Master's thesis

NTNU
Norwegian University of Science and Technology
Department of Geography

Frederic Poulin

Life-cycle Assessment as a Tool for Sustainable Public Transportation Development

The Case of Oslo

Master's thesis in Globalisation and Sustainable Development
Supervisor: Asbjørn Karlsen
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Abstract

With the rapid urbanisation of society being observed on a global scale, urban mobility is a growing issue and it is becoming increasingly important for cities to develop effective public transportation systems In the case of the city of Oslo, public transportation is heavily prioritised over other transportation methods, such as private cars. This thesis applies the life-cycle assessment framework with a focus on the use phase of the life-cycle to establish the carbon footprint of buses operated in Oslo. Another aspect relates to the evaluation of KPI data as a means of measuring policy advancement. Furthermore, the LCA framework is used to determine the ways in which they are useful to guide policymakers seeking to develop sustainable public transportation. The data analysed in this thesis shows that Ruter is rapidly reducing emissions produced by buses in their network, as well as its overall carbon footprint. This comes as a result of its gradual phasing-out of conventional diesel fuel buses, in favour of biodiesel and electric alternatives. This thesis also covers the greenhouse gas and CO_2 emissions produced by buses in Oslo. This shows the extent to which It is also clear that the global Covid-19 pandemic of 2020-2021 has had implications on the carbon footprint of buses, especially in terms of ridership statistics. Furthermore, it is theorised that the changes in commuting practices caused by Covid-19 may have long-term implications on public transportation as a whole. Overall, this thesis contextualises the carbon footprint of buses at the use phase, and in doing so aims to contribute to research on this topic. Additionally, it offers some recommendations on best practices both in terms of climate impact reduction, as well as policy development. This thesis utilises a multidisciplinary approach to produce an analysis of public transportation and its carbon footprint through several different perspectives.

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1 Introduction

As we become increasingly concerned about our changing climate and work more and more on studying the causes of these changes, we are gaining a better understanding of the impact we have on the planet. From this, the question as to what tools exist to facilitate the obtention of data, and information on the carbon footprint of our activities arises. At the root of the issue, one aspect of our society that has a significant impact on our environment is that of transportation. Globally, transportation represents an immense output of carbon dioxide [10]. An important component of transport, in general, is public transportation, which represents a crucial factor in an urbanising society. Therein lies the interest in studying the carbon footprint of public transportation. If we are to consider public transportation as an important conductor for decarbonisation or simply as a key tool for urban development, there is no doubt that it becomes important to understand what is the impact on the environment both currently, and what it can become through technological advances. This is the primary aim of this thesis, evaluating the ways in which life-cycle assessments can be utilised as a tool for sustainable public transportation development.

Given the broadness of transportation as a sector, this thesis focuses on the case of buses in the city of Oslo. This is an interesting case, given the fact that buses represent one of two means of public transportation which are not entirely reliant on electricity, as a means of propulsion. Oslo has long had an electric tram system, as well as an electric subway service. This means that together with ferries, buses are the area that produces the most CO_2 in Oslo's public transportation. Therein lies the interest in studying the current situation as well as the future of buses, as a public service. Furthermore, public transportation is a key component of cities and is destined to experience tremendous changes in the near future. This is especially relevant given the major societal changes taking place as a result of the global coronavirus pandemic which began in early 2020, as well as technological changes. As such, it is interesting to understand how buses operate as thing currently are.

As we observe Western society becoming increasingly urbanised, year after year, thus causing significant growth in urban development, which is no doubt having significant implications on the environment. In the case of Oslo, there is a strong political commitment to the design of infrastructure which enables the use of sustainable modes of transportation. This is something that city authorities are increasingly considering, as cities continue to grow, yet become increasingly concerned with their environmental footprints. Public transportation is one such way in which cities are seeking to reduce their carbon footprint, whilst also discouraging the use of private cars. This is a strategy that has significant potential, as a means of urban development. However, it is important for city governments to consider the tools to use as means to identify the most optimal transport systems, whilst being aware of their carbon footprint. One such tool is a life-cyle assessment.

The life-cycle assessment of public transportation allows for an understanding of the footprint of a product, system or service, such as public transportation as things stand. This can then be utilised to determine the impact which certain changes can have on carbon output, based on data. This is where the interest of conducting a LCA on public transportation stands, understanding the situation as things are, as well as how it can evolve, based on certain changes.

1.1 Context

Transportation represents a significant portion of global carbon emissions of which public transportation is responsible for a significant potion [10]. Knowing this, it is important to evaluate the ways in which existing tools and frameworks can be utilised to develop solutions. As the global trends increasingly turn towards improving sustainability, many countries, cities and regions are turning towards transportation as an important component of green transitioning. The development of efficient, complete and integrated public transportation is becoming a crucial element of urban development in the 21st century. Given the complexity of public transportation, which is comprised of a number of factors that require consideration. Ranging from hardware, such as buses and infrastructure, to routing considerations, developing transit maps that efficiently service the maximum amount of passengers as well as ticket pricing and systems. Finally, another important aspect is that which relates to the carbon footprint of these transportation systems. This is something that is crucial to this thesis, as well as the case it focuses on, given the City of Oslo's ambitious plans to transition its transportation system into one which is entirely carbon-neutral, and that before 2030.

1.2 The situation in Oslo

Oslo has a well developed public transportation system which is comprised of four types of transportation; city buses, metro, tram and ferry [11]. The tram and metro systems have long been electrified [12]. Consequently, the vast majority of carbon emissions from public transportation in Oslo stem from the bus and ferry systems[11]. It is with this context in mind that Ruter AS, the public transport authority responsible for Oslo Municipality and Viken County has committed to its bus system becoming fossil-fuel free by 2020 and for carbon-neutrality by 2028[13]. To achieve that, the City has decided to focus on its bus system, which is collectively responsibly for around 60% of Oslo's transportation-related CO_2 emissions. To achieve that, Ruter has planned to eliminate completely the use of fuel from non-renewable sources from 2020, as well as electrifying over 60% of its fleet by 2028. This is an ambitious plan for a rapid transition. This thesis aims to understand the current situation in terms of Ruter buses' carbon footprint, as well as understand the consequences of this transition, from a carbon footprint perspective.

This is an area that is not extensively researched, as a component of urban and environmental development. Whilst it is generally assumed that buses and public transportation, in general, provide an environmentally conscious method of transportation, there is no extensive research into the extent of their impact on the environment [10]. The aim of this thesis is to provide additional insight as to the carbon footprint of buses in Oslo, to better understand what it represents in the context of urban development. Furthermore, it is interesting to see the implications of increased research in public transportation in general, especially with a better understanding of the factors which influence carbon footprint, something this thesis aims to research.

1.3 On Ruter AS

Ruter is an independent publically owned agency that is responsible for the administration, planning and maintenance of public transportation in the Municipality of Oslo and the County of Viken (formerly Akershus). It was established in 2008 to develop a more coherent public transportation system in the Oslo region[11]. It has 22 subsidiary companies that are responsible for the operations. Ruter is co-owned by Oslo Municipality (60%) and Viken County (40%). As such it follows a mandate established by the Regional governments. This means that policy-wise Ruter is significantly shaped by the city and county authorities that own it. As a transportation operator, it has ambitious plans, surrounding decarbonisation, and a transition from more conventional practices, to fossil-free operations, and finally, to have a fully electric bus system, within the next 10 years.

The operational structure established by Ruter is rooted in contract agreements with sub-contractors who enter agreements with Ruter to operate their buses. This means that the majority of buses in the Ruter network are owned by independent companies. This structure gives Ruter the ability to sign contracts with companies that offer services conforming to Ruter's operating standards[14]. This makes Ruter significantly influential in the ways buses in Oslo and the surrounding area are operated. Given that it is a publicly owned company, there is no doubt that Ruter is heavily influenced by the local governments who share ownership.

1.4 Coronavirus Pandemic

Given the impact which the coronavirus pandemic has had on the world as a whole from its inception in early 2020, it is important to establish the impact which it has had on public transportation. It is clear that public transportation systems have been impacted significantly by this pandemic. In terms of ridership data, caused by multiple lock-downs and restrictions on travel and activities. These have undoubtedly had implications on the use of buses. In Oslo, 2020 saw a 40% decrease in passengers transported in comparison to 2019[2]. This has had implications for their environmental footprint. It is unquestionable that buses are large vehicles, whose carbon footprint is largely determined by the number of passengers who utilise them. As such, in the context of the global pandemic, the public transport service offering was largely required, as a means of maintaining service for essential workers, as well as providing continued service for regular users. Furthermore, this is something which may have significant implication on commuting behaviours in the years to come. However, the number of passengers has greatly reduced. This is something that can be clearly seen in the data which complicates data interpretation.

1.5 Research Aims

The main objective of this research is to understand the carbon footprint generated by buses in the City of Oslo. Another important aim is to obtain a better understanding of the ways in which public transportation systems can become more sustainable through the use of analytical methods which assess their carbon footprints, such as the life-cycle framework. This is something that aims to provide greater insight into the origins of carbon emissions in urban areas, as well as the ways in which cities can become vehicles for decarbonisation.

Knowing that cities are growing year after year, as the global trends point towards continuous urbanisation, something which has inherent implications on transportation[15], it is interesting to study aspects related to this issue. Therein lies the main objective of this thesis. As cities grow, the requirements for transportation increases, giving city government and public transportation service providers the incentive to develop policy and operation practices to fit their needs[10]. There is a need for additional research into public transportation, as it is a critical tool for urban growth, both in terms of land use and efficiency, but also in terms of the environment. This thesis aims to contribute to this issue, based on the assessment of the life-cycle carbon footprint of buses in Oslo.

1.6 Research questions

With this research being rooted in the life-cycle assessment framework, many questions are potential research questions. In the context of this thesis, there are two main research questions:

1. What is the carbon footprint of buses in the public transportation system of the city of Oslo?
2. What is the extent to which a life-cycle assessment can be a useful tool for the development of sustainable public transportation?

The first question aims to clarify the carbon footprint of buses in the city of Oslo. This is important both in terms of understanding the climate aspect of public transportation and of urban development in general. With the aim to provide a better understanding of the factors which contribute to the carbon footprint of buses in Oslo. The second question relates to the use of data assessment tools, such as life-cycle assessments to understand the impact of public transportation on the environment, as well as tools to foster the development of more sustainable public transportation solutions. This thesis seeks to use these two questions as a way to obtain a better understanding of the factors which influence the carbon footprint of buses in urban settings. Furthermore we hope thesis will provide a better understanding of the tools which exists, to facilitate the transition of public services, including those which relate to public transportation. The goal being to better understand how these frameworks can be utilised in development of cities, policies and practices.

1.7 Disposition

This thesis utilises data from a number of sources, including Ruter AS, Volvo buses AB, MAN Truck & Buses AG, among other sources, to obtain information on the carbon footprint of buses, especially in the context of the use phase. It is established that the use phase of a Bus life, from cradle to grave represents around 90% of its carbon footprint[16]. This research is therefore disposed to focus on this phase of the life-cycle. Given that public transportation is such a complex area of study, which requires many different areas of expertise, it is important to set limits to the research disposition.

In this research, the scope is primarily set out to surround the operation of buses in Oslo, which sets the focus on the aspects which surround operations, as opposed to matters of production, infrastructure or disposal. This research will utilise a number of different data sources to assess the carbon footprint of buses, as well as the implementation of the LCA framework.

2 Theory

There are many theoretical approaches that have relevant research implications on public transportation systems. In the scope of a life-cycle assessment, it is important to identify the theories which are most impactful both environmentally and in terms of policy development. This section aims to review the existing literature in relation to this topic which informs the aforementioned research questions. There are a number of factors that are important when considering the total carbon footprint of public transportation in the city of Oslo. Theoretically, it is important to consider a number of theories that can give different perspectives in the data, thus allowing for deeper research outcomes. In the context of establishing the impact of primary materials in public transportation vehicles, it is important to establish the key characteristics of the variables present in this research, namely surrounding the policy and decision making basis for Ruter's operating procedures. This is something that will facilitate the development of a theoretical framework surrounding the analysis of the acquired data. Furthermore, this section aims to provide a greater understanding of the topic and its context.

2.1 Circular Economy

Ruter AS, is a publicly owned company that offers a public service. Within the context of sustainability, it is interesting to see how public transportation in Oslo can work in ways that would increase circularity. Circular Economy is a concept which seeks to fundamentally transform our current economic frameworks, through changes in production and waste creation models [17], which outlines the importance of the production process in waste production. There are multiple aspects to circular economy- firstly in terms of environmental protections, secondly in relation to improving the lifespan of consumer products and finally the reduction of waste [17]. In the context of public transportation, there are a number of ways in which buses can increase their circularity. Especially in terms of environmental protection; greenhouse gas emissions reduction being a significant vector through which buses can become less damaging. As for the lifespan of buses, it is possible to increase these both through technological innovation and through maintenance. In terms of waste production and technological innovation in end-of-life recycling, for example, can provide ways to reduce the waste output of buses.

Circular economy is first and foremost centred on the elimination of waste by design [18]. It is a concept which demands a significant systemic change in order to be implemented successfully [18]. In practice, it means that materials and resources must be recycled or reused, as opposed to being disposed of [17]. To become circular, companies must evaluate their activities, understand the waste generated from their products or services, as well as examine ways to circularise their operations[17]. An often-cited example of circular economy are the various bottle return deposit systems that exist throughout the world, wherein the waste is effectively designed out of the system through the creation of an incentive for companies and consumers alike to recycle bottles and cans [18, 19].

In terms of public transportation, transit systems can be a tool for the creation of circular cities. Cities are in constant evolution. As such, there is a constant need for urban development[20]. There is much to be said about the ways in which cities can promote a circular economy through public procurement processes [20]. Notably through investments in public transportation, as exemplified in the city of Vaasa, Sweden- who launched calls to tender for various biogas options for its transit system [20]. This exemplifies how cities can foster technological and sustainable development through investments in public transit. This promotes a circular economy by encouraging innovation, as well as providing practical examples of sustainable systems successfully implemented [20]. It is important to consider public transportation as a fundamental aspect of urban development. In doing so, it becomes clear that transportation provides a tool for the implementation of circular economy in cities [21]. There are many ways through which transportation can be altered to fit in a circular city, whether it be through optimisation, electrification or diversification in transportation methods [21]. New transportation solutions often go hand in hand with circular economic principles, something which will be examined in this thesis. Furthermore, given the city of Oslo and Ruter's commitment to zero-emission public transportation [13], circular economy provides an interesting theoretical perspective.

2.2 Environmental Considerations

Environmental concerns are becoming increasingly prominent in industrial, governmental and public discourse[22]. As population rises, cities are becoming larger in size, which inherently contributes to their growth, both in terms of population and in terms of physical infrastructure[22], resulting in heightened transportation needs. In Western countries, 75% of the population live in urban settings, a trend which continues[23]. This is a significant number, given the resources required to sustain large cities; every 1% in urban growth requires 2,2% more resources[23]. It is therefore important to understand the environmental impact of cities.

Following this trend, public transportation networks must be adapted to fulfil the required capacity to serve their users, and thus fulfil their main purpose. This often results in large road networks, a greater number of stations and stops, more vehicles, and infrastructure projects, all factors which have significant implications on the environment.

Globally, carbon emissions from the transport industry represent a total of 6.6GtCO_2 of which 72.9% come from road transportation [10]. In terms of energy consumption, road transportation represents 28% of the energy consumed, from which 70% is accountable to the movements of goods and people [10]. This suggests that passenger transportation represents a significant portion of total carbon emissions, as well as significant energy consumption. This, combined with a growing global vehicle fleet, estimated to pass 1.2 billion in 2050 [10] shows that sustainable transportation projects are needed, therein justifying the need for life-cycle analyses of such infrastructures, existing and subsequent.

2.3 Sustainable Development Goals

The United Nations' Sustainable Development Goals are important to consider within the scope of this research, as they provide a framework that informs many decisions taken both at a national and local level. There are a number of goals that have implications for the public transportation sector. As such, the repercussions of these Sustainable development goals, and of Agenda2030 have the potential to be significant. The sustainable development goals were developed with the idea that they would provide a framework for the development of policies targeting both environmental and social issues[24]. It is argued that to solve climate issues, it is paramount to adopt strategies that are at the intersection of environmental, social and economic considerations. This is something that relates closely to the SDGs and their implementation. It is often argued that an integrated approach is a key to a successful implementation[25]. Such an approach would be effective through the possibility of addressing issues that have significant overlap and interlinkage[25]. There is no doubt that public transportation represents one of these areas which contains significant links with other issues. Therein lies the reason for considering the SDGs as an important theoretical framework. The sustainable development goals are designed to be taken into consideration in the development of national and local policies[26]. This means that the goals themselves are not a set of policies, on the contrary, they are a series of goals that aim to encourage governments to develop innovative, modern solutions to both environmental and social problems. In the context of urban mobility, there are two of the 17 goals have significant links to public transportation, and therefore have larger impacts on the contents of this thesis.

2.3.1 SDG 9: Industry, Innovation and Infrastructure

This goal relates to the development of green industries, innovations and infrastructures, seeking to encourage a green shift in these sectors [27]. Given the relevance of green infrastructure development as an important factor in determining the carbon footprint of public transportation, this is the goal that has significant implications on the public transportation landscape.

In terms of encouraging the development of green infrastructure projects and fostering innovation and industry, it is important to consider how environmental assessments and indicators of sustainability are most often used by local governments and communities as a decision-making tool [15]. Hence the importance to take into account the impact which infrastructure has on communities. Goal number 9 permits that, by giving direction to local communities, thus encouraging governments to take into account the environmental impact of potential projects.

2.3.2 SDG 11: Sustainable Cities and Communities

This is a goal that is important due to the inherent links which exist between cities and public transportation[28]. Urban settings are a key factor to the environmental footprint of public transportation systems[10], given that they most often serve cities and urban areas. It is therefore important to consider policy development informed by goal 11, which are aimed at fostering environmentally conscious urban development. This is something which is outlined by the United Nations' sub-goal on sustainable transportation, which is categorised under goal 11[29]. It is evident that the creation of sustainable cities, from an environmental perspective, requires an integrated approach targeting a number of different aspects [21]. These aspects range from street-lighting to large scale infrastructure, and public transportation [21]. The implementation of sustainable, effective and integrated public transportation has a positive impact both environmentally and socially [10].

2.4 Transportation Sustainability

Sustainability in transportation is an area that requires a multi-disciplinary approach, seeing as there are variables that deal with a number of different elements [10]. Beyond environmental considerations, there are geographic and social variables that ultimately have implications on the carbon footprint of a project. It is therefore important to determine which factors have the greater implications on total environmental footprint, as a means of conducting an assessment[15]. Together, these factors contribute to the obtention of a complete overview of all aspects which relate to public transportation in urban areas.

2.5 Efficient Transportation

There is much to be said about the role which efficiency plays in public transportation. From a strictly environmental standpoint, fuel consumption, material durability and total vehicular weight are all examples of how optimally efficient vehicles and routes can reduce the total carbon footprint of transportation. However, there is no doubt that efficiency also relates to user experience; more effective transportation networks result in increased ridership. Reducing the total amount of motor vehicles in urban centres is a key component of sustainability. In the context of the City of Oslo, this is something which is done by making public transportation, cycling and walking more efficient transportation methods- as opposed to private cars, for example[13]. Furthermore, effective transportation, especially in the context of growing cities, relates to the total area which is served by public transportation[10].

2.6 Hardware

Much of the environmental footprint of public transportation relies significantly on the hardware which is utilised, which refers to the vehicles which are utilised by service providers [30]. This is something that is very important to consider in the life-cycle assessment of public transportation, as it is intrinsically linked to the operational aspects of transportation. It is long established that buses with internal combustion engines contribute significantly to pollution in urban areas, more specially CO_2 emissions [30]. As such, it is worth evaluating how vehicle fleets, have an impact on the environment of urban areas, especially with the growing popularity of electric and hybrid buses [30]. Whilst the introduction of electric and hybrid buses to transit networks might reduce CO_2 and N_2O emissions in cities, it is important to consider the environmental impact of such an expansion [30].

2.7 Use Phase

It is established that a large proportion of carbon dioxide output is generated during the use phase of a bus's life cycle. This phase accounts for over 60% of the total carbon footprint of a bus[16]. With this in mind, it seems that a focus on the operational aspects of an assessment represents a significant research opportunity.

From a theoretical perspective, the use phase represents the area that relates most to social aspects, given that it is inherently linked to the passenger experience. Furthermore, given that public transportation is an area that relates to numerous factors which are linked to numerous different areas; environmental concerns, use of resources, social aspect, urban development and more, it is an interesting area to focus on. As such, this thesis, and life-cycle assessment largely focuses on this phase of buses in public transportation, given that it offers the most potential for change.

2.8 Other Considerations

It is well reported that the vast majority of carbon emissions as a product of public transportation occurs at the point of use. As such, this thesis focuses on the aspects which relate to the footprint of Buses in the City of Oslo, over their useful lives. It is, however, important to note that there are many aspects that are important to determine the carbon footprint of buses but are beyond the scope of this research. Among these is the construction of public infrastructure (roads, bridges and stations), the disincentivisation of private car transportation, ticket pricing, among others that are inherent to transportation. This is something that has a significant impact on the environment. However, due to time constraints, they will not be part of this life-cycle assessment.

2.9 Framework

It is important to determine what characteristics are important theoretically when conducting research, in this context, public transportation is a topic that touches a number of areas of expertise, thus requiring a multi-disciplinary approach. It is therefore important to establish which sectors are relevant and to gather a comprehensive understanding of prevailing theories. Existing literature suggests that there is a strong emphasis on the transition from fossil fuel buses, to electric and hybrid models [30], as a means of carbon emissions reduction. Beyond that, there important theoretical considerations as to user interactions with transportation systems [10]. Together, these theoretical frameworks, among others are helpful in determining the weight which each aspect has on total carbon footprint. This is something that is especially helpful in the conduction of a life-cycle assessment, given that these aspects are all to be considered as key parts of the standardised ISO14040/ISO14044 life-cycle assessment framework.

3 Methods

This thesis will be making use of multiple methods to fulfil the research goals presented in the introduction. These methods aim to provide a wide range of data, as a means of understanding the case which is being studied. Primarily relying on a life-cycle assessment of the city of Oslo's public transportation system with a focus on buses. This is achieved through an embedded case study. Furthermore, an assessment of key performance indicators developed from Ruter AS and Oslo Municipality policies will provide important context to the life cycle assessment, as well as providing perspectives for future developments in Oslo's public transportation system. The idea of utilising both of these methods is aimed at obtaining a complete overview of all aspects relating to buses in Oslo. By utilising both of these methods, it is hoped that we can generate a complete overview of Ruter's carbon footprint, as well as a clear understanding of the policies and practices which guide it.

3.1 Life-cycle Assessment

Life-cycle assessments have, for a period of time represented an important resource for decision making at a number of different levels[31]. The prominence of LCAs in policy development, as well as in business decision-making stems from the framework's ability to gather objective data on the total carbon footprint of projects. Furthermore, LCAs are a way to establish the total footprint of a project from cradle to grave, something which is becoming highly desirable in an era of evidence-based decision-making[31].

Life-cycle assessments are rooted in inventory analysis, which seeks to determine the total carbon footprint over the total lifespan of a product, material or project. This is something that is determined by the measuring emissions and resources produced and utilised in the production cycle, the use cycle and the end of life cycle[31]. Different values are attached to each step of the assessment, as a means of establishing which aspect of the production phase generates a higher carbon output, thus allowing for a fair assessment of the total output[31].

There is some theoretical argumentation in relation to the ways in which values are assigned in LCA development, especially surrounding the justification for these valuations[31]. The primary method which will be used in the conduction of this research is one that follows the principles of a life-cycle analysis, which will aim to provide a better understanding of public transportation, more specifically focusing on buses in the city of Oslo. This method follows the standards established in ISO14040 on life-cycle analyses. Furthermore, ridership data, as well as infrastructure and developmental investments will be analysed as a means of determining the efficiency of public transportation from a public perspective, as well as political interests.

3.2 Embedded Case Study

The primary method of this study is a Case study, which focuses on the case of the City of Oslo's bus transportation system, operated by Ruter AS. As already mentioned, Ruter is a publicly owned company that operates public transportation in the counties of Oslo and Viken (formerly Akershus)[13]. It is owned partly by Oslo Municipality (60%) and Viken County) (40%)[13]. As such, Ruter operates a number of different services in different areas, from urban to rural[14]. This adds a number of layers to the study of Ruter's operations, given the fundamental differences which exist between public transportation in urban and rural contexts.

This thesis will therefore follow an embedded case study model[32], which focuses on the City of Oslo's public transportation. This means that this life-cycle assessment will only study aspects related to urban public transportation. As an embedded case study, this thesis will focus on one aspect of public transportation, buses in the urban core of the City of Oslo, within the context of Ruter's operations as a whole.

3.3 Life-Cycle Assessment

Life-cycle assessment is a comprehensive method that explores in detail the carbon footprint of a system from cradle to grave [1]. Meaning that the analysis takes into account each step of the use cycle, from the types of fuel used to the distance travelled, to passenger loads, thus enabling a complete view of the resources and energy required throughout the product's life [1]. To achieve this, the life-cycle assessment has four stages:

1. **The goal and scope definition stage**; it is important to set parameters to a life cycle assessment, given that they are more likely to be effective with a clear goal and scope.

2. **The inventory analysis stage**; this refers to the data collection stage, creating an inventory of available data needed to fulfil the objectives of the study.

3. **The impact assessment stage**; this stage consists of collecting additional data, as a means of better understanding a product, or system's impact in an environmental context.

4. **Interpretation**; this final stage consists of a summary and analysis of the LCA, used to elaborate conclusions, recommendations and take decisions as per the defined objectives of the study [1].

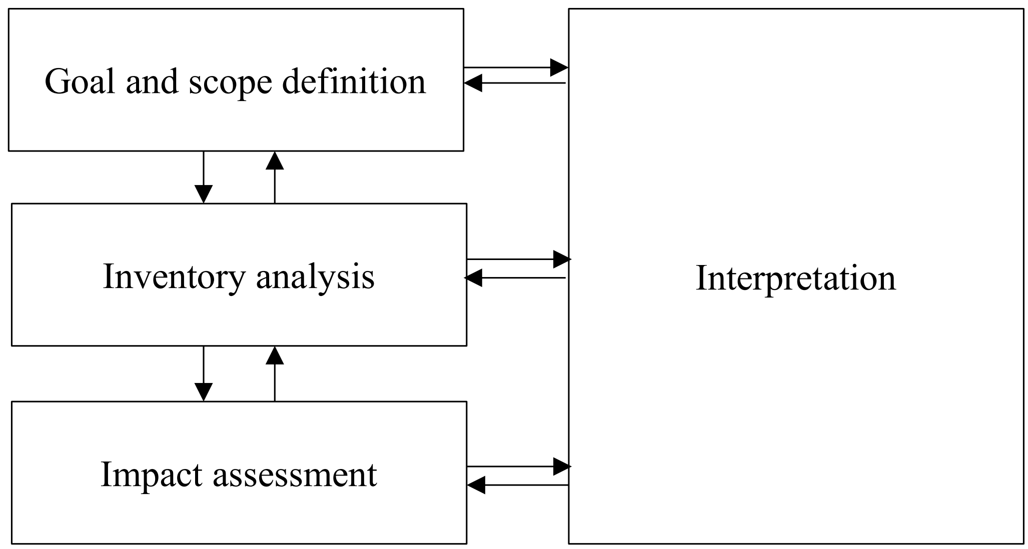

Figure 1: The four phases of a life-cycle assessment[1]

Within the scope of this research, the LCA approach will be utilised to determine the improvements which can be made to the bus fleet currently in use by Oslo's transportation authority. Conducting an analysis from a range of data, to determine the current carbon footprint, and how emissions reductions can be achieved. Utilising a LCA framework is a well-established tool that facilitates decision-making processes at a number of levels [1]. In the context of this research, the framework will allow for a complete analysis of the current system, which in combination with additional information on new technologies, innovative solutions as well as case studies will offer new perspectives both on the current situation, as well as possible solutions.

3.4 Key Performance Indicators

Given that the scope of this research lies both on the carbon footprint of an existing public transportation system, as well as it's capacity to progress towards reduced emissions, it is important to examine the existing policy framework. This is something which is critical, as decision-power is inherently linked to political decisions and policy frameworks [10]. To achieve this, a component of this research will conduct an analysis of the existing steering documents, regulatory frameworks, as well policy intentions, as a means of understanding the direction in which Oslo, and Norway's public transportation authorities are going. To achieve this, a key performance indicator methodology will be applied.

3.5 Identifying key performance indicators(KPI)

There are a number of ways to develop and identify key performance indicators [33], for this research, indicators will be identified through data collection from, various existing case studies, current government guidelines on public transportation, policy commitments to the sustainable development goals and Agenda2030, as well as literature on sustainable public transportation planning and low-carbon emitting vehicles. KPIs are a commonly used tool for measuring the performance of operations, policies or objectives[34]. A key component of KPI modelling is the numerical weights attached to each of the variants. This is important as it provides a numerical ranking of each aspect based on their assigned value, based on their degree of influence, as well as topic-specific characteristics [33].

4 Chapter 1 - Life-Cycle Assessment

The implementation of a Life-cycle assessment that follows the ISO14040 and ISO14044 standards is a complex process that requires multiple data sets from a number of different sources[1, 35]. The data used in this assessment of Ruter's bus operation is primarily acquired from Reports published by Ruter, other data originates from independent reports, as well as various publications and articles. This thesis relies on this data and methodology, as well as the data analysis software MatLab to implement this framework. It is important to follow an approach that corresponds to the established process of this standardised procedure.

4.1 Phase 1 - Goal and Scope Definition

It is important to identify the objectives of a life-cycle assessment prior to starting the data analysis process. As such, this phase is a critical portion of the process [1]. In the context of a LCA of public transportation in Oslo, the goal and scope of this research are focused on buses, as well as on how the transit network can be expanded and developed, as well as to see how it can inform public policy-making, in terms of operational procedures and goal creation.

The intended application of this LCA is to determine the carbon footprint of buses as part of Oslo's public transportation system. The reason for carrying out this study is to provide a better understanding of how LCAs can be utilised as a tool for sustainable transportation development. This application seeks to establish the ways in which transportation data can be utilised to inform future development through the creation of a complete current portrait of the environmental footprint. Furthermore, the aim in this instance is to provide an understanding of LCAs as tools.

4.1.1 Scope

The scope of a LCA is a standardised aspect of life-cycle assessments which seeks to define the focus and depth of the assessment, as a means of addressing the established goal, [1]. This section will outline the scope of this LCA as part of the thesis research.

The product system which is being studied is public transportation in the city of Oslo, with a focus on bus transportation. The scope is determined with the understanding the Ruter provides bus transportation across two regions (Oslo and Viken counties), with multiple contexts in terms of geographic development, to address this, the LCA focuses solely on bus transportation within the urban areas of the City of Oslo, this is done due to time constraints. It is important, however, to note that there is significant potential for further research in relation to public transportation service provision in rural and low-population density areas of Oslo

Municipality and Viken County. Having established that, the main area of focus is, therefore, the yearly provision of effective public transportation to passengers in the city of Oslo, which is defined as the immediate core of the City of Oslo, excluding the more extensive suburban areas. Creating road links between various sectors of the city. To define the system boundaries, the study will focus solely on bus transportation within the immediate city limits of Oslo, thus excluding rail and light-trail transportation as well as regional services. Furthermore, this LCA's focus is primarily set on the operational aspects of bus transportation although there will be some considerations of production and disposal cycles. With that boundary set, the unit processes of bus transportation are threefold;

1. Production of buses
2. Use of buses
3. Disposal or reallocation of buses

To conduct this LCA, there are significant data needs. This requires data on the manufacturing processes of buses that are part of Ruter AS' core fleet. Furthermore, it requires data on the road use, fuel consumption and distance covered over an average period of time. Finally, there is a need for data on the lifetime of the average Ruter bus, as well as data on the disposal process. Given the extent of the data needs, the scope of this LCA will primarily be focused on the use phase of the case. The main assumption is that Ruter operates a network that is rapidly decreasing emissions, yet continues to be a significant emitter in Oslo's total yearly carbon footprint.

There are limitations in terms of the provenance of information. The quality of the data is liable to the manufacturers and operators, whilst it can be assumed to be reliable, there is the potential that it be overly optimistic.

4.2 Phase 2 - Inventory Analysis

The inventory analysis phase seeks to establish the total amount of inputs and outputs within a unit system. This is aimed at identifying the data required to conduct an analysis. The process of inventory analysis is used to establish, define and quantify which process flows exist within the scope of the LCA. Given that the scope of this study is on bus transportation in Oslo, and that transportation is a complex area to understand, the inventory analysis is an important step. There is a clearly defined process through which the inventory assessment phase must be conducted, in order to meet the requirements established in ISO14044 [35]. This section will implement this process.

4.3 System Boundary

For an inventory assessment section to be effective, a system boundary is required, as a means of limiting the scope of the data[1]. This LCA aims to analyse the input and outputs at the use stage of Ruter's operations. As such, the primary input and output flows that are relevant within the scope of this LCA are outlined below.

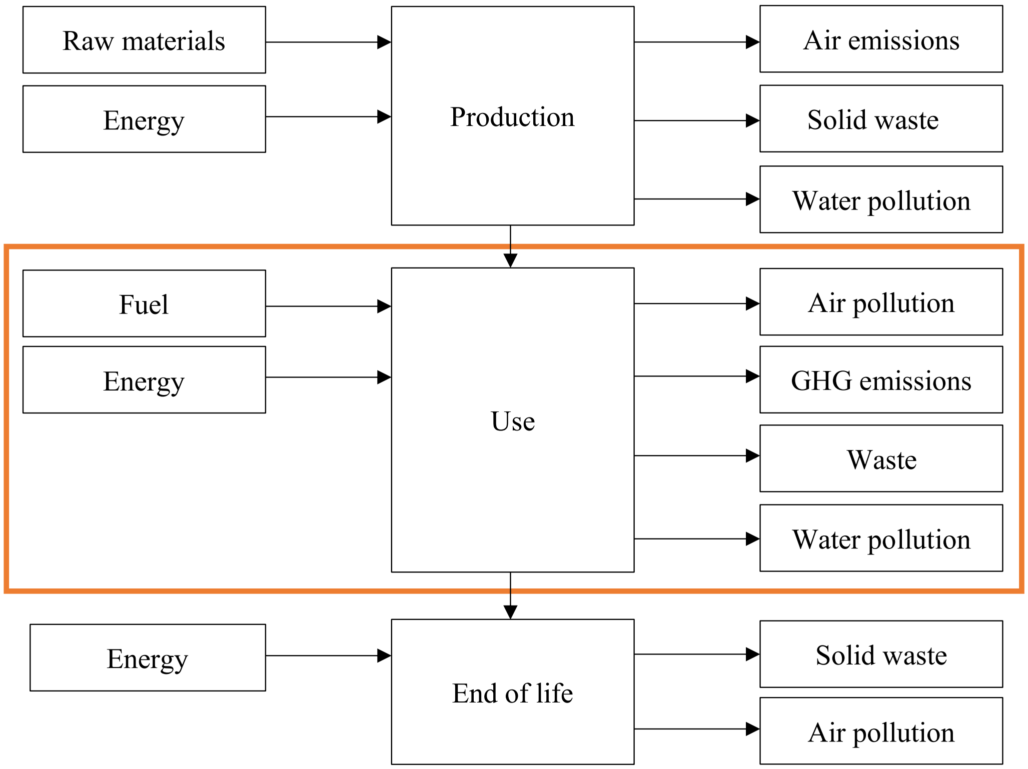

Figure 2: System boundary of Ruter's bus operation, as per this LCA[1]

It is important to note that there are omissions to this inventory assessment as a result of time constraints as well as limitations in scope. Consequently, the extraction and processing of fuel and its outputs are omitted from this inventory assessment. Furthermore, the environmental impact of road and infrastructure construction and maintenance is also omitted from this research.

4.4 Unit Processes

The first step of an inventory analysis is to describes each unit process influencing the input and output flows present in the scope of the LCA [35]. Keeping in mind the scope of this LCA, in this study, there are three main unit processes that impact the carbon footprint of bus transportation in Oslo. These interact as follows:

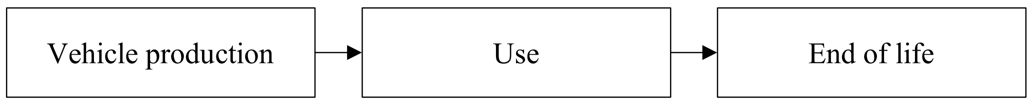

Figure 3: Unit processes in Oslo's bus transportation network

This is a simplified flow graph that outlines the key unit processes which figure in this LCA, it is nonetheless important to provide precisions on what are the inputs and outputs for each of these flows.

4.5 Phases of Assessment

Subsequent to identifying the unit processes, as well as the LCA's boundaries, the inventory analysis identifies the sources of the required data[1].

4.5.1 Vehicle Production

The first unit process refers to the manufacturing process through which Ruter's fleet is produced. Ruter operates around 1100 buses through its twenty-two contracted service providers [11]. Ruter operates five types of buses;

- Standard low-floor city bus, c. 12 metres
- Standard low-floor city bus, c. 13,7 metres
- Articulated low-floor city bus, c. 18 metres
- Regional, c. 13-15,5 metres
- Minibuses 7-10 metres

'Conventional' Bus model information			
	MAN Lion's City 12	MAN Lion's City 18	Volvo 8900
Length	12,2m	18m	13,7m
Weight	19,500kg	28,000kg	24,750kg
Type of drive	Diesel	Diesel	Diesel
Fuel types	Diesel, HVO, FAME biodiesel	Diesel, HVO, FAME biodiesel	Diesel
Emissions Standard	Euro 6	Euro 6	Euro 6
Chassis Material	Steel, aluminium	Steel, Aluminium	Steel, aluminium

Table 1: Technical information on buses used by Ruter prior to 2020 [4, 5, 6, 7]

This is a list that takes into account the Ruter's fleet prior to the end of 60% of its service contracts in 2020 [11]. It is important to take note that starting from 2020, Ruter is rapidly electrifying its fleet, with the aim to achieve 60% electrification of its fleet by 2025 [14]. This invariably has implications on the manufacturing process, which differs between internal combustion engine buses, and electric buses [30].

The manufacturing of both fossil-fuel and electric buses have similar production flows, albeit with different inputs and outputs [30]. It is established that 90% of carbon emissions of buses are emitted during the use phase[16]. This from the outset begins with primary materials.

The manufacturing process is also an important step that demands energy resources, which will have implications on the total carbon footprint of the vehicle production flow, depending on the energy sources. It is established that the majority of buses currently, and projected to join Ruter's fleet originate from European manufacturers [11]. This undoubtedly has implications on the energy sources prevalent in the manufacturing process.

It is important to note the differences in resources that are required to construct conventional diesel buses and electric buses. They have significantly different components and as such require different materials. This is something that has an impact on the carbon footprint of the production process. Something which is clear is that electric buses which utilise batteries have a larger carbon production footprint in comparison to conventional diesel buses[14].

The final input flow which is present in bus production, is the transportation from the manufacturing plant, to the point of use, in this instance on Ruter's bus depots. In the case of Ruter, the majority of its buses are built in Central European countries, such as Germany, which requires some transportation. This is an important step, as the transportation step for a bus represents a significant carbon output. Moreover, as Ruter is rapidly replacing its fleet from conventional diesel buses to electric power trains, this represents an important factor in the total carbon footprint. Many of Ruter's buses are produced by the German manufacturer MAN Trucks & Buses AG. Consequently finished buses must be shipped from Germany to Oslo, either through road transportation or through maritime shipping.

4.5.2 Bus Operations

The main emphasis of this LCA, as outlined in the scope, is on the operational footprint of buses in Oslo, which are largely responsible for Ruter's carbon footprint in over the life-cycle. This refers to the daily operations. There are a number of factors to consider in terms of the footprint. These system flows have a number of inputs which have implications on the total carbon output. In the day to day operation of buses, among the most important aspects to consider is the fuel consumption. This differs according to the type of bus, its size and weight as well as its average load. In Ruter's fleet, in 2016, 77% of buses used diesel fuel [11]. However, more recent data shows a clear decline in diesel use, with a growing use of bio-diesel and electric fuel[2].

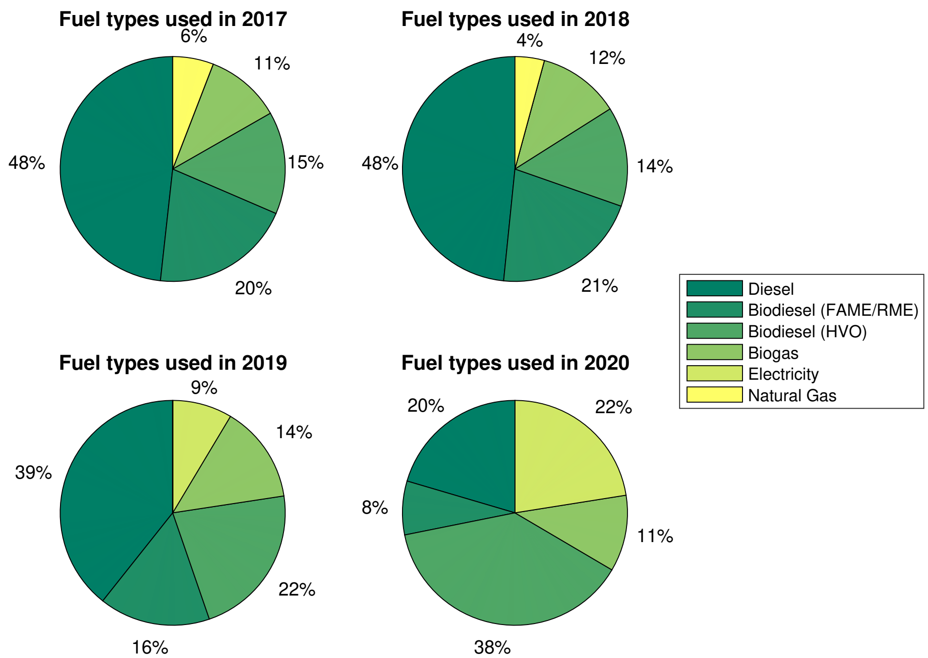

Figure 4: Types of fuel used by Ruter buses in the last 4 years.[2]

In terms of the energy use per passenger kilometre in Oslo city buses, there are a number of outputs to consider; $KgCO_2$, NOx (N_2O), as well as PM emissions.

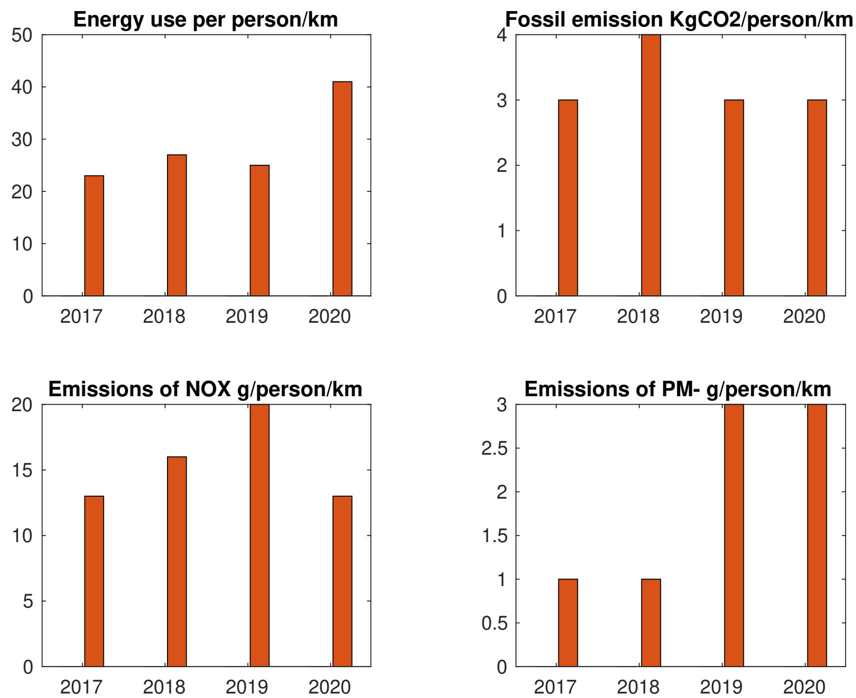

Figure 5: Energy consumption per km for the previous 4 years[2]

Another aspect that is important to consider in the assessment is the output of nitrous oxide, a harmful byproduct of internal combustion engines[36]. In assessing climate change, the main focus is often put on CO_2 emissions, however, nitrous oxide is a significant contributor to greenhouse gas emissions[36]. N_2O emissions are independent of CO_2 emissions and must be accounted for, as a means of establishing the extent of their proportion in the total GHG output from public transportation in Oslo[36]. N_2O emissions data for Ruter's city bus shows a clear decline between 2007-2010 and 2017-2020, although some growth between 2017 and 2019.

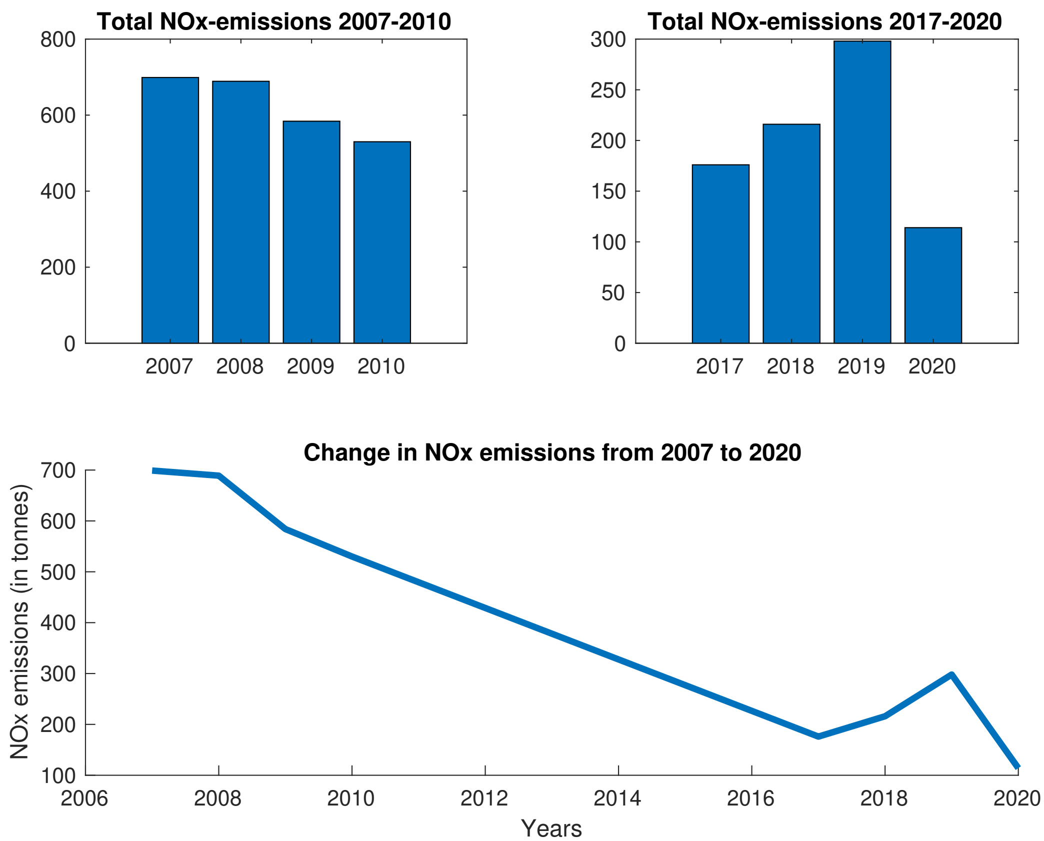

Figure 6: Emissions of Nitrous oxide(N_2O) in tonnes[2]

To determine the extent of the carbon footprint, another flow lies on ridership statistics, which have a significant impact on the total carbon output, given the efficiency implications. As such, this is something that has to be measured according to CO_2e/km/passenger. This has implications both in terms of the amount of fuel required, but also in terms of the efficiency of Ruter's bus service provision. This is especially important in terms of propensity to use public transportation. It is well established that ridership is directly correlated to the proximity of bus stops to homes, central locations as well as the frequency of service[37] and the quality of alternative modes of transportation, such as private cars. This is something that is important given that the total distance covered by the average bus on a daily basis, and that its carbon footprint is inherently related to the passenger load. Ruter's average bus covers 55,000 km on an annual basis [11]. Multiplied by the number of buses in Ruter's fleet (1100 buses) means that buses cover over 60 million kilometres in Oslo on an annual basis.

Figure 7: Map of bus routes in the city of Oslo[3]

This map shows Ruter's network, which is quite extensive. This shows that Ruter buses are required to cover a large territory on any given day. Depending on the ridership data for each of these routes, there would be a difference in CO_2e/Passenger-km according to the type of bus used.

Given that Ruter intends to become zero-emissions by 2028, primarily through electrification[2], it is important to evaluate the methods of electricity generation which will be utilised by Ruter. In Norway, 98% of electricity comes from renewable sources.

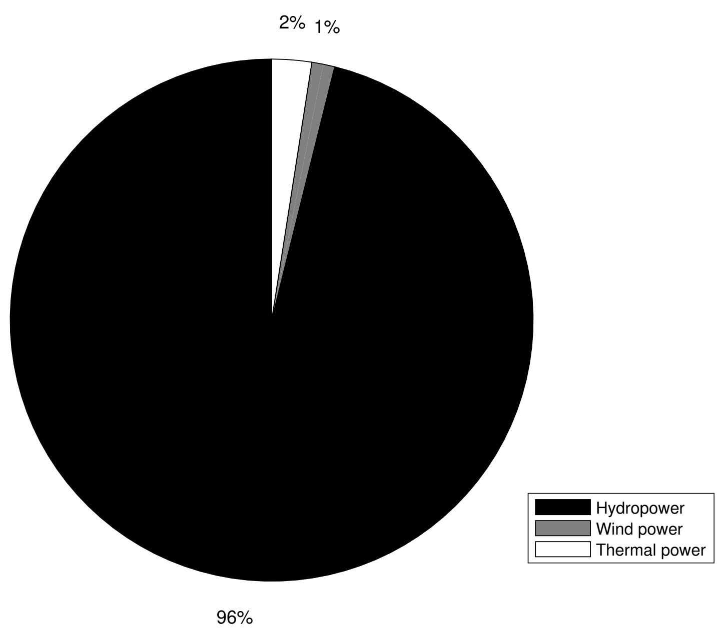

Figure 8: Electricity generated in Norway per source

This chart shows that the vast majority of electricity generated is produced with hydroelectric power, representing 129TWh generated annually. The rest of the electricity generated is produced through thermal power(3,3TWh) and wind power(1,9TWh). This accounts for the 134TWh of electricity produced in Norway annually[38].

4.5.3 End of Life

This phase represents the post-use phase of public transportation. It refers to what happens after the lifetime of the bus expires and it must be replaced. This is especially relevant given Ruter's aggressive plan to decarbonise its operations through electrification[11]. This implies that currently in use diesel, and bio-diesel buses will be phased out in favour of new, electric and hybrid buses[11]. Whilst this is not the main focus of this study, it nonetheless remains important to consider especially in terms of phasing out speed.

The usual bus in Ruter's fleet has a lifetime of 10 years [11] Which represents an average of 550,000km over its lifetime $(km/y/lifetime)$. The output flows generated during the disposal process are dependent on the power trains of the buses. Electric and hybrid buses have fundamentally different disposal processes. There is a well-established process for the disposal or recycling of disused buses. This process differs according to the type of bus which is being disposed of, given the differences in components[39].

Assuming that the majority of buses that will be disposed of in the near future will be internal combustion engine buses, built for conventional diesel fuel, given the plans for electrification. It is important to consider the carbon output generated by the disposal of the replacement of diesel buses in favour of electric buses and batteries. Furthermore, it is relevant to establish the differences which exist between the disposal of internal combustion engine buses and electric power trains.

The disposal phase consists of four main steps:

1. Inspection
2. Draining fluids

3. Removing of parts for recycling
4. Crushing

Referring back to the material data based on buses which are part of Ruter's fleet, the material disposal aspect refers to the outputs resulting from the disposal of the different components present in buses; such as drive-trains, body, interior furnishings and so on. This is something that can have significant impacts on the environment, depending on the methods which are utilised. Removing of parts refers to the re-purposing of certain components present in buses. This is something that significantly reduces the total carbon footprint of the disposal phase[39].

5 Impact Assessment

This section seeks to determine the impact of the processes occurring which have been identified as part of the inventory analysis. This is an important step as a means of identifying the extent of the impact which unit processes have on both the environment as well as on the overall management of Oslo's bus fleet. To achieve this, this section seeks to justify the selection of the assessed categories, furthermore, this section seeks to specify the environmental relevance of each category.

5.1 Impact of bus manufacturing

Whilst this is not within the main emphasis of this assessment, it is important to note that there is an impact on the environment as a result of the manufacturing processes attached to buses. Furthermore, there is an impact linked to a rapid transition from conventional buses and internal combustion engine, to fossil-free and electric buses. The majority of the carbon emissions produced by buses, excluding the use phase stems from the manufacturing process, maintenance as well as infrastructure[40]. Buses are large and complex vehicles that require significant resources to produce[40]. This is something which is important to consider as part of the life-cycle of buses.

5.2 Impact of Use Phase

It is well established that buses have an environmental impact, however, there is a multitude of factors that have implications on the environmental footprint of buses. In the case of the City of Oslo, the key aspects considered include; types of fuels used, the energy use per passenger kilometre, as well as the nitrous oxide output. Furthermore, it is important to establish the data on the utilisation of public transportation. This is something that is informed by a number of factors, such as the routes covered by buses, population density as well as ridership statistics for each route. Combined these elements give a complete assessment of the impact buses have on the carbon footprint of buses in the City of Oslo.

5.3 Environmental relevance

Having established that buses and public transportation as a whole represent a dominant greenhouse gas emitter in Oslo, ca. 4%, the majority of which is caused by buses[11]. Analysing the data shows that buses can be large emitters, thus establishing a significant environmental relevance. The use of different types of fuel, as well as the total ridership, have varying degrees of impact on the environment.

5.4 Impact of bus disposal

The disposal of buses is a process that has significant energy needs[39]. This represents an area that produces a portion of a bus' carbon footprint over its life-cycle. Considering that buses require many components to function[39], it is evident that the disposal of these components is a complex process that requires some attention. However, this aspect of the life cycle assessment goes beyond the scope of this research, though it is important to consider. Furthermore, given that Ruter is rapidly transitioning its fleet from more conventional options, namely diesel and bio-diesel buses[13] to electricity, it can be expected that an increased amount of buses will be disposed of over the coming years.

5.4.1 Interpretation

This final segment of the life-cycle assessment breaks down the findings of the LCA, with the aim of contextualising these findings within the scope of the LCA. It seeks to identify the significant issues based on the results of the assessment, and inventory analysis phases of the LCA, it evaluates that the LCA is complete, and consistent, as well as provides conclusions, an overview of limitations and finally, recommendations[35].

5.4.2 The City of Oslo's Bus Network

This LCA shows the extent to which buses contribute to the total carbon output generated in the city of Oslo over an average year. Buses require a significant amount of resources to operate and are an important contributor to the production of N_2O and PM, which are both significantly damaging to the environment. Furthermore, the LCA finds that bus transportation represents a significant share of Oslo's total carbon emissions caused by transportation. It shows that buses require significant energy resources to operate within the City of Oslo, in comparison to electrified public transportation methods[2]. However, the data shows a clear trend towards emissions reduction.

The data provided by Ruter in their yearly reports show clearly the types of fuels which are used to power their city buses. After converting the units, it becomes possible to determine the percentage of each fuel type that is used. In doing so, we can observe that from 2017 to 2020, conventional diesel usage has significantly decreased; from 48% to 20%. This is a trend which is completely opposite from the use of electric or battery operated buses, which has gone from 0%, or a negligible amount, to 22% of the total fuel usage. This represents a significant difference. Other interesting observations can be made on the use of natural and liquid petroleum gas fuels, which have been completely eliminated from the network.

Whilst it is clear that battery and fuel-cell buses have fundamentally different disposal processes, and that the components for their manufacture have an important carbon footprint, the footprint of their operations, based on the CO_2kg/E/Pkm is significantly more efficient. With the source of energy being overwhelmingly carbon-neutral, it means that they can enjoy a virtually carbon-neutral footprint.

5.4.3 Reduction in CO_2

As it stands, the data analysed in this assessment shows that there are significant benefits for the carbon footprint resulting from the introduction of electric power trains within Ruter's bus fleet. With Ruter's rapid introduction of a continuously growing number of electric-battery operated buses, it is clearly shown in the emissions data that CO_2 emissions have decreased significantly over the past decade. Furthermore, with the near-complete phasing out of conventional fossil-diesel fuels, in favour of HVO and FAME bio-diesels, Ruter's carbon emissions are currently more than halved from the emissions 10 years ago.

5.5 Completeness, sensitivity and Consistency of the LCA

5.5.1 Completeness Check

This LCA focuses on the operational aspects of Ruter's city bus operations in the City of Oslo. As such, there is a significant of data on carbon emissions, energy use, fuel types and greenhouse gas emissions which was analysed as part of this assessment. Given this scope, there is significantly less attention accorded to the manufacturing and end-of-life phases, although some data were analysed. In terms of the operational data, the data which is currently available was assessed. There is a significant opportunity for further assessment in future, given the constant evolution of Ruter's operation, the data on the implications from the disposal and recycling of phased out buses will become more available, as well as the implications of COVID-19 on a number of factors.

5.5.2 Sensitivity Check

Whilst there is significant, reliable data available on the environmental impact of Ruter's operations, there are a number of factors to consider in terms of uncertainties surrounding this assessment. The data provided gives a good understanding of the carbon emissions and the total footprint of buses in Oslo. However, the current situation relating to the pandemic, the numerous lock-downs, as well as work-from-home mandates, have had significant implications on the data for 2020. Furthermore, 2020 was the targeted year for the transition to the exclusive use of fossil-free energy resources in Ruter's bus network, These two events impede the ability to form clear conclusions, given the significant spikes in the data for that year. However, the data from previous years enables the identification of clear trends in relation to the carbon footprint. Further research in years to come will be required, both to determine the impact of the pandemic, as well as to identify further changes in Ruter's operational practices.

5.5.3 Consistency Check

Having established that the scope of this LCA is focused on the use phase of Oslo's bus network, this assessment utilises data relating to the various operational aspects required for bus transportation. As such, the data is consistent with the scope of this assessment. Given that most of the data stems from Ruter's annual reports, which provide clear, complete emissions and operations data year after year, there is no doubt that the data utilised in this assessment is consistent, both in quality and relevance. This life-cycle focuses on a specific case, the city of Oslo, it is therefore quite uniform.

5.6 Limitations

The limitations in this life-cycle assessment have been overwhelmingly related to the issues surrounding data acquisition for the production and end-of-life phases of this assessment as well as the complexity of this field of research. There is significant data available, in relation to the operational aspects. The data relating to production cycles is sparsely available. Not much information on manufacturing is made available by major bus manufacturers, which severely impedes the assessment of this impact. As such, this aspect of the LCA is largely based on assumptions based on other data sources such as studies, something which limits its reliability.

Another limitation relates to the end-of-life phase, given that it is an ongoing aspect of Ruter's operations. There is some information, relating to the average lifetime of buses part of Ruter's fleet, including the average number of kilometres travelled and such, however, not much is available as to what is done with discontinued buses. This can be attributed to the structure of Ruter, which is largely operated through sub-contractors, who do not have the same transparency standards. This impedes certain aspects of this assessment, especially in terms of identifying the resources utilised in the disposal processes, as well as establishing the extent of the circularity of Ruter's bus operation.

6 Chapter 2 - Key Performance Indicator Assessment

Key performance indicators are important tools that can contextualise the findings of a life-cycle assessment. This is achieved through the analysis of commitments and policy priorities on bus transportation, which is then weighted according to the assigned level of importance. The assessment of key performance indicators is an important step in bridging the results of the LCA with the political interests

6.1 Ruter Policies

Ruter being the operator of Oslo's public transportation network is responsible for the administration of its network. It, therefore, holds significant decision power in terms of outlining the priorities for public transportation in Oslo. To this end, it has established a clear policy direction that is aimed at carbon-neutrality, and near-complete electrification by 2025[11]. This suggests a strong commitment to sustainability. Given that the plan as established seeks to electrify completely buses in Oslo starting in 2020, with a view to being completely electrified by 2025. This is an ambitious plan, therefore KPI is necessary to analyse whether it is feasible. Every four years Ruter produces a public transportation strategy. Which aims to produce an overview of the current state of operations, as well as establish clear priorities for the future [8]. In the report published in 2016, Ruter outlines its strategy for the implementation of the Oslo2030 Agenda, from a public transit perspective, as well as establishes the ways in which it can realistically implement these objectives [8]. The report outlines key priorities, which in relation to the significant population growth in the Oslo region[8], as well as the carbon footprint of Ruter's total operation (including rail and boat transportation) which accounts for 60% of Oslo's annual carbon emissions[8]. This context gives a direction to Ruter's policies of which there are many throughout this report.

6.1.1 Ruter Policy Indicators

1. Attractive Public transportation
   - Development of public transportation which is an attractive, first choice option for individual mobility (as opposed to a private car, for example).
2. Integrated public transportation journeys
   - Offering a service which seamlessly integrates the different types of public transportation services, Bus, rail, boat, from point a to point b.
3. Reliable public transportation
   - Offering a service which users can rely on for timely, rapid and effective transportation
4. Public transportation from renewable energy sources
   - A bus fleet which is entirely powered through renewable energy sources from 2020, using; electricity, hybrid power-trains, bio-fuel; bio-diesel and bio-ethanol.
5. Total electrification by 2030
   - A bus fleet which is entirely electrified, through battery and fuel-cell powered electric buses.

These five indicators stem from [8] and outline the priorities which are most relevant to this study. It is important to establish which indicators are most related to the scope of the life-cycle assessment, as it enables the KPI model to complement the data generated, as a means of establishing the extent to which the policies are implemented, which ultimately has implications on the carbon output.

6.2 Oslo Municipality Policies

The City of Oslo has outlined a progressive agenda towards sustainability, which seeks to reduce the number of cars present within its urban core. A component of that plan is to improve the current public transportation service offering, as a means of encouraging use. The city of Oslo has committed to having a fossil-free public transportation system by 2020[41]. Meaning that buses will be powered through renewable sources entirely. This works in conjunction with the Emissions free 2028 commitment[41].

The city of Oslo has a set of policies that are significantly interconnected with those established by Ruter. As a result, this means that they share goals. The importance of performance indicators in the context of Oslo kommune policies lie in the impact these have on Ruter's progress. The city of Oslo is ultimately responsible for the urban planning and physical infrastructure which facilitates the implementation of Ruter's policy. There is, however, no doubt that the policies of Oslo share links with Ruter. Oslo municipality policies are mainly centred on infrastructure development as a result of urban expansion [41]. These seek to alleviate the issues which are susceptible to arise as Oslo experiences significant growth, especially in terms of transportation; increasing numbers of cars, overcrowded public transit, overcrowded vehicles and so on[41]. Furthermore, it is established that Oslo kommune is determined to ensure that alternative transportation methods are prioritised over cars, through the development of effective alternatives, of which buses are an important aspect[41].

6.2.1 Oslo Kommune Performance Indicators

1. Green transportation infrastructure

    - Developing infrastructure projects which support the furthering of green public transportation options.

2. Measures to promote the of public transportation

    • Developing measures to encourage the use of public transportation and electric vehicles as a means of improving the air quality.

3. Prioritising public transport users, pedestrians and cyclists

    • Creating policies which prioritise public transportation users, pedestrians and cyclists over motor-cars, with a view to reduce car traffic by 20% by 2020.

4. Cutting greenhouse gas emissions by 95% by 2030.

    • An ambitious goal which aims to achieve near carbon neutrality by 2030. Intend to completely eliminate emissions from public transportation, which accounts to over 60% of Oslo's total carbon output.

5. Urban development centered on public transportation

    • Ensuring that urban development is designed in relation to the accessibility of public transportation.

These performance indicators have been identified from a number of documents published by the City of Oslo; such as its Strategic plan for 2020-2023 [42], its climate and energy strategy [9] as well as its policies on public transportation [41]. These indicators have been selected to address the gaps in the indicators selected for Ruter's policies, mainly as a result of different roles and responsibilities.

6.3 Weight Distribution and Data Modelling

KPI assessments rely on the attribution of value to the different indicators in terms of their assessed impact on the overall indicators. To that end, it is important to establish indicators from the policies identified as relevant.

Indicators		
Policies	Indicators	Weight
Development of attractive public transportation	Modern buses	Advanced
	High departure frequency	Most advanced
	Rapid transport	Most advanced
	Infrastructure projects for public transportation	Advanced
	Urban development around public transportation	Less advanced
Integrated Transit Journeys	Effective links between methods of transportation	Less advanced
	Prioritising public transportation, walking and cycling over car use	Advanced
Reliable public transportation	Timely service	Most advanced
	Consistent service	Most important
	Rapid transit between key locations	Advanced
Use of renewable energy sources	Fossil-free bus transportation from 2020	Advanced
	Phasing out of conventional diesel fuel	Most advanced
	Use of HVO and FAME biodiesel	More advanced
	Cutting greehouse gas emissions from transportation by 95% by 2030	Advanced
Electrification of the bus fleet by 2030	Gradual replacement of the current bus fleet	Advanced

Table 2: Performance indicators with qualitative attributed weight[8, 9]

It is important to assign a mathematical weight to the qualitative range, as a means of calculating the performance of the indicator. In the scope of this research, the scale goes from most important to least important, as means of determining the extent to which we believe the indicators are important in the successful implementation of the policy it aims to quantify. Whereas the 'most advanced' qualitative weight is assigned a value of 4, the 'least advanced' score is assigned a value of 0. This weighing is developed for the purposes of this thesis. This offers a mathematical calculation of the indicators which are thought to be most critical to the success of a policy.

6.4 Mathematical Scale

After identifying the policies which form the basis of the performance indicator, it is crucial to assign a numerical value, which allows for a quantitative assessment of performance.

Quantitative Scale				
Least advanced	Less advanced	Advanced	More Advanced	Most Advanced
0	1	2	3	4

Table 3: Values assigned to each qualitative assessment valuations

Mathematically, this quantitative scale is put into in a series of mathematical equations, which provides the results of this performance indicator assessment. In this instance, the mathematical model is comprised of this formula:

$$P_1(Performance), \% = \left(\frac{(V - Min_V)}{(Max_V - Min_V)} \right) \times 100$$

This formula calculates the actual performance of the indicators, as well and the progress, in relation to the baseline. This gives significant insight as to where Ruter and the City of Oslo are in terms of progress, from a policy perspective. The

$\mathbf{P}_1$ formula evaluates performance, based on the maximum and minimum values in the scale. Adding the value of the attributed weight for each performance indicator gives the performance percentage amount.

7 Key Performance Indicator Results

This assessment aims to contextualise the LCA results with policies in the City of Oslo. By applying the mathematical models to obtain the performance and progress values of Ruter and Oslo's public transportation policies, we gain important insight into the current and future outlooks. In this analysis of performance indicators developed from Ruter and City of Oslo policies, there are clear signs of advancement for a number of the indicators, which exhibit high levels of advancement in terms of performance. Together these two formulas give an overview of both the performance and the progress achieved for each KPI, which in turn gives insight into Oslo and Ruter policy implementation.

7.1 Achieved Goals and Long-term Objectives

There are a number of policies that have objectives that had 2020 as a deadline. In these instances, the KPIs aim to establish whether these objectives have been fulfilled, as opposed to whether they are on track to be implemented. This is something that is useful as a complement to a life-cycle assessment, given that it gives an added contextualisation to the environmental data. In terms of the 2020 objective to phase out the use of fossil fuels in the operation of buses, the LCA data shows that is near completion. KPI assessment is helpful in that it enables a quantifiable differentiation between achieved goals and policies and the progress made towards long-term objectives.

7.2 Results of the Assessment

The key performance indicator quantitative assessment, based on the established qualitative grading scale, is itself rooted in the policies of Ruter and the Municipality of Oslo. Show a positive outlook on the implementation of these policies.

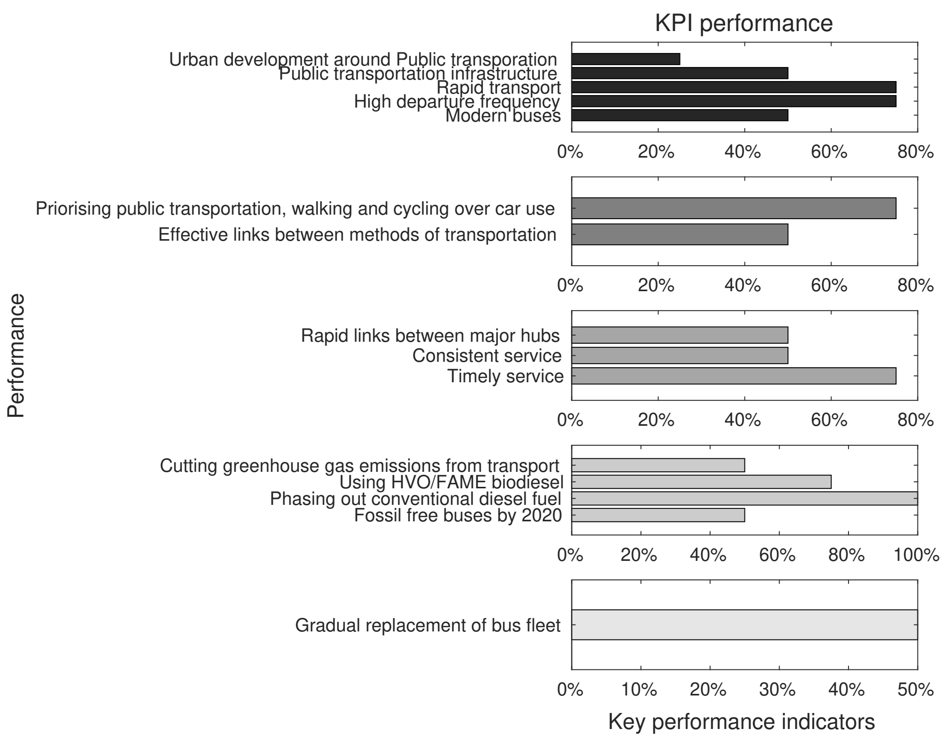

Figure 9: Performance percentages of the KPI analysis

The data produced in the KPI assessment clearly shows that Ruter's bus operation is already a well-functioning, modern operation. This is evidenced by the high performance assessed for advancement in the attractive public transportation policy area. An area that has advanced to a lesser degree than other indicators is urban development around public transportation, which appears to be lagging behind other indicators[11]. Another area where Ruter and the City of Oslo are progressing well towards advancing their policy priorities is in the development of integrated public transportation. Ruter offers an advanced level of service which effectively links between types of transportation. Furthermore, the city of Oslo has a very developed urban planning scheme to prioritise cycling, walking and public transportation, thereby discouraging the use of cars in the city centre, in addition to toll roads, as well as roads where private cars are not permitted to access[42]. The KPI analysis shows clear progress towards near-complete implementation of these priorities. In terms of effective transportation, the data suggests that Ruter is already offering reliable public transportation services[11], with consistent, timely and rapid routes. This is consistent with the policies established in that area and shows clear signs of progress. Ruter and Oslo have designed ambitious policy priorities towards the elimination of fossil fuels and major reductions in carbon emissions. Given that 2020 was the deadline for the elimination of fossil fuels from Ruter's bus fleet, the data present in the 2020 report shows that it is very near completion, with a major reduction in fossil energy consumption in 2020. Conventional diesel fuel has more or less been completely eliminated from regular service. The transition to non-fossil fuels, such as HVO and FAME bio-diesel is advancing rapidly. Overall, the KPI analysis shows that this policy area is significantly advanced. This is perhaps most evident in relation to the elimination of conventional diesel fuels, which was largely achieved in 2020. This represents the completion of a significant policy objective in 2020.

7.2.1 Development of Attractive Public Transportation

This policy section relates to the public perception of public transportation services. This is an important aspect to consider, given that it is established that ridership data significantly influences the carbon footprint data, based on the carbon emissions per passenger/km. It is well established that attractive public transportation is more likely to attract higher ridership numbers, thus the importance for Ruter as a policy aspect. The assessment of the indicators assigned to this category shows that this is an area that has progressed significantly, as is evident in ridership data, as well as the passenger/km data. However, there are other areas that are progressing at slower rates, namely the prioritisation of urban development designed around public transportation.

7.2.2 Integrated Transit Journeys

This is an area that is important, especially in the case of large cities, such as Oslo. Given that cities cover an extensive area, it is important for public transportation users to have the ability to reach destinations across the city, effectively. This is important in terms of public satisfaction with the system, but also in terms of the ability to limit the routes of each transportation category. Limiting the routes covered by buses reduces the distance travelled, which can have implications on the carbon footprint. This category shows that Ruter's transportation system is efficiently integrated. There is a high level of integration between the various available modes of transportation. Furthermore, the Municipality of Oslo's ambitious policies has resulted in clear advances regarding public infrastructure designed around pedestrians, cyclists and public transportation users.

7.2.3 Reliable Public Transportation

Reliable public transportation is an important metric to measure the effectiveness of a transport service. In the first place, it is an area that is important in terms of customer satisfaction. In the context of a carbon footprint assessment, this is important as it has an inherent impact on the public use of the bus network [10]. Increased reliability is generally understood to be an important factor for ridership data [10]. The data from the KPI assessment shows that Ruter operates a generally reliable service with a high level of advancement.

7.2.4 Use of renewable energy sources

The use of renewable energy sources is not only a crucial aspect of the LCA data but also a significant aspect of Ruter's operating principles and policy objectives. Renewable energy use is directly linked to the carbon footprint of buses, especially in the operational phase. This aspect represents a very effective way of reducing the carbon footprint of buses in Oslo, as well as reducing GHG emissions, thus limiting air pollution. The indicators in this policy category show clear progress. Especially in relation to the elimination of conventional diesel. The proportion of renewable energy sources, such as HVO and FAME bio-diesel is growing, as is electricity. This shows good levels of performance as well as progress.

7.2.5 Electrification of bus fleet by 2030

Electrification is a significant aspect of Ruter's policy objectives. This is something that will have a major impact on Oslo as a city and on Ruter as a public transportation operator. This is something that has the potential to significantly reduce the carbon emissions of buses in Oslo, especially considering that the majority of the electricity used by Ruter comes from renewable sources [14]. In this assessment, this indicator is another which clearly shows a high degree of performance. There have been significant advances in electrification, aided by a rapidly growing electric drive bus fleet. as of 2020, over 22% of the fuel used in buses by Ruter is electricity, which shows that it has progressed, but that significant work is needed to reach the 2030 objectives.

8 Chapter 3- Results and Discussion

The analysis of the data provided by Ruter, as well as data provided by third party agencies, (such as EnTur) offers a clear portrait of the carbon footprint which Ruter produces through its urban bus service offering. Furthermore, it clearly shows the extent to which it is progressing towards its carbon neutral commitments. The data exhibits trends towards great reductions in carbon output, as well as a rapidly declining carbon footprint. There is also an indication of the declining use of resources, as indicated by the lower energy use per person/km. Another outcome that is exhibited by the life-cycle assessment is the insight it provides into sustainable transportation development. It is clear that it can be an effective tool for decision-making. As for the KPI analysis, it is a method which allows for a quantitative assessment of qualitative factor, in this case, public policy, based on the progress and performance of the established metrics. This thesis has proven to effectively provide significant added context in terms of the policies and operational aspects relating to Ruter and the city of Oslo. Furthermore, this assessment has clearly shown the advancement and progress made by Ruter in a number of key policy areas.

8.1 Results of Life-cycle Assessment

The life-cycle assessment of Ruter operated buses in the City of Oslo gives significant insight into the carbon footprint of public transportation in the context of a decarbonising European capital city. More specifically, it shows the many ways in which buses have the potential to significantly reduce their footprints, through the adoption of new technologies. In terms of the carbon footprint which Ruter's buses produce, the LCA gives a complete overview of the carbon output, and resources used in the course of the use phase. All of which were assessed, to evaluate the extent of Ruter's footprint on the environment. The results show that there are clear links between the types of energy technology used and the greenhouse gas emissions produced by buses in Oslo. The analysis also indicates that there have been major reductions in terms of carbon footprint by Ruter, over the previous decade. The evaluation of data in this framework provides a clear overview of Ruter's operations and shows the carbon footprint generated by buses in Oslo. It gives precise insight into which aspects are most important in the carbon footprint of a bus network as is indicated by the data produced in the LCA.

8.1.1 Use Phase

The scope of this LCA was focused on the use phase of the life cycle. As such, the LCA of the use phase gives significant insight into the total footprint of buses. Furthermore, it illustrates the extent to which this footprint is dependant on a variety of factors. These factors are; the types of fuel used, the resources required per passenger kilometre, the distance covered as well as the number of passengers transported. The LCA shows clear differences from 2010 to 2020, with 2020 numbers being much lower, both in terms of carbon output and in terms of resources used. A more detailed analysis of the various factors shows significant progress towards the objectives outlined by Ruter, in relation to the reductions of its carbon footprint produced at the use phase.

8.1.2 Types of Fuel Used

The first output factor which was examined in the inventory analysis is fuel types. This shows the extent to which Ruter has rapidly transitioned from primarily using diesel fuel (48%) in 2017 to 20% in 2020. representing a 58% decrease. Another interesting observation is Ruter's departure from liquid petroleum gas and natural gas, which after a short rise in 2019 (from 6% in 2017 to 9% in 2019), seems to have been entirely discontinued in 2020. The data shows that there is an emphasis on the use of biodiesel (HVO) which is steadily growing year after year. Finally, there is a clear rise in the use of electricity, which rapidly grew to over 22% of the total fuel used. The data clearly shows that Ruter is undergoing significant changes, in terms of the types of fuels it uses. Furthermore, it indicates that it is rapidly transitioning from using conventional, fossil fuels to fuels from renewable sources, such as HVO biodiesel and electricity. This is a clear indication of progress, in a transition to a carbon-neutral operation. This is an area that has significant implications on the downstream carbon footprint of Ruter, given that it gives a basis for carbon reduction, thus giving

8.1.3 Energy Consumption and Emissions per Passenger Kilometre

The types of fuels used by Ruter buses is especially relevant when it is analysed with data on the fossil emissions per passenger/kilometre. This number is heavily dependent on the number of passengers who use the buses, as this translates to more effective use of resources. Given that buses require a minimum amount of resources to be effective, more passengers translates to better use of resources

In the case of Ruter, the energy use per passenger/kilometre is more or less stable, at around 0,30/passenger/km over the years. It is important to note that the coronavirus pandemic has to lead to a significant increase in energy use per passenger/km, as a result of the pandemic's impact on passenger numbers. It is useful to contextualise these numbers with data on the carbon emissions per passenger kilometre. In the case of Oslo, the number is at around 3kgCO_2/Pkm, for the year 2020. This is another number that has been relatively stable, barring a small increase to 4KgCO_2/Pkm in 2018, since 2017. However, the current carbon output is much lower than the data from the previous decade. The analysis of N_2O and PM emissions is a bit less conclusive, given that they display both a significant decrease in emissions from 2010 to 2020, yet an increasing trend, starting in 2017. In terms of assessing the current carbon footprint, we can note that the numbers show low emissions of both N_2O and PM.

8.1.4 Carbon Footprint of Ruter Buses

The life-cycle assessment provides a clear overview of the carbon output of bus operations in the city of Oslo. It also shows clear signs of carbon reduction progress. As things are currently, Ruter operated buses have a carbon footprint which is significant. This is partly due to the continued use of bio-diesel which, whilst non-fossil, release greenhouse gases. The LCA, therefore, shows clear signs of progress, but outlines the need for continued progress, especially in terms of electrification. The LCA also shows the extent to which Ruter has progressed towards its objectives. With the majority of Ruter operated buses in Oslo now functioning with renewable energy sources, such as bio-diesels and electricity, their total footprint is greatly reduced. The analysis of the data using the LCA framework clearly shows that Ruter is fulfilling its objectives in terms of decarbonisation. However, it is also clearly established that buses continue to produce a large share of total transportation carbon emissions in Oslo. Relying mostly on data from the use stage, which is the most important stage in terms of carbon footprint.

The LCA shows that, whilst the production of damaging GHGs, such as N_2O and PM has been significantly reduced over the previous 10 years, the emissions have been experiencing growth in 2019 and 2020. This is something to keep in mind, given that Ruter buses will continue to use non-electric fuels for the foreseeable future. Whilst Ruter is using a majority of non-fossil fuel-based energy sources, it is important to take into account the GHG gas emissions which it releases as part of its current carbon footprint. Furthermore, as it works towards carbon neutrality, it is worrying to see N_2O and PM emissions growing.

8.2 Results of Key Performance Indicator Assessment

The analysis of key performance indicators gives an added context to the results of the LCA. It provides a framework for the analysis of policies that guide Ruter. The results of this assessment clearly show that Ruter is an effective transportation agency, which fulfils its objectives effectively, both in terms of environmental commitments, as well as efficient transportation services. Another aspect that is clear in the KPI assessment is the influence of the City of Oslo, and its ambitious objectives towards carbon-neutrality.

Utilising the results from the LCA to conduct the KPI assessment shows that Ruter is progressing well towards achieving its policy aims. Furthermore, it shows that it is advancing well in the majority of its goals, suggesting a more global approach to policy implementation, as opposed to a more single-issue approach. This is interesting, as it suggests that the majority of these policies are deemed to be equally important. Furthermore, in terms of implementation, it means that Ruter is less likely to have areas that fall behind, as they progress. The area which is advancing to a slower rate, as per the KPI assessment, is in the urban development aspect, though an area managed by the Municipal authorities. It is an area that is important to consider as a key element of an environmental strategy.

8.2.1 Policy Implications

This life-cycle assessment shows the extent to which these data assessment mechanisms can have implications for policy decisions. In the context of the city of Oslo and Ruter's bus operations, it confirms that the policy decisions are being implemented and that there is significant political capital to further reduce emissions. As a tool for the development of sustainable public transportation, the LCA provides a framework for the assessment of existing infrastructure. Furthermore, it allows for a periodic assessment of changes, thus measuring the impact of new policy implementations and such. Therein lies the value of LCAs as a policy development tool.

Given that this KPI assessment is rooted in the policies established by Ruter and the city of Oslo, their implications are inherently correlated. Policy-wise, there is no doubt that KPI assessments provide an interesting way to calculate, and measure - based on valuations and targets - the progress made in policy implementation. As such, the implications of this KPI assessment relate to the use of measurable data in policy development. For Ruter and Oslo, this KPI assessment is overwhelmingly positive, as it clearly shows that they have developed policies that are being implemented, something which is exhibited in the results of the KPI assessment.

8.2.2 Life-cycle Assessment as a Tool

As a tool for policy development, the LCA framework is no doubt useful. It provides verifiable, tangible data analysis which in turn can be utilised to develop more effective policies. Given the complexity of public transportation, which is an area that requires a number of different areas of expertise, there are no doubt significant benefits to the use of such a framework, to analyse implementation. Though there are challenges associated with data acquisition. The LCA framework provides a method to analyse the carbon footprint of a system by categorising each aspect of its life-cycle, which is useful for such large-scale development projects. In terms of public transportation, an LCA enables the separation of the production cycle, from the use phase and finally the disposal phase. Furthermore, given the numerous flows which exist for each phase of the cycle, LCAs can focus on a single issue. This is something that is useful in this area, as it allows for the assessment of a specific area, based on current priorities.

8.3 Interpretation

This thesis is rooted in a multi-disciplinary approach, which aims to facilitate the analysis of a wide range of technical areas. This is done through the implementation of a LCA framework and a KPI assessment. As such, this provides a wide range of data. From which a wide range of interpretations can be developed. The scope of this research is based on the carbon footprint of buses in the city of Oslo, as well as the use of a LCA framework as a tool for decision-making and as such, the results must be interpreted through that lens. In terms of carbon footprint, the research shows that the vast majority of emissions from buses in public transportation occurs during the use phase. This is significant, given that the ways in which buses are utilised differ from city to city, thereby resulting in vastly different carbon footprints. In the case of Oslo, buses are largely run with renewable energy types, thus greatly reducing their footprint. We also see that Ruter is adopting a gradual approach to its transition to full electrification. Rather than immediately replacing its entire existing fleet of buses, which would no doubt have significant implications on the use-phase carbon output of its operation, Ruter is gradually upgrading its buses, whilst utilising in a majority of cases, fuel from renewable sources, which reduces its footprint whilst it works towards electrification. This is something that is evident in the LCA data.

The results of this LCA show that there is significant progress that has been made towards Ruter's environmental objectives. The data shows clearly that there has been significant progress towards carbon neutrality. This means that Ruter is committed to altering its operational procedures, and is rapidly working towards meeting its ambitious climate targets. The current data shows clearly that Ruter is on the right path towards meeting its objectives in 2030.

8.4 Implications

In terms of climate footprint, the implications of the LCA are that Ruter has reduced its carbon footprint, and is working towards full electrification rapidly, as is indicated in the data.

The implications of this research in terms of decision-making related to the tools which are available to facilitate the development of effective, data-based decision making. The LCA framework offers a method for the Administration of companies to assess their operations and utilise the results of such assessments as a basis for policy development. In the context of this LCA, the implications clearly show that Ruter is developing ambitious, but realistic policies, which it is able to successfully implement.

Something which can be seen in the results of the LCA is the impact of the global Covid-19 pandemic on public transportation in Oslo. Whilst Ruter was steadily reducing its carbon emissions, and utilising few resources per passenger/km it is clear in the data that the significant decline in passenger numbers has had implications on the efficiency, from a carbon perspective of its buses. It is difficult to say what the consequences of the pandemic will be on public transportation in the long run, but as things are, the data shows that Ruter buses utilised more fuel and energy per passenger-km in 2020 than in 2019. This is especially important to show the extent to which the number of passengers in buses affects their efficiency. Furthermore, it shows that further research is important, as a means of determining what the impact of the pandemic was on Ruter's operations.

As it relates to the implications of this data on Ruter's operations, it will be interesting to see how it adjust its services to a reality where less emphasis is put on commuting. Beyond that, it is interesting to think about the extent to which Ruter's bus services will evolve over the next decade. Especially considering the major changes between 2010 and 2020, which saw GHG emissions nearly halved. That, in addition to the KPI assessment, suggests that significant changes could happen in the next few years. It is also interesting to consider the ways in which technological advances relating to transportation coordination throughout the value chain will have implications on public transportation as a whole.

8.5 Limitations

The life-cycle assessment framework is based on the data which is available at the time of its application. It gives a view of the total life-cycle carbon footprint of an operating system which is limited to the time of the assessment. Whilst it is possible to assess data from previous years, as is done in this research, it is not possible to assess data that is not yet available, such as the outputs produced by the phasing out of Oslo's buses. As such, the LCA framework relies heavily on data trends to determine what the most likely outcome of an operation cycle is. In the context of this research, the implications of the global pandemic mean that the data for the last available year does not offer a reliable view of a normal year of operation, something which limits the development of conclusions.

Another limitation to this method lies in the availability of data. It is evident that there are significant data, given the overwhelming reliance on commitments to transparency. It is significantly challenging to obtain data on the manufacturing cycles of industrial buses. Whilst the scope of this research is rooted in the operational aspects relating to Ruter's bus service offering, there is no doubt that the manufacturing of buses is an important component that must be taken into account. With greater availability of data, research in this aspect of the production cycle would be more easily achieved, thus providing added insight. There is no doubt this is a complex field of study, which adds a layer of challenges to the research.

8.6 Recommendations

The results of this thesis form the basis for a number of recommendations. In terms of recommendations relating to Ruter's operations, it is clear that it must continue on its current trajectory. As things are, Ruter is progressing rapidly towards its objectives, in a way that is sustainable and realistic. It has taken a trajectory that clearly favours long-term objectives over instant achievement, something which the data proves to be effective. In recommending that Ruter continues on this current trajectory, we establish that the trends in carbon footprint project a sustained reduction in carbon emissions, based on the fact that the data shows clear changes over the previous decade. Furthermore, it is expected that these trends will continue to 2030 and beyond when Ruter is expected to have reached its objectives of a fully electrified bus fleet.

As for the future, we would advise Ruter to continue evaluating its emissions data, as well as to focus on ridership statistics. This is important as the world, and Ruter recovers from the global pandemic. As the data shows, there have been significant reductions in the number of passengers transported by Ruter, up to a 40% reduction from 2019 to 2020. As the emissions data, this has severe implications on the emissions data per passenger/km. It is difficult to see how the pandemic will affect Ruter's operations in the long term. However, through the implementation of an LCA framework, as well as other data analysis frameworks, it will be possible for Ruter to assess the emissions data on a continuous basis. This recommendation is based on the data currently available, which shows the extent to which ridership is important for the carbon footprint of buses. Furthermore, it is based on the idea that continuous data assessment will enable Ruter to adjust its operations to provide more effective public transportation for its customers, as well as limit waste and most importantly, reduce its carbon footprint.

As for recommendations in terms of future research, there is significant potential for further research in this area. There is no doubt that public transportation and transportation, in general, will continue to be important as a study area. This is something that is based on the importance of transportation as a carbon-emitting sector, both in Oslo and on a global scale. More specifically, we would advise that more research be conducted on the infrastructure which is required to support public transportation. This is an area that is not approached in this thesis, but it is a very important component of the carbon footprint generated by public transportation. As such, we would recommend the application of this methodology to this aspect, as it would provide for a different outlook of Ruter's operations.

Another area which we would recommend as an area for further study is no doubt the aspects relating to the impact of the coronavirus on urban areas in general, as well as public transportation. The data which is currently available gives a small idea of these implications, but there is no doubt that in future, as more data becomes available, it will be possible to analyse this data more deeply and formulate clear conclusions. This is both interesting and important, given the space occupied by public transportation in the daily lives of cities and their inhabitants. This is something that would be important to study both from an urban perspective as well as a climate and carbon footprint standpoint.

The results of this research have given an outlook of Ruter and the operation of its buses from a climate perspective as things currently stand, but there is no doubt that there is space for further research, which would give an interesting perspective as things continue to evolve year after year.

9 Conclusion

In conclusion, the consequences of climate change are severe, and there are many ways to address these issues, and works towards reducing the carbon footprint of our society's daily activities. One area which represents a significant carbon footprint, thus the interest in assessing its footprint. Society is constantly evolving towards increasing urbanisation, which in turn results in increased urban construction, something which has a significant carbon footprint. Cities, especially growing cities, require a tremendous amount of resources, whether for housing or transportation, thus the importance of public transportation. Public transportation is often considered to be a far more environmentally friendly way of travelling around a city, but to what extent do we understand the carbon footprint of buses? Furthermore, how can life-cycle assessment be used as tools for sustainable public transportation development?

These questions are the main objectives of this thesis. Utilising the LCA framework gives an opportunity to get an understanding of the carbon footprint produced by buses operated by Ruter in the City of Oslo. What is clear in the data is that buses continue to produce greenhouse gases, however, the emissions produced by buses have greatly declined over the last decade. Another indication in the data is that the emissions per passenger/km have also greatly declined, and were declining year after year until 2020. The types of fuels used by Ruter have also changed over the past few years, with current fuels being primarily from renewable sources, as opposed to conventional fossil fuels. An area that is more concerning relates to the emissions of dangerous greenhouse gases, such as N_2O and PM1 which while being emitted to a much lower level than in the past, have risen in the previous two years. Overall the data produced in the LCA shows that Buses in Oslo continue to be a large emitter and that they have a significant carbon footprint. However, the data also shows clear signs of a reduction in emissions. Furthermore, the data shows that the transition to electricity is rapidly progressing.

As for the second question; the extent of LCA as a tool for sustainable public transportation development is no doubt significant. Based on the application of this standardised framework, it is evident that it provides a method that can be utilised to assess operations, as well as develop effective policies and practices which address the more important or pressing issues.

The scope of this research touches a number of theoretical perspectives, among those most prominent are the Sustainable Development theories, which are largely influenced by the 17 goals established by the United Nations. These goals, and more specifically goals 9 and 11, inform policy development, something which is evident in Ruter and Oslo policies. As such they are highly influential in the carbon footprint of Buses in the City of Oslo. Another theoretical area is that of circular economy, which aims to further reduce the carbon footprint of day-to-day activities, through economic and industrial restructuring. This relates to buses in public transportation as it represents an industrial system that has the potential to become more circular, through innovation. Furthermore, discourse on circular economy suggests that governments and government-owned enterprises hold significant influence in that transition, thus concerning Ruter and its corporate practices.

9.1 Theoretical Conclusions

Theoretically, this thesis roots itself in the concepts which relate to Sustainability and environment and circular economy. One of which relates to the United Nations' Sustainable Development Goals, and Agenda 2030. These aim to create a framework for policy development that is sustainable. In the context of public transportation, two of the 17 goals are especially important SDG 9: Industry, Innovation and Infrastructure as well as SDG 11: Sustainable Cities and Communities. These are especially important as they relate most to the factors which inform the ways in which public transportation services operate. They have the most potential, as conceptual frameworks, to influence the ways in which these services are developed, and the ways in which they impact the environment. Given the scope of this thesis, it is evident that buses in Oslo are operated in such a way that fosters the development of sustainable infrastructure; through its electrification plan, for example. Furthermore, there is even more evidence that these SDGs are important in the context of the KPI assessment, which shows a number of policies across a number of categories that closely relate to both SDGs 9 and 11.

Another theoretical framework that is important in the context of this research is that of circular economy, which is no doubt, closely related to matters relating to public transportation. Circular economy relates to the operation cycles of industries, with the overall aim of designing out waste. In the context of public transportation, and more specifically buses, there is space for greater circularity. This is evident in the LCA, given the continued reliance on some fossil fuels, which produce the most waste. The data suggests that there continues to be potential for circularity, through electrification. What is clear in this research is that circular economy is an interesting way to look at the issues which have implications on the climate. Furthermore, it is an interesting theoretical perspective as it relates to public transportation. Furthermore, with the methods employed in this research rooted in the life-cycle assessment framework, the circular economy gives context to the results and helps inform the implications of Ruter's carbon footprint.

Looking at the results of the LCA through the circular economy theoretical perspective gives insight into how more circular practices have implications on the environment. This is most evident in the context of Ruter's transition to renewable energy sources. The LCA data clearly shows that the increased use of renewable energy sources has greatly reduced its carbon footprint. Seeing as the circular economy as a theoretical concept encourages the implementation of more renewable practices as a means of reducing a company's carbon footprint by design, the data shows the ways in which this theoretical framework relates to this case. Overall observing Ruter through the perspective of circular economy theories gives an added context to the results of the LCA and KPI assessments, as well as exemplifies the ways in which organisations can work towards reducing their footprints, by altering aspects of their operations.

9.2 Methodological Conclusions

The methods employed in this research are not new, however, there is no doubt that the results from applying the LCA framework, as outlined in ISO 14044, and ISO 14040 are constantly evolving, as the data changes. The LCA conducted in this thesis shows the carbon footprint of Ruter as things currently are, and shows the progress which has been done over the years, yet is constantly evolving. Therein lies the interest in this method as a study tool, especially as Ruter moves towards electrification. There is no doubt that this framework will be relevant in

10 years, and that the results will be different, offering a different perspective of buses in the City of Oslo.

The LCA approach is applicable to many different areas of operation. Given that it is a standardised practice, it can be utilised to analyse the carbon footprint of any industry, service or product. In this instance this meant that the LCA had to be more limited in scope, considering the complexity of public transportation as a system. Focusing on the aspects relating to operations of buses in Oslo gives this LCA a more limited scope, which eliminates a number of aspects.

9.3 Reflections

There are a number of outcomes from the data analysis which provide the basis for greater reflections on the carbon footprint of buses, and public transportation in general. Using the data as well as the LCA frameworks shows clearly that buses and their carbon footprint are significantly impacted by the types of fuels which they use for propulsion. What is especially interesting in the case of Ruter in Oslo, is the speed at which they have transitioned from using - principally conventional fuels, such as Diesel, and nearly no electricity at all, to electricity being their largest fuel type used in four years. This shows the commitment Ruter has towards a sustainable transition. In terms of the emissions data, the difference in carbon emissions from 2010 to 2020 was very interesting to see. It shows the extent to which progress has been made in terms of sustainable transportation.

However, the fact that emissions for the previous two years were trending upwards is something of concern. To an extent, there have been clear ramifications from the global pandemic on Ruter's carbon footprint. On a passenger/km basis, emissions data is heavily dependent on the number of passengers who use the service. This reduces the emissions per passenger, as buses are vehicles that are heavily dependent on ridership to alleviate their carbon footprint. In the context of a global pandemic, where a majority of people are asked to remain at home unless, for essential travel, buses are unable to be filled to an efficient amount. Thus the higher emissions per passenger/km for 2020. It will be interesting to see in future how this affects Ruter's transportation strategy and how long these practices last beyond Covid-19.

Overall, this research provides an interesting perspective in relation to the development of transportation systems. It is clear that there is value in data, and that its analysis through a standardised framework in which an established scope, such as operational aspects, has the potential to give great, significant insight into the operations, procedures and policies of a public transportation operator. Furthermore, this analysis gives an encouraging viewpoint as it relates to the progress which is possible to achieve through ambitious objectives in relation to sustainable public transportation development.

9.4 Recommendations

The implementation of the LCA framework and the results from the data analysis gives a clear view of Ruter's current operations. They have established clear and ambitious objectives towards carbon-neutral operations, and that the data suggests they are working well towards that. In saying that, there is no doubt that the upcoming years will require special attention, in terms of ridership data, as well as it will become important to evaluate ridership data regularly, considering that commuting behaviours are expected to change post-pandemic. This is something that can have a significant impact on Ruter's carbon footprint in the upcoming years.

In terms of data availability, the greatest challenge in the course of the LCA was the access to data from manufacturers, in terms of the carbon data from their production cycle. This is an issue that could be addressed, especially in terms of publicly available data transparency. This would facilitate the acquisition of data for a more complete overview of the footprint generated over different process flows.

9.5 Future Outlook

As things evolve, there is no doubt that there will be changes to the data analysed in this research, which is something that gives a tremendous opportunity for both ongoing, and later research. It will no doubt be interesting to apply the same framework used in this thesis in the future, to grasp to the full extent the impact of the pandemic on public transportation in Oslo. Furthermore, it will be interesting to study the ways in which public transportation changes as the world transitions to a new normality. In terms of environmental data, it will no doubt be interesting to assess the emissions of Ruter's operations as it continues to increase its use of electricity as its primary fuel type. Furthermore, future technological developments will also provide an opportunity for further study, given the potential for impact.

The analysis of key performance indicators will also be something that is suspected to change in the upcoming years. Considering that the performance indicators which were assessed in this study were significantly advanced on the established scale, future study might present an opportunity for the identification of different performance indicators. As a means of evaluating different aspects of Ruter's operations.

Overall, this is an area that has significant space for future study, both in terms of Ruter's life-cycle assessment, but also in terms of public transportation in general. It will be interesting to see how public transportation develops in the future, and how this impacts urban areas. It is an area that has potential for expansion. Furthermore, public transportation is fundamentally linked to the growth trends experienced by cities on a global scale, as it provides a necessary service for urban transportation.

9.6 Final Words

With the growth observed in urban areas on a global scale, it is clear that transportation is an issue that is slated to become increasingly important. There are many different types and methods of transportation, which exist in cities, including buses. With this in mind, there is no doubt that buses can provide an effective, rapid and reliable transportation service. Furthermore, as evidenced by the data analysed in this thesis and the case of Ruter in Oslo, it is possible to make significant advances in reducing the carbon footprint of buses. This can be done through the use of renewable energy sources, such as electricity, and bio-diesel. Overall, there is no doubt that Ruter and Oslo's successful approach to de-carbonisation can inspire cities around the world. Especially in terms of setting ambitious goals, with realistic timelines, which seems to be a significant aspect of Ruter and Oslo's success.

References

[1] International Organization for Standardization [ISO]. Iso 14040:2006 environmental management - life cycle assessment - principles and framework. https://www.standard.no/no/Nettbutikk\protect\discretionary{\char\hyphenchar\font}{}{}/produktkatalogen/Produktpresentasjon/?ProductID=236802, 07 2006. Accessed on 03/10/2021.

[2] Ruter AS. Annual Report 2020. https://aarsrapport2020.ruter.no/no/, 2020. (Accessed on 04/20/2021).

[3] Ruter AS. Route maps. https://ruter.no/en/journey/route-maps/. (Accessed on 05/25/2021).

[4] MAN Truck & Bus AG. City Bus to Perfection: The new MAN Lion's City. https://www.man.eu/ntg_media/media/et/content_medien/doc/bw_master/bus_1/man-bus-lions-city.pdf. (Accessed on 05/11/2021).

[5] MAN Truck & Bus AG. MAN Lion's City 12 Efficienthybrid. https://www.man.eu/ntg_media/media/en/content_medien/doc/bw_master/bus_1/datenblaetter/man_lions_city_12.pdf. (Accessed on 05/11/2021).

[6] MAN Truck & Bus AG. MAN Lion's City 18 Efficienthybrid. https://www.man.eu/ntg_media/media/en/content_medien/doc/bw_master/bus_1/datenblaetter/man_lions_city_18.pdf. (Accessed on 05/11/2021).

[7] Volvo AB. Volvo 8900 specifications. https://www.volvobuses.com.pt/pt-pt/our-offering/buses/volvo-8900/specifications.html, 2021. (Accessed on 05/11/2021).

[8] Ruter AS. M2016: Fra dagens kollektivtrafik til morgendagens mobilitetsløsninger. https://m2016.ruter.no/en/, 13/8/ 2015. (Accessed on 04/06/2021).

[9] Oslo kommune. Climate and Energy Strategy for Oslo. https://www.oslo.kommune.no/getfile.php/13166797-1480690482/Content/Politics%20and%20administration/Green%20Oslo/Plans%20and%20programmes/Climate%20and%20Energy%20Strategy%20Oslo.pdf, 22/06 /2016. (Accessed on 04/07/2021).

[10] Maria J Figueroa and Suzana Kahn Ribeiro. Energy for road passenger transport and sustainable development: assessing policies and goals interactions. *Current opinion in environmental sustainability*, 5(2):152–162, 2013.

[11] Roland Berger Strategy Consultants and Ruter. Renewable energy powertrain options for ruter: A report for ruter. https://ruter.no/globalassets/dokumenter/fossilfri-2020/ruter-fossil-free-2020_report-on-renewable-energy-powertrain-options_june-2015.pdf, 04 2015. (Accessed on 03/24/2021).

[12] Sporveien AS. Sporveishistorien. https://sporveien.com/inter/omtbanen/historie. (Accessed on 05/05/2021).

[13] Ruter AS. Om Ruter: Selskapsinformasjon. https://ruter.no/om-ruter/selskapsinformasjon/. (Accessed on 05/04/2021).

[14] Ruter AS. H2017: Handlingsprogram med økonomiplan 2017-2020. https://ruter.no/globalassets/dokumenter/ruterrapporter/2017/h-2017-2017-2020.pdf. (Accessed on 03/24/2021).

[15] Jason Zheng, Norman W. Garrick, Carol Atkinson-Palombo, Chris McCahill, and Wesley Marshall. Guidelines on developing performance metrics for evaluating transportation sustainability. *Research in Transportation Business*

& Management, 7:4–13, 2013. Valuing Transportation: Measuring What Matters for Sustainability.

[16] MAN Truck & Bus AG. Corporate Social Responsibility at MAN. `https://www.corporate.man.eu/man/media/en/content_medien/doc/global_corporate_website_1/verantwortung_1/man_gri_bericht_2015_de_final.pdf`, 31/03 /2016. (Accessed on 04/14/2021).

[17] Juana Camacho-Otero, Casper Boks, and Ida Nilstad Pettersen. Consumption in the circular economy: A literature review. *Sustainability*, 10(8), 2018.

[18] Julian Kirchherr, Laura Piscicelli, Ruben Bour, Erica Kostense-Smit, Jennifer Muller, Anne Huibrechtse-Truijens, and Marko Hekkert. Barriers to the circular economy: Evidence from the european union (eu). *Ecological economics*, 150:264–272, 2018.

[19] Guangli Zhou, Yifan Gu, Yufeng Wu, Yu Gong, Xianzhong Mu, Honggui Han, and Tao Chang. A systematic review of the deposit-refund system for beverage packaging: Operating mode, key parameter and development trend. *Journal of Cleaner Production*, 251:119660, 2020.

[20] Katriina Alhola, Sven□ Olof Ryding, Hanna Salmenperä, and Niels Juul Busch. Exploiting the potential of public procurement: Opportunities for circular economy. *Journal of industrial ecology*, 23(1):96–109, 2019.

[21] Sharon Prendeville, Emma Cherim, and Nancy Bocken. Circular cities: Mapping six cities in transition. *Environmental Innovation and Societal Transitions*, 26:171–194, 2018.

[22] Yoshitsugu Hayashi, Shigeru Morichi, Tae Hoon Oum, Werner Rothengatter, and Takehiko Sugiyama. *Intercity Transport and Climate Change: Strategies for Reducing the Carbon Footprint*, volume 15 of *Transportation research, economics and policy*. Springer International Publishing AG, Cham, 2014.

[23] WBCSD. Energy effiency in buildings: Business realities and opportunities. https://www.wbcsd.org/contentwbc/download/2472/30510/1, Oct. 2007. (Accessed on 03/02/2021).

[24] Linda Too and George Earl. Public transport service quality and sustainable development: a community stakeholder perspective. *Sustainable Development*, 18(1):51–61, 2010.

[25] Mark Stafford-Smith, David Griggs, Owen Gaffney, Farooq Ullah, Belinda Reyers, Norichika Kanie, Bjorn Stigson, Paul Shrivastava, Melissa Leach, and Deborah O'Connell. Integration: the key to implementing the sustainable development goals. *Sustainability science*, 12(6):911–919, 2017.

[26] United Nations. The Sustainable Development Agenda – United Nations Sustainable Development. https://www.un.org/sustainabledevelopment/development-agenda-retired/. (Accessed on 05/25/2021).

[27] UN Department of Economic and Social Affairs. Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. https://sdgs.un.org/goals/goal9. Accessed on 03/03/2021.

[28] UN Department of Economic and Social Affairs. Goal 11:. Makecitiesandhumansettlementsinclusive,safe,resilientandsustainable. (Accessed on 03/03/2021).

[29] UN Department of Economic and Social Affairs. Sustainable transport. https://sdgs.un.org/topics/sustainable-transport. (Accessed on 03/03/2021).

[30] Bogdan Ovidiu Varga, Florin Mariasiu, Cristian Daniel Miclea, Ioan Szabo, Anamaria Andreea Sirca, and Vlad Nicolae. Direct and indirect environmen-

tal aspects of an electric bus fleet under service. *Energies (Basel)*, 13(2):336, 2020.

[31] Edgar G. Hertwich, James K. Hammitt, and William S. Pease. A theoretical foundation for life-cycle assessment. : recognizing the role of values in environmental decision making. *Journal of Industrial Ecology*, 4(1):13–28, December 2000.

[32] Robert K Yin. *Case study research : design and methods*. SAGE, Los Angeles, Calif, 5th ed. edition, 2014.

[33] O.O Ugwu and T.C Haupt. Key performance indicators and assessment methods for infrastructure sustainability—a south african construction industry perspective. *Building and environment*, 42(2):665–680, 2007.

[34] Rocio Cascajo and Andres Monzon. Assessment of innovative measures implemented in european bus systems using key performance indicators. *Public transport.*, 6(3):257–282, 2014.

[35] International Organization for Standardization. Iso14044:2006 environmental management - life cycle assessment - requirements and guidelines. `https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=236803`, 2006. Accessed on 03/24/2021.

[36] Timothy E Lipman and Mark A Delucchi. Emissions of nitrous oxide and methane from conventional and alternative fuel motor vehicles. *Climatic change*, 53(4):477–516, 2002.

[37] Yung-Hsiang Cheng and Ssu-Yun Chen. Perceived accessibility, mobility, and connectivity of public transportation systems. *Transportation Research Part A: Policy and Practice*, 77:386–403, 2015.

[38] Government.no. Renewable energy production in norway. https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/, 11/05 2016. (Accessed on 05/26/2021).

[39] Juan Antonio García Sánchez, José María López Martínez, Julio Lumbreras Martín, and Maria Nuria Flores Holgado. Comparison of life cycle energy consumption and ghg emissions of natural gas, biodiesel and diesel buses of the madrid transportation system. *Energy*, 47(1):174–198, 2012.

[40] Mikhail V Chester, Arpad Horvath, and Samer Madanat. Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions. *Atmospheric environment (1994)*, 44(8):1071–1079, 2010.

[41] Oslo kommune. Public transport in Oslo: Best practices. https://www.oslo.kommune.no/politics-and-administration/green-oslo/best-practices/public-transport-in-oslo/#toc-3. (Accessed on 03/30/2021).

[42] Oslo kommune. Planstrategi for Oslo kommune 2020-2023. https://www.oslo.kommune.no/getfile.php/13389411-1608022773/Tjenester%20og%20tilbud/Politikk%20og%20administrasjon/Politikk/Kommuneplan/Planstrategi%202020-2023/Planstrategi%20for%20Oslo%20kommune_2020-2023.pdf, 11 2020. (Accessed on 04/07/2021).

[43] Kristoffer W Lie, Trym A Synnevåg, Jacob J Lamb, and Kristian M Lien. The carbon footprint of electrified city buses: A case study in trondheim, norway. *Energies (Basel)*, 14(3):770, 2021.

[44] International Energy Agency. *Energy Technology Perspectives 2012: Pathways to a Clean Energy System*. Energy Technology Perspectives. OECD Publishing, Paris, 2012.

[45] Joyashree Roy, Anne-Maree Dowd, Adrian Muller, Shamik Pal, Ndola Prata, Sylvie Lemmet, and Global Energy Assessment Writing Team. *Lifestyles, Well-Being and Energy*, page 1527–1548. Cambridge University Press, 2012.

[46] Roland Scholz and Olaf Tietje. *Embedded Case Study Methods: Integrating Quantitative And Qualitative Knowledge*. Sage Publications, Inc, Thousand Oaks, 01/ 2002.

[47] Volvo AB. Volvo 8900: Your hard work partner. `https://www.volvobuses.com/content/dam/volvo-buses/markets/master/our-offerings/documents/Brochure_8900_2015_EN.pdf.coredownload.pdf`, 2021. (Accessed on 05/11/2021).

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