ODENSE LETBANE

A Life Cycle Assessment of Odense’s Light Rail Project

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2 Foreword

This paper was written as part of an Individual Student Activity. The Activity was conducted during a third semester of a master’s course in Energy Technology, at SDU Odense. Thanks are owed to the supervisor Mariannes Wesnæs and Morten Birkved, who provided valuable input and instruction during the process

1. Executive Summary

This paper presents the results of a Life Cycle analysis of the *Odense Letbane* Project, expected to be completed in late 2020. The light rail is expected replace part of the service currently provided by busses in the Danish city of Odense. The LCA considers the project from the construction phase, 30 years of operation and the end of life phase, with a functional unit of person kilometers. The project is being compared to the so-called "*nulalternativ"*, in which the transportation of people continuous via the established bus services.

The LCA has been conducted using the *OpenLCA* software and the Ecoinvent process and method databases. The LCA methods used were the *ILCD 2011 Midpoint+* and *Cumulative Energy Demand*. The impact categories considered were *Climate Change, Human Toxicity, Cancer*, *Particulate Matter, Photochemical Oxidation, Cumulative Energy Demand: non-renewable fossil* and *Cumulative Energy Demand: renewable biomass*.

In order to cover for inaccuracies in assumptions, a number of parameter analysis' have also been conducted. The projects have been modeled with different electricity productions, electricity consumptions, traffic consequences and passenger levels.

The result of the LCA is, that the light rail scores lowers impact across all impact categories in the base scenario. While the absolute impacts were significant, the per person kilometer impact is minimal. When compared to the normalization, the average impact per EU citizens, the light rail represents a minimal impact per passenger.

Much of the impact is associated with construction, however proper recycling of the raw materials heavily mitigates said impacts. Nevertheless, this means that the impact per passenger kilometer is only expected to decrease if usage is higher than expected. Another great contributor is the electricity consumption powering the trains. However, even if electricity consumption were significantly higher than expected the light rail would still remain at much lower impacts

2. Abbreviations

Eq	Equivalent
kWh	Kilo Watt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NMVOC	Non Methane Volatile Organic Compound
PFD	Process Flow Diagram
PKM	Person Kilometers
SDU	*Syddansk Universitet*, University of Southern Denmark
VKM	Vehicle Kilometer
VVM	*Vurdering af Virkninger for Miljøet*, Enviromental impact assessment

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3 Introduction

The reduction of climate changing emissions is a stated goal. With fossil fuels being the prime cause of CO2 emission, the need for the reduction and outright removal of said fuels from the energy sector is becoming an ever more present priority. With the transport sector representing a third of the everyday energy consumption (Energistyrelsen, 2017, s. 20), change is needed if such goals are to be realistic. Consumption of fossil fuels have been at the core of the transport sector, and if national governments around the world are to meet their climate ambitions, this needs to change.

In the Danish municipality of Odense, the public transport sector is undergoing such a change. A light rail project was initiated in 2014 and has been commissioned for completion in the year 2020. It is intended to not only replace part of the existing bus fleet, but also to strengthen operations in preparation for the future. With the electric light rail replacing the diesel fueled busses, the project is set to help with the transition towards a fossil fuel less transport sector. The light rail is expected to cater to a growing number of passengers, as the light rail facilitates not only easier transportation, but also strengthen urban development.

In this paper, this project is being investigated from a Life Cycle Analysis perspective. It will include the operation of the light rail, as well as the construction, maintenance and end of life processes of the entire project. The project is being compared to the so-called "*nul-alternativ*" in which the project is not being completed, and transportation instead is resumed with the established busses.

This paper will divert from the traditional IMRAD structure and instead follow a structure more suitable for presenting an LCA. This decision was based on

In the next chapter, chapter 4, the goal of the report will be defined, the LCA methodology will be described as will the commissioner of the study.

In the following chapter, chapter 5, the Scope will be presented, alongside with the deliverables and limitations.

Then, in chapter 6, comes the Inventory analysis, where each process and its underlaying assumptions and sources will be described.

After that, in chapter 0 the Results of the study, and the Impact Assessment of each of the scenarios will be presented.

Finally, in chapter 8, the Conclusion and Recommendation, which will be based on the results chapter.

4 Goal Definition

4.1 Study Commissioner and Audience

This paper was conducted as the product of a "*Fagligt Selvstudie"* – a self-chosen, independent student activity as part of the ninth semester of the SDU's Energy-technology course. As such, no commissioner, other than the author, exists.

Nevertheless, the result of the paper ought to be interesting for several stakeholders, as the results of this paper relates to their operations. These stakeholders include:

- Odense Municipality
- Citizens of Odense Municipality
- *Fynbus*, the current operator of busses in Odense Municipality
- Anyone involved with urban planning or development
- The suppliers of the trains (*Stadhler*), rails (*Comsa SAU)* and civil works (*M.J. Erikson, Arkil A/S* and *Barslund A/S*)
- Any involved in the planning or operation of a light rail, or considers doing so in the future (such as the establish *Århus Letbane* or the planned *Hovedstadens Letbane* in Copenhagen)
- Any with an interest in the electrification of the transport sector (such as the Danish Transmission System Operator *Energinet*, *Energistyrelsen* or the Danish Ministry of Transportation Building and Housing.

As this is an independent study activity, this paper was not completed with the intent of publication.

4.2 Study Methodology

This paper is centered around the completion of a consequential Life Cycle Analysis. The purpose of such an analysis is to assess the full and complete impact of a project, throughout its lifetime. A consequential LCA involves, as the name suggests, all processes that occurs as a <u>consequence</u> of the project. The result of the LCA is tied to a central metric, the Functional Unit, which exemplifies the core service of the project – this allows for comparisons across several different projects. For a more in-depth description of LCA's and their guiding principles see the ILCD handbook (Wolf, Chomkhamsri, & Brandao, 2010).

For the modeling of the LCA the open source software *OpenLCA*, and the consequential Ecoinvent database was used. The methods used where the ILCD 2011 Midpoint+ (a digitalized version of the ILCD Handbook) and the Cumulative Energy Demand (based on the method published by Ecoinvent) methods as utilized by the OpenLCA software.

4.3 Study Goal and application

The LCA described in this report is intended to shed light on the impact, environmental and otherwise, of the Odense Light rail project (*Odense Letbane*), in the first thirty years of its lifetime. The result could potentially be used by Odense Municipality to either market themselves as a green city, should the report show that the Light Rail is a beneficial project. Alternatively, it can inspire the decision makers to in the future delay such decisions until a in depth LCA study has been completed. The stated motivation for the *Odense Letbane* project was to strengthen the public transportation of Odense Municipality (Heunicke, Boye, & Mathiasen, 2018) – the report can therefore shed light on the costs, other than the financial, that will be accrued over the course of the light rail.

This paper is based on a great deal of assumptions and data that are specific to the project of *Odense Letbane*. As such the applicability of the results are limited to that of *Odense Letbane* and cannot be transferred to similar projects. The result can however inspire other municipalities to either adopt or reject similar projects of their own. The data and methods of the report should also be applicable in very narrow scope to other similar reports.

5 Scope Definition

5.1 Deliverables

This report will deliver the LCA results of two primary scenarios, which are the two scenarios considered in the VVM report (COWI A/S, 2013) – the *Odense Letbane* project and the so called *nulalternativ,* in which the project is not initiated at all, and the transportation will be carried by the existing bus network.

The report will go though in detail the difference between the two scenarios, how the two scenarios are modelled and on what data and assumptions the model is based on. It will include interpretation of the results, as well as uncertainty analysis on specific critical assumptions. Finally, a recommendation for future actions will be given, based on said analysis and results.

5.2 Functional Unit

The project is intended to transport passengers along the extend of its tracks. The alternative will be a continuation of status quo, with the project not having been initiated.

	Obligatory Properties	Positioning Properties
Properties	The transportation of people. High safety standard. Reliable.	Environmentally friendly. Affordable.
Quantitity	The kilometers driven by the trains and the people traveling with them. Expected to be 1 million vehicular kilometers per year (Cowi A/S, 2013, s. 269) and 11 million people per year (Cowi A/S, 2013, s. 31).	
Duration	30 years, equal to the expected lifetime of the train carts (Cowi A/S, 2013, s. 270)	
Functional Unit	Person Kilometers [pkm]	

The functional unit will be person kilometers – the transport of 1 person for 1 kilometer - and the results of the LCA will be presented in accordance with the functional unit – for example, the impact category of climate change will be presented as kg CO2 equivalent/pkm.

5.3 Temporal, spatial and technical scope

The project is considered over the course of 30 years. The project is considered between the years 2020 and 2050, which is the year the trains are open to the public and thirty years ahead - which equals the assumed lifetime of the trains. The "building structure" has an assumed lifetime of 120 years, while the wiring is at 50 years – these two processes are included to the extent that the

The spatial scope is for the most part restricted to the municipality of Odense. While several processes are from outside this scope – the electricity is produced in the nation of Denmark as a whole, the trains are constructed in Germany, and the granite used in construction is being imported from Norway – the actual light rail operates in Odense. Therefore, the results of the LCA cannot be readily applied to projects elsewhere.

The technological scope is restricted to tried and tested technologies. In the case of the changing electrical grid, the assumption is that the mix changes, but the technologies that the mix is comprised of, is assumed to be as they are now. The scrapping and recycling processes are modeled as they would likely be in the year 2018 – despite the likelihood that things would change in 2050, when the trains are likely to be recycled, or even 2140, when the buildings are expected to have run their course. The justification for this is a need for reliable data – it is difficult to made statements about the future, and the LCA as it is already relying on a significant amount of assumptions. It has therefore been desirable to reduce the amount of assumption and speculation to a minimal.

5.4 System Boundaries

Processes that have been included in the Light Rail Scenario

- The construction, maintenance and scrapping of the train carts
- The construction, maintenance and scrapping of the rail works, the tracks, electrical masts and stations.
- The construction, maintenance and scrapping of the civil works, the roads, walkways and bicycle paths needed for the use of the Light Rail.
- The electricity needed to run the trains, as well as the resources and infrastructure needed to produce it.
- The expected increase and decrease in transport that will occur as a consequence of the project.
- The garbage generated by the demolition of preexisting buildings due to the construction work.
- The deforestation of 4.600 m^2 of planted forest around SDU Odense and *Jelstrup Plantage*.

Processes that have been included in the Bus Scenario

- The maintenance of busses and roads
- The production and consumption of diesel during bus operation
- The production and scrapping of replacement busses

Processes that have <u>not</u> been included

- The expected change in urban development due to the completion of the project[1].
- Construction of fabrication plants[2].
- The construction and maintenance of machines and tools associated with construction work[3].

[1] This would be an interesting addition, but does not seem to be within the scope of this paper
[2] The completion of the project does not seem to be so grand in scope as to demand new production facilities.

- The scrapping of the replaced buses[4].

5.5 Process Flow Diagrams

Two different scenarios are being introduced and studied in this paper: the *Odense Letbane* project and the socalled *nulalternativ*, henceforth reference as the *Bus Scenario*. The Process Flow Diagrams (PFDs) will detail the differences between them.

The PFDs are intended to show the processes that occur as a consequence of the implementation of the project. The PFD are to be read from left to right: with the left most being the extraction of raw materials, then the production of products, then: the use phase and finally: the end phase.

The PFDs consists of boxes and lines, some dotted, some full. Each box notes a process, and each line a connection between the processes. A full line and box note the implementation of a process, a dotted line and box notes the avoidance of a process. Each PFD is centered around a specific process – that of the primary service, described via the metric of the functional unit.

5.5.1 Reference Scenario – busses

The bus scenario is relatively simple, as it is merely a continuation of already establish practice. Therefore, no new large investments are needed. Instead the equipment and infrastructure that has already been constructed is maintained as used as it has been in the past. A purchase of a few busses is also included, to reflect the need for keeping the bus fleet up to date over the 30 years. The fuel used is diesel, despite the fact that Odense Municipality in these days are testing gas busses (Ritzau, 2018) – this is done to reflect the wish for restricting the study to tried and tested technology.

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[3] This is deemed to be represent too small an impact to justify the work required for their inclusion.

[4] These are instead assumed to be held in reserve in case breakdowns and maintenance of the rest of the bus fleet. They will therefore be scrapped at the same time as they would have if the *Odense Letbane* had not been constructed.

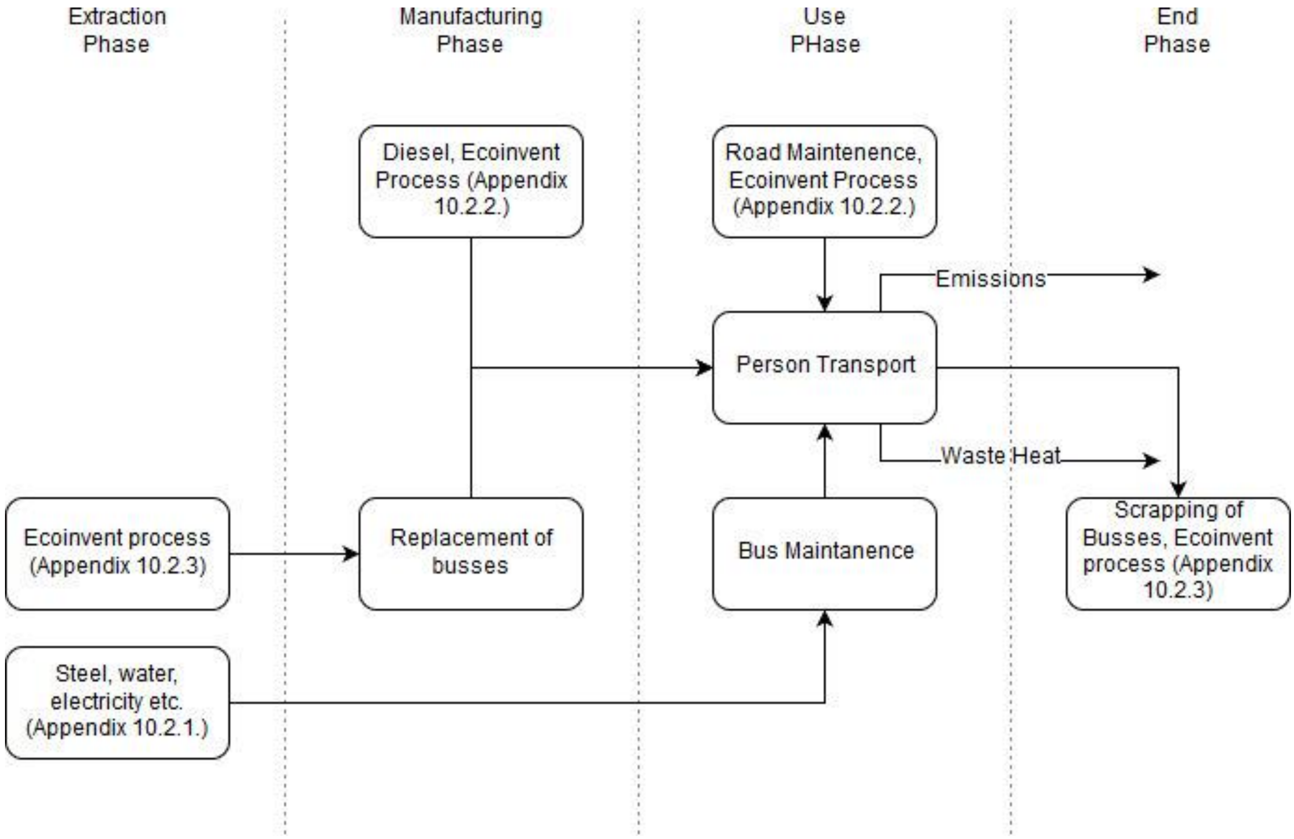

Figure 1 - PFD of Bus scenario

5.5.2 Alternative Scenario – *Odense Letbane*

This scenario includes the implementation of significant infrastructure changes, as rail tracks, rail stations, roads, bicycle paths and assorted works need to be accomplished before the light rail can even function. The procurement of a fleet of trains is also included.

Furthermore, in order for this to be accomplished, the previous status quo needs to be removed – this includes the demolition of buildings, the removal of forests and the tearing up of roads. When this is done, some of the raw materials can be reused – asphalt from the roads, wood chips from the forests - meaning that they replace the procurement of new raw materials. Other materials cannot be reused and need to be treated accordingly.

All the new additions need to eventually be torn down as well, so the scrapping of trains, tracks and civil works is included.

The VVM report expects the Light rail to result in an increased transport of goods, noted here as “Expected Traffic Effects”. Unlike the case of the busses, no emissions are added to the operation of the light rail, as said emissions are expected to occur in relation to the electricity production.

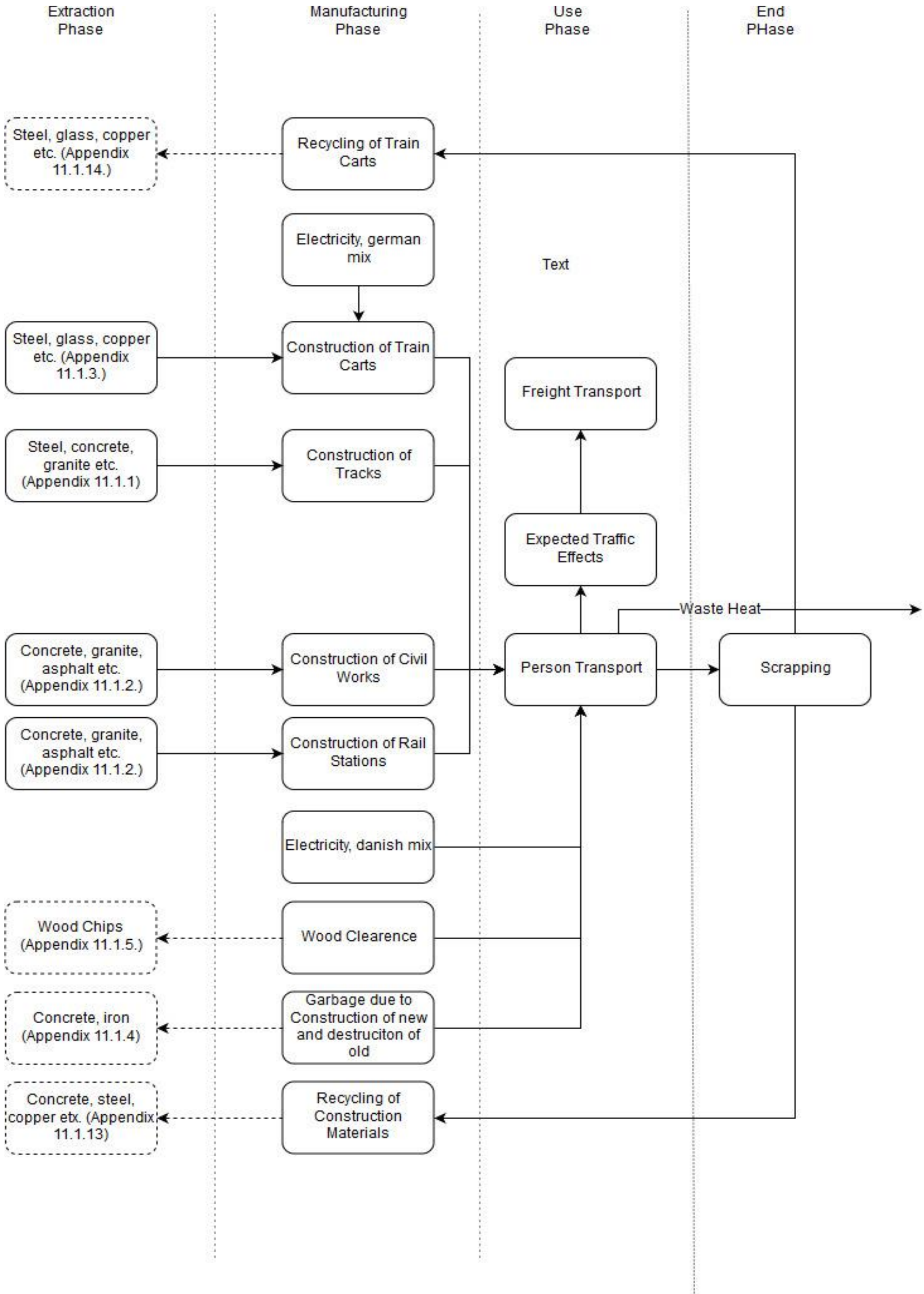

Figure 2 - PFD of Odense Letbane Scenario

6 Life Cycle Inventory Assessment

6.1 Data Collection

It should be noted that while accuracy is important complete adherence to reality is unrealistic. The model and its associated results will not be a perfect reflection of reality. The goal of this paper is to give as accurate an assessment of the projects in question as time and circumstance allows. As such certain processes have been prioritized in the data collection, as they were estimated be of greater importance to the final result, than others. Some, as were detailed in the system boundaries section, have been excluded entirely.

Much of the data used in the model have been collected from three sources in particular

- The VVM report of Odense Letbane, completed by the Danish company COWI A/S (Cowi A/S, 2013)
- A Swedish LCA of public transport options in Jönköping in Sweden (Jonel, 2016)
- An American LCA of various public transport option in California (Chester & Horvath, 2008)

For the assessment of transportation, data from the website Eurostat was used. For the simulation of electricity production, the ecoinvent consequential database was used. For the end-of-life processes, and an overview of material recycling for trains (Merkisz-Guranowska, Merkisz, Jacyna, Pyza, & Stawecka, 2014), and a guide from Mariagerfjord Municipality was used in the case of constructions (Mariagerfjord Kommune).

6.2 Basis for Impact Assessment

The primary motivation for the decision of constructing the light rail was not climate change concerns – instead it was an interest in strengthening local transportation and urban development (Heunicke & Holst, 2018). Nevertheless, greenhouse gasses, expressed by CO_2 kg equivalents remain of interest in any project, especially one concerning the electrification of the transport sector. Therefore, Climate Change will be included as a primary Impact.

Factors such as land use change and resource depletion of metals and minerals are relevant, but are not considered to be critical, due to the relative limited scope. 4.600 m^2 of forest is expected to be cut down, and while the VVM report states that while import of granite from Norway may be necessary, the neither steel, concrete nor gravel is deemed to be “small” compared to a national level and not represent any significant issue. This, combined with the fact that the production of the trains does not include any rare materials, excludes the Resource Depletion and Land Use Change as impacts of critical concern to this project.

The same can not necessarily be said of the consumption of primary energy resources. Fossil fuels, such as the diesel that fuel busses and the coal and natural gas that fuel the electricity sector are nonrenewable. The depletion of said resources are what motivated the Danish Energy Agenct (*Energistyrelsen*) to include the electrification of the transport sector as a major assumption of their 2035 and 2050 energy scenarios (Energystyrelsen, 2014). As such, the Energy Ressource Depletion will be considered as well. The method Cumulative Energy Demand, available to OpenLCA differentiates between Non-Renewable Resources like fossil and Renewable resources such as wind – this Method will therefore be used.

Furthermore, as the project is enclosed by Odense Municipality, most of any adverse health effects will be felt by the citizens living there. While the trains, electricity[5] and raw materials will be produced elsewhere, the construction, demolition and actual transportation will all occur within city limits. Therefore, focus will also be put on any Human Toxicity, Particulate Matter and Photochemical Ozone Formation that may arise due to the project.

While the energy resource depletion appears to necessitate its own separate method, the remainder: Climate Change, Human Toxicity, Particulate Matter and Photochemical Oxidation are all included in the ILCD 2011, midpoint method, available to the OpenLCA software.

6.3 Critical Review Needs

The paper, and the work behind it, has been the subject of supervision by supervisors Marianne Wesnæs and Morten Birkved, both from SDU Life Cycle Engineering at the Department of Chemical Engineering, Biotechnology and Environmental Technology, SDU (*Institut for Kemi-, Bio- og Miljøteknologi*). At the conclusion of the fall semester of 2018, the paper will be the subject of an examination.

No other review has been conducted.

6.4 System Modelling per Life Cycle Stage

Following is an overview of the processes that are included in the LCA, divided by scenario. An in-depth description of each process will be provided in the appendix.

6.4.1 Manufacturing Phase

In the manufacturing stage the construction of train rails (appendix 10.1.1) stations and civil works (appendix 10.1.2) and trains (appendix 10.1.3). Furthermore, the garbage accumulated during the construction and demolition processes (appendix 10.1.4) and the removal of 4,600 m^2 (appendix 10.1.5) is included.

For the bus scenario, this includes the construction of replacement busses (appendix 10.2.3)

6.4.2 Use Phase

In the use phase is included all processes associated with the operation and maintenance of *Odense Letbane*. This includes the maintenance of the rails (appendix 10.1.6), the civil works (appendix 10.1.7) stations (appendix 10.1.10) and trains (appendix (10.1.11), as well as the energy consumed during operation (appendix 10.1.10) and the expected increases in freight traffic due to the light rail (appendix 10.1.12)

For the bus scenario, this includes the road and bus maintenance, as well as the fuel consumption (appendix 10.2.2)

6.4.3 End of Life Phase

In end of life phase is included all processes that occur at the end of the expected lifetime of the respective elements of *Odense Letbane*. This includes the construction elements, meaning rails, stations and civil works (appendix 10.1.13) and the trains (appendix 10.1.14)

[5] Except for what little the nearby *Fynsværket* to the national energy mix

For the bus scenario this includes the scrapping and recycling of the replacement busses (appendix 10.2.3)

6.5 Calculated LCI Results

In this section, the most pressing results will be presented. For a complete overview, see appendix.

As stated previously, the project will be modelled twice, once with the ILCD 2011, midpoint method, for the purpose of the Climate Change, Human Toxicity, Particulate matter and Photochemical Oxidation – then for the second time, for the purpose of Energy Resource Depletion. The results will be presented in this section, with a few comments. For a more in-depth analysis, see the interpretation and Conclusion sections below.

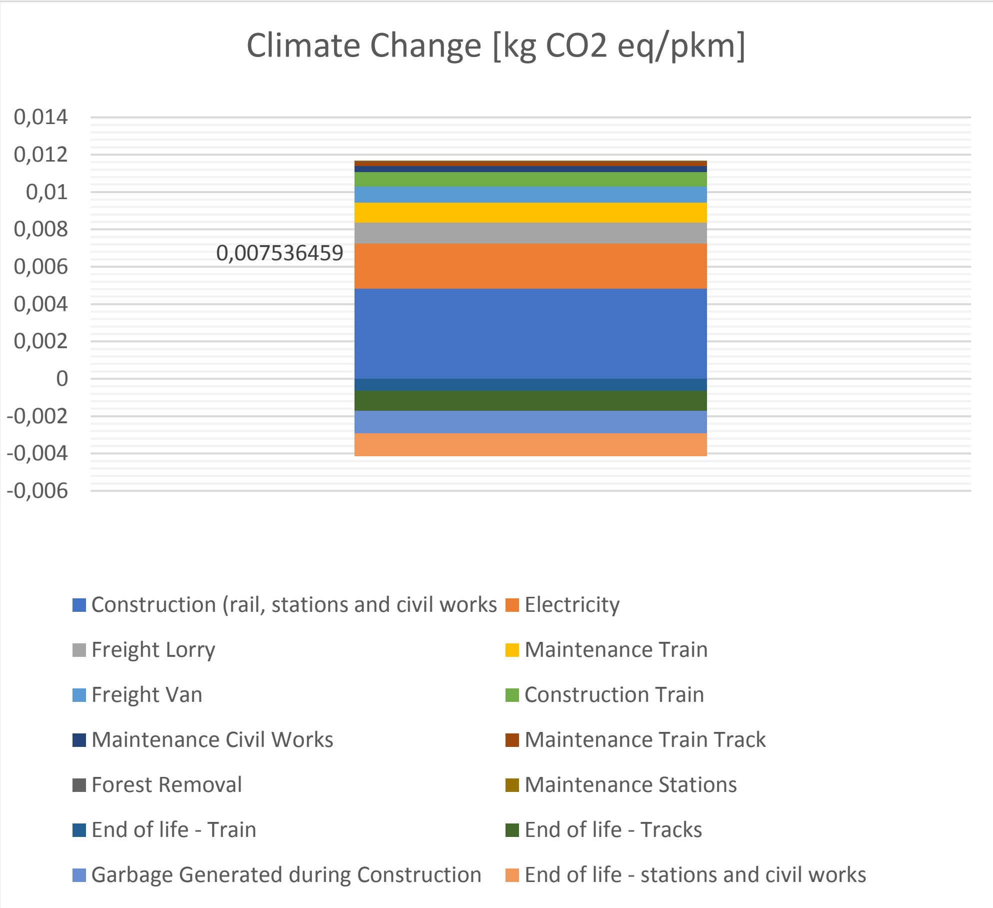

Figure 3 - Coloumn Graph of LCI Results - Climate Change

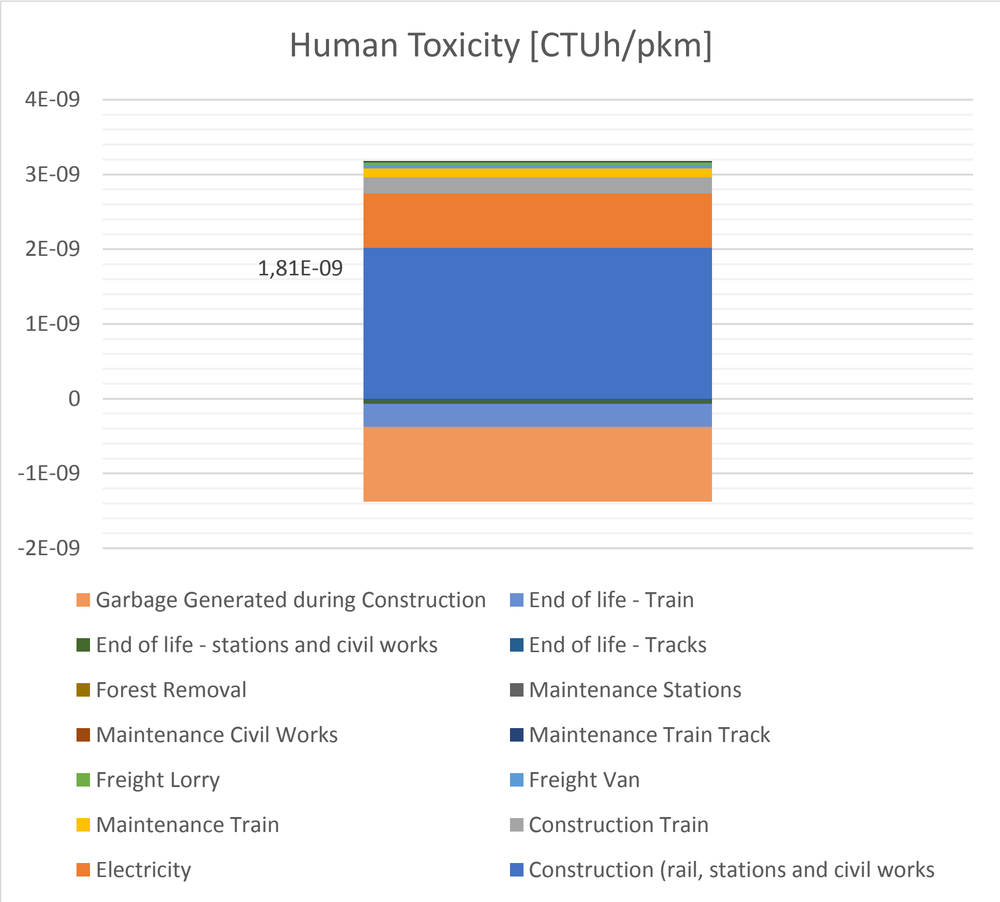

Figure 4 - Coloumn Graph of LCI Results - Human Toxicity, cancer

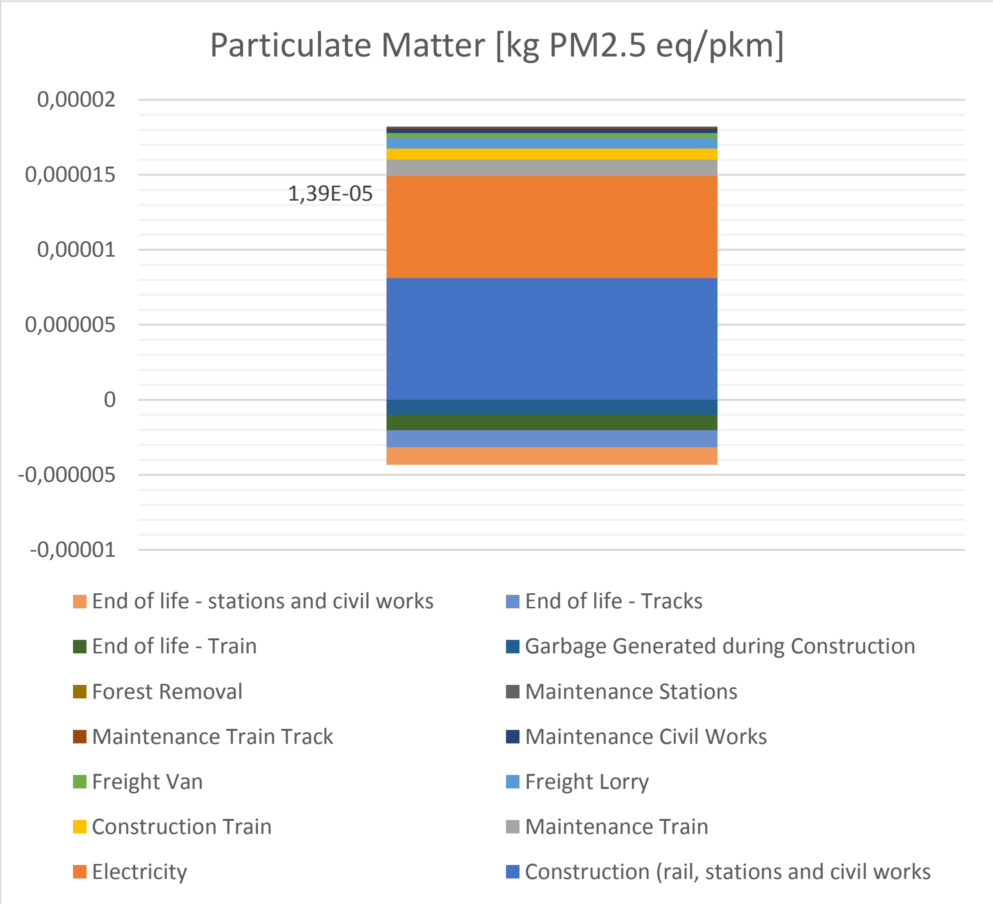

Figure 5 - Coloumn Graph of LCI Results - Particulate Matter

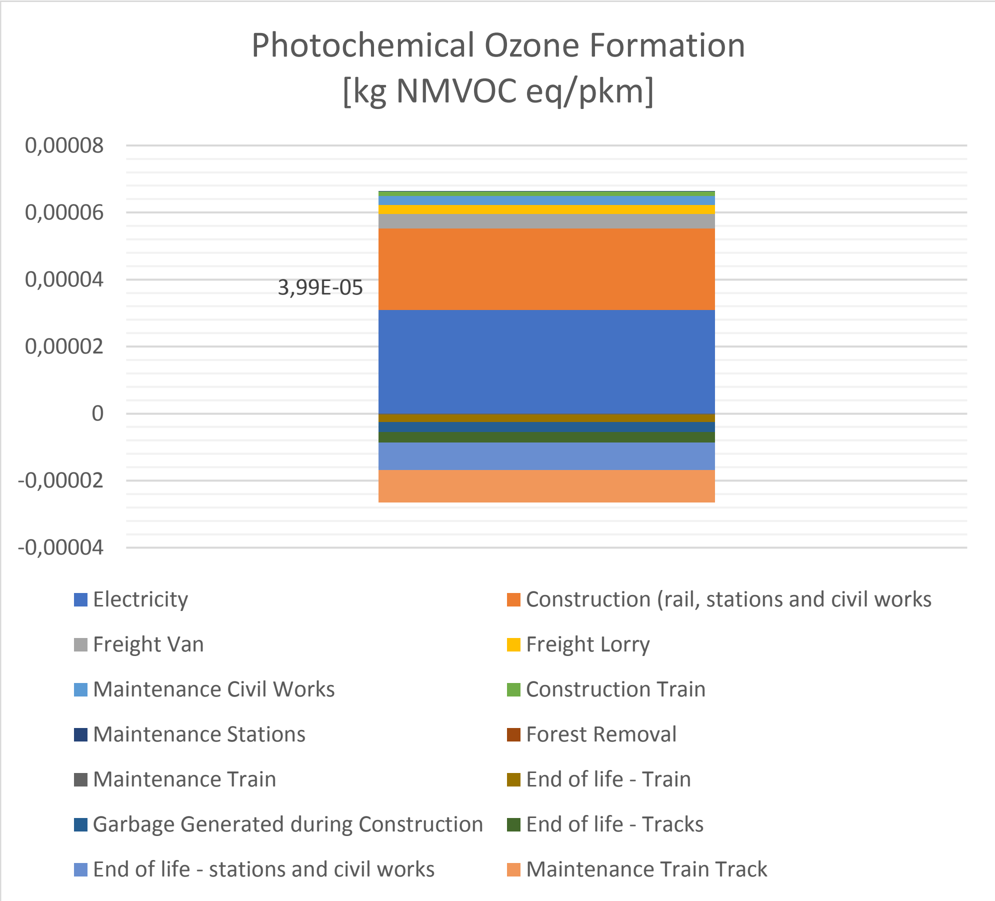

Figure 6 - Coloumn Graph of LCI Results - Photochemical Ozone Formation

Common for all the midpoint impact categories, including the four in focus in this paper, is that two processes in particular represent the majority of the impacts: the construction and the electricity usage. In most cases construction is the primary contributor, while in photochemical ozone depletion, it is the electricity that generates the most.

Some, noticeably the end of life processes, has a negative contribution – this does not mean that they do not generate any CO2 equivalent or the like, but merely that they avoid an even greater amount, resulting in a net reduction.

The OpenLCA results are in appendix 10.3.

6.6 Basis for Sensitivity and Uncertainty Analysis

The *Odense Letbane* project has not yet been completed, and many of the data used for this LCA are based on assumptions. Furthermore, the sheer temporal scope of the project comes with uncertainties of its own – the Danish electricity mix, methods for maintenance, recycling and scrapping, even the fundamental operation of the rail, and much more can change before the estimated lifetime is up. As such, a rigorous sensitivity analysis well be helpful if any recommendations are to be given.

First and foremost is the electricity mix. Denmark is projected to undergo large changes up to the year 2050 – which coincides with the end of the train carts expected lifetime. Denmark is supposed to have changed to a completely fossil free mix by that year (Energystyrelsen, 2014) – but even if that is to occur, relatively little can be said of the intervening years.

Likewise, the electricity usage of the trains. Data from other carts are available, which are similar in terms of size, mass, passenger capacity, top speed and age – but not from the exact same product. For example, the same source states that the Boston Green Line use 7.9 kwh/vehicular mile, while the San Francisco Municipail light rails cars use 4.4 kwh/vehicular mile (Chester, 2008, s. 76) (or 4.9 kwh/vkm and 2.73kwh/vkm, respectively), while the train type Bombadier Flexity is reported to use 3.7 kwh/vkm (Fröne, 2016, s. IX). As such this is a central assumption that could tip the results either way.

The expected transport effects of the project include changes to both busses and private cars, but also to trains, trucks and lorries (COWI A/S, 2018, s. 271). Not only will this have a large impact on the overall project, but the data were derived from a simulation.

The number of passengers and their transport habits are also a large assumption – the functional unit is Person kilometers, and as such any results of the analysis are entirely based on this assumption. For comparison, the Copenhagen Metro expansion, planned for completion in 2019, was in 2006 expected to transport 85 million passengers (Folketinget.dk, 2018) – this expectation was in 2013 reduced to 69 million (Behrendt, 2018), a reduction of almost twenty percent. If the *Odense Letbane* project experience similar differences, the result of the LCA will likewise change, which necessitates a sensitivity analysis.

7 Life Cycle Impact Assessment

7.1 Interpretation

Odense Light Rail does results in significant CO_2 emission – but compared to the amount of people transported the emissions are close to negligible, when compared to the bus scenario. The light rail scores significantly lower in every impact category considered relevant.

The construction of the project is the greatest impactor, but this process includes all of construction – both rails, stations and civil works. Furthermore, this does not include the eventual recycling and reuse of the raw materials, which results in the avoided manufacturing of said materials. If the establishment and end of life processes are summarized for the construction, then the electricity production becomes the greatest contributor in all of the categories.

Likewise, the maintenance of the tracks, with its large consumption of steel would have exceeded electricity in contribution in several impact categories, if said steel had not been recycled.

Another great impact is that of the associated traffic results, the lorries and vans. This does not come as a surprise, as the VVM states that the combined increase of freight transport is estimated at 2,000,000 vehicular kilometers – compared to the 1,000,000 vehicular kilometers of the light rail itself. The light rail, being a considerably larger and heavier vehicle requires far more energy in the form of electricity, resulting in this being a greater contributor. Nevertheless, the diesel fueled vehicles have a combined contribution that is comparable.

Certain processes, namely the maintenance of the civil works and stations, as well as the removal of forests, have almost zero or very little impact. This is due to the sheer comparable sizes in place – the steel concrete used in construction, and the electricity used over thirty years is quite simply much greater.

The ILCD 2011 Midpoint methods contains normalization factors for each of its impact categories. These factors represent "the total impact occurring in a reference region for a certain impact category (e.g. climate change, eutrophication, etc.) within a reference year" (Benini, et al., 2014, s. 11). In order to give a point of reference for the results in this paper, the results will now be compared to said normalization factors.

Table 1 - Table of Normalization factors compared to scenario results

Impact Category	Unit	Normalization Factor	Odense Letbane	Bus Scenario
Climate Change	kg CO_2 eq	9220[6]	0.00753	0.11391
Human Toxicity, cancer effects	CTUh	3.7E-5	1.8E-9	3.7E-9
Particulate Matter	kg PM2.5 eq	3.8	1.4-5	8.5E-5
Photochemiical Ozone Formation	kg NMVOC eq	31.7	4.0E-5	0.00117

[6] This appears to be a "domestic" figure – meaning the sum of the CO_2 emissions produced domestically. It is also a figure for Europe as a whole – the World Bank report the Danish figure to be 5,936 kg in 2014 (World Bank Group, 2018). Another source states that if the imported figures are included the number rises to 14.5 tons (Jex, 2018).

Said figures come from the LCA opens version of ILCD 2011 Midpoint+. The set of normalization factor denoted as "EU27 2010, equal weighting – ILCD 2011 Midpoint+".

When comparing the normalization factor with the emissions per person kilometer, it is highly unlikely that any single person will

If, for example, an out-of-town student at SDU were to travel four times a week, 32 weeks a year, back and forth between *Banegården* station and *SDU Nord* station, a distance of approximately 10 kilometers, this would results in

Equation 1 - Climate Change Impact - Student Example - Light Rail

$$0.00753\frac{kg\ CO_2\ eq}{pkm} * 10\frac{pkm}{trip} * 2\frac{trips}{day} * 4\frac{days}{week} * 32\frac{weeks}{year} = 19.27\ kg\ CO_2\ eq$$

It results in a little less than 19.27 kg CO_2 eq per year. If the same person were to use the bus scenario instead:

Equation 2 - Climate Change Impact - Student Example - Bus

$$0.11391\frac{kg\ CO_2\ eq}{pkm} * 10\frac{pkm}{trip} * 2\frac{trips}{day} * 4\frac{days}{week} * 32\frac{weeks}{year} = 291.60\ kg\ CO_2\ eq$$

If said transport was to occur by car, assuming a CO_2 emission of 126 grams per pkm (Trafikstyrelsen, 2018), it would result in

Equation 3 - Climate Change Impact - Student Example - Car

$$0.126\frac{kg\ CO_2\ eq}{pkm} * 10\frac{pkm}{trip} * 2\frac{trips}{day} * 4\frac{days}{week} * 32\frac{weeks}{year} = 322.56\ kg\ CO_2\ eq$$

Or almost 17 times the emission from using the light rail.

Likewise, if a hypothetical passenger was to use the full length of the light rail to go to work, five days a week, 46 weeks a year:

Equation 4 - Climate Change Impact - Work Example - Light Rail

$$0.00753\frac{kg\ CO_2\ eq}{pkm} * 14.4\frac{pkm}{trip} * 2\frac{trips}{day} * 5\frac{days}{week} * 46\frac{weeks}{year} = 49.87\ kg\ CO_2\ eq$$

It results in a little less than 50 kg CO_2 eq per year, compared to:

Equation 5 - Climate Change Impact - Work Example - Bus

$$0.11391\frac{kg\ CO_2\ eq}{pkm} * 14.4\frac{pkm}{trip} * 2\frac{trips}{day} * 5\frac{days}{week} * 46\frac{weeks}{year} = 754.53\ kg\ CO_2 eq$$

And

Equation 6 - Climate Change Impact - Work Example - Car

$$0.120 \frac{kg\ CO_2\ eq}{pkm} * 14.4 \frac{pkm}{trip} * 2 \frac{trips}{day} * 5 \frac{days}{week} * 46 \frac{weeks}{year} = 794.88\ kg\ CO_2 eq$$

Even the largest of these fails to represent a tenth of the average emission for an EU citizen. However the bus and car examples are so close to each other, that the diesel busses cannot be said to be justified from a global warming perspective. If two coworkers drove together to work in a carpool, the impact per pkm would be much lower than with a bus.

7.2 Significant Issues

Due to necessity, many of the processes have been modeled as European or global processes - meaning they reflect production in Europe or the world as a whole, rather than Denmark or Germany which would have been more accurate. Some of the processes have a significant impact, which could have differed with a more accurate model. Especially the processes of manufacturing concrete and steel – the two greatest contributors in the construction phase – could possibly have a reduced impact, if they reflected Danish conditions rather than the world as a whole.

The Danish Transport Authority (*Trafikstyrelsen*) has released guide to the average CO_2 emission per personkilometer for the most used transport methods (Trafikstyrelsen, 2018). According to this source, an electric rail vehicle in an urban environment has a CO_2 emission of 44-60 gram (or 0.044-0.060 kg) per personkilometer. This is significantly higher than the 0.00753 kg calculated. The same source also noted that a bus emits 83 gram (or 0.83 kg eq per personkilometer, compared to the modeled 0.11391 kg eq)

It should, however also be noted that the Danish State Rail company (*Danske Stats Baner*) reports 14 gram per personkilometer for their electric urban trains – or as low as 3.2 per "space kilometer" (DSB, 2018). It seems, not surprisingly, that the emissions are highly dependent on any underlying assumptions, especially the number of passengers.

7.3 Sensitivity and Uncertainty Checks

7.3.1 Electricity mix

The first sensitivity analysis compares the electricity production between the current Danish market – being the base scenario – with electricity based on wind turbine and coal fueled production. For the wind case, the process "electricity production, wind <3MW turbine, onshore, electricity, high voltage" was used. For the coal case, the process "hard coal, electricity, high voltage, consequential, U" was used. The transformation and transmission losses were neglected in these cases. The onshore option was chosen, due to a lack of offshore equivalents.

Table 2 - Table of Sensitivity Check results: Electricity Production

Impact Category	Danish lov voltage market (Base)	Wind	Hard Coal
Climate Change [kg CO2 eq]	0.00753	0.00655 (-13.0%)	0.07143 (+848.6 %)
Human Toxicity, cancer	1.80559E-9	1.54151E-9 (-14.6 %)	2.48257E-9 (+37.4 %)
Particulate Matter	1.38832E-5	8.52883E-6 (-38.5 %)	1.21418E-5 (-12.5 %)
Photochemical ozone	3.99116E-5	1.34828E-5 (-66.2 %)	5.85447E-5 (+46.6 %)

formation			
Nonrenewable Fossil	0.10146	0.09397 (-7.3 %)	0.83369 (+721.6 %)
Renewable Biomass	0.28975	0.00765 (-97.3 %)	0.01728 (-94.0 %)

What is remarkable by this result is two things in particular. One is how little the "Climate Change" and "Nonrenewable Fossil" categories changed in the wind case. The two certainly decreased, the majority of CO_2 emissions and fossil fuel consumption remains separated from the electricity consumption. Most of it is consumed in other processes, such as the construction and maintenance phases, as well as the expected increase freight transport.

The other interesting result is, that the "Climate Change" category increased with almost a thousand percent in the Hard Coal case, from 0.007 to 0.07 kg CO_2 eq. In this case the electricity consumption becomes the overwhelmingly dominant contributor to the climate change category, and significantly increases very other category as well. It is also interesting to see that the hard coal case actually has a slightly higher biomass consumption than the wind case. When looking into the documentation, it becomes evident that this stems from the mining industry, partially for the wood used in constructing the mine, partially from heating the mine via district heating (see appendix 0).

7.3.2 Train Electricity Usage

If electricity usage is Like Boston Green line and if electricity usage is like San Francisco Municipal light rail - 4.9 and 2.73 kWh's respectively.

Table 3 - Table of Sensitivity Check results: Electricity Usage

Impact Category	3.7 kwh/vkm (Base)	4.9 kwh/vkm	2.73 kwh/vkm
Climate Change [kg CO2 eq]	0.00753	0.00832 (+10.4 %)	0.00690 (-8.3 %)
Human Toxicity, cancer	1.80559E-9	2.04264E-9 (+13.1 %)	1.61397E-9 (-10.6%)
Particulate Matter	1.38832E-5	1.60906E-5 (+15.8 %)	1.20988E-5 (-12.8 %)
Photochemical ozone formation	3.99116E-5	4.99729E-5 (+25.2 %)	3.17788E-5 (-20.4 %)
Nonrenewable Fossil	0.10146	0.10867 (+7.1 %)	0.09562 (-5.7 %)
Renewable Biomass	0.28975	0.38147 (31.6 %)	0.21561 (-25.5 %)

Not surprisingly, each impact category goes up when the energy consumption is increased, and the opposite when it is reduced. The increase is not, however, enough to push it above the bus scenario – as such the light rail is still recommendable no matter the type of vehicle.

7.3.3 Expected Transport Effects

Impact Category	1 million vkm of lorry and van transport each (Base)	No freight Transport	Double freight Transport
Climate Change [kg CO2 eq]	0.00753	0.00559 (-25.7 %)	0.00948 (+25.8 %)
Human Toxicity, cancer	1.80559E-9	1.72381E-9 (-4.5 %)	1.88736E-9 (+4.5 %)
Particulate Matter	1.38832E-5	1.28600E-5 (-7.3 %)	1.49063E-5 (+7.3 %)
Photochemical ozone formation	3.99116E-5	3.29489E-5 (-17.4 %)	4.68744E-5 (+17.4 %)
Nonrenewable Fossil	0.10146	0.07047 (-30.5 %)	0.13244 (+30.5 %)

Renewable Biomass	0.28975	0.28774 (-0.6 %	0.29176 (+0.6 %)

7.3.4 Number of Passengers

Results if number of passengers, and yearly personkilometers, were to be increased or reduced by 20 %.

Table 4 - Table of Sensitivity Check results: Number of Passengers

Impact Category	58627486.25 pkm/year	70352983.5 pkm/year	46901989 pkm/year
Climate Change [kg CO2 eq]	0.00753	0.00628 (-16.6 %)	0.00942 (+25.0 %)
Human Toxicity, cancer	1.80559E-9	1.50466E-9 (-16.6 %)	2.25699E-9 (+25.0 %)
Particulate Matter	1.38832E-5	1.15693E-5 (-16.6 %)	1.73539E-5 (+25.0 %)
Photochemical ozone formation	3.99116E-5	3.32597E-5 (-16.6 %)	4.98895E-5 (+25.0 %)
Nonrenewable Fossil	0.10146	0.08455 (-16.6 %)	0.12682 (+25.0 %)
Renewable Biomass	0.28975	0.24146 (-16.6 %)	0.36219 (+25.0 %)

Seeing as person kilometers is the functional unit and that the total impact of the project does not depend on the number of passengers, it comes as no surprise that the more passengers using the light rail, the smaller the impact is per person kilometer.

The projected amount of vehicle kilometers is 1,000,000. With the track being 14.4 km long, this allows for a number of yearly trips equal to

Equation 7 - Number of light rail trips per year

$$\frac{1{,}000{,}000\,\frac{vkm}{year}}{14.4\,\frac{vkm}{trip}} = 69{,}444.4\,\frac{trips}{year}$$

With an expected passenger capacity of 216, this means that the full capacity per year is

Equation 8 - Estimated passenger capacity per year

$$69{,}444.4\,\frac{trips}{year} * 216\,\frac{passenger\ capacity}{trip} = 15{,}000{,}000\ \frac{passenger\ capacity}{year}$$

Meaning that the utilization rate in the three different case equals

Table 5 - Utilisation rates of different passenger levels

	Base	+ 20 %	- 20 %
Passengers per year	10-11 million	12-13.3 million	8-8.8 million
Passenger capacity per year	15 million		
Calculation	$\frac{\frac{Passengers}{year}}{\frac{Passenger\ capacity}{year}} * 100$		
Utilisation rate	66.6-73.3 percent	80-88.66 percent	53.3-58.6 percent

A twenty percent increase in total amount of costumers is therefore technically possible – in that the utilization rate does not surpass one hundred percent – but this would mean that the system would be stretched, and the trips around the most used hours and stations would likely not be able to accommodate the increase in passengers.

7.4 Completeness and Consistency Checks

A number of processes have been excluded, as have been mentioned in the System Boundaries chapter.

The LCA does not consider any changes in urban development, even though this remains a significant part of the VVM report (Cowi A/S, 2013). The light rail is likely to results in changes to the development of Odense Municipality, which likely will result in significant impacts. An LCA over these developments however would be fraught with uncertainty and would in either case be beyond the scope of this paper.

While *Odense Letbane* is a project of significant size, the LCA assumes that it does not necessitate the establishment of production facilities, such as mines, plants or refineries. This is due to the reasoning that the materiel used were neither rare nor in excessive amounts. The VVM report states that the amount “does not appear to be problematic from a resource extraction perspective” (Cowi A/S, 2013, s. 284).

It is with this reasoning that the maintenance and replacement of tools used in construction and maintenance was not modelled either. Furthermore, the impact of these processes appears to be too small to justify their inclusion.

The Light Rail replaces a number of busses, but the scrapping of said busses have not been included. This is due to the reasoning that the busses would likely remain in the bus-fleet. The fleet would then shrink over time, as older models becomes obsolete. The time of scrapping would therefore likely remain the same.

8 Conclusion, Limitations and Recommendations

According to internal documents[7] the Light Rail project was not motivated by a need of reducing emissions – but rather to strengthen the transport sector and urban development (Heunicke & Holst, 2018). Nevertheless, the overall result of this paper shows, that the light rail project is the greener option, as both the total emissions and emission per person kilometer are smaller for the light rail compared to the busses.

The paper does not consider a number of items, which has been touched upon in the *System Boundaries* chapter. It should also be reiterated that the conclusion can only be applied to the context of *Odense Letbane*.

By implementing the Light Rail, each person kilometer will save an approximate hundred grams of CO_2 as well as consume less energy resources. A few kilometers are not likely to change much in the overall balance – but if a user chooses the light rail consistently over busses or cars, they can significantly reduce their overall impact, compared to the average EU citizen.

The analysis also showed that further implementation of wind energy is not likely to sway the conclusion significantly, meaning that the Light Rail is already the greener option, and will likely remain that. However, it also showed that the production of electricity is a significant influence on the impact of the project, and any “relapse” into larger fossil fuel consumption in the electricity grid will hamper the Light Rail.

[7] Namely the principal agreement between Odense Municipality, region *Syddanmark* and the Danish Ministry of Transport, Building and Housing.

A very large part of impacts occurs in manufacturing phase – while electricity is still a significant contributor, the size of the construction phase still means that once the project has been established, the project becomes less impactful per personkilometer, the longer it is being used. It also means that any initiative that could affect the lifetime of the project should keep this fact in mind.

9 Bibliography

Benini, L., Mancini, L., Sala, S., Manfredi, S., Schau, E. M., & Pant, R. (2014). *Normalisation method and data for Enviromental Footprints.* Luxemborg: Publications Office of the European Union.

Birgisdóttir, H., Pihl, K., Bhander, G., Hauschild, M., & Christensen, T. (2006). *Enviromental assessment of roads constructed with and without bottom ash from municipal solid waste inceneration.* Lyngby: Technical University of Denmark.

Chester, M., & Horvath, A. (2008). *Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air v.2.* Berkely: University of California.

Cowi A/S. (2013). *Odense Letbane. VVM og miljøvurdering.* Kongens Lyngby: Cowi A/S.

DSB. (10. December 2018). *Fakta om miljøet*. Hentet fra Webpage of DSB: https://www.dsb.dk/om-dsb/samfundsansvar/miljo/fakta-om-miljoet/

Energistyrelsen. (2017). *ENERGISTATISTIK 2016.* København: Energistyrelsen.

Global Combustion Systems. (19. December 2018). *Oil Fuel Properties*. Hentet fra Website of Global Combustion System: http://www.globalcombustion.com/oil-fuel-properties/

Heunicke, M., & Holst, C. (13. November 2018). *Principaftale for Odense Letbane*. Hentet fra Website of Odense Letbane: https://www.odenseletbane.dk/media/1062/principaftale-for-odense-letbane.pdf

Heunicke, M., Boye, A., & Mathiasen, T. (13. December 2018). *Principaftale for Odense Letbane.* Hentet fra Website of Odense Letbane I/S: https://www.odenseletbane.dk/media/1062/principaftale-for-odense-letbane.pdf

Jex, C. (29. November 2018). *Average Danish household has fifth highest carbon footprint in Europe*. Hentet fra Website of Science Nordic: http://sciencenordic.com/average-danish-household-has-fifth-highest-carbon-footprint-europe

Jonel, F. (2016). *Buss eller spårvagn? Miljövänligare infrastruktur för lokaltrafik i Jönköpings kommun.*

King, H. M. (u.d.). *Granite*. Hentet 7. November 2018 fra Geology.com: https://geology.com/rocks/granite.shtml

Mariagerfjord Kommune. (u.d.). *Genanvendelse og genbrug af bygge- og anlægsaffald.* Hentet 16. November 2018 fra Website of Mariagerfjord Municipality: https://www.mariagerfjord.dk/Affald/~/media/AE97839610BE4F33938640C171577EDD.ashx

Merkisz-Guranowska, A., Merkisz, J., Jacyna, M., Pyza, D., & Stawecka, H. (2014). *Rail vehicles recycling in WIT Transactions on The Built Environment, Vol 135.* Southhampton: WIT Press.

Odense Letbane P/S. (7. December 2018). *Hvor kommer letbanen til at køre?* Hentet fra Webpage of Odense Letbane: https://www.odenseletbane.dk/om-odense-letbane/sp%C3%B8rgsm%C3%A5l-og-svar/hvor-kommer-letbanen-til-at-k%C3%B8re/

Plastindustrien. (7. December 2018). *Elastomer*. Hentet fra Website of Plastindustrien - Brancheforeningen for danske plastvirksomheder: https://plast.dk/det-store-plastleksikon/elastomer/

Ritzau. (7. December 2018). *På vej til Odense: Gasbusser ruller ud på de danske veje* . Hentet fra Website of Fyens Stiftidende: https://www.fyens.dk/erhverv/Paa-vej-til-Odense-Gasbusser-ruller-ud-paa-de-danske-veje/artikel/2612444

Stadler. (7. December 2018). *Stadler secures contract in Denmark - Odense Letbane orders 16 trams*. Hentet fra Website of Stadler Rail: https://www.stadlerrail.com/en/meta/news-media/article/stadler-secures-contract-denmark-odense-letbane-orders-16-trams/

Trafikstyrelsen. (3. December 2018). *Gennemsnitlig CO2-emission per personkilometer fordelt på transportmidler*. Hentet fra Webpage of Trafikstyrelsen: https://www.trafikstyrelsen.dk/~/media/Files/Plan%20og%20kollektiv%20trafik/Bog%202010/Opdateret%20tabel%201%20og%20figur%2016%20august%202010.pdf

Tran, J. (16. November 2018). *Energy in a Cubic Meter of Natural Gas*. Hentet fra Website of The Hypertextbook: https://hypertextbook.com/facts/2002/JanyTran.shtml

U.S. Forest Service. (29. March 2007). *Website of United States Derpartment of Agriculture, Forest Service*. Hentet 14. 11 2018 fra All Live Tree Biomass per Acre of Timberland, 2002: https://www.nrs.fs.fed.us/fia/maps/nfr/descr/xlivebio.asp

Wolf, M.-A., Chomkhamsri, K., & Brandao, M. e. (2010). *ILCD Handbook - General Guide for Life Cycle Assessment - Detailed Guidance.* Luxemborg: Publications Office of the European Union.

World Bank Group. (25. November 2018). *CO2 Emissions (metric tons per capita)*. Hentet fra Website of The World Bank: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=DK

10 Appendix

10.1 Odense Light Rail scenario

10.1.1 Construction of Rails

For modeling the rails, the VVM report was used – it contains a list of the materials expected to be used for the project (Cowi A/S, 2013, s. 284). The rail work has an expected lifetime of 30 year (Cowi A/S, 2013, s. 270), which is equal to the temporal scope – as such the entirety of the of the rail construction process will be considered.

Table 6 - Table of Raw Materials used during Rail Construction - in accordance with source: (Cowi A/S, 2013, s. 284)

Materials Used During Rail Construction		
Material (*Description in source)*	Amount	Modelled as
Concrete (*Beton*)	97,000 tons	”concrete, normal” – 40416.66666 m^3
Granite (*Skærver*)	11,300 tons	”feldspar”
Steel (*Stål – skinner og master*)	4,600 tons	”steel, low alloyed”
Copper (*Kobber*)	510 tons	Product flow ”copper”
Plastics (*Plast*[8])	260 tons	”polyvinchloride”

The source states that ”granite” was used, but no ”granite” option was available in the database used. Instead “feldspar” option was used, the reasoning being that granite mainly consists of feldspar and quartz (King, u.d.). With no quartz option available, feldspar was used as a substitute.

In order to model the work of the equipment used during the rail construction – the work of fork lifts, welding equipment, rail cutters and the like – an LCA

10.1.2 Construction of Stations and civil works

Likewise, for the construction of the stations and civil works of the project, the VVM report is also used (Cowi A/S, 2013, s. 284). The report does not differentiate between materials used for the stations and for the rest of the works, and they have the same expected lifetime of 120 (Cowi A/S, 2013, s. 270) and therefore they have been included as the same process. As the temporal scope of 30 year is one quarter of the life time of 120 years, one quarter of the process is included in the LCA.

Table 7 - Table of Rawmaterials used during construction of stations and civil works - in accordance with source: (Cowi A/S, 2013, s. 284)

Rawmaterials used during construction stations and civil works		
Material (*Description in source)*	Amount	Modelled as
Gravel (*Grus*)	105,000 m^2	”gravel, crushed” 170,625 tons
Asphalt (*Asfalt*)	3,000 tons[9] + 43,000 tons	”mastic asphalt”

[8] During a supervisor meeting on the 12th of November, the *Plast* material was deemed to likely consist of pvc pipes.
[9] According to the VVM report, a total of 46,000 tons is expected to be used, of which 43,000 tons will be reuse of old asphalt, generated during the deconstruction of old roads – the net use of newly produced asphalt will therefore be 3,000 tons. This has been modelled as an input of 46,000 tons total, and an avoided process of 43,000 tons.

Concrete (*Beton*)	15,000 tons	”concrete, normal” – 6250 m^3
Granite (*Granit*)	240 tons	”feldspar”

10.1.3 Train Production

The light rail project has purchased 16 trains of the model “Variobahn” to be produced by Stadler Rail (Stadler, 2018), with an estimated lifetime of 30 years (Cowi A/S, 2013, s. 270). The model of its construction is based on the LCI of a Swedish analysis of a similar train[10]. The source was chosen on the basis of the similar weights, capacities and maximum speed. The Variobahn weighs – compared to 43,340 kg and 257 passengers (Jonel, 2016, s. 19).

Table 8 - Table of the "Train Construction" process – in accordance with source: (Jonel, 2016, s. VII-VIII)

Process of train construction (1 train)		
Material (*Description in source)*	Amount	Modelled as
Steel (*Stål, forstärkt*)	16,700 kg	”steel, low-alloyed”
Aluminium (*Aluminium, mix*)	588 kg	”aluminium, cast alloy”
Copper (*Koppar, lokal*)	1,460 kg	”wire drawing, copper”
Polyethelene (*HDPE, granulat*)	850 kg	”polyethelene, high density, granulate”
Rubber (*Gummi, syntet*)	196 kg	”synthetic rubber”
Glass (*Glas, Plant*)	763 kg	”flat glass, coated”
Paint (*Färg, vit*)	371 kg	”toner, colour, powder”
Electricity (*El, medium volt*)	24,200 kwh	”electricity, medium voltage”
Light fuel oil (*Lätt, eldningsolja*)	17,400 MJ	”light fuel oil” - 3954.54 kg
Lead (*Bly*)	64.1 kg	”lead”

10.1.4 Garbage generated during construction

A certain amount of garbage is expected to be generated during construction, as per the VVM report (Cowi A/S, 2013, s. 286) – as buildings need to be removed in order for new ones to be erected. Said garbage is being handled in accordance with a guide published by Mariagerfjord Kommune on the handling and recycling of construction garbage (Mariagerfjord Kommune). The guide specifies what types of garbage can be recycled, which can be used as replacement for natural resources, and which need special treatment.

Table 9 - Table of Garbage generated during demolition of Bridges and Tunnels - in accordance with source: (Cowi A/S, 2013, s. 286)

Garbage generated during the demolition of bridges and tunnels		
Material (*Description in source)*	Amount	Modelled as
Concrete (*betonbrokker og tegl*)[11]	2,200 tons	“waste concrete”

[10] The train in question being a “fusion variant” of three different types, a *Zaragosa,* an *Urbos AXL* and a *Flexity Outlook* (Jonel, 2016, s. 19). While neither of the three are the *Variobahn* in question, the fusion variant modelled in the Swedish source is quite similar.
[11] This amount also includes the waste concrete generated during the demolition of buildings (Cowi A/S, 2013, s. 286).

Asphalt (*Opbrudt asphalt*)[12]	2,050 tons[13]	"waste asphalt"
Steel[14] (*Metal*)	10 tons	"scrap steel

Table 10 - Table of Garbage generated during demolition of buildings – in accordance with source: (Cowi A/S, 2013, s. 286)

Garbage generated during demolition of buildings		
Material (*Description in source)*	Amount	Modelled as
Concrete (*Betonbrokker og tegl*)	6,500 tons	"waste concrete"
Waste, not suited for inceneration[15] (*Ikke forbrændingsegnet affald*)	850 tons	"waste mineral plaster"
Hazardous waste (*Farligt affald*)	500 tons[16]	"hazardous waste, for incineration"[17]
Iron (*Jern og Metal*)	425 tons	"iron scrap, unsorted"
Waste for Incineration (*Forbrændingsegnet affald*)	425 tons	"process-specific burdens, municipail waste inceneration"

10.1.5 Forest Removal

To model the forest cut down, the options of transformation from "aerable land, organic" to "urban, continuously built" in accordance with advice given at supervisor meeting the 6th of November 2018[18]

The amount of wood chips assumes 41 tons of biomass per acre, in accordance with (U.S. Forest Service, 2007). With 4046.85642 square meters per acre, this equals to 10.13 kg/m^2, equaling 46604.07 kg for the entire area.

Table 11 - The Removal of Forest – in accordance with source: (Cowi A/S, 2013, s. 176)

Removal of Forest		
Process	Amount	Modelled as
Removal of forest[19]	4,600 m^2	"Transformation, from arable, fellow" and "Transformation, to

[12] This amount also includes the waste asphalt generated during the demolition of buildings (Cowi A/S, 2013, s. 286).
[13] This amount does not include the 43,000 tons being reused as part of the construction of the civil works, hence the relatively small amount.
[14] The report does not specify the type of metal, however as the process is that of garbage during construction, it has been deemed to most likely consist of steel primarily
[15] Source does not specify the type of garbage – hence its modeling as plaster
[16] Described in the source as "< 500" tons.
[17] Source provides examples of hazardous waste, but does not estimate amounts of each type norm, specify what is done with it. All garbage is assumed to be incinerated.
[18] This was reasoned with the observation that the forest were planted, rather than naturally occurring. Only the forest removal was modeled as land use change, as the remainder of the land used in the project can be considered "urban, continuously built" already, as they are within the city of Odense.
[19] This covers the 3,300 m^2 of forest around the SDU in Odense, and the 1,300 m^2 around *Jelstrup Plantage*.

		urban, continuously built”
Avoided wood chip production	46604.07 kg	“wood chips, wet, measured as dry mass”, as avoided process

10.1.6 Rail Maintenance

The maintenance of the rails was derived from the Swedish LCA of tram carts. While tram tracks is not the same light rails track, this source was chosen nevertheless, as it is an LCA of tracks of an electricity powered, light rail vehicle in a Scandinavian inner city.

The source does not specify the recycling of steel – however it does not that the steel comes almost entirely from the rails themselves. This usage does not prevent recycling, hence its inclusion.

Table 12 - Table of Rail Maintenance Process per meter per 30 years – in accordance with source: (Jonel, 2016, s. XII)

Rail Maintenance		
Process	Amount	Modeled As
Concrete (*Betong, exakt+salt*)	0.111 m^3	“concrete, normal”
Diesel (*Diesel*)	390 MJ 9.33 kg	“diesel”
Excavation *(Utgrävning*)	0.3 m^3	“excavation, skid-steerloader”
Gravel *(Grus, krossad*)	23.5	“gravel, chrushed”
Bitumen (*Bitumen*)	1.2	“mastic asphalt”
NMVOC (*NMVOC*)	1.24	“NMVOC, non-methane volatile organic compound, unspecified origin”
Steel (*Stål, 900A* & *Stål, finperliticering*)	130.35	“steel, low-alloyed”
Transportation (*Lastbil, 28t*)	14.1 t*km	“transport, freight, lorry 16-32 metric ton EURO6”
Recycling of Steel	130.35 kg	Waste treatment of “scrap steel”
Recycling of Steel	130.35 kg	Avoided Manufacture of“steel, low-alloyed”

10.1.7 Maintenance of Civil Works

The maintenance of the stations is modeled separately. Estimating the maintenance of the civil works is difficult, as the primary source does not specify the detail of the civil works: how many bridges does it entail, how many bicycle paths, and so forth. As the civil works do not include roads for vehicle transport, but rather include bicycle paths, bicycle parking and pavements, the entirety of the “civil works” maintenance is modeled as if it were bicycle paths in accordance with an environmental assessment of Danish road construction (Birgisdóttir, Pihl, Bhander, Hauschild, & Christensen, 2006, s. 363). The source includes the inventory 1 km of roads maintained over a hundred years. As this LCA spans over 30 years, the materials named in the inventory will be multiplied with 0.3. The model will assume that a bicycle path runs the entire length of the rail – meaning that 14.4 km of bicycle path will need to be constructed.

According to the source, three types of asphalt is used. The source does not state the amounts used for roads, compared to that used for bicycle paths, but does provide a figure the amounts of materials used for each element of the road – 20 mm by 1.5 m of asphalt concrete was used on bicycle paths for every 30 mm by 3.5 m on the road, 80 mm by 1.5 m of soft concrete was used on the bicycle path for every 100 mm by

3.5 m of soft concrete used on the road and 150 mm by 1.5 m for 200 mm by 3.5 plus 200 mm by 1.5 m for asphalt concrete (base course).

This means that the ratio of materials used on bicycle paths versus materials used on the entire project is

Equation 9 - Ratio of Asphalt Concrete Used in Bicycle Paths Compared to that of the Road as a Whole (surface course)

$$Ratio\ of\ Asphalt\ concrete\ (surface\ course) = \frac{Asphalt\ used\ in\ bicycle\ path}{Asphalt\ used\ in\ entire\ road}$$
$$= \frac{(20\ mm * 1.5\ m)}{(20\ mm * 1.5\ m + 30\ mm * 3.5\ m)} = 0.2222$$

Equation 10 - Ratio of Soft Asphalt Used in Bicycle Paths Compared to that of the Road as a Whole

$$Ratio\ of\ soft\ asphalt = \frac{Asphalt\ used\ in\ bicycle\ path}{Asphalt\ used\ in\ entire\ road} = \frac{(80\ mm * 1.5\ m)}{(80\ mm * 1.5\ m + 100\ mm * 3.5\ m)}$$
$$= 0.2553$$

Equation 11 - Ratio of Asphalt Concrete Used in Bicycle Paths Compared to that of the Road as a Whole (base course)

$$Ratio\ of\ Asphalt\ concrete\ (base\ course) = \frac{Asphalt\ used\ in\ bicycle\ path}{Asphalt\ used\ in\ entire\ road}$$
$$= \left(\frac{150\ mm * 1.5\ m}{150\ mm * 1.5\ m + 200\ mm * 3.5\ m + 200\ mm * 1.5\ m}\right) = 0.1836$$

The ratio of diesel used will correspond with the volume of the materials used on the bicycle path compared to that of the entire road:

Equation 12 - Estimate of Ratio of Diesel Used on Sidewalk Construction Compared to Road as a Whole

$$Ratio\ of\ Diesel\ used = \frac{700\ mm * 1.5\ m}{700mm * (2.1\ m + 1.5\ m + 1.5\ m + 3.5\ m)} = 0.1744$$

The Ecoinvent database does not have separate flows for “asphalt concrete” and “soft asphalt” – as such, both will be modeled as “mastic asphalt”. The model in this paper will assume that the ratio of materials used in construction corresponds to the ratio of materials used in maintenance[20].

[20] Although this assumption is likely not true, as the wear and tear from bicycles are not the same as that from cars.

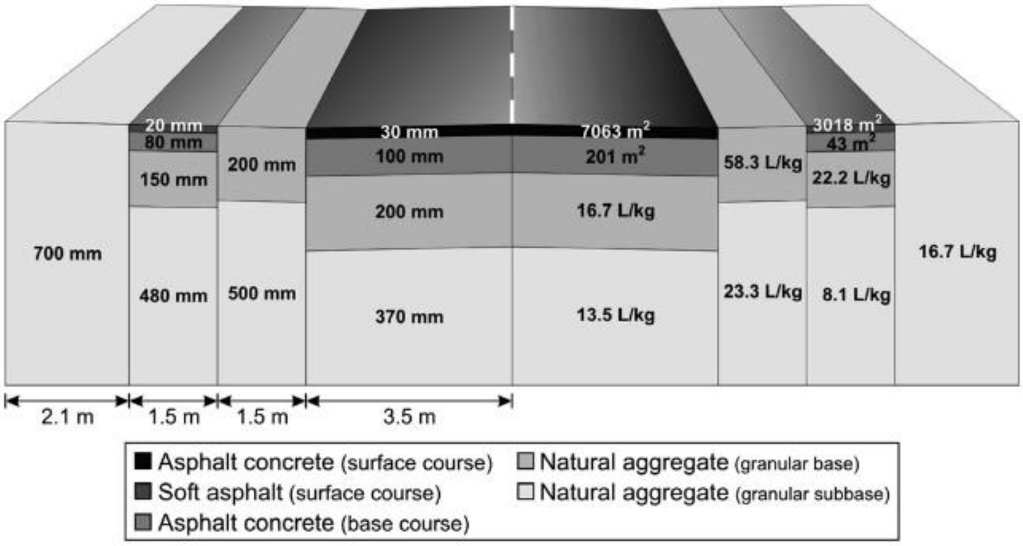

Figure 7 - Cutaway of Road (Birgisdóttir, Pihl, Bhander, Hauschild, & Christensen, 2006)

Table 13 - Table of Civil Works Maintenance process - in accordance with source: (Birgisdóttir, Pihl, Bhander, Hauschild, & Christensen, 2006)

Civil works maintenance		
Process	Amount	Modelled as
Asphalt Concrete (surface course)	2060 tons * 14.4 *0.3 * 0.2222 = 1977.40224 tons	Manufacture of "mastic asphalt"
Soft Asphalt (surface course)	576 tons * 14.4 * 0.3 * 0.2553 = 635.26 tons	Manufacture of "mastic asphalt"
Asphalt (base course)	3000 ton * 14.4* 0.3 * 0.1836 = 2379.45 tons	Manufacture of "mastic asphalt"
Diesel	6800 l * 0.3 * 14.4 * 0.1744 / 1182[21] = 4.33 tons	Manufacture of "diesel"

10.1.8 Maintenance of stations

According Mikhail Chester, one can assume that the maintenance of a rail station requires "5 % of initial construction impacts" (Chester & Horvath, 2008). The VVM does not differentiate between materials used for stations, and those use for the remainder of the construction – an estimate is therefore needed. Chester assumes that every station for a light rail[22] requires 5,100 ft^3 of concrete – or 144.41 m^3. With Odense Letbane having 26 stations this would require 3754.66 m^3 of concrete or, assuming a density of 2400 kg/m^3, 9011.184 tons of concrete for the construction of the stations[23]. Five percent of this equals

[21] Assuming a density of diesel of 1182 l/ton, in accordance with (Elert, 2018)

[22] Of the "*Green Line*" example. The report includes a photo of one such station, which visually appears quite similar to examples which Odense Letbane have projected.

[23] This appears to be within the realms of possibilities, as the VVM has stated that a total of 15,000 tons is to be used for stations and civil works (Cowi A/S, 2013, s. 284) – leaving a little less than 6,000 tons for the remaining construction.

450.55 tons of concrete. In accordance with the life time of the project and stations, 25 % of said maintenance is assumed to occur during the first 30 years.

Table 14 - Table of Train Station Maintenance process in accordance with (Chester & Horvath, 2008)

Maintenance of Train Stations (all 26 stations)		
Process	Amount	Modelled as
Replacement Concrete	450.55 tons	"concrete, normal", 0.25 of the process.

10.1.9 Train Maintenance

The Maintenance of the train is modeled to occur periodically per 250,000 vkm driven.

Maintenance of Train (per 250,000 vkm)		
Process	Amount	Modelled as
Natural Gas (*Naturgas*)	22156.86 MJ / 40.6 MJ/kg = 598.83 m^3[24]	Manufacture of "natural gas, high pressure"
Electricity (*el, medium volt*)	18314 kWh	Electric Power Generation "electricity, medium volt"
Light Fuel Oil (*Lätt eldningsolja*)	22156.86 MJ / 37 MJ/m^3 = 545.73 kg[25]	Manufacture of "light fuel oil"
Tap water *(Kranvatten*)	113725.49 kg	Water collection "tap water"
Steel (*Stål, förstärkt*)	1671 kg	Manufacture of "reinforcing steel"
Polyethylene (*HDPE*)	45.9 kg	Manufacture of "polyethylene, high density, granulate"
Polybutadiene[26] (*Elastomer*)	52.1 kg	Manufacture of "polybutadiene"
Lubricating Oil (*Smörolja*)	25.53 kg	Manufacture of "lubricating oil"
Refrigerant (*Koldmedie R134*)	25.53 kg	Manufacture of "refrigerant 134a"
Sand *(sand*)	10294.11 kg	Quarrying of "sand"
Waste water (*Avloppsvatten*	1160 m^3	Sewerage "wastewater, average"
Freight by train (*Järnväg, gods*)	2049 tkm	Transport via railways "transport, freight train"
Freight by lorry (*Lastbil, 28t*)	512.74 tkm	Other land transport "transport, freight, lorry 16-32 metric ton, EURO6
NMVOC (*NMVOC*)	29 kg	Emission to air, high density population[27] "NMVOC, non-methane volatile organic compounds, unspecified origin"
Waste Heat (*Värme, förlust*)	66264 MJ	Emission to air, high density

[24] Assuming an energy density equal to 40.6 MJ/kg, in accordance with (Global Combustion Systems, 2018)
[25] Assuming an energy density equal to 37 MJ/m^3, in accordance with (Tran, 2018)
[26] Polybutadiene was chosen due to souce not specifying the type of elastomer being used, and polybutadiene has been descriped as an "important example" (Plastindustrien, 2018)
[27] The "high density population" was chosen due to the urban environment in which *Odense Letbane* is situated

		population “Heat, waste”

10.1.10 Energy Usage

The trains use electricity at 750 V (Cowi A/S, 2013, s. 38) – this requires transformer stations to supply the trains, but is still so low as to be “low voltage”. Furthermore, the train emits waste heat. The amount of electricity and heat is modeled as a “Bombardier Flexity”, meaning 3.7 kwh/vkm and 13.7 MJ/vkm (Jonel, 2016, s. IX).

10.1.11 Person Kilometers

An official estimate of the number of person kilometers is seemingly not available. Figures of vehicle kilometers per year and daily or yearly users exist though.

One graph, included in the VVM report, shows the expected passengers per station, traveling towards Hjallese and towards Tarup.

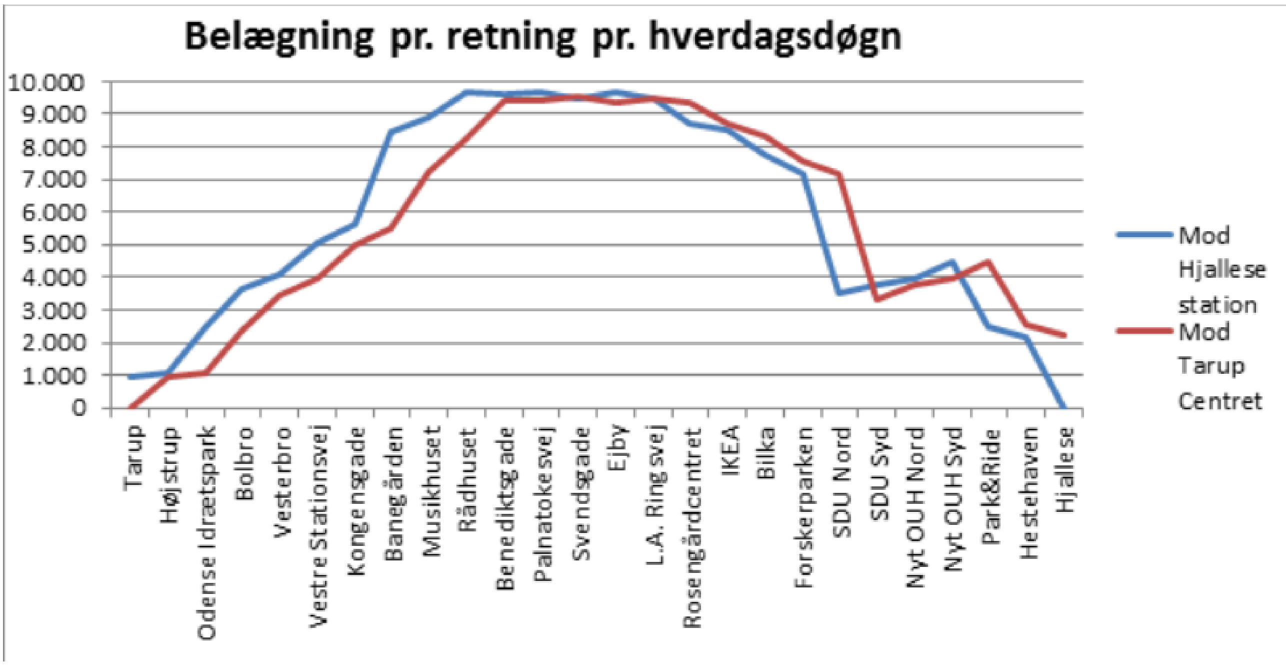

Figure 8 - Utilisation per direction per day in accordance with (Cowi A/S, 2013, s. 85)

The number behind this graph were not provided – as such, the figures were derived via an online tool by the name of *WebPlotDigitizer*. The next datapoint needed is the distance between each station. This was done by inspecting the following image, from the official webpage of *Odense Letbane*, and recreating it in google maps and using it to measure the distance between stations.

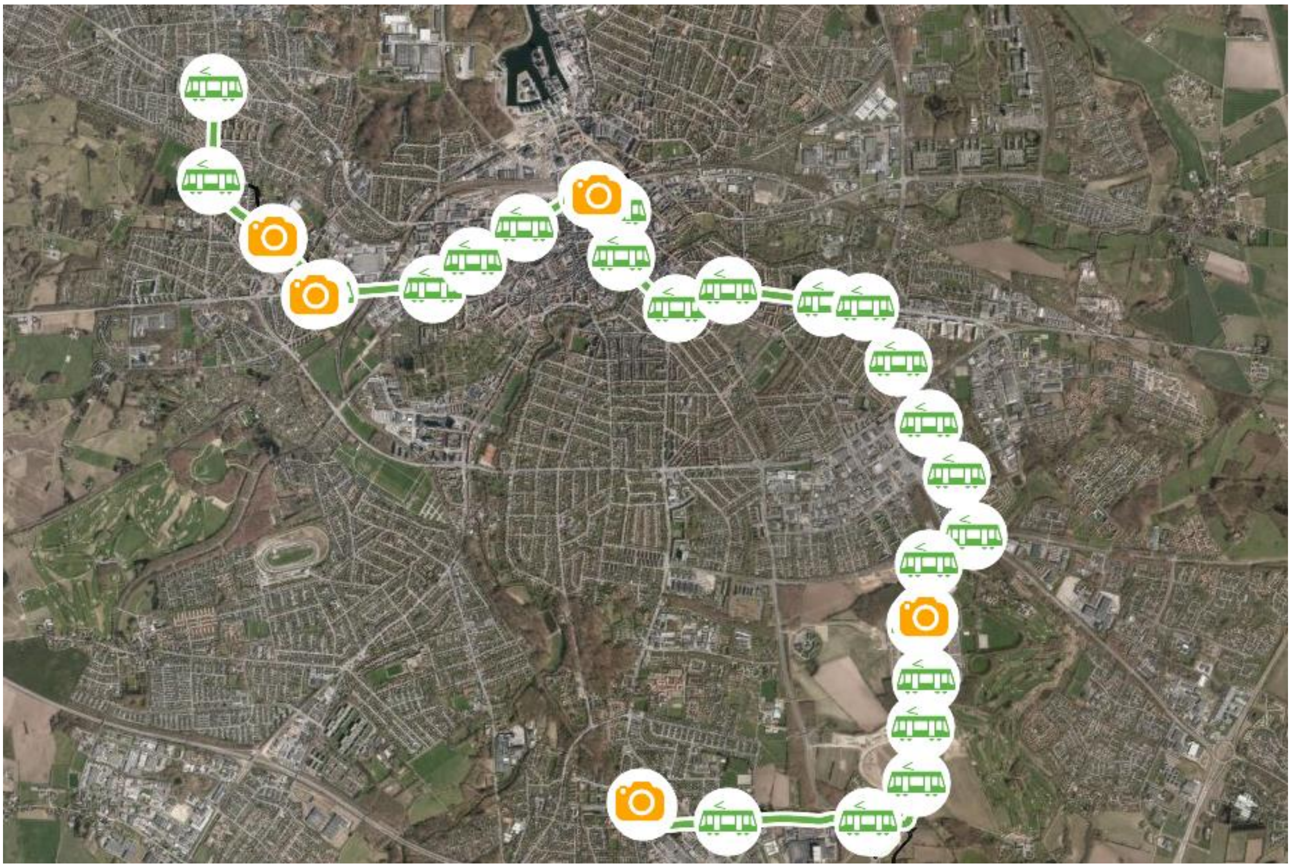

Figure 9 - Station Placement - (Odense Letbane P/S, 2018)

Via these two methods, the following data were derived:

Table 15 - Table of estimated Personkilometers per station per day

	Distance [meters]	Passengers - towards hjallese	Pkm hjallese	Passengers towards Tarup	Pkm tarup
Tarup	0	950	0	0	712.5
Højstrup	750	1050	712.5	950	735
Odense Idrætspark	700	2450	735	1050	1875
Bolbro	750	3550	1837.5	2500	2720
Vesterbro	800	4000	2840	3400	1560
Venstre Stationsvej	400	5100	1600	3900	2227.5
Kongensgae	450	5600	2295	4950	3270
Bandegården	600	8450	3360	5450	2592
Musikhuset	360	8900	3042	7200	3366
Rådhuset	360	9650	3204	9350	5395
Benediktsgade	650	9600	6272.5	8300	4207.5
Palnatokesvej	450	9700	4320	9350	7600
Svendsgade	800	9450	7760	9500	4185
Ejby	450	9750	4252.5	9300	5197.5

L.A. Ringsvej	550	9550	5362.5	9450	5115
Råsengårdcentret	550	8750	5252.5	9300	3915
Ikea	450	8650	3937.5	8700	5362.5
Bilka	650	7700	5622.5	8250	3397.5
Forkserparken	450	7250	3465	7550	3625
SDU Nord	500	3500	3625	7250	1485
SDU Syd	450	3750	1575	3300	1950
Nyt OUH Nord	520	3900	1950	3750	1283.75
Nyt OUH Syd	325	4450	1267.5	3950	2091.5
Park and Ride	470	2450	2091.5	4450	3960
Hesthaven	1100	2450	2695	3600	1760
Hjallese	800	0	1960	2200	0
Total	14335	n/a	81035	n/a	79588.25

By using the graph and the distance between each station, an estimate of person kilometers per day can be made. For example – if an estimated 950 passengers are onboard the train a day while traveling from station A to station B, an estimated 750 meters away, then that represents

Equation 13 - Example of PKM calculations

$$Pkm_{A-B} = Passenger_{A-B} * Distance_{A-B} = 950\ Passengers * 0.750\ km = 712.5\ pkm$$

In total this results in an estimated 160623.25 person kilometers traveled on a normal day. If all days are treated as normal days[28] this results in

Equation 14 - Total number of PKM per Year

$$160623.25\ \frac{pkm}{day} * 365\ \frac{days}{year} = 58627486.25\ \frac{pkm}{year}$$

10.1.12 Expected Traffic Effects

The VVM report states that a relatively small increase in freight transport is expected as a consequence of the rail projec (Cowi A/S, 2013, s. 266-269). The increase is small in comparison to the total freight already in place (a 1 million vkm increase for both trucks and van, compared to 172 million and 125 million vkm respectively) and is a source of great uncertainty. Nevertheless, it has been included.

Table 16 - Table of Estimated increase in traffic, due to the completion of Odense Letbane - in accordance with source: (Cowi A/S, 2013, s. 266-269)

Increased Traffic Due to the completion of *Odense Letbane*		
Process (*Source Description*)	Amount	Modelled as

[28] Obviously, some days are more can be expected to cater to more passengers than others – the days up to Christmas can for example not be expected to be equally as busy as a normal Sunday. However, the most reliable data available only details an average weekday, so this will be the basis for all modeled days.

By Truck (*Lastbilstrafik*)	1,000,000 vkm	"transport, freight, lorry, unspecified" "14 million ton km"[29]
By Van (*Varebilstrafik*)	1,000,000 vkm	"transport, freight, light commercial vehicle" "0.97 million ton km"[30]

10.1.13 Construction End-of-Life

After the lifetime of the project, the station and civil works need to be deconstructed, and the raw materials need to be processed. According to a source, from the Danish municipality of Mariagerfjord, certain materials may be reused for the same purpose, while others may be "without permission, and after processing, reused as replacement for primary rawmaterials" (Mariagerfjord Kommune). This source will be dictating what is to happen with which materials during the end of life processes of the constructions. The materials that are present of the list of materials that may be recycled are recycled or reused directly (*Bygge og Anlægsaffald – hvad må genanvendes?*), while those that are not present are disposed of.

Table 17 - Table of End-of-Life process for Train Tracks, in accordance with (Cowi A/S, 2013) and (Mariagerfjord Kommune)

End-of-Life for Rail		
Process	Amount	Modelled as
Recycling of Concrete (*Beton*)	97.000 tons	Material recovery of "waste concrete, gravel" and avoided process of Manufacture "concrete, normal"
Reuse of Granite (*Skærver*)	11.300 tons	Avoided process of Quarrying "feldspar"
Recycling of Steel (*Stål – Skinner og Master*)	4.600 tons	Waste treatment of "scrap steel" and avoided process of Manufacture "steel, low alloyed"
Recycling of Copper (*Kobber*)	510 tons	Waste treatment of "scrap copper" and avoided process of Manufacture of "copper"
Disposal of Plastic (*Plast*)	460 tons	Waste treatment of "waste polyvinylchloride"

Table 18 - End-of-Life process for stations and civil works, in accordance with (Cowi A/S, 2013) (Mariagerfjord Kommune)

End-of-life of stations and civil works		
Process	Amount	Modeled as
Reuse of Gravel (*Grus*)	105.000 m^3	Avoided Quarrying of "gravel, crushed"

[29] According to ecoinvent database, surveyed under an educational account, this process only includes "EURO 3 Emission class". The trucks are assumed to transport an average of 14 tons, in accordance with (Larsson, 2009, s. 20)
[30] The average load for a van (or light commercial vehicle), was estimated on the assumption of an average utilisation rate of 80 % and an average max payload of 1210.96 kg – based on the average payload of vans produced by ford (Ford, 2017)

Recycling of Asphalt (*Asfalt*)	46.000 tons	Waste treatment of "waste asphalt" and avoided Manufacture of "mastic asphalt"
Recycling of Concrete *(Beton*)	15.000 tons	Materials recovery of "waste concrete gravel" and avoided Manufacture of 6250 m^3 "concrete, normal"
Reuse of Granite (*Granit*)	240 tons	Avoided Quarrying of "feldspar"

10.1.14 Train End-of-Life

For the recycling of the train, a report called *Rail Vehicles Recycling* (Merkisz-Guranowska, Merkisz, Jacyna, Pyza, & Stawecka, 2014) was used to determine which materials, and in what quantities, they were recycling. The recycling was modelled as avoided flows – meaning for example that if a kilo of steel was recycled, it was modelled as if the production of a kilo of steel was avoided. The percentage of each material being recycled is being stated as an interval in the source – in the modeling the percentage used is the average of said intervals.

Table 19 - Table of Scrapping and Recycling of Train Carts (1 train) – in accordance with sources: (Jonel, 2016, s. VII-VIII) and (Merkisz-Guranowska, Merkisz, Jacyna, Pyza, & Stawecka, 2014)

The Scrapping and Recycling of Train Carts (1 Train)		
Material	Amount	Modelled as
Aluminium	588 kg * 0.875 = 514.5 kg	Avoided process of "aluminium, cast alloy"
Copper	1,460 kg * 0.70 = 876 kg	Avoided process of product flow "copper"
Glass	763 kg * 0.75 = 572.25 kg	Avoided process of "flat glass, coated"
Lead	64.1 kg * 0.89 = 57.049 kg	Avoided process of "lead"
Polyethylene	850 kg * 0.60 = 510 kg	Avoided process of "polyethylene, high density, granulate"
Steel	16,700 kg * 0.94 = 15698 kg	Avoided process of "steel, low-alloyed"

10.2 Bus Scenario

10.2.1 Bus Maintenance

In accordance with the Swedish source. The maintenance occurs periodically for every 60.000 vkm. As the bus alternative is supposed to run for 1.000.000 vkm per year, this equals to

Equation 15 - Number of Bus Maintenance Processes

$$\frac{1\ Maintenance\ process}{60\ vkm} * 1{,}000{,}000\ vkm/year * 30\ years = 500\ maintenance\ processes$$

Table 20 - Table of Bus Maintenance process - in accordance with source: (Jonel, 2016, s. X)

Maintenance of Busses (per 60.000 vkm)		
Process	Amount	Modelled as
Steel (*Stål, reinforcing*)	55 kg	Manufacture of "steel, low alloyed"
Polyethylene (*HDPE, granulat*)	1.4 kg	"polyethylene, high density, granulate"
Rubber (*Gummi, syntetisk*)	133 kg	"synthetic rubber"
Electricity (*El, låg volt*)	67,800 kwh	Electricity, low voltage
Light fuel oil (*Lätt eldningsolja*)	40400 MJ/40.6 MJ/kg[31]= 995.073 kg	"light fuel oil"
Tap water (*Kranvatten*)	484,000 kg	"tap water"
Lubricating oil (*Smörolja*)	824 kg	"lubricating oil"
Lead (*Bly*)	17.9 kg	"lead"
Freight transport, train (*Järnväg, gods*)	207 t*km	"transport, freight train"
Freight transport, truck (*Lastbil, 28t*)	51.7 t*km	"trainsport, freight lorry 16-32 metric ton, EURO6"
Plastic (*Plast, blandat*)	55 kg	"polycinylidenchloride, granulate
Waste water (*avloppsvatten*)	794 m^3	"wastewater, average"
Waste heat (*Värme, förlust*)	254,973 MJ	"Heat, waste"
Natural Gas (*Naturgas*)	40400 MJ/37 MJ/m3[32]=1091.89 m^3	"natural gas, high pressure"

10.2.2 Bus fuel

For modeling the operation of the bus, the Ecoinvent database was use in the form of the product flow "transport, regular bus". This is a consequential representation of bus transport, and as such includes both fuel use, as well as maintenance of the bus and the roads. This can be documented when looking into the database – the product flow is produced by the "transport, regular bus | transport, regular bus | Consequential, U" process, the description of which specifies that the maintenance of both busses and roads are included. The inputs to the process also reflect this.

[31] Source states that 40,400 MJ of light fuel oil was used – an energy density of 40.6 MJ/kg was used (Oil Fuel Properties, 2018)

[32] Source states that 40,400 MJ of natural gas was used – and energy density of 37 MJ/m^3 was used (Elert, Energy in a Cubic Meter Of Natural Gas, 2018)

Inputs

Flow	Category	Amount	Unit	Costs/R...	Uncerta...	Avoide...
bus	291:Manufacture ...	7.14290E-8	Ite...	0.00561...	lognor...	
diesel, low-sulfur	192:Manufacture ...	0.00539	kg	0.00215...	lognor...	
diesel, low-sulfur	192:Manufacture ...	0.01960	kg	0.00784...	lognor...	
maintenance, bus	452:Maintenance ...	7.14290E-8	Ite...	0.00078...	lognor...	
road	421:Construction ...	0.00046	m*a	0.00215...	lognor...	

Figure 10 - Inputs for the consequenctial "transport, regular bus" ecoinvent process

The road that the bus travels on exists in both scenarios – the road maintenance part of the bus transport merely represents the marginal increase in road maintenance that the bus causes.

10.2.3 Bus replacement

As the bus scenario assumes the continuation of the already existing bus services, the operating company Fynbus, will likely not have to expand their fleet of busses in this scenario. However, continuing the bus services over thirty years mean that they will have to keep their fleet at its current size – whenever a bus goes out of service, they need to replace it with a new one. This means, that if one assumes a bus lifetime of thirty years, Fynbus will have to purchase a number of busses equal to the number necessary to operate said line.

The light rail replaces the operation of busses on a one-to-one basis in terms of vehicle kilometers. However, the light rail does not replace the services of an actual bus line. When comparing the maps of Fynbus and Odense Letbane, it appears that the bus line 40-41 operates in between what is to become stations Tarup and SDU. The line starts in Snestrup further to the south, and does not continue all the way to Hjallese.

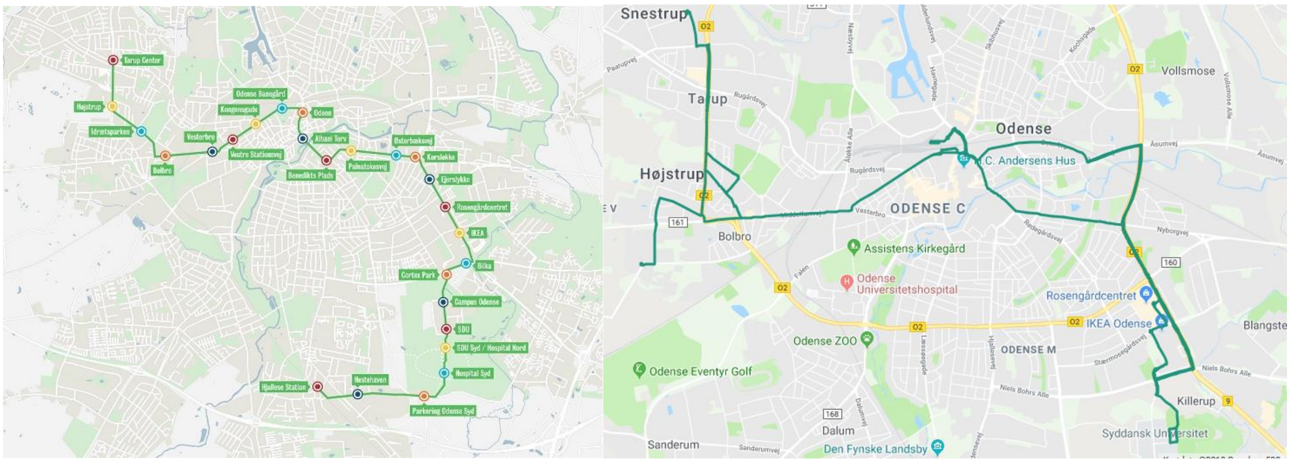

Figure 11 - Comparison between the "Odense Letbane" route and the bus "Linje 40-41" route

In order to determine how many busses would need purchasing to maintain operation, the operations of the light rail will be examined – if they both represent the same amount of vehicle kilometers, this Based on this, an estimate of how many busses would have to operate simultaneously at peak operation will be made. At the very least, it can be argued that this peak number is what will be made superfluous by the introduction of the light rail.

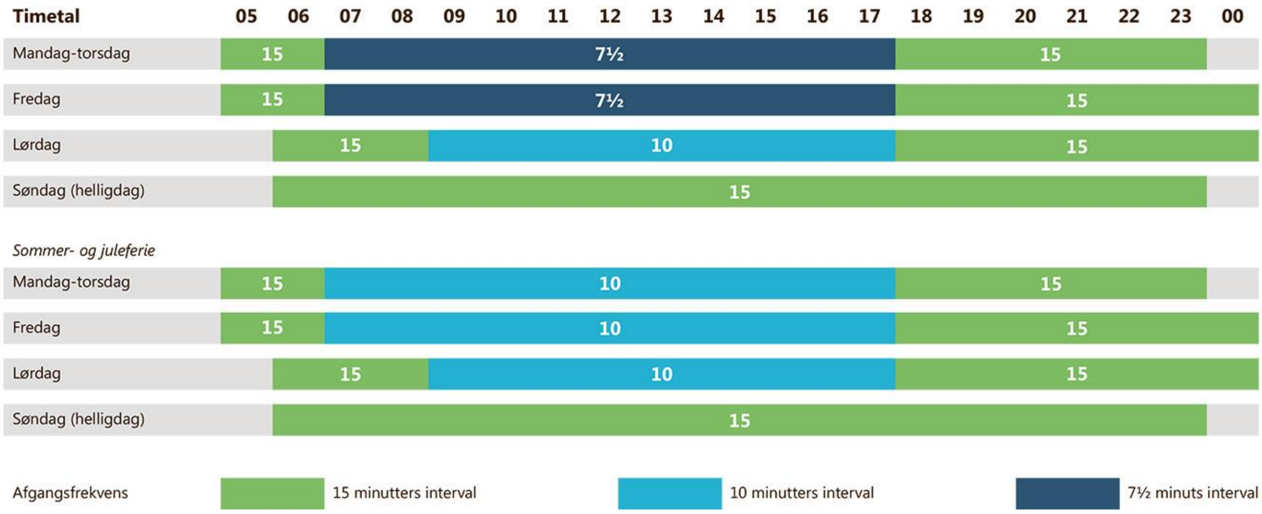

Figure 12 - Expected Schedule of Odense Letbane

In peak operations, in weekdays Monday till Friday, a light rail is projected to leave a station every seven and a half minutes. The entire trip is scheduled to take 42 minutes. This mean that six trains will have left the two end stations, before a new arrives, allowing for a three-minute break before resuming transportation in the opposite direction. This results in a need of 12 busses.

This is two vehicles less than the light rail is projected to need, at 14 train carts – however this also likely reflects the need for spare trains in case of breakdowns. Fynbus, having a larger fleet with many different lines, already have this spare capacity, and do not need to purchase it.

Table 21 - Tabel 13 - Table of replacement buss processes

Replacement busses		
Process	Amount	Modeled as
Manufacture of bus	16	Manufacture of motor vehicles “bus”
Scrapping of bus	16	Materials recovery “used bus”

10.3 LCI Results

Contribution	Process	Amount	Unit
100.00%	Odense Letbane - DK	0.00753	kg CO2 eq
64.21%	Construction (rail, stations, civil works) (VVM) - DK	0.00484	kg CO2 eq
32.07%	Electricity - market for electricity, low voltage | electricity, low vol...	0.00242	kg CO2 eq
14.64%	Trafic Truck (1 vkm) - DK	0.00110	kg CO2 eq
14.31%	Maintenance of Train (per 250.000 vkm) - DK	0.00108	kg CO2 eq
11.15%	Trafic Van (1 vkm) - DK	0.00084	kg CO2 eq
10.43%	Construction (1 train) (swedish source) - DE	0.00079	kg CO2 eq
04.32%	Maintenance of civil works - DK	0.00033	kg CO2 eq
02.96%	Maintenance of Track per meter (30 years) - DK	0.00022	kg CO2 eq
00.63%	Forest Removal (4600 square meters) - DK	4.72272E-5	kg CO2 eq
00.12%	Maintenance of Stations (all 26 stations, their entire lifetime) - DK	9.23192E-6	kg CO2 eq
-08.34%	Scrapping of train (1 train) - DK	-0.00063	kg CO2 eq
-14.30%	Scrapping of Tracks - DK	-0.00108	kg CO2 eq
-16.03%	Garbage Generated Curing Construction (VVM) - DK	-0.00121	kg CO2 eq
-16.19%	Scrapping of stations and civil works - DK	-0.00122	kg CO2 eq

Figure 13 - LCI results - Odense Letbane - Climate Change [kg CO2 eq/pkm]

Contribution	Process	Amount	Unit
100.00%	Odense Letbane - DK	1.80559E-9	CTUh
111.73%	Construction (rail, stations, civil works) (VVM) - DK	2.01740E-9	CTUh
40.48%	Electricity - market for electricity, low voltage | electricity, l...	7.30913E-10	CTUh
12.03%	Construction (1 train) (swedish source) - DE	2.17199E-10	CTUh
06.52%	Maintenance of Train (per 250.000 vkm) - DK	1.17771E-10	CTUh
02.31%	Trafic Van (1 vkm) - DK	4.17611E-11	CTUh
02.22%	Trafic Truck (1 vkm) - DK	4.00156E-11	CTUh
00.43%	Maintenance of Track per meter (30 years) - DK	7.78717E-12	CTUh
00.39%	Maintenance of civil works - DK	7.00079E-12	CTUh
00.01%	Maintenance of Stations (all 26 stations, their entire lifetime...	1.66282E-13	CTUh
-00.00%	Forest Removal (4600 square meters) - DK	-2.36635E-14	CTUh
-01.33%	Scrapping of Tracks - DK	-2.39575E-11	CTUh
-02.28%	Scrapping of stations and civil works - DK	-4.12452E-11	CTUh
-17.42%	Scrapping of train (1 train) - DK	-3.14454E-10	CTUh
-55.09%	Garbage Generated Curing Construction (VVM) - DK	-9.94749E-10	CTUh

Figure 14 - LCI results - Odense Letbane - Human Toxicity, cancer [CTUh/pkm]

Contribution	Process	Amount	Unit
100.00%	Odense Letbane - DK	1.38832E-5	kg PM2.5 eq
58.51%	Construction (rail, stations, civil works) (VVM) - DK	8.12373E-6	kg PM2.5 eq
49.03%	Electricity - market for electricity, low voltage | electricity, l...	6.80640E-6	kg PM2.5 eq
07.94%	Maintenance of Train (per 250.000 vkm) - DK	1.10178E-6	kg PM2.5 eq
05.36%	Construction (1 train) (swedish source) - DE	7.44391E-7	kg PM2.5 eq
04.85%	Trafic Truck (1 vkm) - DK	6.74006E-7	kg PM2.5 eq
02.52%	Trafic Van (1 vkm) - DK	3.49171E-7	kg PM2.5 eq
02.20%	Maintenance of civil works - DK	3.05184E-7	kg PM2.5 eq
00.67%	Maintenance of Track per meter (30 years) - DK	9.23681E-8	kg PM2.5 eq
00.01%	Maintenance of Stations (all 26 stations, their entire lifetime...	1.93315E-9	kg PM2.5 eq
-00.00%	Forest Removal (4600 square meters) - DK	-4.20394E-10	kg PM2.5 eq
-07.28%	Garbage Generated Curing Construction (VVM) - DK	-1.01082E-6	kg PM2.5 eq
-07.42%	Scrapping of train (1 train) - DK	-1.03023E-6	kg PM2.5 eq
-08.09%	Scrapping of Tracks - DK	-1.12256E-6	kg PM2.5 eq
-08.30%	Scrapping of stations and civil works - DK	-1.15178E-6	kg PM2.5 eq

Figure 15 - LCI results - Odense Letbane - Partoculate Matter [kg PM2.5 eq/pkm]

Contribution	Process	Amount	Unit
100.00%	Odense Letbane - DK	3.99116E-5	kg NMVO...
77.73%	Electricity - market for electricity, low voltage | electricity, l...	3.10222E-5	kg NMVO...
60.77%	Construction (rail, stations, civil works) (VVM) - DK	2.42545E-5	kg NMVO...
10.69%	Trafic Van (1 vkm) - DK	4.26836E-6	kg NMVO...
06.75%	Trafic Truck (1 vkm) - DK	2.69440E-6	kg NMVO...
06.62%	Maintenance of civil works - DK	2.64241E-6	kg NMVO...
03.51%	Construction (1 train) (swedish source) - DE	1.40274E-6	kg NMVO...
00.05%	Maintenance of Stations (all 26 stations, their entire lifetime...	1.84146E-8	kg NMVO...
-00.02%	Forest Removal (4600 square meters) - DK	-6.38649E-9	kg NMVO...
-00.86%	Maintenance of Train (per 250.000 vkm) - DK	-3.43965E-7	kg NMVO...
-05.44%	Scrapping of train (1 train) - DK	-2.17054E-6	kg NMVO...
-07.38%	Garbage Generated Curing Construction (VVM) - DK	-2.94745E-6	kg NMVO...
-08.00%	Scrapping of Tracks - DK	-3.19466E-6	kg NMVO...
-20.53%	Scrapping of stations and civil works - DK	-8.19484E-6	kg NMVO...
-23.89%	Maintenance of Track per meter (30 years) - DK	-9.53355E-6	kg NMVO...

Figure 16 - LCI results - Odense Letbane - Photochemical Ozone Formation [kg NMVOC eq/pkm]

Contribution	Process	Amount	Unit
100.00%	Odense Letbane - DK	0.10146	MJ
64.55%	Construction (rail, stations, ...	0.06549	MJ
21.92%	Electricity - market for elect...	0.02224	MJ
17.88%	Trafic Truck (1 vkm) - DK	0.01814	MJ
17.01%	Maintenance of Train (per 2...	0.01726	MJ
14.75%	Maintenance of civil works ...	0.01496	MJ
12.66%	Trafic Van (1 vkm) - DK	0.01285	MJ
09.65%	Construction (1 train) (swe...	0.00979	MJ
05.49%	Maintenance of Track per ...	0.00557	MJ
00.04%	Maintenance of Stations (al...	4.35074E-5	MJ
-00.01%	Forest Removal (4600 squar...	-1.17579E-5	MJ
-05.29%	Scrapping of train (1 train) -...	-0.00537	MJ
-07.14%	Scrapping of Tracks - DK	-0.00724	MJ
-12.16%	Garbage Generated Curing ...	-0.01233	MJ
-39.35%	Scrapping of stations and ci...	-0.03993	MJ

Figure 17 - LCI results - Odense Letbane - Cumulative Energy Demand, non renewable fossil [MJ/pkm]

Contribution	Process	Amount	Unit
100.00%	Odense Letbane - DK	0.28975	MJ
97.60%	Electricity - market for elect...	0.28280	MJ
07.70%	Construction (rail, stations, ...	0.02230	MJ
02.90%	Maintenance of civil works ...	0.00840	MJ
00.38%	Trafic Truck (1 vkm) - DK	0.00109	MJ
00.32%	Trafic Van (1 vkm) - DK	0.00092	MJ
00.18%	Construction (1 train) (swe...	0.00052	MJ
00.15%	Maintenance of Train (per 2...	0.00045	MJ
00.12%	Maintenance of Track per ...	0.00034	MJ
00.00%	Maintenance of Stations (al...	2.78482E-6	MJ
-00.14%	Scrapping of train (1 train) -...	-0.00041	MJ
-00.16%	Scrapping of Tracks - DK	-0.00045	MJ
-00.18%	Forest Removal (4600 squar...	-0.00052	MJ
-02.01%	Garbage Generated Curing ...	-0.00583	MJ
-06.86%	Scrapping of stations and ci...	-0.01987	MJ

Figure 18 - LCI results - Odense Letbane - Cumulative Energy Demand, renewable biomass [MJ/pkm]

10.4 Biomass consumption – Hard Coal case

Contribution	Process	Amount	Unit
100.00%	electricity production, hard coal | electricity, high voltage | Conse...	0.16376	MJ
96.92%	market for hard coal | hard coal | Consequential, U - WEU	0.15873	MJ
94.18%	hard coal mine operation and hard coal preparation | hard coal | ...	0.15423	MJ
48.36%	market for heat, district or industrial, other than natural gas | heat...	0.07920	MJ
37.14%	market for mine infrastructure, underground, hard coal | mine inf...	0.06082	MJ
34.37%	mine construction, underground, hard coal | mine infrastructure, ...	0.05629	MJ
02.77%	mine construction, underground, hard coal | mine infrastructure, ...	0.00453	MJ
03.80%	market for electricity, high voltage | electricity, high voltage | Con...	0.00622	MJ
03.59%	market for electricity, high voltage | electricity, high voltage | Con...	0.00588	MJ
00.57%	market for electricity, high voltage | electricity, high voltage | Con...	0.00093	MJ
00.40%	market for electricity, high voltage | electricity, high voltage | Con...	0.00066	MJ
00.11%	market for diesel, burned in building machine | diesel, burned in ...	0.00018	MJ
00.08%	market for electricity, high voltage | electricity, high voltage | Con...	0.00013	MJ
00.05%	market for tap water | tap water | Consequential, U - CH	8.40907E-5	MJ

Figure 19 - Contribution Tree for Electricity Production, Hard Coal