of diesel, natural gas and hydrogen fuel cell bus transport systems in an Australian case study. Their results showed that the hydrogen fuel cell buses were competitive with the natural gas bus and the diesel bus systems in terms of global warming potential and eutrophication. The natural gas bus had the highest global warming potential, due to lower fuel efficiency observed in the buses included in the case study, in addition to the emissions of methane from unburned natural gas.

Ou et al. (2010) quantified the life cycle fossil energy use and GHG emissions of conventional diesel and gasoline buses and a number of alternative bus technologies in a case study of bus transport in China. Alternative bus technologies included in this study was CNG, LPG, diesel-hybrid and electric. Electrical buses were found to give a 20% reduction in fossil energy use and 13% reduction in GHG emissions compared to diesel buses. The CNG buses showed similar fossil depletion results, but emitted 26% less GHGs.

2.4.3. Summary of LCA studies

Table 2.2 summarizes the results from the studies included in the literature review. Important assumptions about passenger load and lifetime km traveled are also included. The numbers presented apply to intercity buses when possible.

Table 2.2.: Summary of results from literature

Bus technology	g CO_2-eq/vkm	g CO_2-eq/pkm	Type of study	Reference
Diesel	2001*	439	Case s.	Chester (2008)
Diesel	1377,2**	114**	Generic	Simonsen (2012a)
Diesel	1202	81	Case s.	Sundvor(2013)
Diesel	2860**	-	Generic	Cooney (2012)
Diesel	1171,2***	-	Case s.	Ou et al (2010)
B20	1381,7	109,7	Generic	Simonsen (2012a)
Hybrid	957,3	78,7	Generic	Simonsen (2012a)
CNG	1123	76	Case s.	Sundvor (2013)
CNG	840***	-	Case s.	Ou et al (2010)
CNG	957	79	Generic	Simonsen (2012a)

***Excluded infrastructure construction and maintenance**
****Only CO_2 emissions**
*****Not included bus manufacture and maintenance**

As seen in table 2.2, the results from the literature ranges from 1202 to 2860 g CO_2-eq per vehicle km for diesel buses. The two studies that included natural gas fuelled buses generated quite different results. Differences occur due to different system boundaries and assumptions about key parameters. When only considering operation, most of the studies that evaluated diesel are more consistent and in the range of 900-1700g CO_2 eq. per vkm. One exception is the study by Cooney (2011), which gave 50% higher emissions than the average. The fuel consumption in this study is however twice as high as in the study by Sundvor (2013). The methodology applied ranges from the conventional LCA study by Sundvor (2013), following the ISO 14000 standards for LCA, to hybrid LCAs. From the literature reviewed, there is no single approach that stands out as the most appropriate to assess the environmental impact of bus transport.

Most of the studies focused on different fuel technologies. In fact, four studies explicitly stated that the goal of the study was to compare different fuel technologies (Cooney (2011),Ally and Pryor (2007),Simonsen (2012a),Ou et al. (2010)). Two of the studies aimed to develop complete life cycle inventories for passenger transportation (Sundvor (2013),Chester (2008)).

While Ou et al. (2010)and Simonsen (2012a) only evaluated energy use and GHG emissions, other studies have extended their scope to evaluate other pollutants and impacts such as NOx, SO2, VOC, PM10, ozone depletion, eutrophication and acidification [1]. **?** found that it was important to include other pollutants than those contributing to global warming to improve the whole transportation system. When only considering GHG emissions, operation of the buses contributed with the highest share of emissions, but when looking at the other impacts, non-operational processes comprised the major part of emissions.

The differing results can be explained by the variation in system boundaries among the studies, as they often reflect the goal of the study. The studies included many of the same processes related to bus transport, but there is still some variation among them. All studies included fuel production and the operation phase of the vehicle. The most comprehensive study was the one by Chester (2008), which included all upstream processes related to bus transport. Ou et al. (2010) and Cooney (2011) did not consider manufacture of buses, although other studies found that this process accounted for a significant share of the total emissions , between 3 and 10%. The operation phase was found to contribute with the highest share of emissions in all studies, ranging from 66% to 98% of the total GHG emissions. The relatively small contribution from operation in Chester (2008)can be explained by the inclusion of both road infrastructure construction and maintenance, in addition to higher emissions from bus manufacture than the other studies. With a few exceptions (Sundvor, 2013), the impacts from the end-of-life phase are not included, due to lack of data of the

[1] An overview of the included impact categories, bus technologies, system boundaries and functional unit of the included studies, can be found in appendix C.1 on page 91

disposal and waste treatment of the bus components.

Identifying the Gaps

To sum up the this section on previous LCA studies, the following paragraphs aims to evaluate the quality of the reviewed literature, and usefulness to this thesis.

The literature available in the field is scarce, and is varying in methodology approach. Among the studies evaluated here, there is a lack of transparency in the developed life cycle inventories, which makes it difficult to reproduce the results of the studies. There is also a lack of a standardized methodology framework to ease the comparison between studies. The studies can still serve as comparison for the results of this thesis, but the differences discussed above and later in this section should be kept in mind.

The most complete LCA study identified of bus transport in Norway is Sundvor (2013). This study is also based on empirical data from the Trondheim bus fleet and should therefore provide a good starting point for this thesis.

Very few studies discussed the importance of key parameters in the analysis, namely fuel consumption in the use phase and the importance of driving patterns. As the use phase by far has the highest impact of the life cycle phases, more attention should be given to this phase. Chester (2008) stress the environmental performance of bus transport at various times of the day, i.e. during and outside rush traffic hours. The same author emphasized the importance of regional environmental inventories due to differences in energy use and emissions caused by influencing variables such as vehicle occupancy, fuel types, vehicle age and vehicle speed, among others. The fuel use in Ou et al. (2010) was also based on actual in-city operation of buses in China, but regional or route differences were not identified. The two Norwegian studies (Sundvor, 2013; Simonsen, 2012a) differentiated between fuel consumption of intercity buses and coach buses. The impact of various slope gradients, number of bus stops and rush traffic was however not tested in any of the included studies. Fuel use may however be relatively less important in parts of the reviewed literature, due to the focus on different bus technologies.

In order to evaluate the environmental performance of bus transport in urban areas, the results should be compared to other modes of transport. This is done to some extent in both

Chester (2008) and Sundvor (2013). Chester (2008) included a sensitivity analysis where the impact of changing passenger load is tested. Both Sundvor (2013) and Chester (2008) showed that the results are sensitive to changes in passenger load, which varies depending on time of the day and during the week.

3. Method

3.1. Presentation of Case

3.1.1. bus transport in Trondheim

Sør-Trøndelag county authority is the superior administrator of public administration in the Trondheim area (Sætre, 2013). The county municipality owns the transportation agency AtB, which is responsible for the planning of the bus routes, customer services and purchases of transportation services. Several bus companies operate the bus routes on behalf of AtB. In 2015 there are four bus companies, Tide Buss, Nettbuss, Trønderbilene and Boreal, operating in total 48 different bus routes in Trondheim. (AtB, 2015a). The bus fleet comprises three different bus types: diesel buses, natural gas buses and hybrid electric buses. The distribution of the different bus types, as well as the transportation work for 2014, can be seen in table 3.1.

Table 3.1.: Presentation of the bus fleet in Trondheim. Share of transportation work is calculated according to vehicle km (vkm) traveled. All information is from Krokstad (2015a)

Bus type	Share of transportation work in 2014	Brands
Diesel	11%	Man, Volvo 8900 EEV
CNG	85%	Solaris, Man Lions City, Iveco
Hybrid	4%	Volvo 7700 Hybrid

Greener Trondheim is a partnership aiming at reducing emissions caused by transportation in Trondheim (Trondheim kommune, 2014). The project is developed in collaboration between several public bodies: the city council, county council and the National Public Road Agency. The overall goals of this project are reductions in CO_2 emissions in the city, in addition to improved urban air quality by increasing the share of transport by foot, by bicycle or public transportation. The estimated investments in the period from 2010 to 2025 amount to 11 billion NOK. Half of these investments should be invested in road projects, whereas the other half should be spent on updating and improving pedestrian/cyclists facilities, local roads and public transportation. Since the founding of Miljøpakken, or Greener Trondheim, in 2008, there has been a greater focus on improving public transportation, both in terms of the environmental impact and ridership (STFK, 2014).

The measures implemented so far have proven to be successful, and have increased both the amount of bikers and bus travels. Since 2010, bus travels have increased by 33%, which is the highest in Norway (Miljøpakken, 2015). Bus travels today comprise 10% of all travels in Trondheim. The growth is made possible by a higher frequency of bus service, and introducing measures that give incentives to shift to public transportation, such as decreased parking and toll roads surrounding the city centre. In order to improve air quality and reduce local pollution, AtB and Miljøpakken have invested in CNG and hybrid buses (Miljøpakken, 2015a). 85% of the transportation work was performed by CNG buses in 2014. From the end of April 2015, 70% of the CNG buses will run on a mix of biogas and natural gas as a trial project (AtB, 2015b). The trial period is one year and the aim is to explore possibilities to include biogas in future tendering processes.

3.1.2. Presentation of the Included Bus Routes

Seven different bus routes from AtB have been evaluated in this thesis. Choosing specific bus routes allows for collection of specific empirical data for bus transport. The choice of which bus routes to include were taken on the basis of:

1. The bus routes should reflect the whole bus fleet, i.e. among the routes both diesel, CNG and hybrid buses should be represented.

2. The bus routes should represent a variation in passenger load, to enable comparison of the environmental performance of bus transport with different passenger loads.

With these aims in mind, AtB was conferred in order to choose the appropriate bus routes. A presentation of the included bus routes, in terms of passengers and share of the different bus types, can be seen in table 3.2 on the following page.

Table 3.2.: Presentation of the bus routes considered in this study. Historical figures from 2014.

Bus number	Bus types	Passengers per year	Vehicle kilometer per year
4	78% CNG, 28% Diesel	2,25E+06	8,54E+05
5	78% CNG, 28% Diesel	3,48E+06	8,82E+05
6	78% CNG, 28% Diesel	1,74E+06	9,48E+05
7	100% Hybrid	1,20E+06	6,55E+05
9	78% CNG, 28% Diesel	2,39E+06	9,11E+05
777	78% CNG, 28% Diesel	1,87E+04	2,19E+04
75	100% CNG	1,34E+05	2,27E+05

The bus routes 4,5,6,7,9 and 777 are operated by Nettbuss, while bus route 75 is operated by Tide bus company (Krokstad, 2015b). From table 3.2 it can be seen that bus routes 4-7 and 9 are busy, passenger intensive bus routes, while 777 and 75 have less passengers. This can be explained by their geographical location, and length of the bus route. 4-7 and 9 are operating in areas within the city with high population densities, whereas bus number 75 runs to Byneset, a place outside the city with sparse population. A geographical overview of the bus routes can be seen in figure 3.1 on the following page

3.2. LCA methodology applied in the case study

In this subchapter the inventory and data collection for the three bus types will be described. Explanation of important assumptions and the potential implications of these will be explained. How the modeling choices potentially will affect the validity of the results will however not be included in this subchapter, but will be thoroughly discussed in chapter 5.

The environmental performance of the different bus routes will be compared to car transportation in terms of average passenger kilometers per year. The details for the comparison will be covered, together with the parameters used for car travels. An analysis of the development in the carbon footprint (CF) of passenger transportation has also been conducted. The reasoning behind this analysis was to compare the relative importance of a more efficient and environmentally-friendly bus and car fleet to modal shifts for the total GHG emissions. The calculation methods for this analysis will be presented in detail, and an overview of the parameters used in the calculations will be given.

The subchapter is structured after the four phases of an LCA as described in the theory chap-

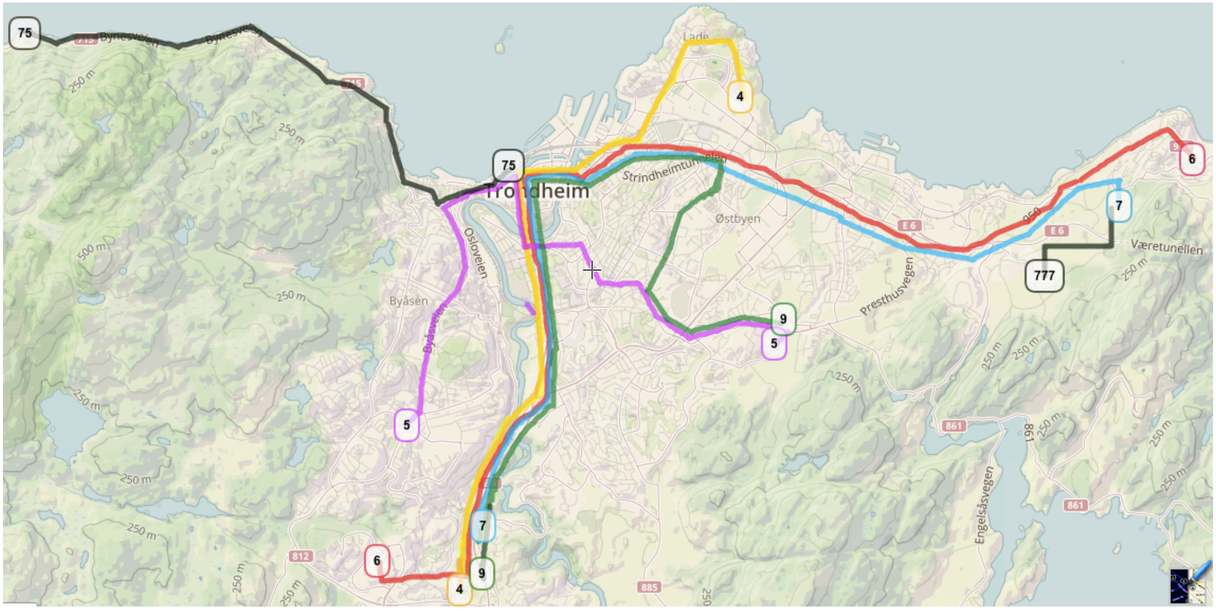

Figure 3.1.: Geographical overview of the included bus routes. Based on AtB (2015c)

ter. An interpretation of the results will be given in chapter 5.The analysis has been conducted by the use of the computer program Arda, with background data from the database ecoinvent v.2.2.

The aim has been to develop an LCI as case-specific as possible, which are reflected in some of the modeling choices made. Choosing a case study allows collection of empirical data from the use phase of the vehicle. For this reason, the main focus of this assessment will be directed towards the use phase of bus transport, which includes operation and maintenance of the vehicle.

3.2.1. Goal and Scope

The main goal of this thesis is to compare the environmental impact of different bus technologies and passenger loads. The functional unit was chosen so that the different bus routes are comparable over the same lifetime. AtB reported a lifetime of 15 years, or 1 000 000 km driven for the vehicles included in their bus fleet. For this reason, the functional unit in this

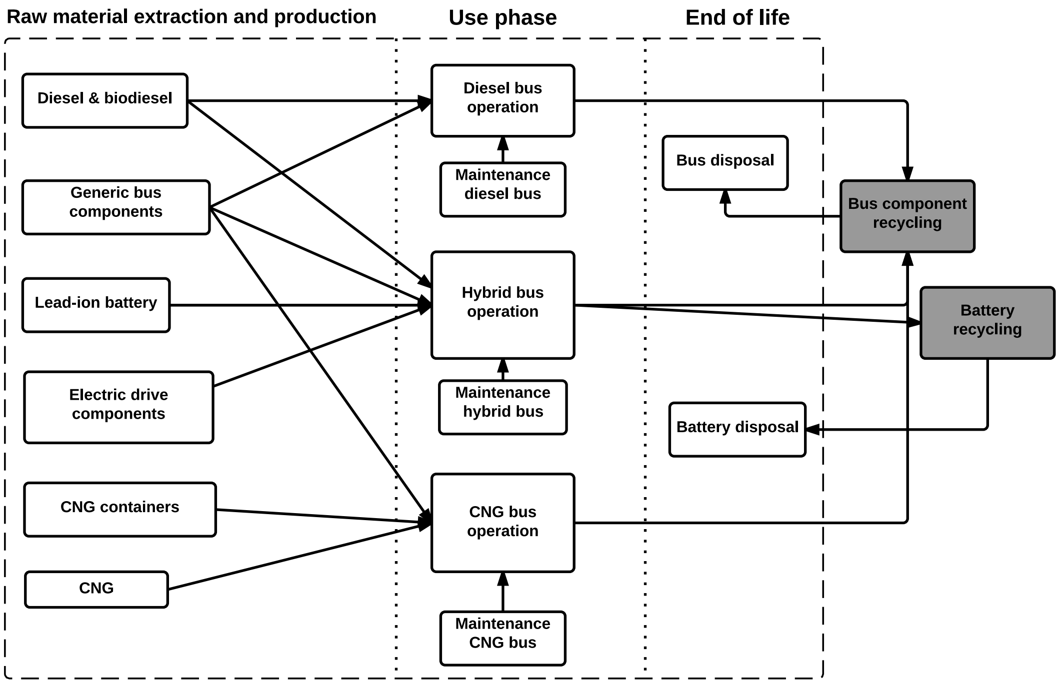

Figure 3.2.: System boundaries for the life cycle analysis performed in this study. The processes modeled in this study are those included inside the dashed lines, marking the system boundary.

study is defined as:

1 passenger kilometer traveled in Trondheim by an average citizen.

This enables comparison of the environmental performance of the different bus routes, despite their difference in bus types covering the service and passenger loads throughout the year. The functional unit also allows comparison of passenger transportation by car and by bus.

The results from the life cycle assessment will also be normalized to 1 vehicle-kilometer over a lifetime of 15 years, enabling comparison to other studies.

System boundaries

The system boundaries determine which processes should be included and quantified in the LCI (ISO 2006b).The whole life cycle of bus transport is included. The three bus types were modeled after the life cycle phases production, use and EOL treatment. Figure 3.2 gives an overview of the system boundaries applied in this study.

Production includes extraction of raw materials used in the production of the bus components, as well as manufacture of the different components and the final assembly of the bus. A well-to-wheel approach is taken for the use phase, which means that both energy and material use associated with the production of fuel, as well as the downstream effects of vehicle operation are accounted for. The use phase includes also energy and material required in the maintenance of the buses. Disposal and treatment of the bus components are included in the EOL phase. Recycling of metals and other materials are defined outside of the scope of this study because of limited data available on these processes. The definition of the different life cycle phases is similar to the approach in Sundvor (2013) and Cooney (2011).

3.2.2. Life cycle inventory

Data compilation

Many of the studies in the literature utilized a hybrid LCA approach, or did not provide transparent life cycle inventories for their studies. This means that the data availability for a conventional LCA study is limited. Sundvor (2013) provides a transparent LCI for, even though not entirely comprehensive, it has provided a starting point for this thesis. The non-operational processes have mostly been modeled with this LCI, with some modifications from other sources. The use phase is mostly based on empirical data provided by AtB and the respective bus companies. Data from the bus producers' websites have also been used to collect information about the vehicle's drivetrain and technical performance.

Production

This process has been split into production of generic bus components, and production of specific components for the different bus types: Lithium-ion battery and electric drive components for the hybrid bus, and CNG containers for the CNG bus. Final assembly of the buses is also included in the production phase.

Generic bus components A report by the Western Norwegian Research Institute gives the material composition of a VOLVO 8500 low-entry city bus (Simonsen, 2012c). The material composition is modeled after an environmental product declaration (EPD) from VOLVO. Unfortunately, this EPD is no longer available to the public. The material intensities are given according to the weight of the bus, and was scaled linearly according to the weight of the average diesel bus from AtB. Simonsen (2012c) does not provide material intensities for each of the components in the bus, i.e. engine, transmission, brake system and so forth. For this reason, it was assumed that the CNG and hybrid buses had the same chassis and body as a diesel bus, with a few modifications that will be explained below.

Neither Sundvor (2013), nor Simonsen (2012c) include the electronic devices for control units. This was therefore taken from a study by Kärnä (2012), which provides the weight of electronics in diesel and hybrid buses.

Table 3.3.: Specifications of the different bus types

Bus type	Kerb weight [tons]	Length [m]	Capacity	Engine
Diesel	15	15	90	Volvo D8K, 6 cylinder
CNG	14,26	14,78	87	Cummins ISLG8.9E6 (239kW)
Hybrid	12,1	12	72	Volvo D5, 210 hp

Final assembly Manufacture of the buses including final assembly, engine production and testing was taken from ecoinvent, in line with the modeling choices of Sundvor (2013). For further information about the material and energy requirements for this process, the reader is referred to the ecoinvent report about transport from the version 2.0 (Spielmann et al., 2007).

CNG buses According to Sundvor (2013), the CNG engine is made of almost the same materials as the diesel engine. The engines are therefore assumed to be similar. The only difference between the two buses is the natural gas cylinders mounted on the roof of the bus. The CNG buses in this study was modeled after a Solaris Urbino Low-entry CNG bus with six 214L CNG cylinders on the roof with associated housing (Solaris, 2014).

Hybrid buses The hybrid buses in the bus fleet are VOLVO 7000 hybrid buses (Volvo Bus Corporation, 2008, 2011).This is a parallel hybrid bus, where both the electric motor and the ICE can provide the motive power.

According to Volvo Bus Corporation (2011) the hybrid driveline consists of the following four components:

- Engine: Volvo 4 cylinder 5-litre engine producing 210hp.
- Energy storage system: Lithium-ion battery with peak power of 120kW (220kg).
- Electric motor/generator: Volvo I-SAM electric motor with maximal output of 120kW.
- Volvo I-Shift automated gearbox.

The hybrid bus is modeled by modifying the generic bus components (chassis and body) as described earlier, and adding a lithium-ion battery and electric motor separately.

As described in the theory, the hybrid driveline makes it possible to downsize the diesel engine. Comparing a hybrid vehicle to a petrol vehicle, Daimler AG (2009) found that the steel and iron content is reduced by 1% in the hybrid vehicle. The decrease in steel and iron was substituted by an equivalent increase in non-ferrous metals, light alloys and electronics. It is assumed here that the decrease in steel and iron comes exclusively from downsizing the engine. The steel and iron content in the generic bus components is thus decreased by 1% to model the hybrid bus. The increase in the other materials was assumed to come from the lithium-ion battery and the electrical drive train that were added separately.

The weight of the electrical motor was modeled after a study by Kärnä (2012), and the material composition is based on an inventory of an electrical vehicle from Notter et al. (2010). The material intensities were calculated from Notter and his colleagues' inventory and scaled linearly according to weight to the electrical motor used in the hybrid bus. Process energy for the production of the materials was added with the use of ecoinvent v.2.2 processes (Ecoinvent Centre, 2010).

The lithium-ion battery has been modeled after the inventory available from Ellingsen et al. (2012). This includes both material requirements and manufacture processes. The battery is grouped into four main components: cooling system, battery cell, packaging and battery management system (BMS). According to Dahle (2015), the battery has a lifetime of approximately 5 years. There has however not been any battery replacements in the current hybrid bus fleet, so no empirical data is available on battery replacements (Krokstad, 2015a). In the literature, the lifetime of lithium-ion batteries ranges from 3 to 10 years (FTA, 2005; Aramli, 2011; Hallmark et al., 2012). In order to establish an LCI that best reflects the bus fleet in

Trondheim, a lifetime of 5 years was chosen for the lithium-ion battery. This means that the battery will need to be replaced two times during the lifetime of the bus. The effect on the results of choosing a longer battery lifetime will be tested in the sensitivity analysis.

Use

As explained earlier, the use phase includes operation of the bus and maintenance processes. The life-cycle impacts of fuel production have also been allocated to this phase.

Fuel production The diesel and hybrid buses in Trondheim are running on a mix of biodiesel and diesel, which varies with the season. According to Nettbuss (Sætertrø, 2015), the biodiesel is 100% rape seed oil imported from Europe. The diesel is a low-sulfur diesel in line with the specifications from the distributor Statoil (Statoil, 2009). LNG is produced outside of Bergen and transported by ship to Trondheim (Krokstad, 2015e). The indirect emissions caused by fuel production were modeled by the use of ecoinvent processes from version 2.2 (Ecoinvent Centre, 2010).

The fuel consumption per kilometer was provided by AtB, as well as the blend of biodiesel. The fuel use in terms of mass and energy for the different bus types can be seen in table 3.4 on the following page.

The diesel used by the bus fleet in Trondheim was assumed to be an average blend of 44% biodiesel (B44), based on information from AtB (Krokstad, 2015d). This represents a weighted average over a year, and across several operators which run the bus services on AtB's behalf. B44 will thus be the blend assumed here when comparing bus technologies.

For the analysis of the specific bus routes (4, 5, 6, 7, 9, 777) a different blend was assumed: These routes are all operated by a single operator (Nettbuss), for which the specific blend, averaged over a year, was known to be B70 (Sætertrø, 2015).

Direct emissions from operation As mentioned earlier, the emissions generated from vehicle operation can be split into exhaust emissions, or tailpipe, and non-exhaust emissions. Spielmann et al. (2007) classifies emissions further into six different groups according to their source and method for calculation of the emission factors. The same classification has been

Table 3.4.: Fuel consumption of the modeled buses in terms of energy and mass. Estimated fuel consumption from AtB (Krokstad, 2015e)

Bus type	MJ/km	kg/km		
		Diesel	Biodiesel	CNG
Diesel	15,94	0,21	0,17	
CNG	24,42			0,49
Hybrid	11,16	0,15	0,11	

used for the calculation of direct emissions in this thesis.

In order to make the direct emissions as case-specific as possible, the regulated emissions were quantified according to fuel use of the different bus types. A report by EEA and EMEP[1] written by Kouridis et al. (2014) provides an extensive emissions inventory for light and heavy-duty vehicles for the most important pollutants emitted by road vehicles. This report gives emissions coefficient per kg fuel, and are available in EU averages or country-specific emission coefficients. Swedish estimates were used as an approximate for the diesel buses in Trondheim. Minimum values are used in the calculations, which reflect an average bus fleet in 2005, before the Euro 4 standard was implemented. As the current bus fleet in Trondheim complies with the Euro 5 standards, this might lead to an overestimation of the emissions. An increase in regulated emissions will be tested in the sensitivity analysis.

The direct emissions from operation of the hybrid bus were calculated with the same emission coefficients per kg fuel combusted as the diesel bus. The difference in direct emissions between the two bus types comes therefore solely from the reduction in fuel consumption. Some of the previous studies have reported decreases in emissions beyond the improved fuel economy, but this was neglected here. The impact of changing the most affected pollutants will be tested in the sensitivity analysis.

The fuel dependent emissions for the on road bus were taken from the same report, but assuming an European average. Emissions of lead, ammonia and sulfur dioxide are negligible for the CNG bus. (Kouridis et al., 2014; Transeoceanenergy.com, 2015).

Non-exhaust emissions from tire abrasion and road wear were taken from ecoinvent and scaled linearly according to the weight of the buses (Spielmann et al., 2007).

All emission coefficients and their respective sources and calculation method can be found

[1] EEA is short for the European Environmental Agency. The abbreviation EMEP stands for The European Monitoring and Evaluation Programme

in appendix B.1

Bus Maintenance

The maintenance process includes both energy use for the service garages, materials required for replacement of bus hardware, and replacement of liquids during the lifetime of the bus. Two service garages in Trondheim provided empirical data for the maintenance activities. They were asked about the regular service checks, liquids and bus components replacements. The service garages could not give an estimate for their energy use throughout the year, but a study by the Western Norwegian Research Institute provided the energy use per hour of service for a service garage in Sogn (Simonsen, 2012b).

For both diesel and CNG buses, MAN Truck and Bus in Trondheim perform regular service checks. According to Mjøen (2015), the CNG buses have regular service checks every 30 000km, or approximately twice a year. The service check is 16 hours each time. This adds up to 32 hours a year, which is much lower than the estimate by Simonsen (2012b) of 150 hours per year. The difference can be explained by age of the CNG buses. The buses are less than 5 years old, and might not have required replacement of any major bus components yet. Other specifications for the maintenance of CNG buses can be seen in table X.

The hybrid buses have regular service checks at Wist Last and bus, which estimates the yearly average of maintenance per bus to 45hours (Dahle, 2015). This estimate has also been used for diesel buses, even though it might lead to underestimation of the energy use due to less wear on hybrid buses. In addition to the yearly check-ups, the lithium-ion battery is replaced two times during the lifetime of the hybrid bus. According to Dahle (2015), it takes 2 hours to replace the battery in the bus. Other requirements besides the new battery are not discussed in the literature.

Tires are changed with a frequency of 55 000 kilometers for all buses (Krokstad, 2015f).This corresponds to a total of 18 times replacement of tires with a lifetime of 1 000 000 kilometer. Replacement of other bus hardware, as well as water consumption associated with the maintenance process, was modeled by the use of ecoinvent processes (Spielmann et al., 2007). This includes steel used in oil filters, brake shoes and exhaust treatment. According to Mjøen (2015), other components that need to be replaced during the vehicle's lifetime include shock absorbers, bushings and brake discs. The frequency of these replacements will however vary

Table 3.5.: Assumptions made for calculation of the maintenance requirements

	Frequency	Bus type	Reference
Engine lubricating oil	30 000km	CNG & Diesel	a
Gear box, lubricating oil	Every 4.y	CNG & Diesel	a
Coolant	Every 3. y	CNG & Diesel	a
Diesel filter	2 times/year	CNG & Diesel	a
Brake pads	n.a	CNG & Diesel	a
Service hours /bus/year	32 h	CNG	a
Engine lubricating oil	25 000km	Hybrid	b
Gear box, lubricating oil	180 000km	Hybrid	b
Coolant	Every 2.year	Hybrid	b
Diesel filter	Once a year	Hybrid	b
Brake pads	400 000km	Hybrid	b
Service hours /bus/year	45 h	Diesel & Hybrid	b
Battery lifetime	5 y	Hybrid	b
Hours/battery replacement	2,5 h	Hybrid	b

a = Mjøen, Man Truck and Bus (2015) ,
b = Dahle, Wist Last and Bus (2015)

greatly depending on the bus route and driving pattern. Due to lack of data on replacement the maintenance of these components have been omitted. It is however expected that the omissions of these processes have minor impacts on the life cycle environmental performance of the buses.

End of Life

After 15 years, or operation of 1 000 000km, the buses are assumed to be scrapped. EOL treatment of bus components is based on ecoinvent v2.0(Spielmann et al., 2007). All metals are assumed fully recycled, outside the scope of this study. For the rest of the bus materials a full disposal is assumed.

According to Sundvor (2013), the lifetime of the CNG cylinders range beyond the lifetime of the bus and are thus not replaced in the bus' lifetime. When reaching the end of life of the vehicle, the aluminum used in the CNG cylinders can not be recycled. The composite materials degrade the quality of the aluminum after 20 years in use and must therefore be destroyed separately from the vehicle

End of life treatment of the battery is modeled after Hawkins et al. (2013). Their LCI gives material and energy processes required per kg of battery recycled. This was scaled according to the weight of the battery in the hybrid bus. The processes included in battery treatment are dismantling of the battery components and a cryogenic shattering.

For the electrical motor, it was assumed that the metals in the electrical motor were completely recycled, outside the scope of this study. For the rest of the materials, a full disposal was assumed.

Lifetime

Since the functional unit in this analysis is 1 passenger kilometer traveled, the lifetime has been incorporated in the LCI calculations. According to Krokstad (2015e), the buses in Trondheim are estimated to have a lifetime of 15 years, or 1 000 000 kilometer. In the literature, the applied lifetimes were identified in the range of 500 000 to 1 000 000 kilometer (see chapter 2.4). The emissions per vehicle kilometer for non-operational processes are directly linked to the lifetime. It is therefore expected that changes in lifetime will have a significant impact on the LCA results and thus will be tested in the sensitivity analysis.

3.2.3. Omissions

Construction and maintenance of road infrastructure is not included. Even though Chester (2008) found that such non-operational processes have a significant impact on total life-cycle emissions of passenger transportation, it has been defined outside of the scope of this thesis due to time constraints.

3.2.4. Passenger Load

In order to compare the carbon footprint of passenger transportation by bus and car, the number of passengers must be considered. Buses have on average a higher environmental impact per vehicle kilometer than private vehicles because of larger engines, higher weight and more frequent starts and stops. On the other hand, buses also have a higher capacity of transporting passengers than cars.

The passenger load is a measure of the utilization of the passenger capacity in the bus. The load factor can be defined by either the seating capacity in the bus, or both the seating and standing capacity. For the purpose of this study, passenger load refers to the total capacity, i.e. both sitting and standing capacity is taken into account. This is reasonable since the buses considered are city buses, which are expected to utilize the full capacity during rush hours. The passenger load is calculated as follows

$$\text{Passenger load} = \frac{Pkm}{Ckm} \tag{3.1}$$

Where:

Pkm = Passenger kilometers traveled per year

CKm = Capacity kilometers traveled per year

Passenger kilometers are calculated by multiplying the yearly amount of passengers by the average distance traveled by each passenger. Passengers are embarking and disembarking the bus at different stop, which makes it hard to estimate the travel distance of passengers. AtB assumes an average of 6 kilometer per passenger in their own calculations (Krokstad, 2015f). According to SSB (2014), the estimated travel distance per passenger in Trondheim is however 7 kilometers. By comparing the average passenger load for Trondheim from own calculations to the statistical data from SSB, it turned out that the travel distance from SSB offered a better approximation of the average passenger load. The distance of 7 kilometers was therefore chosen as the average distance.

Capacity kilometers were calculated by a weighted average of the different bus types and their respective capacities. The yearly average of operation by the different bus types can be seen in table 3.6. Afterwards, the average capacity of each bus service was multiplied with the total yearly vehicle kilometer traveled.

Table 3.6.: Calculated Pkm, Ckm and passenger loads

Bus number	Pkm	Ckm	Passenger load
4	1,57E+07	7,49E+07	21,02 %
5	2,44E+07	7,73E+07	31,55 %
6	1,22E+07	7,39E+07	16,51 %
7	8,38E+06	4,71E+07	17,78 %
9	1,67E+07	7,10E+07	23,58 %
777	1,31E+05	1,70E+06	7,67 %
75	9,35E+05	1,67E+07	5,61 %

3.2.5. Impact assessment

A range of environmental impact categories can be covered in an LCA. For this assessment, the ReciPe method by Goedkoop et al. (2009) has been used to classify the emissions and quantify their environmental impacts. All the environmental impact categories included in the ReCiPe method has been calculated, but only those relevant to the purpose of this thesis are presented. Global warming potential (GWP), expressed in kg CO_2-equivalents (CO_2-eq) is chosen as an indicator for the carbon footprint. In addition, other impact categories has been chosen for comparison of the environmental performance of the different bus types. The production of biodiesel and the lithium-ion battery for the hybrid bus may cause other environmental impacts that are not reflected in GWP. For this reason, the study also includes marine and freshwater eutrophication, fossil depletion and terrestrial acidification. The use of CNG buses is promoted to reduce the local pollution problems in urban areas. The impact on particulate matter formation is therefore also included.

3.2.6. Comparison to private vehicles

As stated in the introduction, the bus routes were compared to private vehicles in terms of kg CO_2-equivalents per passenger kilometer. The car fleet in Trondheim consists of 52%diesel cars, 46 % petrol cars and 2 % electric vehicles (EV)(SSB, 2015).

Documentation of the data and their respective sources can be found in table 3.7

A report by Vå gane (2009) provided the average passenger load for a car in Trondheim. In 2009 there was on average 1,62 persons in a car, including all types of travels. Kg CO_2 equivalents per passenger kilometer were calculated for each passenger car. The average car used

Table 3.7.: Overview of the emission coefficients used in the comparison between cars and buses. All values in kg CO_2-equivalents per vehicle kilometer. A lifetime of 150 000km is assumed for all fuel technologies according to Hawkins et al. (2013).

	Production	Use	EOL	Assumptions	References
Diesel	0,043	0,21	0,0034		a,b
Petrol	0,043	0,23	0,0034		a,b
EV	0,091	0,0053	0,091	0,10 kWh/km NO electricity mix	a, b

a =Ecoinvent Centre (2010), b = Hawkins et al. (2013)

in the comparison was then constructed by calculating the weighted average according to the share of fuel technology in the car fleet.

3.2.7. Carbon footprint of work travels in Trondheim

Calculations/data

One of the goals of the partnership Greener Trondheim is to decrease the passenger transportation by car, and increase the share of public transport, walking and biking. For this reason, it is interesting to investigate how the different measures have influenced the carbon footprint (CF) of passenger transportation in Trondheim. Work travels have been chosen as an indicator for passenger transportation because of their importance for dimensioning both the road infrastructure and the public transportation system. In addition, data on number of work travels and length of travel can be extracted from travel surveys. The choice of model years was based on the founding of Greener Trondheim in 2008, and the latest available data points from 2014.The carbon footprint will be calculated for the two years 2009 and 2014, and compared.

The carbon footprint in year "i" is calculated as follows:

$$CF_i = (R_{ci} * T_{ci} + R_{bi} * T_{ci}) * P_i * WT_i * D_i \tag{3.2}$$

Where:

$R_{ci,bi}$ = share of travelers by bus/car in year i

$T_{ci,bi}$ = kg CO_2-e/pkm for an average bus/car in year i

P_i = population in year i

WT_i = average number of work travels per person over 13 years in year i

D_i = Average distance to work per person over 13 years in year i

The parameters used in the calculations, and their respective references can be seen in table 3.8

Table 3.8.: Parameters used in CF of work travels

	2009	**2014**	**Reference**
Diesel car *	0,065	0,11	a,b,c
Petrol car *	0,17	0,1	a,b,c
EV *	0,0001	0,02	a,b,c
Average car *	0,23	0,22	
Diesel bus *	0,11	0,01	d
CNG bus *	0	0,08	d
Hybrid bus *	0	0,003	d
Average bus *	0,11	0,09	
Passengers/km bus	14,3	17,7	e,f,c
Passengers/km car	1,19	1,19	g
Population	141294	154073	h
WT	0,75	0,87	i,j,k
Distance (km)	5,8	6,3	i,j,k

* = kg CO2-e /pkm
a =Ecoinvent v2.2,b = Hawkins et al (2013), c = own calculations, d = See chapter 3.2.2 and 4, e = SSB (2015a), f = Krokstad (2015), g =Vågane (2009), h =SSB(2015b), i =Vågane et al (2011), j= Hjorthol et al (2014), k = Hoem (2015)

Transport modes

Travel surveys were used to determine modal split in work travels. Travel surveys are conducted by the Ministry of Transport and the national transportation agencies every four years (Avinor et al., 2015). The results are compiled both for the national and regional level. This makes it possible to assess travels surveys for Trondheim for the two model years. The survey from 2009 is publicly available, while the results from the survey in 2014 are not published yet, however they were provided through personal communication with employees in the

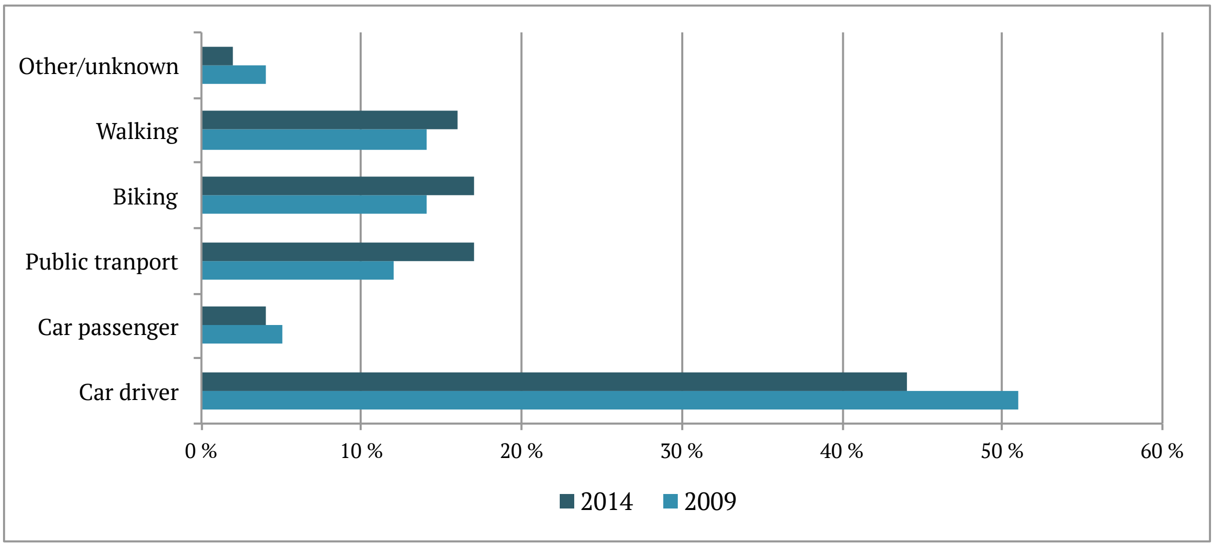

Figure 3.3.: Distribution of transportation means for work travels from the travel surveys in 2009 and 2014

Municipality of Trondheim (Hoem, 2015).

The share of transportation by car, bus, foot and bike can be seen in figure 3.3.

Buses dominate public transportation in Trondheim. There is a tram going from the city center to Byåsen, but it has been omitted in these calculations due to a low passenger volume compared to buses. Comparing the two, the tram transports only 4% of the total passenger volume (Boreal Transport Midt-Norge AS, 2015).

Travel distances

The travel surveys present the number of work travels per person over 13 years, and the average travel distance per worker. As mentioned earlier, the analysis for 2014 is not finished yet. Therefore, it was assumed that the development in Trondheim follows the development on a national level. According to the national travel surveys in 2009 and 2014, there was an increase in the amount of work travels by 16%, and an increase in the distance traveled to work by 9% (Vågane et al., 2011; Hjorthol et al., 2014). This was applied to estimate the travel distance and amount of work travels per person in 2014.

Emission coefficients

Emission coefficients are expressed in kg CO_2-equivalents per passenger kilometer. The LCA of buses performed in this study is representative for the bus fleet in Trondheim in 2014. In 2009, the bus fleet consisted of diesel buses running on regular diesel (Krokstad, 2015g). Biodiesel was not introduced to the bus fleet yet. The original diesel bus was therefore modified to represent the 2009 diesel buses.

The average car for 2014 was constructed in the same way as for the comparison with the different bus routes. For 2009, average car fleets for Europe in 2010 were used. The environmental impact of the EV was assumed to be the same for the two years.

Passenger loads

The passenger load for buses was based on total capacity kilometer and passenger kilometer for Trondheim available from Statistics Norway. Average passengers per bus was then calculated by multiplying the passenger loads by the average capacities of the bus types. The capacity in 2014 is the same as discussed earlier, while the capacity in 2009 is based on a smaller bus type from Sundvor (2013).

The previously mentioned report by Vå gane (2009)also gives the average number of passengers in a car for different types of travels. The passenger loads are also specified for work travels in Trondheim. It was assumed that the number of passengers per car has been constant, and the same numbers were applied for 2009 and 2014.

Breakdown of the change in carbon footprint of work travels

In order to allocate the change in emissions between the two years to the different factors that make up the CF– changes in travel behavior, change in technology, population growth and change in amount and distance of the work travels – an approach from input-output methodology was applied. Structural decomposition (SDA) is used in environmental input-output models to analyze the observed changes in emissions within a certain time period. There are many approaches to perform an SDA (Seibel, 2003). The starting point is however the same for all approaches: An equation where the variable of interest is written as a product of the factors causing the changes. If the analysis excludes mixed effects, and there are n factors included, there exists $n!$ different decomposition forms. According to Seibel (2003), the best approach is to calculate all possible decomposition forms and proceed by taking the average of all the changes.

For the purpose of this study average values for the factors were used to perform a decomposition analysis. This generates a residual, but so small that it is considered negligible. This method is in line with the recommendations from Seibel (2003). Choosing this approach may reduce the reliability of the results, but can still be considered a good approximation.

The parameters used in the calculations can be seen in table 3.9.

Table 3.9.: Parameters used in the SDA. See table 3.8 for references. Delta is calculated as 2009-2014.

	2009	**2014**	**Delta**
Rc	0,56	0,48	-0,08
Tc	0,23	0,22	-0,02
P	141 294	154 073	12 779
WT	0,75	0,87	0,12
D	5,80	6,34	0,54

Where:

$R_{ci,bi}$ = share of travelers by bus/car in year i

$T_{ci,bi}$ = kg CO_2-e/pkm for an average bus/car in year i

P_i = population in year i

WT_i = average number of work travels per person over 13 years in year i

D_i = Average distance to work per person over 13 years in year i

Matlab was used to perform the decomposition. The difference in the factor between the two years was used to allocate the change to that factor. For simplicity, car travels and bus travels were calculated separately and the effect from population, distance and number of work travels were added in the end.

4. Results

This chapter will present the results from the life cycle assessment and the aforementioned comparisons. First, the life cycle impacts of the three bus technologies that are modeled for this study will be presented and compared on a vehicle (vkm) and capacity kilometer (ckm) basis. The highest contribution to GHGs are evaluated in detail and elaborated further in a sensitivity analysis. Note that the diesel bus is abbreviated to B44 in this comparison according to the blend of biodiesel in the fuel.

Results based on the second functional unit will be presented afterwards. The different bus routes are also compared to different types of cars. A presentation of GHGs associated with the different bus technologies at different times during the day will also be provided.

Lastly, this chapter will present the results from the analysis of the development in CF of work travels in Trondheim. The change in emissions between 2009 and 2014 are broken down on the different factors that make up the total carbon footprint.

4.1. Environmental impact of different bus technologies

The total GHG emissions per vkm assuming a lifetime of 15 years for the three different bus types are presented in table 4.1. A breakdown of the GHG emissions is presented in figure 4.1

Table 4.1.: Total GHG emissions from the three bus types and their percentage difference from the hybrid bus

Bus type	kg CO_2-e/vkm	Difference from hybrid bus
B44	1,26	35,64%
Hybrid, B44	0,92	0%
CNG	1,75	88,47%

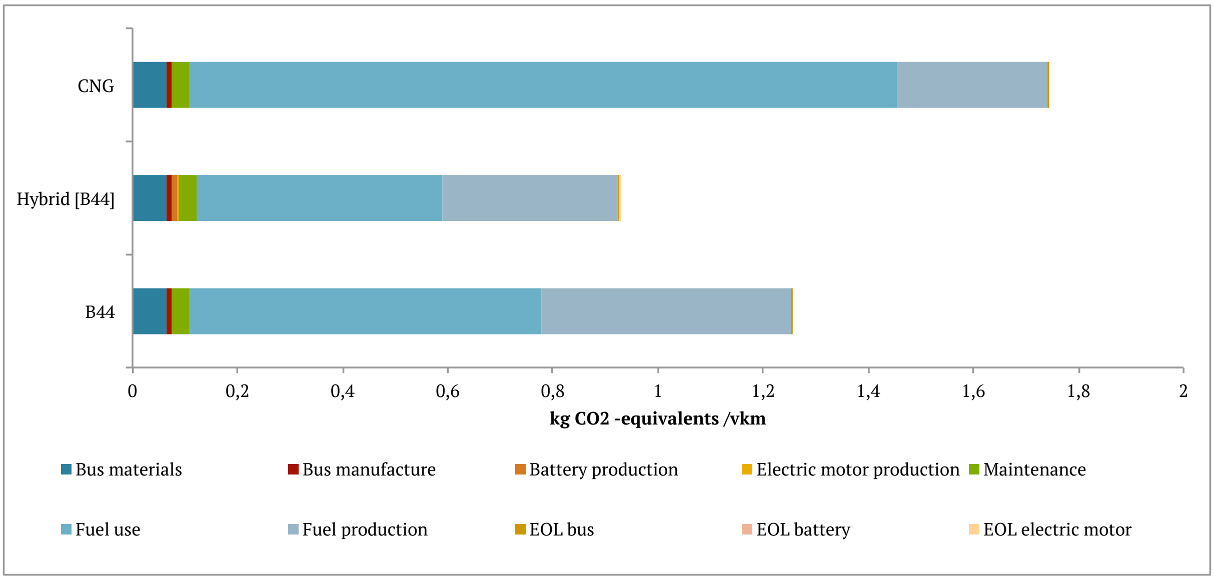

Figure 4.1.: Total GHG emissions per vehicle kilometer of the different bus and fuel technologies

The hybrid bus was found to generate the lowest total GHG emissions of the three bus types, while the CNG bus gave the highest. Emissions associated with the CNG bus are roughly 88% higher than from the hybrid bus.

The use phase, mainly operation, is the main contributor to GHG emissions for all buses, with 90-96% of total emissions. The logic behind the high emissions from the operation phase are the emissions of CO_2 from combustion of the fuel. A difference can be observed in the distribution between direct and indirect emissions from operation of the buses, where a larger share of GHG emissions comes from production of the fuel for the hybrid and B44 buses. This can be explained by the more GHG-intensive production of biodiesel than natural gas, but also by the large share of biogenic CO_2 emissions, which are assumed to have a net zero impact on global warming. Production of the buses accounts for 5-10% of total emissions among the buses. The highest share per vkm comes from hybrid buses, due to the production of the battery and the additional electronics required. The EOL treatment has minor impacts for all buses.

Normalizing the results to capacity kilometers (ckm) changes the picture slightly, as can be seen in figure 4.2. This takes into account the buses' capacity to transport passengers, which should be considered when evaluating their environmental performance. Per ckm, the hybrid bus is only slightly better than the B44 bus, because of a lower capacity. The difference from the hybrid bus is now reduced to 8,63% and 56% for the B44 and CNG buses respec-

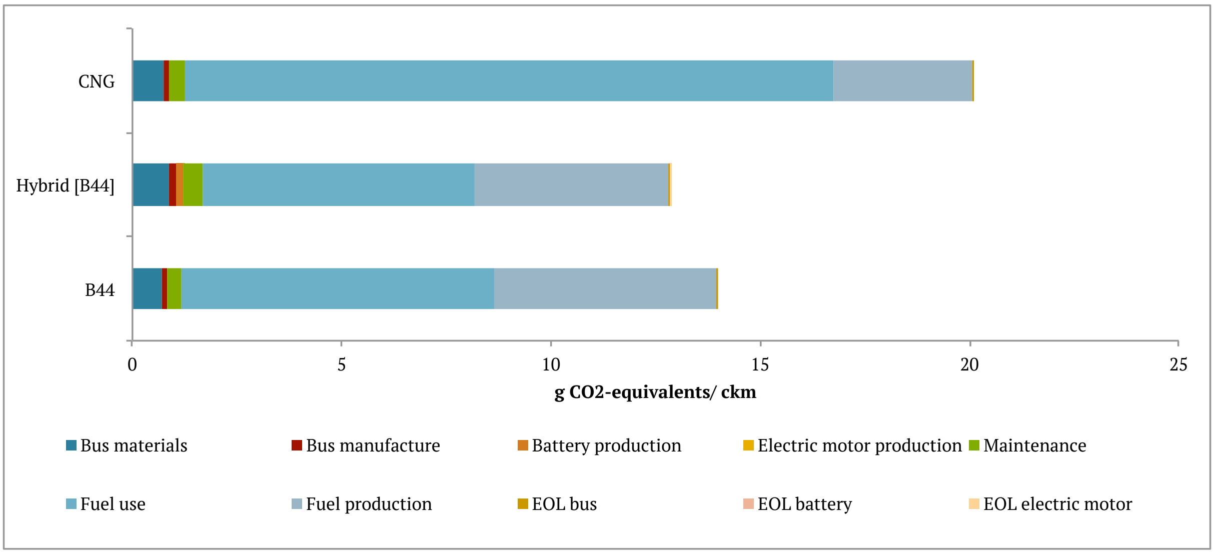

Figure 4.2.: Total GHG emissions per capacity kilometer of the different bus and fuel technologies

tively.

4.1.1. All impact categories

The total environmental impact for the three bus types is given in figure 4.3. The chosen impact categories are assessed in line with ReCiPe methodology. This figure presents a relative comparison of the different bus types. A numerical comparison will not be provided, since there is a lack of studies to compare the results to.

Figure 4.3 shows that the CNG bus has the lowest environmental impact in 5 out of 7 impact categories. This includes agricultural land occupation, freshwater and marine eutrophication, particulate matter formation and terrestrial acidification. In the two other impact categories, the hybrid bus has the lowest environmental impacts. The B44 bus has the highest impact in 5 out of 7 categories.

As can be seen in figure 4.4, the operation phase is responsible for the majority of impacts across all categories. The exceptions are freshwater eutrophication and agricultural land transformation. In freshwater eutrophication, the production of bus materials contributes with the highest impacts, mainly because of primary copper causing leaching of phosphorus from the disposal of sulfidic tailings. Copper is also used to produce the lithium-ion battery for the hybrid bus.

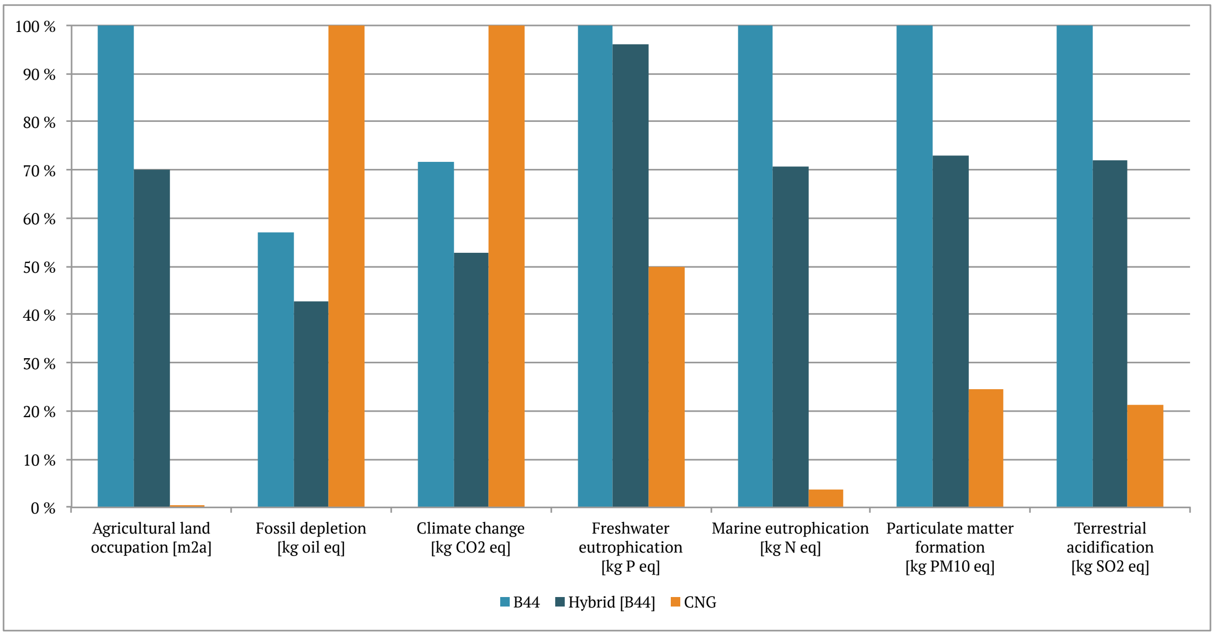

Figure 4.3.: Total environmental impact of the different bus types. The impacts are shown relative to the maximum impact in each category.

The impacts on agricultural land occupation for the CNG bus are almost evenly distributed between the different life cycle phases. Production of the bus materials and maintenance have the highest impacts, mainly because of the synthetic rubber used in the tires.

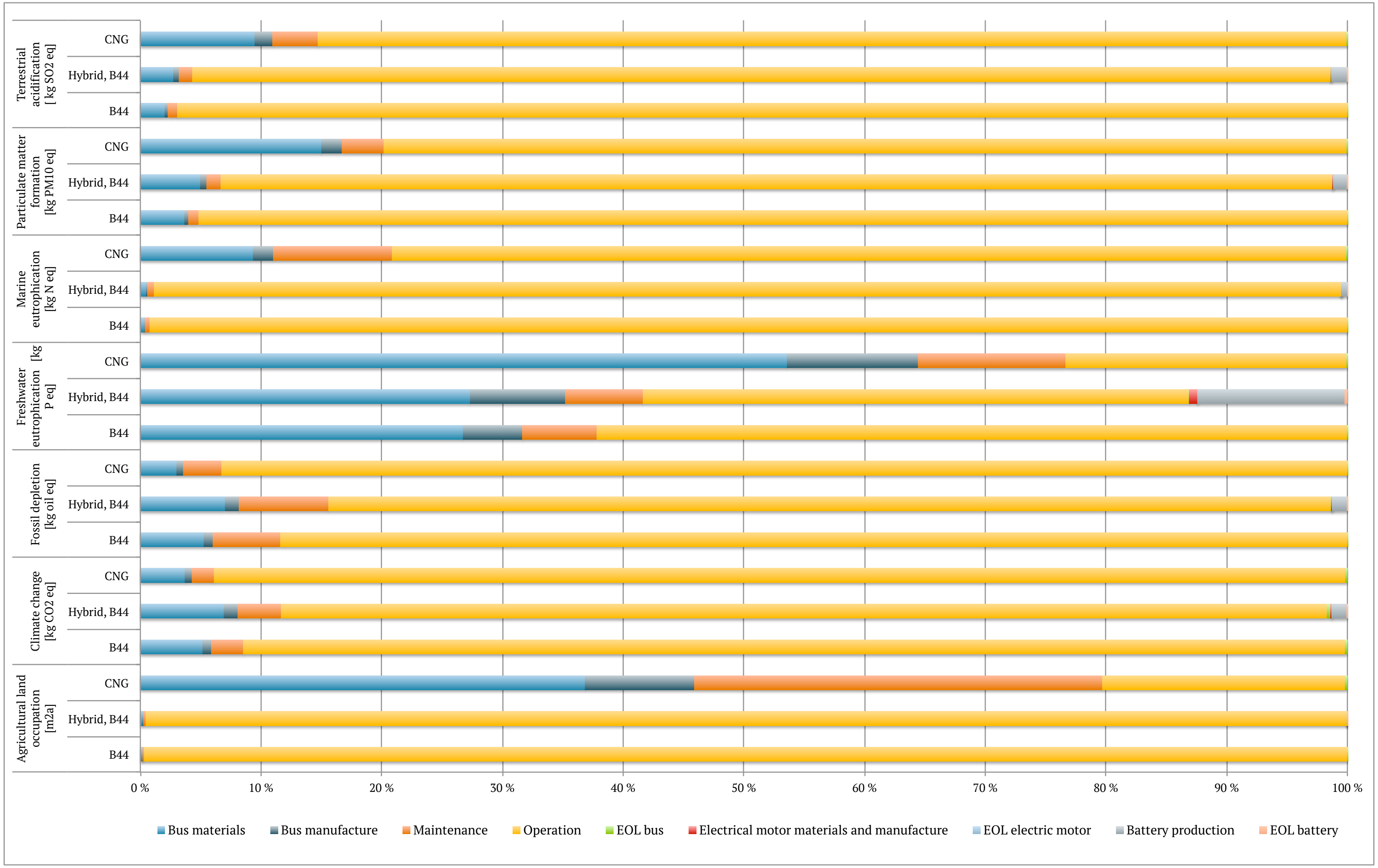

Figure 4.4.: The relative contribution of the different life cycle phases to the respective impact categories for the three bus types

4.2. Carbon footprint of different bus routes

The GHG emissions per pkm from the different bus routes can be seen in table 4.2. Note that the Nettbuss bus fleet runs on an average of B70 throughout the year, as opposed to the assumed average B44 in Trondheim. Bus routes 4,5,6,9 and 777 are driven by B70 and CNG buses, while 7 and 75 are operated by hybrid and CNG buses.

Table 4.2.: Overview of the calculated passengers per km for the different bus routes, and the corresponding GHGs per passenger kilometer

Bus number	Passenger load	g CO_2-e/pkm
4	21	73,34
5	28	54,94
6	14	104,94
7	13	63,08
9	21	73,50
777	7	225,86
75	5	358,58

Bus route 5 has the lowest impact on a per pkm basis. This bus route is the only route in Trondheim today that has articulated buses, which increases the capacity to transport passengers. The high passenger load and associated low carbon footprint can also be explained by the geographical location of the bus. This bus route bus goes from the city centre in Trondheim up to NTNU Dragvoll, a campus with over 10 000 students. Many students live in the city centre, which means that there is a large passenger volume to be covered by this bus route. Bus 7 has only the forth highest passenger load of the included bus routes, but still the second lowest impact because of the hybrid buses. Bus 777 and 75 have the highest emissions of GHG per pkm, because of few passengers. These bus routes are also mainly operated by CNG buses, which was found to have the highest impact per ckm of the modeled bus types.

4.3. Comparison to other means of transportation

The bus routes were compared to different types of cars in terms of GHG emissions per pkm. The comparison can be seen in figure 4.5.

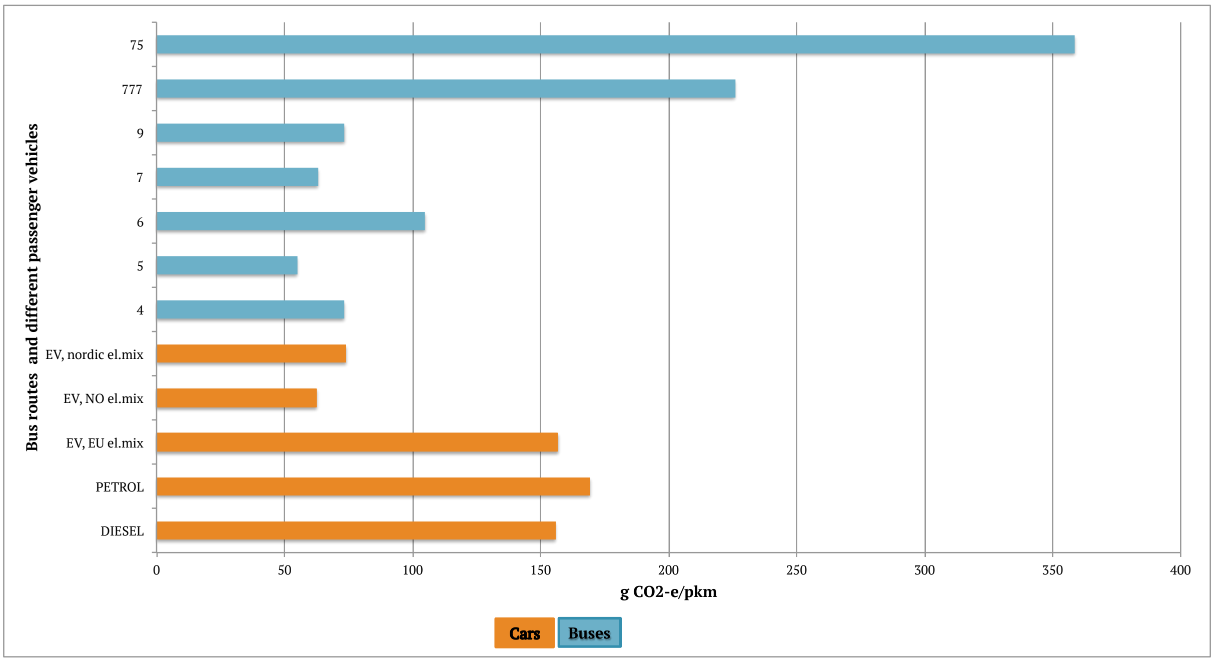

Figure 4.5.: Comparison of the included bus routes and different types of cars.

Figure 4.5 shows a comparison of the different bus rotes to the different types of cars that are included in the car fleet in Trondheim. As there is no consensus on which electricity mix that should be used for LCA studies in Norway, the GHG emissions for the EV is shown for a Norwegian, Nordic and European electricity mix. With a Norwegian electricity mix, only bus 5 and 7 outperform the EV. The EVs however only constitute 2% of the car fleet in Trondheim, so it is more likely that a person drives a diesel or petrol car. Comparing the bus routes to the petrol and diesel car with an average of 1,62 persons, 5 of the 7 included bus routes have lower impacts than the car. This is further emphasized in figure 4.6 where the difference between an average car and the bus routes is calculated.

The environmental performance of the different bus routes compared to an average car follows the same pattern as presented in section 4.2. Bus routes 4,5,6,7 and 9 have lower GHG emissions per pkm, whereas 7 and 777 have higher GHG emissions than an average car in Trondheim per pkm. Route number 777 generates 63,7g CO_2 equivalents more than the average car, while the emissions for bus route 75 are three times larger than the car.

The passenger loads presented in table 4.2 are averages per kilometer. There is however a significant difference in passenger load during the day. It peaks at rush hours when people are traveling to and from work and school, and is lower during the day and at night. AtB has made a rough estimation of the average passenger load during the day based on historical

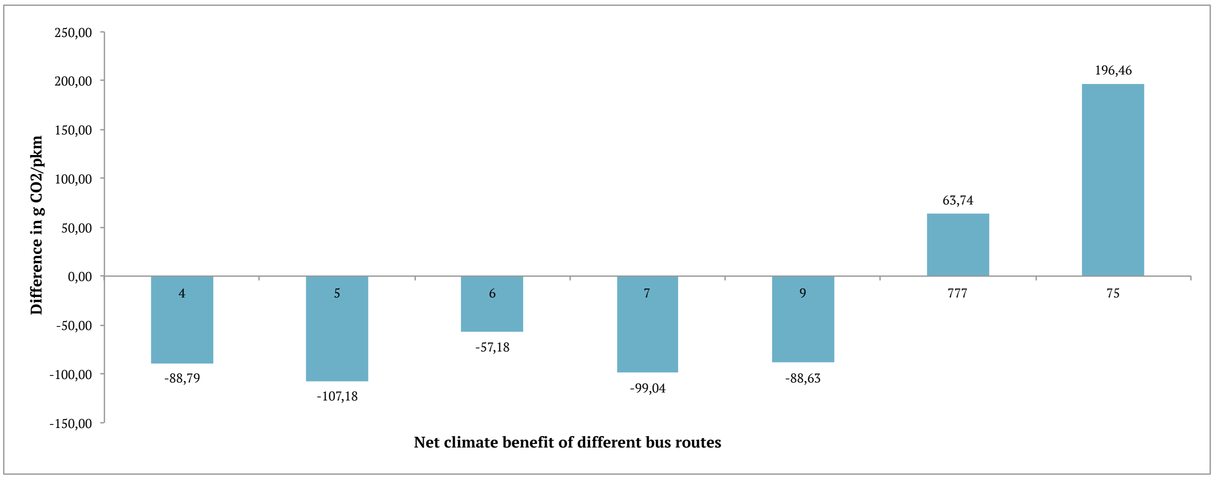

Figure 4.6.: The evaluated bus routes compared to an average car in terms of kg CO_2-eq per pkm. The net climate benefit is calculated as follows: $CF/pkm_{bus\ route}$ - CF/pkm_{car}

figures. The distribution of passengers during the day can be found in appendix C.3. GHG emissions of bus transport per pkm, compared to a car, can be seen in figure 4.7.

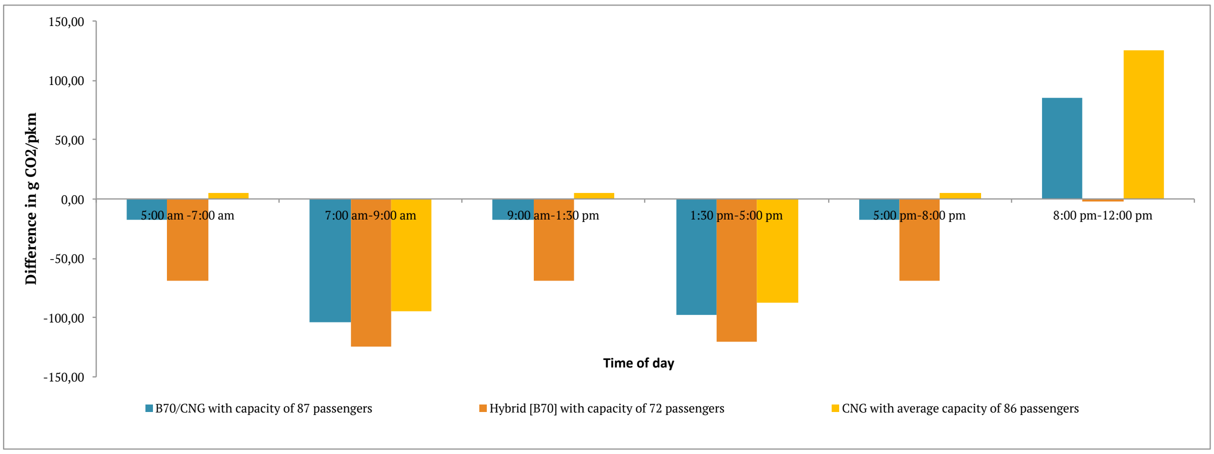

Figure 4.7.: GHG emissions of bus transport according to varying passenger loads during the day. The results are presented as the difference from a car, calculated as CF/pkm_{bus} - CF/pkm_{car}

The effect of variable passenger loads during the day are not presented for each bus route. Since the passenger loads are average, and not related to a specific bus route, presenting results per bus route would be confusing. The comparison is therefore rather based on the what bus and fuel technologies are included in the different bus routes: Bus routes 4,5,6,9 and 777 have an average of 28% B65 and 62% CNG, while 7 have only hybrid buses and 75 are operated only by CNG buses.

Comparing the passenger loads during the day, the B65/CNG bus and the hybrid bus performs better than the average car from 5:00AM to 8:00PM. After 8:00PM, the hybrid bus has lower emissions, but the mix of B65 and CNG has not. The CNG bus with a capacity of 86 passengers has lower emissions than the car only during rush hours.

4.4. Carbon footprint of work travels in Trondheim

This section presents the results from the calculation of the CF of work travels in Trondheim. The carbon footprint is calculated for one year, assuming an average of 230 work days. The CF of work travels in 2009 and 2014 can be seen in table 4.3, distributed on car and bus travels. The CF was calculated with two assumptions for the distance to work and the number of work travels per day. CF1 assumes the same relative change in the number of work travels per person per day (WT) and distance traveled to work (D) as the national travel surveys. CF2 assumes constant WT and D. The background for assuming a constant WT and D is based on the strategy for compact city development in Trondheim, passed in 2007 (Trondheim kommune, 2007). With a more compact city centre, it is likely that the parameters WT and D have not changed for Trondheim.

Table 4.3.: The CF (ton CO_2- eq/year) of work travels in Trondheim in 2009 and 2014. Delta is calculated as CF_{2014}-CF_{2009}

	2009			**2014**			**Delta**
	Total	%Car	%Bus	**Total**	%Car	%Bus	
CF1	20 199	91%	9%	23 545	87%	13%	3347
CF2	20 199	91%	9%	18 546	87%	13%	-1653

It can be seen from table 4.3 that car travels by far make up the major part of the CF for both years. The relative share of car travels is however different in 2009 and 2014. Due to a modal shift from car to bus, the share of car travels of the total CF has decreased from 91% to 87%.

As it was described in the method chapter, the CF is built up of a number of factors, all of which have changed from 2009 to 2014 (see table 3.9). There has been a modal shift from car transport to public transport, biking and walking for the work travels. Between the two years, technology advancements have also contributed to reduce the emissions per individual car and bus. At the same time, the population in Trondheim has increased, and for CF1 it was also assumed an increase in the number of work travels per day per person and distance to

Figure 4.8.: Breakdown of the changes in carbon footprint of work travels from 2009 to 2014, by contributing factors. Rc = share of car travels, Rb = share of bus travels, Tc = kg CO_2-eq/pkm car, Tb = kg CO_2-eq/pkm bus, WT = number of work travels in one day, D = average distance per work travel per person, P = population. The difference in CF between the two years can be seen to the right in the figure.

work. How much of the change in CF that can be allocated to each of these parameters can be seen in figure 4.8.

Which of the factors that are responsible for the majority of the changes, varies with the assumptions of the development in WT and D. The increase in the number of work travels per day has the highest impact on the change in CF1. The modal shift from car to bus, as well as technology advancements changes CF in the opposite direction, but is not sufficient to offset the increased total travel distance per day.

Assuming constant WT and D, lead to an improvement in CF2 between 2009 and 2014. From figure 4.8 it can then be seen that most of the changes can be allocated to the modal shift, or in other words, a decrease in traffic volume. This shows that the largest reductions in work travels can be achieved by a shift to more efficient transport modes. Some reductions can be observed by the improved technology, however it takes more time to reduce emissions in this way. For instance, EVs still only constitute 2% of the total vehicle fleet despite political measures that give incentives to purchase an EV in Norway (Miljøverndepartementet, 2012). The relative importance of technology advancements and modal shifts will be further elaborated in section 5.3.2

4.5. Sensitivity Analysis

A sensitivity analysis was performed to test the influence of changing key parameters. The sensitivity analysis is performed by changing one parameter at a time by an increment of 10%. Both an increase and decrease by 10% was tested to ensure that the model produced similar results for changes in either direction. Only the results for a 10% increase in the parameters will be shown here. The choice of parameters is based on the associated uncertainty that was identified in the LCI modeling. The sensitivity analysis will be presented separately for each of the three bus types.

4.5.1. B44 bus

The results from the traditional sensitivity analysis of the B44 bus is presented in figure 4.9. Figure 4.9 shows that the LCA results are most sensitive to changes in total fuel use and increased share of biodiesel in the fuel. An increase in fuel use increases the impact in 4 out of the 7 categories by the same percentage as the initial increase. This makes sense since many of the pollutants that affects these impact categories are based on the fuel consumption. Increasing the share of biodiesel will however increase the impact on agricultural land occupation and marine eutrophication by more than 10%. The increased demand of 10% increases the impact on agricultural land occupation by more than 25%. The impact on marine eutrophication follows the same pattern due to the increased fertilizer use.

Increasing direct fossil CO_2 emissions, NO_x emissions and lifetime have smaller, yet significant effects on the included impact categories.

NO_x emissions have a significant impact on the formation of particulate matter and the acidity of the soil. As explained in the theory chapter, combustion of biodiesel may increase the emissions by NO_x. In some cases, the increase was up to 20%. Due to the considerable share of biodiesel in the fuel, there is a significant uncertainty associated with this parameter.

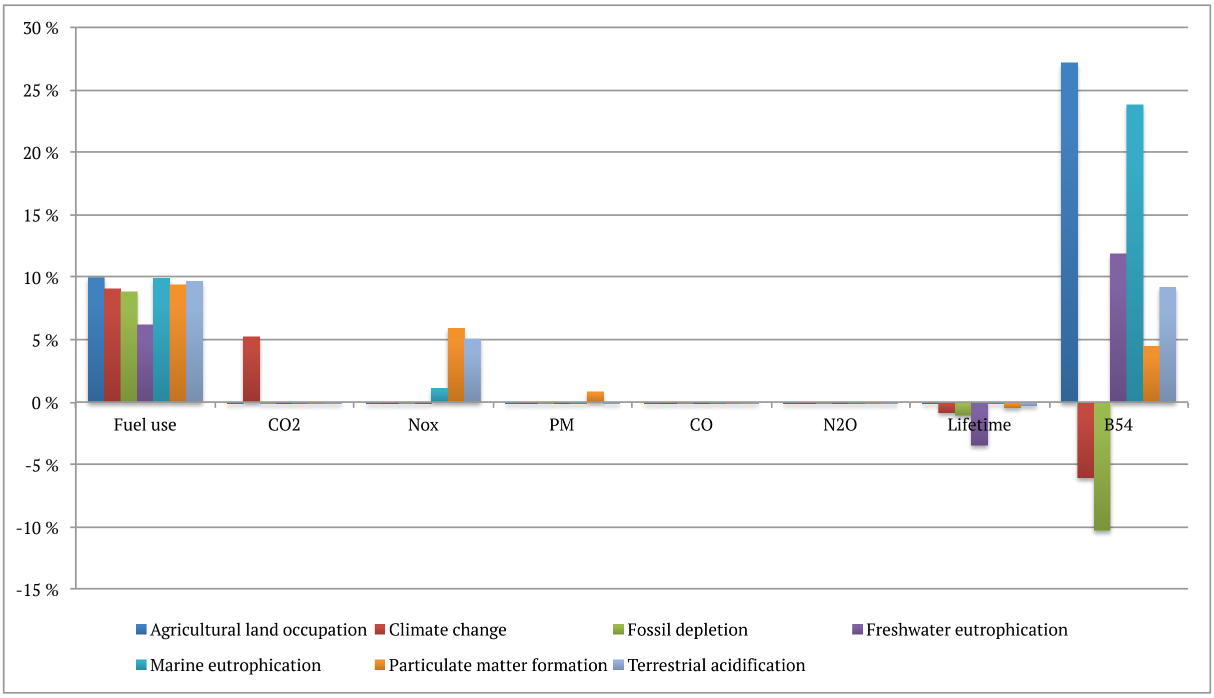

Figure 4.9.: Sensitivity analysis of B44 buses per vehicle kilometer. Every parameter is changed by 10%. CO2, NO_x, PM, CO and N2O refers to changes in the direct emissions from the operation of the bus.

Increasing the lifetime affects the relative contribution of the non-operational processes in the LCA results. An increase of 10% corresponds to an increase in lifetime of 100 000 km. The literature however identified lifetimes with a range of 500 000 km. Two additional lifetime scenarios were therefore tested: 500 000km and 800 000km. The results can be seen in table 4.6 and 4.7.

4.5.2. Hybrid bus

Figure 4.10 shows the results from the sensitivity analysis of the hybrid bus. The sensitivity of fuel use, direct emissions, lifetime and share of biodiesel follow the same pattern as for the B44 bus. These will therefore not be elaborated further. Two additional parameters associated with the modeling of the battery were tested for the hybrid bus. First of all, the a large variation in battery lifetime was found in the literature. It can be seen that changing battery lifetime (decreasing frequency of replacements) has minor environmental impacts. Increasing lifetime by 10% corresponds to a total lifetime of 5,5 years, while the lithium-ion battery can last up to 10 years.

An increase in battery mass was also tested. As can be seen in figure 4.10, this causes minor

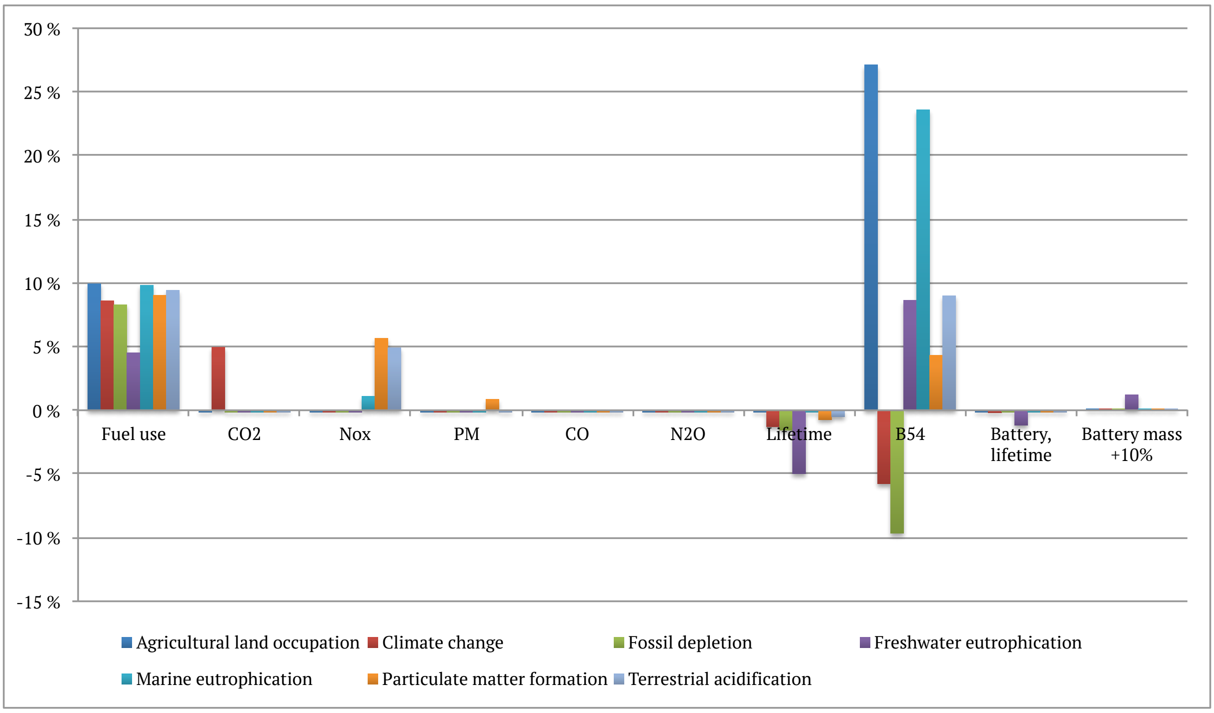

Figure 4.10.: Sensitivity analysis of hybrid buses per vehicle kilometer. Every parameter is changed by 10%. CO2, NO_x, PM, CO and N2O refers to changes in the direct emissions from the operation of the bus.

changes in the results.

4.5.3. CNG bus

Figure 4.11 shows that the LCA results for the CNG bus are most sensitive to changes in total fuel use, direct CO_2 and NO_x emissions, and lifetime. Changes in PM, CO and CH_4 emissions have not been found to significantly impact the results. This may however be explained by small initial values. An increase of 10% is then not sufficient to alter the results.

Increase in fuel use per kilometer mainly influences GHG emissions, but the other impact categories are also affected. Increasing the direct NO_x emissions have a significant impact on particulate matter formation, marine eutrophication and acidification. The relative change in environmental impact is higher than for the B44 and hybrid buses, because NO_x emissions mainly are direct for the CNG buses. As we saw in the contribution analysis, bus materials and manufacture contributed with a higher relative share for the CNG bus than for the other bus types. This also explains why the agricultural land occupation and freshwater eutrophication are more sensitive to changes in lifetime, since this decreases the relative

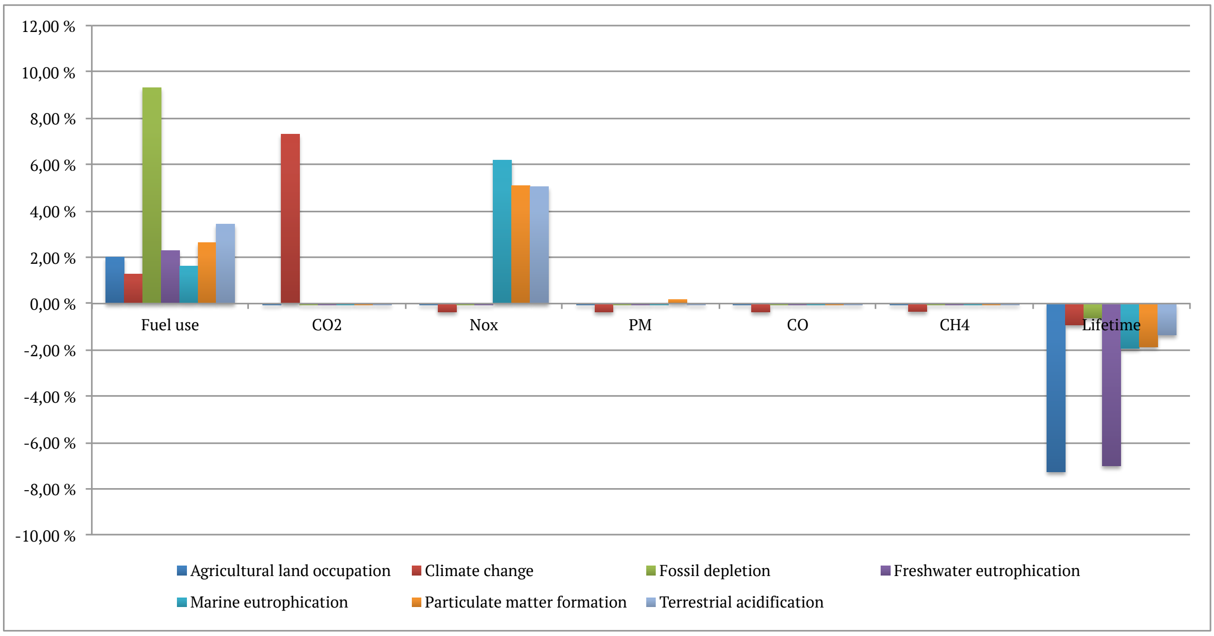

Figure 4.11.: Sensitivity analysis of CNG buses per vehicle kilometer. Every parameter is changed by 10%. CO2, NO_x, PM, CO and CH_4 refers to changes in the direct emissions from the operation of the bus.

contribution of non-operational processes.

4.5.4. Scenario-based sensitivity analysis

Fuel type

A sensitivity analysis of the type of fuel was conducted. Biodiesel used in the B44 and hybrid buses was changed to soybean oil from Brazil and biodiesel produced from waste cooking oil. This is based on the EU average of biodiesel, which SenterNovem (2008) documented to comprise about 48% RME, 22% soybean oil, 11% palm oil, 4% sunflower seed oil and the remaining 15% was vegetable oil from biomass residues or waste oil.

Since AtB has a trial project with biogas for the CNG buses, a scenario with 50% biogas was also developed. Two types of biogas was tested: Swiss production mix and biogas from bio waste.

From table 4.4 it can be see that the results are sensitive to the type of biodiesel that is used. Using soybean methyl ester (SME) increases the impact on climate change, particulate matter formation and freshwater eutrophication. SME however represents a reduction potential in agricultural land occupation, fossil depletion, marine eutrophication and terrestrial acid-

Table 4.4.: Different fuel scenarios for biodiesel. SME=soybean methyl ester, VME = vegetable oil methyl ester, from waste cooking oil.

Impact category	B44 bus	
	SME	VME
Agricultural land occupation	-27 %	-85%
Climate change	22 %	-22 %
Fossil depletion	-4 %	-13 %
Freshwater eutrophication	34 %	-43 %
Marine eutrophication	-16 %	-75 %
Particulate matter formation	26 %	-18 %
Terrestrial acidification	-21 %	-33 %

ification. If vegetable methyl ester produced from waste cooking oil is used, reductions can be obtained in all impact categories, compared to using RME.

Table 4.5.: Different fuel scenarios for the CNG bus. MIX = biogas, production mix, BW =Biogas from bio waste.

Impact category	MIX	BW
Agricultural land occupation	-5 %	-10 %
Climate change	-37 %	-47 %
Fossil depletion	-43 %	-47 %
Freshwater eutrophication	-1 %	-12 %
Marine eutrophication	1 %	-8 %
Particulate matter formation	-6 %	-13 %
Terrestrial acidification	-4 %	-17 %

Introducing a blend of 50% biogas and 50% CNG means that the direct fossil CO_2 emissions is reduced according to the share of biogas. Due to indirect emissions associated with the production of biogas, the impact on climate change is not reduced by the same percentage. From table 4.5 it can be seen that the largest reduction potential comes from using biogas produced from bio waste. This might be explained by the large share of biogas from sewage sludge in the production mix, which has a lower energy content than bio waste and contains more heavy metals that must be treated (Carlsson and Uldal, 2009).

Lifetime scenarios

In line with findings in literature, lifetime was reduced to 800 000 and 500 000 km. Table 4.6 and 4.7 shows the effect on both the non-operational processes, as well as the change in total life cycle-impacts.

Table 4.6.: Lifetime reduced to 800 000. The effect on non-operational processes (production, maintenance and EOL), as well as the total effect is shown.

Impact category	Non-operational processes	Total
Agricultural land occupation	25 %	0%
Climate change	25 %	2%
Fossil depletion	25 %	3%
Freshwater eutrophication	25 %	9 %
Marine eutrophication	25 %	0 %
Particulate matter formation	25 %	1 %
Terrestrial acidification	25 %	1 %

It was found the impacts from non-operational processes (production, maintenance and EOL) increase linearly according to the reduction in lifetime. I.e. reducing the lifetime by 25% (to 800 000km), increases the impacts from production of the bus components, maintenance processes and EOL treatment by the same size. The total increase, when including the operation of the bus, is however smaller because of the long lifetime of the bus. Decreasing the lifetime to 800 000 km increases the total environmental impacts by 0-9% across the categories. Decreasing the lifetime by 50% increases total impacts by 0-38%.

Table 4.7.: Lifetime reduced to 500 000. The effect on non-operational processes (production, maintenance and EOL), as well as the total effect is shown.

Impact category	Non-operational processes	Total
Agricultural land occupation	100 %	0%
Climate change	100 %	9%
Fossil depletion	100 %	12 %
Freshwater eutrophication	100 %	38 %
Marine eutrophication	100 %	1 %
Particulate matter formation	100 %	5 %
Terrestrial acidification	100 %	3 %

Note: The lifetime scenarios are only performed for the B44 bus. The hybrid bus follows the same pattern, but as we saw from the traditional sensitivity analysis of the CNG bus, it is likely that total impacts will increase more for the CNG bus.

Note 2:An additional scenario related to energy use in the maintenance process was carried out, but has been left out of the results section because they caused small variations in the initial results. The results can be found in appendix C.4.

5. Discussion

This chapter will discuss the main findings, which were presented in the previous chapter. Moreover, the chapter will aim to answer the research questions outlined in the introduction (see section 1.3). The main findings and the correspondence with literature will be discussed first, followed by a comprehensive discussion of the uncertainty associated with modeling choices and key parameters. The last section of the discussion will elaborate on the overall benefits of this thesis, and how the results can provide support for policy decisions in Trondheim.

In the end, this chapter will also suggest potential improvements and give recommendations for further development of the work carried out in this thesis.

5.1. Main findings and correspondence with literature

This subchapter will discuss the results in the same structure as they were presented in the previous chapter. Two of the bus types are assumed to run on a blend of biodiesel and low sulfur diesel equal to B44 (44% share of biodiesel). None of the previous studies reviewed in section 2.4 included buses with this biodiesel blend. The results will therefore be compared to previous LCA studies of conventional diesel and hybrid buses.

5.1.1. Per vehicle kilometer

The results for the B44 bus are in line with the results from the LCA studies identified in the literature, which ranged from 1,2 (Ou et al., 2010)9 to 2,0 (Chester, 2008) kg CO_2 -eq per vkm. GHG emissions of 1,26 kg CO_2 -eq per vkm are similar to the diesel city bus in Sundvor (2013). Even though the use of biodiesel reduces direct emissions, the fuel consumption in this study is 26% higher than in Sundvor (2013). Production of biodiesel from rape crops also increases upstream emissions, compared to production of diesel. In Sundvor (2013), the indirect emissions from fuel production accounted for 16% of emissions from the operation phase, compared to 38% in this study. The higher fuel consumption, as well as the increased upstream emissions may therefore explain the similarities in results.

The hybrid bus showed results comparable to those found by Simonsen (2012c). With a B44 blend, the hybrid bus generated 0,92 kg CO_2 -eq per vkm, compared to 0,95 kg CO_2 -eq in Simonsen (2012c). The similar results are again unanticipated, since the B44 blend gives considerably lower direct GHG emissions. Indirect emissions from fuel production, as discussed above can explain this, in addition to the impacts from production of the electric drive components, i.e. the electric motor and the battery, which are not included in (Simonsen, 2012c). These two components were found to contribute to 2% of the total emissions.

The climate change impact for the CNG bus was found to be higher than all CNG buses in the literature with 1,75 kg CO_2 -eq per vkm. The results from the LCA studies was in the range of 0,96 (Simonsen, 2012c) to 1,1 (Sundvor, 2013) kg CO_2 -eq per vkm. The difference in results can be explained by a higher fuel consumption in this thesis. According to AtB, the CNG buses in use in Trondheim today has a fuel economy of 0,49kg/km, while for instance Sundvor (2013) assumed 0,3kg/km in his calculations.

5.1.2. Per passenger kilometer

The results showed that the impact per passenger kilometer varies with the difference in passenger load among the bus routes, but also to a certain extent the bus technology that is employed. The literature also showed large variations in results per passenger kilometer. With average passenger loads, the results per pkm ranged from 79 g (Sundvor, 2013) to 439 g (Chester, 2008) CO_2 -eq. Sundvor (2013) investigated the emission break-even points where the GHG emissions per pkm where similar for private and transit vehicles. With 1-2 passengers in a small subcompact car, the buses needed to have 4-9 passengers, while for a larger car, modeled by a SUV and hatchback, 3-6 passengers were required for the two transport modes to have similar emissions. In this study it was found that the similar break-even points were 9 passengers for the routes with 28% and 72% shares of B70 and CNG respectively. One more passenger needed to be added if the bus route was driven only by CNG buses. For the hybrid bus, the GHG emissions per pkm were similar to an average car with 1,62 passengers at a passenger load of 5 passengers.

The results are in the same range as those from Sundvor (2013). This is surprising, since the GHG emissions per vkm were found to be higher in this thesis, and also because Sundvor (2013) only included seating capacity in the buses in the comparison. Chester (2008) also distinguished between the impacts of bus transport at different times of the day, more specifically during peak and off-peak hours. The difference between these two periods was found to be 370g CO_2 -eq per pkm. In this thesis, results were even further disaggregated according to specific hours during the day. GHG emissions were found to vary from 122g to 220 g peak hours and night time, and 56-220 g between peak hours and during the day. The variations in emissions between peak hours and other times of the day are considerably lower than in Chester (2008). However, Chester (2008) used a hybrid-LCA results, which gave considerably higher emissions than the conventional LCA studies in the literature.

5.2. Uncertainties

Uncertainties can arise at every step of the modeling. According to PRé Consultants (2013), there are two types of uncertainty in LCA:

- **Variation in the data.** Data uncertainties can be described statistically, by a range or a standard deviation. Uncertainty arising from variation in data will not be quantified here, but the implications for the results will be discussed.
- **Model uncertainties.** When modeling a system, many subjective choices need to be taken. These choices can result in significant impacts on the results. It can be hard to quantify the effect of the assumptions, but the sensitivity analysis can be used to provide some insight.

5.2.1. Variation in data

Fuel consumption

Even though the fuel use from AtB is based on historical figures, the fuel consumption can vary greatly between the different bus routes. Frequent starts and stops increases fuel consumption, as well as increased road gradients. The sensitivity analysis showed that the results are sensitive to increases in fuel consumption. Different factors that potentially can affect the fuel consumption in the case study are discussed below.

- *Road gradients:* Joumard et al. (2007) found that the increase in fuel consumption at a positive road gradient is not offset by the reduction in fuel consumption at a negative road gradient. The buses going up to Dragvoll and Byåsen have significant inclination. The inclination from the city centre to Dragvoll is roughly 3%. According to the road gradient factors [1] given in Joumard et al. (2007), this gives an increase in NO_x and PM emissions of 65% and 30% respectively.

- *Increased number of bus stops* increases the need for acceleration. As pointed out in the theory, acceleration takes up the largest share of fuel consumption in buses. Number of bus stops per kilometer have been calculated for each bus route according to the bus schedule. It was found that the bus routes have similar driving patterns in terms of the number of stops and starts per km: From 2 to 2,4 stops per kilometer. It is not expected that significant differences between the bus routes will arise from this factor.

- *Ridership varies between bus routes.* Number of passengers vary significantly between the bus routes. Increased vehicle loading has been found to be positively correlated with fuel consumption. Simonsen (2012b) found that adding one passenger to a bus increased fuel consumption by 0,02 L per 10 kilometer on a highway. Adding this to the fuel consumption by the B44 bus corresponds to an increase of 0,44% per km. Adding 10 passengers gives an increase of 4%. This can influence the comparison between the bus routes significantly. However, this is of less concern than the difference in road gradients (Joumard et al., 2007).

- *Biodiesel has a lower energy content than conventional diesel.* Comparing the B20 bus

[1] The road gradient factors are calculated as the emissions at x % road gradient, divided by the emissions at 0% road gradient.

in Simonsen (2012c) to the diesel bus from the same study, there is a slight increase in kg CO_2 -eq. The decrease in CO_2 emissions is thus fully offset by the increased energy use due to a lower energy content in biodiesel. Biodiesel has a 13% lower calorific value than mineral fuel. But since biodiesel has a higher density, the difference in fuel consumption measured by mass is only 5-6% (Verhé et al., 2004). The lower energy content in biodiesel compared to conventional diesel has not been accounted for here, but this can potentially increase fuel consumption with high shares of biodiesel.

Other variations in data

- The share of biodiesel in the fuel varies between the different bus agencies operating the bus routes on behalf of AtB, and with the season. The bus routes included in the analysis are operated by Nettbuss, which has a higher share of biodiesel in their buses than other bus agencies in Trondheim. The share of biodiesel can impact the results significantly. The direct CO_2 emissions decreases linearly with increasing share of biodiesel. Higher share of biodiesel also decreases the depletion of fossil resources, but increases the impact on eutrophication, land occupation and acidification.
- According to Krokstad (2015g) there are some hidden statistics in the passenger counting because of the use of mobile phone tickets. Regular bus travelers will usually purchase a bus pass for one or several months which needs to be validated every time entering the bus. The hidden statistics therefore apply mostly to the occasional travelers, which take the bus every now and then. Hidden statistics can potentially increase the passenger volume and alter the comparison of GHG emissions among the bus routes. In addition, the incorrect statistics may not show the whole picture of the modal shift from car to bus transport.

5.2.2. Model uncertainties

The data is gathered from many sources, especially for the production and EOL processes. For some processes there was limited, or no data available. For this reason, many assumptions were made in modeling the LCI, which can lead to uncertainties in the results.

Materials required to produce the body and chassis of the bus were scaled linearly by weight.

This approach is effective, but not necessarily accurate. With the same approach for private vehicles, Sundvor (2013) found that the share of iron and steel in the vehicles was higher than the numbers given by industry.

Electric drive components (electric motor and battery) were upscaled from private vehicles. The same problems as mentioned above, or even higher uncertainties, can arise from this assumption.

Operation and maintenance emissions are scaled linearly with vehicle lifetime. This is most likely not accurate. Cooper et al. (2012) identified a significant correlation between the vehicle's mileage and increased NO_x emissions. It is also reasonable to assume that the demand for maintenance will increase with increased mileage.

Choice of emission factors to estimate emissions from operation

The emission factors from Kouridis et al. (2014) were averages for earlier Euro models than the bus fleet in Trondheim. As mentioned in the method chapter, this can have resulted in an overestimation of the results. Previous research have however shown that regulated emissions from operation of vehicles have not decreased in line with the limits set by the Euro standards (ICCT, 2014). ICCT (2014) showed by real-world emissions measurements that NO_x emissions from diesel vehicles had only been reduced by 40% from the Euro 3 to the Euro 6 standard, while according to the Euro standards, they should have decreased by 85%. For this reason, the average Swedish fleet can still be seen as a good approximate for the regulated emissions in the current bus fleet.

The sensitivity analysis showed that increasing direct emissions of CO_2 and NO_x have significant impacts on the results. Changes in CO, PM, CH4 and N2O did not affect the results significantly. This can be explained by small absolute values to begin with, which means than an increase of 10% will not increase their value significantly. An increase of 10% in CO_2 emissions increased the impact on climate change by 5%-8%. NO_x emissions increases the impact on marine eutrophication, particulate matter formation and terrestrial acidification by around 5% for all buses.

Using biodiesel can also affect other emissions than CO_2 , which have not been accounted for here. Verhé et al. (2004) found significant reductions in CO, HC and PM, and slightly higher emissions of NO_x. There were however large variations in the emissions of NO_x and PM. NO_x emissions were found to increase by 7-20%, whereas both reductions and increases have been observed for PM emissions. The carcinogenic content of PM emissions have however proved to be reduced, compared to mineral fuel.

The blending biodiesel and fossil diesel can also cause environmental impacts itself (Andersen, 2013). Andersen (2013) points at three possible unintended consequences of using biodiesel to reduce the environmental impacts of transportation. First, the mixing of biodiesel and diesel may increase the toxicity of the exhaust gas from the vehicles. New types of nanoparticles can also be formed in combustion of the fuel blend. This can alter the exhaust composition and make bio-blended diesel more carcinogenic than the exhaust from ordinary diesel. Finally, Andersen (2013) found that the increased use of additives to obtain the same quality as fossil fuels, increases NO_x emissions and the frequency for motor parts replacements.

Lifetime

The lifetime of the buses is uncertain. Not only are there large variations in the literature, but there is also not a lot of empirical data available on the buses in the current bus fleet since they are all relatively new. Meanwhile, the functional units in this assessment are vkm and pkm, which means that the lifetime only impacts the relative importance of the non-operational processes. If operation is not taken into account, the results changes linearly with the change in lifetime. Some differences can however be observed between the bus types. The CNG bus is more sensitive to changes in lifetime. This is not the case for the B44 and hybrid buses because the production of biodiesel has a large impact in all impact categories.

Calculation of passenger loads

The average distance traveled per passenger per bus trip was taken from Statistics Norway. It was assumed that each passenger travels on average 7 km per bus trip, while AtB assumes 6 km in their calculations. Distance traveled per passenger is important for the estimation of passenger loads for the respective bus routes. An increase or decrease in the average distance will change the passenger load in the same direction.

Uncertainties in the calculation of CF of work travels

Many assumptions had to be made when calculating the carbon footprint of work travels in Trondheim. All these assumptions may have influenced the final results.

The average passenger load for buses in Trondheim was used in the calculations. A lower or higher ridership will influence the relative share of emissions allocated to bus transport. The passenger low is usually higher at times during the day when the work travels take place.

There is also a significant uncertainty associated with the total travel distance per person per day in 2014 , since it was estimated from the relative change in the national average. As it was shown in section 4.4, this can significantly alter results, from a higher CF in 2014 compared to 2009, to a lower CF in 2014. The analysis can still give some indications of which parameters have the largest effect on the CF of passenger transportation in Trondheim, and this will be discussed in more detail in section 5.3.2

5.3. Implications for policy support in AtB and STFK

Increasing the share of public transport has been promoted as one of the measures that can help Norway achieve carbon-neutrality by 2050 (Miljøverndepartementet, 2008). As it has been stated earlier, increasing public transport is also one of the goals in the partnership Greener Trondheim. Greener Trondheim has a specific goal of a 20% reduction in GHG emissions below 1990 levels by 2018 (Trondheim kommune, 2014). The project is also targeting local air pollution.

The county council in Sør-Trøndelag has also adopted ambitious climate targets. They aim to cut CF within its own organization to 50% of 1990 levels by 2020. Bus transport is today one of the largest contributor to the CF in the organization, which means that drastic measures are required to reduce emissions within this sector.

In this thesis, I have looked at the environmental impacts of bus transport in Trondheim. The results provide a framework for policy makers and the like in order to appropriately mitigate emissions from passenger transportation.

5.3.1. Recommendations for bus and fuel technology

The results show that the operation phase (including fuel production and combustion) is responsible for the majority of environmental impacts across the bus technologies, with a few exceptions [2].These findings are in line with findings in literature. Since operation of the buses are responsible for the major share of emissions, the largest reduction potential per vkm comes from technology advancements and substituting fossil fuels, as suggested by Chester and Horvath (2009). In this subchapter the mitigation potential, in terms of environmental impacts, of the modeled fuel and bus technologies will be discussed. The mitigation potential is presented as the difference from a conventional diesel bus. This can be seen in table 5.1.

Table 5.1.: The modeled bus and fuel technologies, and their respective difference in environmental impact from a conventional diesel bus (running on low-sulfur diesel)[3]

	B44	Hybrid, B44	CNG
Agricultural land occupation	25401%	177845%	0,73%
Climate change	-18%	-40%	14%
Fossil depletion	-27%	-46%	27%
Freshwater eutrophication	77%	70%	-12%
Marine eutrophication	684%	453%	-71%
Particulate matter formation	19%	-13%	-71%
Terrestrial acidification	178%	9%	-68%

Main benefits and drawbacks of the included bus technologies

As can be seen in table 5.1, the use of biodiesel reduces the dependency on fossil fuels, as well as GHG emissions because of the carbon-neutral operation. The environmental impact from the fuel production phase is however higher, which offsets some of the initial reduction potential. The use of biodiesel generates considerable higher impacts on eutrophication, acidification and land occupation. The impact is non-linear with the share of biodiesel in the fuel. Increasing the share of biodiesel by 10%, increases the impacts on land occupation and marine eutrophication by more than 20%.

[2] In freshwater eutrophication and terrestrial acidification for the CNG bus, the production of bus materials and manufacture of the bus accounts for the major share of emissions.

Mitigation potential is also dependent on the type of biodiesel used. As we saw in the sensitivity analysis, changing to soybean oil methyl ester increases emissions, while biodiesel produced from waste cooking oil reduces the impact in all categories compared to RME. First generation biodiesel, which is used in Trondheim, has also been criticized for occupying farm land, which otherwise could be used to produce food (SenterNovem, 2008). Another negative consequence comes from the mixing of biodiesel and fossil diesel, which can increase the toxicity of the exhaust gas and emissions of NO_x.

Biodiesel is not subject to CO_2 taxes in Norway, and has reduced road taxes (Miljødirektoratet, 2015a). These measures promote the use of biodiesel in bus transport, and has made it financially feasible to introduce biofuels in the bus fleet in Trondheim(Krokstad, 2015g). The Environmental Agency in Norway emphasizes that second generation biofuels should be developed in Norway because of the larger potential reduction potential in GHG emissions, and less conflict with food production(Miljødirektoratet, 2010). To reduce the negative impacts of biofuels sustainability criteria for biofuels have been legislated in Norway. The criteria have been developed by the European Union (EU) and specifies criteria the biofuel must fulfill to be considered sustainable (Miljødirektoratet, 2013). In short, the biofuel must reduce GHG emissions by at least 35% compared to fossil fuels, considering the whole fuel chain. There are also regulations on the land used to produce food crops: Areas that are important for biodiversity or are carbon intensive can not be used. These two criteria can help reduce the negative impacts on arable land, and emissions of N_2O. The effects on eutrophication and acidification will however not be affected by the legislation.

The hybrid bus modeled in this study showed significant improvements in emissions compared to the B44 bus. The reductions are a result of improved fuel economy. Other potential reductions have not been accounted for here, but has been documented in other studies (see section 2.2). The battery pack in the hybrid bus is smaller than the lithium-ion battery in EVs. Still, the battery contribute with significant impacts in 5 out of 7 impact categories, with the highest share in freshwater eutrophication at 12,2%. The main difference between the B44 and hybrid bus is in the relative contribution from the production phase to total emissions. 9,4% of GHG emissions stem from the production phase for the hybrid bus, while the share is 6% for the B44 bus. EVs are critized for the higher upstream emissions caused by production of electronic equipment which requires a variety of metals(Hawkins et al., 2013). Previous studies have found that the production phase accounts for half of GHG emissions for an EV. The hybrid electric vehicle, on the other hand, offers improved fuel economy and lower direct emissions, without the conflicting metal depletion and substantial emissions from production.

The hybrid bus modeled in this thesis does not provide enough propulsion power for the bus routes in Trondheim with considerable inclination (such as number 5 and 9), which means that the use of this bus type in service is limited (Krokstad, 2015g). This creates uncertainty in the functional unit, as it is questionable whether the bus types fulfills the same function of transporting a passenger in Trondheim.

The CNG bus is beneficial for local air pollution problems, indicated by the lowest impact in particulate matter formation. However, this bus type showed the highest GHG emissions and fossil depletion potential. Because of a high energy use, GHG emissions are higher also compared to diesel buses (see table 5.1). However, introducing a blend of biogas has the potential to make this bus technology the overall best technology. Nonetheless, the reduction potential is dependent on the type of raw materials used in the production of the biogas, as well as the biogas production system (Börjesson and Berglund, 2006). A Swedish study of different biogas plants showed that the fuel cycle emissions could vary by a factor of 3-4 among the different biogas plants. In the sensitivity analysis, the potential reductions were illustrated by two ecoinvent processes. The biogas produced from municipal household waste showed the largest improvements compared to CNG. The ecoinvent processes do however not include upgrading of biogas to CNG quality, which can increase the upstream emissions significantly (Börjesson and Berglund, 2006). The reduction potential of biogas is case-specific, and the results from the sensitivity analysis can only provide an indication of the relative reduction.

Between the modeled bus and fuel technologies there is no single technology that stands out as the best overall technology. However, switching from CNG to biogas, or mixing biogas with CNG, can potentially make this bus type the best alternative across all environmental impacts evaluated here.

5.3.2. Increasing the share of bus travels

The passenger transport system is a complex system, which requires a combination of several measures in order to appropriately mitigate emissions. The Environmental Agency in Norway has adopted three different strategies, all of them associated with different measures, to combat emission problems (Miljødirektoratet, 2015b):

- Trigger shift to more efficient and environmentally-friendly transport modes, such as public transport, biking and walking.
- Technology advancements to decrease emissions per individual vehicle.
- Compact cities that reduce the overall need for transportation.

New and emerging technology needs to be introduced rapidly in order to realize the full potential of this measure. This can however be difficult in a short-term perspective because of the long lifetime of vehicles. The modal shift from car to bus transport, cycling and walking showed the largest reduction in the CF of work travels in this thesis (when assuming a constant travel distance to work). These results differ from the recommendations from public bodies and scenarios developed by the European Energy Agency, where technology advancements and carbon-neutral fuels showed the largest reduction potentials until 2030 (EEA, 2008; Avinor et al., 2010). This might be explained by difference in transport systems considered. While this thesis only looked at passenger transportation in urban areas, IEA and public bodies considers both urban and rural areas. Nevertheless, this shows that measures to mitigate emissions from passenger transportation must be designed according to the specific area. Nenseth and Nielsen (2009) emphasizes that cities provides the largest potential for environmentally sound transport systems, if they are developed in a way that decreases the overall need for transportation.

EEA also emphasizes the important role of modal changes to cut CO_2 emissions from the transport sector (EEA, 2008). Shifting to public transport provides other societal benefits, such as less traffic congestion and improved air quality in urban areas. It might however be hard to trigger changes in people's travel behavior, since mobility is a highly appreciated social good (Hermansen, 2011). In order to accommodate the shift to public transport and decrease dependency on cars in urban areas, combined measures are required. First of all, if sustainability come at the cost of reduced mobility, the measures will achieve little public acceptance. For instance, decreasing car travels by introducing road pricing might be hard if there in reality are no other alternatives to driving a car. This measure must therefore be combined with an improved public transport system, or improved cycling infrastructure. Hermansen (2011) also underlines the importance of building up and maintaining the trust in public transport in order for people to rely on bus service. Punctuality and better accessibility can serve as indicators for an efficient system. Statistical data have shown correlation between high share of public transport and high efficiency public transport, i.e. the time spent is similar to driving a car (Engebretsen, 2003).

Many measures are already in place in Trondheim, thanks to the partnership Greener Trondheim. Results from the travel surveys (see section 3.2.7) indicates that the measures have accommodated a shift in passenger transportation. A shift towards more environmentally sound transport modes have decrease the share of car travels by 11% within the city (Miljøpakken, 2015). The results from this thesis show that there is still room for improvement in terms of bus passenger loads. Some bus routes have a very low ridership, and in general, passenger loads are lower during the evening. The low passenger load in the evening can be explained by a smaller share of bus travels for leisure travels. This is confirmed by local travel surveys. 6,1% of the respondents used public transport for leisure travels, while the share for work travels was 17% (Hoem, 2015). According to Krokstad (2015g), AtB has increased frequency of bus service during football matches to and from the Lerkendal Stadium. Increasing this type of measures for activities after work/school hours, would give incentives to choose public transport over the car also at this time of the day. Avinor et al. (2015) also states that time-differentiated pricing should be considered for roads and public transport to mitigate congestion peaks and utilize the capacity in the transport system better over larger parts of the day.

Bus route 75 has the lowest passenger load throughout the year out of the evaluated bus routes. The lower passenger load can be explained by the low population density in Byneset, but at the same time there is no road pricing on the main road from Byneset to the city centre (SNL, 2013; Miljøpakken, 2015c). The road tax system has proven to be an effective policy instrument to reduce the traffic volume in the city centre (Miljøpakken, 2015b). Through the toll gates, the number of cars have been reduced by 20%. Linked to the discussion above, this measure must be combined with other measures, such as improved public transport, in order to be effective. However, travel surveys have shown that there is a difference in choice of transport mode outside and inside the city centre (Engebretsen, 2003). Car driving tend to be higher outside the city, where destinations are very scattered and often located outside the city center. With travels going in different directions, it is hard to offer a competitive public transport system. The result is a public transport system that only covers a small part of the travel needs of urban mobility, and corresponding low share of public transport. Gathering work places close to the city centre might be the key to increase public transport for these areas, at least for work travels.

This thesis has focused on climate mitigation potential for everyday travels, as policies are often directed towards this type of travel (Holden and Linnerud, 2011). Studies have however documented rebound effects towards increased leisure travels as a consequence to these measures. Leisure travels are responsible for half of CO_2 emissions from passenger transport, and this type of travels are increasing rapidly with increasing wealth. This shows that in order to appropriately mitigate CO2 emissions from passenger transportation, the whole system, including all type of travel, should be considered.

5.4. Recommendations for Future Work

The work carried out in this thesis can be improved and extended. The improvements related to modeling choices, as well as suggestions to how the model can be extended are listed below.

- *Modeling choices.* The fuel consumption for the B44 and hybrid buses can be converted to the energy needed, terms of MJ per km in order to account for the lower energy content in biodiesel. Linked to the discussion about uncertainty, the lower energy content increases the fuel needed to make the vehicle move forward.
- *The effect of different exhaust treatment technologies.* The theory chapter explained that reduction potential of new bus and fuel technologies are often dependent the exhaust treatment applied. The LCA model developed here can be improved and extended by looking at the effects on direct emissions by applying different exhaust treatment technologies. This would give more attention to the different technologies' potential to reduce local pollution problems, since CO_2 emissions can not be reduced by these technologies.

- *Extension of the LCA model and framework.* The life cycle framework established here can be extended by a life cycle costing analysis. As it has been discussed earlier, natural gas buses and hybrid buses are more expensive than conventional diesel buses , but they require less maintenance. By comparing the cost of a bus or fuel technology throughout the lifetime of the buses, higher purchase cost of environmentally sound technologies may even out. Monetary units often also provide better foundation for decision support.

  The travel surveys include also travels to school/university, service related travels and leisure travels. CF of passenger transportation can be developed by calculating the change in these travels as well.

  The model can also be extended by including more bus and fuel technologies, in order to provide a comprehensive LCI of the technologies available for public transport in Norway.

6. Conclusion and final remarks

The overall aim of this thesis has been to assess the carbon footprint of transport by bus in the Trondheim region. To reach this overarching goal, an LCA model was developed for the three bus technologies included in the AtB bus fleet: hybrid, biodiesel and CNG. The main focus has been GHG emissions, but the buses has also been evaluated in terms of their impact on agricultural land occupation, fossil depletion,particulate matter formation, marine and freshwater eutrophication and terrestrial acidification. All life cycle phases were included in the analysis, from production of the buses, to the use phase until EOL treatment.

The main findings show that the hybrid bus, running on a blend of biodiesel equal to B44, is the most beneficial for reducing GHG emissions and fossil depletion of the three bus technologies. Per vkm, the hybrid bus generated 0,92kg CO_2-eq during a lifetime of 15 years. In terms of CO_2-eq, the B44 and CNG buses were shown to have 35% and 88% higher emissions than the hybrid bus. Some of the mitigation potential of the hybrid bus was however offset by the use of biodiesel, because production of biodiesel causes significant impacts in the other included impact categories. For these impact categories, the CNG bus was found to have the lowest emissions. The CNG buses have proven to be effective in reducing local air pollution, indicated by the lowest impact in particulate matter formation in the LCA. By introducing a blend of 50% biogas, these buses also have the potential to become the overall best technology. Biogas produced from municipal household waste was found to reduce GHG emissions and fossil depletion by 47%, compared to a bus running on 100%CNG. Nonetheless, the reduction potential is dependent on the type of raw materials used in the production of the biogas, as well as the biogas production system.

The sensitivity analysis showed that the results for all buses were sensitive to increases in fuel consumption, which is directly linked to CO_2 emissions. The environmental impact of the biodiesel and hybrid buses are also sensitive to the share of biodiesel in the fuel, especially land occupation and eutrophication. Changing the type of biodiesel also significantly altered the results. Biodiesel produced from waste cooking oil was found to reduce GHG emissions by 22% and total environmental impacts by 13-85%, compared to RME.

Looking at specific bus routes, it was found that buses with 5-10 passengers (dependent on the bus technology) had lower GHG emissions than a car with 1-2 persons. The comparison of the two different transport modes was sensitive to the change in number of passengers on the buses, which is also documented in other studies.

Furthermore, the LCA results were also used to quantify the CF of work travels in Trondheim, to see the effect of policy measures introduced between 2009 and 2014. When assuming a constant travel distance to work between the two years, there was an improvement in the CF. The largest share of these improvements was allocated to the shift in transport modes, from car driving to increased biking, walking and public transport.

These results can provide support for future planning of the public transport system in Trondheim. Emissions reductions per vehicle kilometer can be achieved by choosing the appropriate bus technology according to the results from the LCA. However, modal shifts should be promoted in the short term to reduce the overall emissions from passenger transportation, as it can take long time to realize the full potential from technology advancement in private cars. There is also room for improvements in the current bus service, in terms of utilizing the capacity throughout the day and in bus routes with few average passengers. It might however be hard to offer a public transport system that fulfills the demand in mobility for the while population. Nonetheless, policy makers should aim at developing a sustainable transport system which does not conflict with mobility, as this is considered an important social good.

Even though the operation of the buses causes the highest environmental impacts, the indirect impacts from the production phase should not be neglected. Evaluating life cycle emissions is especially important for electric drive components. With a larger lithium-ion battery it is expected that larger share of the emissions will be attributed to the production phase. Also a decrease in lifetime of the buses will increase the relative importance of the non-operational processes. Including the whole life cycle is also important to avoid problem shifting when biofuels are used as a mean to reduce GHG emissions.

Bibliography

Ally, J. and Pryor, T. (2007). Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems. *Journal of Power Sources*, 170(2):401–411.

Andersen, O. (2013). Unintended Consequences of Renewable Energy. *Green Energy and Technology*, 140:35–45.

Aramli, M. (2011). Adding Hybrid Buses to Your Fleet. Retreived 1 April, 2015, from `http://www.masstransitmag.com/article/10256164/adding-hybrid-buses-to-your-fleet`.

AtB (2015a). Anbud. Retrieved 24 April, 2014, from `https://www.atb.no/anbud/`.

AtB (2015b). Miljø i tankene.

AtB (2015c). Rutekart Trondheim. Retrieved 3 June, 2015, from `https://www.atb.no/getfile.php/Filer/Reiseinformasjon/AtB_BY_HOVED15_kart.pdf`.

Avinor, Jernbaneverket, Klima-og forurensningsdirektoratet, fartsdirektoratet, S., and vegvesen, S. (2010). Klimakur 2020 :Sektoranalyse transport.

Avinor, Jernbaneverket, Kystverket, and vegvesen, S. (2015). Utfordringer for framtidens transportsystem. Hovedrapport fra analyse- og strategifasen.

Barth, M. and Boriboonsomsin, K. (2010). Real-World Carbon Dioxide Impacts of Traffic Congestion. *Transportation Research Record*, (2058).

Baumann, H. and Tillman, A.-M. (2004). *The hitch hiker's guide to LCA: an orientation in life cycle assessment methodology and application.* Studentlitteratur, Lund.

Boreal Transport Midt-Norge AS (2015). Gråkallbanen - Boreal Transport Midt-Norge AS - Forside. Retrieved 2 June, 2015, from `http://www.graakallbanen.no/`.

Börjesson, P. l. and Berglund, M. (2006). Environmental systems analysis of biogas systems—Part I: Fuel-cycle emissions. *Biomass and Bioenergy*, 30(5):469–485.

Brunvoll, F. and Monsrud, J. (2013). Samferdsel og miljø 2013. Utvalgte indikatorer for samferdselssektoren. Technical report, Statistics Norway.

Camobreco, V., Duffield, J., Sheehan, J., Shapouri, H., and Graboski, M. (1998). Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Final report. (May).

Carlsson, M. and Uldal, M. (2009). Substrathandbok för biogasproduktion. Technical report, Svenskt Gastekniskt Center.

Chester, M., Pincetl, S., Elizabeth, Z., Eisenstein, W., and Matute, J. (2012). Infrastructure and automobile shifts : positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. 015041.

Chester, M. V. (2008). *Life-cycle Environmental Inventory of Passenger Transportation in the United States.* Doctor of philosophy, University of California, Berkeley.

Chester, M. V. and Horvath, A. (2009). Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, 4:024008.

Chester, M. V., Horvath, A., and Madanat, S. (2010). Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions. *Atmospheric Environment*, 44(8):1071–1079.

Cooney, G. A. (2011). *Life Cycle Assessment of Diesel and Electric Public Transportation Buses.* Master thesis, Pennsylvania State University.

Cooper, E., Arioli, M., Carrigan, A., and Jain, U. (2012). Exhaust emissions of Transit buses: Sustainable Urban Transportation Fuels and Vehicles.

Dahle, R. (2015). Email correspondence. 19.05.2015.

Daimler AG (2009). Life Cycle Environmental certificate for the S400 Hybrid. Technical report.

Dieselnet (2012). Emission Standards - European Union. Retrieved 6 May, 2015, from `https://www.dieselnet.com/standards/eu/hd.php`.

Ecoinvent Centre (2010). Ecoinvent data and reports v2.2. Technical report, Swiss Centre for Life Cycle Inventories.

Ecoinvent Centre (2015). About. Retrieved 5 May, 2015, from `http://www.ecoinvent.org/about/organisation/organisation.html`.

EEA (2008). Beyond transport policy — exploring and managing the external drivers of transport demand: Illustrative case studies from Europe. Technical Report 12, Technical report no 12. Environmental Energy Agency, Copenhagen.

Ellingsen, L. A.-W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valø en, L. O., and Strømman, A. H. (2012). Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack.

Engebretsen, O. y. (2003). Byreiser. TØI rapport 677. Technical Report september, Transportøkonomisk institutt (TØI). Institute of Transport Economics Norway.

FTA (2005). Analysis of Electric Drive Technologies For Transit Applications: Battery-Electric, Hybrid-Electric and Fuel Cells. Technical report, Federal Transit Administration (FTA), U.S. Department of Transportation.

Goedkoop, M., Heijungs, R., Huijbergts, M., De Schreyver, A., Struijs, J., and Zelm, R. V. (2009). ReCiPe 2008 . Report 1 : Characterisation. Technical report, Ministry of Housing, Spatial Planning and Environment (VROM).

Hagman, R. (2002). Rene og effektive naturgassmotorer for tunge kjøretøy. TØI rapport 613. Technical report, Transportøkonomisk institutt (TØI) Institute of Transport Economics.

Hallmark, S., Wang, B., Qiu, Y., and Sperry, B. (2012). Assessing the Costs for Hybrid versus Regular Transit Buses.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., and Strømman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, 17(1):53–64.

Hermansen, E. A. (2011). How can we avoid the tragedy of the commons in the transport sector ? Technical report, CICERO - Center for Climate Research, Norway.

Hjorthol, R., Engebretsen, O. y., and Uteng, T. P. (2014). Den nasjonale reisevane undersøkelsen. Technical report, Transportøkonomisk institutt (TØI) Institute of Transport Economics.

Hoem, J. (2015). No Title.

Holden, E. and Linnerud, K. (2011). Troublesome Leisure Travel: The Contradictions of Three Sustainable Transport Policies. *Urban Studies*, 48(14):3087–3106.

ICCT (2014). Real-world emissions from modern diesel cars. Retrieved 31 May, 2015, from `http://www.theicct.org/sites/default/files/ICCT_PEMS-study_diesel-cars_2014_factsheet_EN.pdf`.

ISO (2006a). 14040:2006. Environmental managment - Life cycle assessment - Principles and framework.

ISO (2006b). ISO 14044:2006: Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

Joumard, R., André, M., Rapone, M., and Zallinger, M. (2007). Emission factor modelling and database for light vehicles - Artemis deliverable 3. 2007. <hal- 00916945>. Technical report.

Kärnä, P. (2012). *Carbon Footprint of the Raw Materials of an Urban Transit Bus.* Bachelor thesis, Lahti University of Applied Sciences.

Kouridis, C., Samaras, C., Hassel, D., Mellios, G., Mccrae, I., Zierock, K.-h., Keller, M., Rexeis, M., Andre, M., Winther, M., Pastramas, N., Gorissen, N., Boulter, P., Katsis, P., Joumard, R., Geivanidis, S., and Hausberger, S. (2014). EMEP/EEA emission inventory guidebook 2013 update Sept 2014 1. Technical report, EMEP/EEA.

Krokstad, F. E. (2015a). Email correspondence. 08.04.2015.

Krokstad, F. E. (2015b). Email correspondence. 10.03.2015.

Krokstad, F. E. (2015c). Email correspondence 15.04.2015.

Krokstad, F. E. (2015d). Email correspondence. 16.03.2015.

Krokstad, F. E. (2015e). Email correspondence. 18.03.2015.

Krokstad, F. E. (2015f). Email correspondence. 28.04.2015.

Krokstad, F. E. (2015g). Personal communication, 19.05.2015.

Lindqvist, K. (2012). Emission standards for light and heavy road vehicles. Technical Report 17, Air Pollution Climate Secretariat.

Luftkvalitet.info (2015). Luftkvalitet in Norge.

Luján, J. M., Tormos, B., Salvador, F. J., and Gargar, K. (2009). Comparative analysis of a DI diesel engine fuelled with biodiesel blends during the European MVEG-A cycle: Preliminary study (I). *Biomass and Bioenergy*, 33(6-7):941–947.

Miljødirektoratet (2010). Norge bør satse på utvikling av neste generasjons biodiesel. Retrieved 16 June, 2015, from `http://www.miljodirektoratet.no/no/Nyheter/Nyheter/Old-klif/2010/Oktober_2010/Norge_bor_satse_pa_utvikling_av_neste_generasjons_biodiesel/`.

Miljødirektoratet (2013). Veileder om nye krav til biodrivstoff og flytende biobrensel. Retrieved 16 June, 2015, from `http://www.miljodirektoratet.no/no/Nyheter/Nyheter/2013/September-2013/Veileder-om-nye-krav-til-biodrivstoff-og-flytende-biobrensel/`.

Miljødirektoratet (2015a). Miljøstatus i Norge : CO2-avgift. Retrieved 16 June, 2015, from `http://www.miljostatus.no/Tema/Klima/Klimanorge/Tiltak-og-virkemidler/CO2-avgift/`.

Miljødirektoratet (2015b). Miljøstatus i Norge : Utslipp av klimagasser fra transport. Retrieved 20 June, 2015, from `http://www.miljostatus.no/Tema/Klima/Klimanorge/Kilder-til-utslipp-av-klimagasser/Transport/`.

Miljøpakken (2015a). Gass- og hybridbusser. Retrieved 24 April, 2015, from `http://miljopakken.no/prosjekter/biogass-og-hybridbusser`.

Miljøpakken (2015b). Miljøpakken » Biltrafikktall. Retrieved 20 June, 2015, from `https://miljopakken.no/trafikken-i-trondheim/biltrafikktall`.

Miljøpakken (2015c). Miljøpakken » Prosjekter. Retrieved 18 June, 2015, from `https://miljopakken.no/hva-skjer#/bompunkter`.

Miljøpakken (2015). Vi reiser mer miljøvennlig. Retrieved 24 April, 2015, from http://miljopakken.no/om-miljoepakken/bakgrunn.

Miljøverndepartementet (2008). Enighet om nasjonal klimadugnad. Retrieved 2 June, 2015, from https://www.regjeringen.no/no/aktuelt/enighet-om-nasjonal-klimadugnad/id496878/.

Miljøverndepartementet (2012). Norsk klimapolitikk . St.meld. nr 21 (2011–2012).

Mjøen, T. (2015). Email correspondence. 19.05.2015.

Nenseth, V. and Nielsen, G. (2009). Indikatorer for miljøvennlig bytransport - en kunnskapsstatus. TØI rapport 1029. Technical report, Transportøkonomisk institutt (TØI). Institute of Transport Economics Norway.

Notter, D. a., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., and Althaus, H. J. (2010). Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environmental Science and Technology*, 44(17):6550–6556.

Nylund, N.-O., Lappi, M., Ikonen, M., and Erkkilä, K. (2004). Transit bus emission study: comparison of emissions from diesel and natural gas buses. Technical report, VTT Processes, Finland.

Ou, X., Zhang, X., and Chang, S. (2010). Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations. *Energy Policy*, 38(1):406–418.

Pelkmans, L., Keukeleere, D. D., Bruneel, H., and Lenaers, G. (2001). Influence of Vehicle Test Cycle Characteristics on Fuel Consumption and Emissions of City Buses. *Cycle*.

PRé Consultants (2013). Introduction to LCA with SimaPro. Technical report.

Seibel, S. (2003). Decomposition analysis of carbon dioxide-emission changes in Germany - Conceptual framework and empirical results. Technical report, European Commission.

Selfors, A., Thorsen, K., Hofstad, K., Fagerlund, K. H., and Wiggen, T. M. (2004). Naturgass - en generell innføring. Technical report, Norges vassdrags- og energidirektorat.

SenterNovem (2008). Participative LCA on biofuels. Technical report.

Simonsen, M. (2012a). Buss. Technical report, Vestlandsforskning.

Simonsen, M. (2012b). Energibruk til produksjon og vedlikehald av buss. Technical Report 11, Vestlandsforskning.

Simonsen, M. (2012c). VOLVO 8500 Energi- og utslippsvirkninger av produksjon av Volvo 8500 busser. Technical report, Vestlandsforskning.

SNL (2013). Byneset – tidligere kommune. Retrieved 18 June, 2015, from `https://snl.no/Byneset/tidligere_kommune`.

Solaris (2014). Vehicles catalog 24 low-entry. Retrieved 9 May, 2015, from `http://www.solarisbus.com/vehicles_catalog/24/low-entry`.

Spielmann, M., Bauer, C., Dones, R., and Tuschmid, M. (2007). Transport Services. ecoinvent report no.14. Technical report, ecoinvent centre, Villigen and Uster.

SSB (2014). Kollektivtransport - årlig - Tabeller. Retrieved 2 June, 2015, from `http://www.ssb.no/transport-og-reiseliv/statistikker/kolltrans/aar/2014-06-27?fane=tabell&sort=nummer&tabell=184944`.

SSB (2015). Mitt SSB: Statistikkbanken. Retrieved 2 June, 2015, from `https://www.ssb.no/statistikkbanken/SelectVarVal/Define.asp?MainTable=RegKjoretoy2&KortNavnWeb=bilreg&PLanguage=0&checked=true`.

Statoil (2009). Statoil Diesel. Technical report.

STFK (2014). Rapport : Klimaregnskap og miljørapport 2013 for STFKs egen virksomhet. Technical report.

Strømman, A. H. (2010). Methodological Essentials of Life Cycle Assessment.

Sundvor, C. F. (2013). *Life Cycle Assessment of Road Vehicles for Personal and Public Transportation*. Master thesis, Norwegian University of Technology and Science.

Sætertrø, J. O. (2015). Email correspondence. 21.05.2015.

Sætre, M. (2013). Kollektivtransport.

TCRP (2009). Assessment of Hybrid-Electric Transit Bus Technology. Technical report, Transportation Research Board.

Transeoceanenergy.com (2015). About CNG. Retrieved 23 April, 2015, from http://www.transecoenergy.com/pages/About_CNG.htm.

TransLink (2006). Bus Technology Alternative Fuels Demonstration Project Final Phase 1 - Test Program Report. Technical report, TransLink.

Trondheim kommune (2007). Kommunedelplan 2007-2018. Arealdel: Kort innføring. Technical report.

Trondheim kommune (2014). Trondheim Kommunes miljøpakke for transport - et forlik mellom 6 partier i Trondheim bystyre.

Vå gane, L. (2009). Flere i hver bil? Status og potensial for endring av bilbelegget i Norge. TØI Rapport 1050. Technical report, Transportøkonomisk institutt (TØI) Institute of Transport Economics.

Verhé, R., Mittelbach, M., Mateo, S., Eychenne, V., De Caro, P., Mouloungui, Z., and Stevens, C. V. (2004). Industrial Products from Lipids and Proteins. In Stevens, C. V. and Verhé, R., editors, *Renewable Bioresources. Scope and Modification for Non-food Applications*, chapter 9. John Wiley Sons, Ltd.

Volvo Bus Corporation (2008). VOLVO 7700 Hybrid BUS. Technical report.

Volvo Bus Corporation (2011). Volvo 7700 Hybrid: This is how it works. Retrieved 24 April, 2015, from http://www.volvobuses.com/bus/sweden/sv-se/products/Citybuses/Volvo7700Hybrid/Pages/factchart.aspx.

Vågane, L., Brechan, I., and Hjorthol, R. J. (2011). Den nasjonale reisevaneundersøkelsen 2009 - Nøkkelrapport. Technical report, Transportøkonomisk institutt (TØI) Institute of Transport Economics.

A. Acronyms

CF Carbon footprint

ckm Capacity kilometers

CNG Compressed natural gas

CH_4 Methane

CO Carbon Monoxide

CO_2 Carbon Dioxide

CO_2-eq Carbon Dioxide equivalents

EEA European, Environmental Agency

EIO-LCA Economic input-output life cycle assessment

EOL End of life

FU Functional unit

HC Hydrocarbons

ICE Internal combustion engine

IPCC The Intergovernmental Panel on Climate Change

LCA Life cycle assessment

LCI Life cycle inventory analysis

LCIA Life cycle impact assessment

LNG Liquified natural gas

LPG Liquified petroleum gas

N_2O Dinitrogen oxides

NMHC Non-methane hydrocarbons

NOx Nitrogen oxides

O_3 Ozon

OECD Organization for Economic Co-operation and Development

ODP Ozone depletion potential

pkm Passenger kilometers

PTW Pump-to-wheels

RME Rape oil methyl ester

SDA Structural decomposition analysis

SME Soybean oil methyl ester

SO2 Sulfur dioxide

SOx Sulfur oxides

SSB Statistics Norway (Statistisk sentralbyrå)

THC Total hydrocarbons

UNEP United Nations Environment Programme

vkm Vehicle kilometers

VME Vegetable oil methyl ester

VOC Volatile organic compounds

WTP Well-to-pump

WTW Well-to-wheels

B. Life cycle inventory calculations

Table B.1.: Direct emissions from operation of the three bus types. Pollutants and their sources are included, as well as the references from which they are calculated. All values are expressed in kg/km

		B44	Hybrid, B44	Reference, assumptions	CNG	Reference, assumption
Carbon Dioxide, Fossil	Airborne exhaust emissions	6,65E-01	4,65E-01	a *	1,34E+00	a
Carbon dioxide, biogenic		5,22E-01	3,66E-01	a *	0	
Sulfur Dioxide		4,23E-05	5,29E-05	b	0,00E+00	e
Cadmium	Airborne exhaust emissions: Trace element in fuel	3,71E-09	3,71E-09	c	0	h
Copper		9,86E-07	9,86E-07	c	0	h
Chromium		2,33E-08	2,33E-08	c	0	h
Nickel		2,95E-08	2,95E-08	c	0	h
Zinc		7,45E-07	7,45E-07	c	0	h
Lead		6,05E-09	4,23E-09	a	0,00E+00	h
Selenium		3,50E-09	3,50E-09	c	0	h
Mercury		7,00E-12	7,00E-12	c	0	h
Chromium VI		3,50E-11	3,50E-11	c	0	h
Carbon monoxide, Fossil	Airborne exhaust emissions	2,94E-03	2,06E-03	a	1,07E-03	a
Nitrogen Oxides		1,27E-02	8,86E-03	a	2,69E-03	a
Particulates, <2,5 µm		3,40E-04	2,38E-04	a	4,88E-06	a
Particulates, >10 µm		7,40E-05	6,28E-05	d	1,77E-05	d
Particulates, >2,5 µm, and <10 µm		8,06E-05	6,84E-05	d	4,45E-06	d
NMVOC		6,69E-04	4,68E-04	a	4,88E-05	a
Methane, fossil		6,62E-05	4,63E-05	a	3,89E-04	f
Benzene		3,36E-06	2,85E-06	d	0,00E+00	g
Toluene		1,77E-05	1,50E-05	d	1,98E-05	h
Xylene		8,43E-06	7,15E-06	d	2,03E-05	h
Formaldehyde		8,63E-05	7,33E-05	d	1,00E-08	g
Acetaldehyde		4,70E-05	3,99E-05	d	0	h
Ammonia		3,78E-06	2,65E-06	a	0	a
Dinitrogen monoxide		1,13E-05	7,94E-06	a	0,00E+00	a
PAH, Polycyclic aromatic hydrocarbons		4,00E-10	3,39E-10	d	4,03E-09	d

Zinc, ion	Emissions to water and soil from tyre abrasion and road wear	6,57E-06	5,57E-06	d	2,65E-09	d
Copper, ion		1,56E-07	1,32E-07	d	3,96E-08	d
Cadmium, ion		2,33E-09	1,98E-09	d	2,38E-08	d
Chromium, ion		1,11E-08	9,41E-09	d	2,12E-08	d
Nickel, ion		3,01E-08	2,55E-08	d	2,12E-06	d
Lead		9,56E-08	8,11E-08	d	3,72E-08	d
Zinc		6,57E-06	5,57E-06	d	5,98E-06	d
Copper		1,56E-07	1,32E-07	d	1,12E-07	d
Cadmium		2,33E-09	1,98E-09	d	7,45E-09	d
Chromium		1,11E-08	9,41E-09	d	6,70E-08	d
Nickel		3,01E-08	2,55E-08	d	5,96E-08	d
Lead		9,56E-08	8,11E-08	d	2,82E-08	d
Heat, waste [MJ]		1,58E+01	1,58E+01	b	1,69E+01	d

* CO_2 emissions are split into fossil/biogenic according to the share of biodiesel a = Kouridis et al (2014) b = Calculated according to 10ppm in fuel c = Ecoinvent d = Ecoinvent (Spielmann, 2007) e = Ecoinvent, scaled according to weight (Spielmann, 2007) f = Cooper (2012) with 3WC g = Nylund et al (2004), SM CNG h = Sundvor (2013)

Table B.2.: Buses included in the Nettbuss bus fleet. (Krokstad, 2015c)

	Diesel	**CNG**	**Hybrid**	**Weight [tons]**	**Length [m]**	**Amount**	**Capacity**
Man Lions city		x		13,1	12	109	74
Volvo 7700 Hybrid			x	12,1	12	10	72
Solaris		x		12,9	12	20	72
Solaris		x		15	15	21	95
Man Lions City		x		15,8	15	43	97
Man Lions City leddbuss		x		18,6	18	20	144
Iveco		x			10,5	1	16
Man	x				10,5	2	50
Volvo 8900 EEV	x			15	15	38	92
Sum	2	6	1			264	

Table B.3.: Average weight, length and capacity of the buses in Nettbuss bus fleet. Calculated as weighted averages according amount in bus fleet.

	Diesel	**Hybrid**	**CNG**
Weight [tons]	15	12	14
Length [m]	15	12	13
Capacity	90	72	87/ 73*
*Articulated/not articulated buses			

C. Additional Information

Additional information about studies included in the literature review

Table C.1.: Summary of the studies in the literature review according to functional units, bus technologies and emissions/impact categories covered

Study	Functional unit	Bus technologies	Emissions/impact categories
Chester (2008)	vkm/pkm	Diesel Electric	GHGs, CO, NOx, SO2, PM10, VOC
Sundvor (2013)	vkm/pkm	Diesel CNG	GWP,FDP, HTP, EP, PM, MDP, POCP, AP
Simonsen (2012a)	vkm/pkm	Diesel, CNG Hybrid, Biodiesel	Energy use, CO_2 emissions, ozone formation
Cooney (2011)	vkm	Diesel Electric	GWP, ODP, resperative inorganics carcinogens, non-carcinogens , respiratory organics, ETP, EP
Ally and Pryor (2007)	vkm	Diesel, CNG Hydrogen	Energy use, GWP, EP, AP, POCP
Ou et al (2010)	MJ per km/vkm	Diesel, CNG LNG, Hybrid Electric	Energy use, CO_2 emissions

LCA studies of passenger cars identified in the literature

Table C.2.: Presentation of LCA studies of passenger cars

	Fuel	kg CO2 eq./km	Lifetime	Comments
EcoInvent 2.2	Diesel, fleet average	0,214	-	Use phase only.
	Diesel, 5% RME	0,206	-	
	Petrol, fleet average	0,237	-	Includes fuel production and distribution
	Petrol, 5% ethanol	0,239	-	
Andersen, 2010	Diesel and petrol	0,201	-	
Daimler AG, 2005	n.a.	0,200	300000	Mercedes S class, includes all life cycle phases
Daimler AG, 2007	n.a.	0,173	200000	Mercedes C class, includes all life cycle phases
Schweimer and Levin, 2010	Diesel	0,331	150000	Volkswagen Golf A4, 66kW engine, full LCA
	Petrol	0,245	150000	Volkswagen Golf A4, 55kW engine, full LCA

Table C.3.: Average passenger loads in bus transport in Trondheim at various times during the day (Krokstad, 2015a).

Time	Load factor
5.00 a.m.- 7.00 a.m	12%
7.00 a.m.- 9.00 a.m	30%
9.00 a.m.- 1.30 p.m.	12%
1.30 p.m.- 5.00 p.m	27%
5 p.m.- 8 p.m.	12%
8 p.m. - 12 p.m.	7%

Sensitivity of maintenance processes

As pointed out in the method chapter, the hours of service per year is uncertain and may vary a lot with bus type, as well as its mileage. A Norwegian electricity mix is used to model the indirect impacts of electricity generation.

Two scenarios for maintenance were developed. First, the number of service hours were increased to 150 hours, in line with the findings in Simonsen (2012b). Second, the type of electricity mix was changed. As there is currently no consensus among LCA practitioners on which electricity mix that should be used when performing an LCA for Norwegian conditions, the indirect effects of electricity generation are uncertain. The electricity mix was changed to Nordic production mix to assess the sensitivity of this parameter.

Table C.4.: Sensitivity analysis of maintenance processes

Impact category	150 hours service/year	NORDEL electricity mix
Agricultural land occupation	0,01 %	0,03%
Climate change	0,05 %	0,14%
Fossil depletion	0,08%	0,15 %
Freshwater eutrophication	0,16 %	0,25 %
Marine eutrophication	0 %	0 %
Particulate matter formation	0,04 %	0,07 %
Terrestrial acidification	0,02 %	0,04 %

It can be seen from table C.4 that these maintenance scenarios cause small variations in the total impacts.

D. Detailed LCA results

Table D.1.: GHG emissions for the three bus types.

	B44	% of total	Hybrid [B44]	% of total	CNG	% of total
Bus materials	6,48E-02	5,16 %	6,42E-02	6,93 %	6,48E-02	3,71 %
Bus manufacture	9,00E-03	0,72 %	1,04E-02	1,12 %	9,96E-03	0,57 %
Battery production		0,00 %	1,17E-02	1,27 %		0,00 %
Electric motor production		0,00 %	7,03E-04	0,08 %		0,00 %
Sum production	7,38E-02	5,88 %	8,70E-02	9,40 %	7,48E-02	4,29 %
Maintenance	3,33E-02	2,65 %	3,34E-02	3,61 %	3,24E-02	1,86 %
Fuel use	6,70E-01	53,32 %	4,69E-01	50,62 %	1,35E+00	77,14 %
Fuel production	4,77E-01	37,94 %	3,34E-01	36,02 %	2,89E-01	16,56 %
Operation	1,15E+00	91,25 %	8,02E-01	86,64 %	1,64E+00	93,70 %
Sum use	1,18E+00	93,91 %	8,36E-01	90,25 %	1,67E+00	95,56 %
EOL bus	2,74E-03	0,22 %	2,74E-03	0,30 %	2,74E-03	0,16 %
EOL battery		0,00 %	5,27E-04	0,06 %		0,00 %
EOL electric motor		0,00 %	6,65E-06	0,00 %		0,00 %
Sum EOL	2,74E-03	0,22 %	3,27E-03	0,35 %	2,74E-03	0,16 %
Total	1,26E+00	100,00 %	9,26E-01	100,00 %	1,75E+00	100,00 %

Table D.2.: All impact categories calculated from the Recipe impact assessment

	B44	Hybrid [B44]	CNG
Agricultural land occupation [m2a]	1,01E+00	7,08E-01	3,99E-03
Climate change [kg CO2 eq]	1,26E+00	9,26E-01	1,75E+00
Fossil depletion [kg oil eq]	3,69E-01	2,75E-01	6,45E-01
Freshwater ecotoxicity [kg 1,4-DB eq]	9,79E-03	8,46E-03	3,10E-03
Freshwater eutrophication [kg P eq]	1,75E-04	1,69E-04	8,75E-05
Human toxicity [kg 1,4-DB eq]	2,97E-01	2,84E-01	1,09E-01
Ionising radiation [U 235 eq]	1,02E-01	8,63E-02	1,09E-01
Marine ecotoxicity [kg 1,4-DB eq]	5,13E-03	5,34E-03	3,58E-03
Marine eutrophication [kg N eq]	4,51E-03	3,19E-03	1,68E-04
Metal depletion [kg Fe eq]	7,82E-02	8,50E-02	6,54E-02
Natural land transformation [m2]	3,68E-04	2,67E-04	3,99E-04
Ozone depletion [kg CFC-11 eq]	2,97E-07	3,02E-07	3,99E-07
Particulate matter formation [kg PM10 eq]	4,72E-03	3,44E-03	1,15E-03
Photochemical oxidant formation [kg NMVOC eq]	1,62E-02	1,15E-02	4,38E-03
Terrestrial acidification [kg SO2 eq]	1,40E-02	1,01E-02	2,97E-03
Terrestrial ecotoxicity [kg 1,4-DB eq]	2,57E-02	1,80E-02	8,23E-05
Urban land occupation [m2a]	1,92E-02	1,39E-02	1,94E-03
Water depletion [m3]	1,95E+00	1,75E+00	1,93E+00