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Feasibility study of dual-mode buses in Gothenburg's public transport

Practical and economical possibilities of utilizing energy from the tram network

Master of Science Thesis in the Master Degree Programme, Quality and Operations Management

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Cover:
Photomontage of tram bus 16 in Gothenburg between Wavrinskys plats and Chalmers with an additional pantograph taken from a tram. © Oscar Olsson, 2011.

Abstract

Due to nature and political circumstances new environmentally friendly solutions for public transport are called for. In order to reduce the environmental impact, especially in the urban areas, usage of electric machines in the city buses is in this report investigated for possible benefits in this matter. The tram infrastructure is investigated as the energy source possibly combined with a battery that is used in addition to the diesel engine. This bus with connection to an external power supply is called a dual-mode bus since both the electric machine as well as the diesel engine are strong enough to solely propel the vehicle.

The purpose of this report is to investigate the possibility of implementing dual-mode buses in Gothenburg's public transportation system. It includes both an investigation of the capabilities of the tram network to handle these new vehicles but also to develop technical concepts for collecting the current from the overhead wires and return it to the tram rails.

With knowledge gathered from experts and observations, simulations were used as a method to see how the energy consumption was affected by the set parameters, such as efficiencies, drive cycle, weight etc. for different options and also to determine the prerequisites for this dual-mode bus. Three different options were created indicating the most efficient powertrain setup as well as the fuel savings possible.

The economical result shows a possibility to implement dual-mode buses in Gothenburg's public transport. About half of the solutions are profitable with savings up to 33 000 SEK annually. Even though the acquisition cost is higher, the propulsion cost could be reduced to 3,60 SEK per kilometre, which is comparable to 5,65 SEK per kilometre for a regular diesel bus.

The total costs for this project including the technical concepts is calculated and weighted against the risks for the stakeholders and the reduced environmental impact. The conclusion from this pilot study is that the project has potential to become beneficial for many stakeholders, which is why the conclusion is a recommendation to further develop the solutions presented.

Keywords: Dual-mode bus, Public transport, Tram network, Electricity, Sustainability, Energy consumption, Battery, Current collector concept, Current return concept, powertrain setup

Preface

This thesis is written as an initial part of the work to investigate possible solutions for a more environmentally friendly transport infrastructure in the Gothenburg urban area. It is the result from collaboration between Chalmers University of Technology and Viktoria Institute. Viktoria Institute was founded in 1997 from the initiative of the local industries in Gothenburg in order to achieve sustainable growth for the Swedish automotive and transport industry. There are five main application areas within Viktoria Institute, where this thesis belongs to the Electric- and Hybrid Vehicles division. The researchers' background is from Industrial Engineering and Management at Chalmers within the master degree program Quality and Operations Management.

Acknowledgements

First of all we would like to thank our supervisors Henrik Engdahl at Viktoria Institute for all the support and ideas but also for giving us this opportunity to realize this project and to Lars Trygg at Operation Management at Chalmers technical university for your guidance in this wide subject and valuable resource for discussion.

Further on we would also express our greatest appreciation to the interviewees and to all who with great enthusiasm have shared information and knowledge and thereby contributed to the quality of this report. We are also grateful to all employees at Viktoria Institute for all their ideas and interesting discussions.

We hope that you find this report interesting and useful!

Michael Johansson **Oscar Olsson**

Gothenburg, June 2011

Vocabulary and abbreviations

A Ampere

AC Alternating current

DC Direct Current

J Joule = Watt seconds = [Ws]

V Volt

W Watt

Wh Watt hours

Concept

The developed current collector and current return arm needed to enable dual-mode buses to use the tram network

Current distributor

Used in the tram network to distribute the current to be used by the trams

EM Electric Machine (Electric engine)
Usable both as an engine and a generator, i.e. possible to convert electrical energy into mechanical motion and vice versa

ESS Energy Storage System
Examples of energy storage systems are batteries and supercapacitors

GPS Global Positioning System
Device capable of receiving coordinates for the actual position

ICE Internal Combustion Engine
An engine which by the combustion of a fuel (diesel in this report) converts chemical energy into mechanical motion

Nord Pool

Market for electrical energy where the Nordic price for electricity is set

Option

A simulated setup with a specific powertrain and rules for how to utilize the energy from the tram network

Pantograph
A type of current collector commonly used on trams

Powertrain

The combination of components, such as engines and battery, and the settings for how to propel the buses

SOC State Of Charge
The battery's energy level in percentage

Solution

A combined option with a concept used for estimating the total cost of implementing dual-mode buses in Gothenburg's tram network

Trolley pole

A type of current collector capable of moving sideways commonly used on trolley buses.

Trunk bus

A type of bus used in Gothenburg's public transport that could be compared to trams with high capacity and high frequency departures

VAT Value added tax

A consumption tax for the end consumer

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1 Introduction

Due to the present politics caused by alarming reports all over the world, environmentally friendly transport systems are called for in order to reduce the emissions in urban areas partly caused by heavy-duty traffic. The heavy-duty traffic are not only causing long term damages to the global eco system but is also polluting the air in the cities with smog and causing noise which are affecting the citizens negatively (Environmental Protection UK, 2011). Although this problem has been highlighted since long, one problem has been to agree upon standards for how to propel the vehicles, which would reduce the costs for the change to more environmentally friendly systems. Many researchers agree that electric powered engines could be the future for transport vehicles to supersede today's combustion engines partly due to the reduced emission but also because of the limited supply of non-renewable propellants such as oil. The information varies about the cause of the increased oil price, possibly partly due to the diminishing supply (DeMorro, 2011) and increased demand (BBC, 2004). Irrespective of which, the crude oil price from the Organization of Petroleum Exporting Countries (Opec) has almost constantly increased during the last decade, see Diagram 1. Opec jointly stands for roughly 40 percent of the sales and estimated 80 percent of the oil reserves in the world (Opec, 2011a). In Sweden, the emissions from combustion of oil has also led to an increased tax as well as value added tax (VAT) which further increases the prices, see Appendix I.

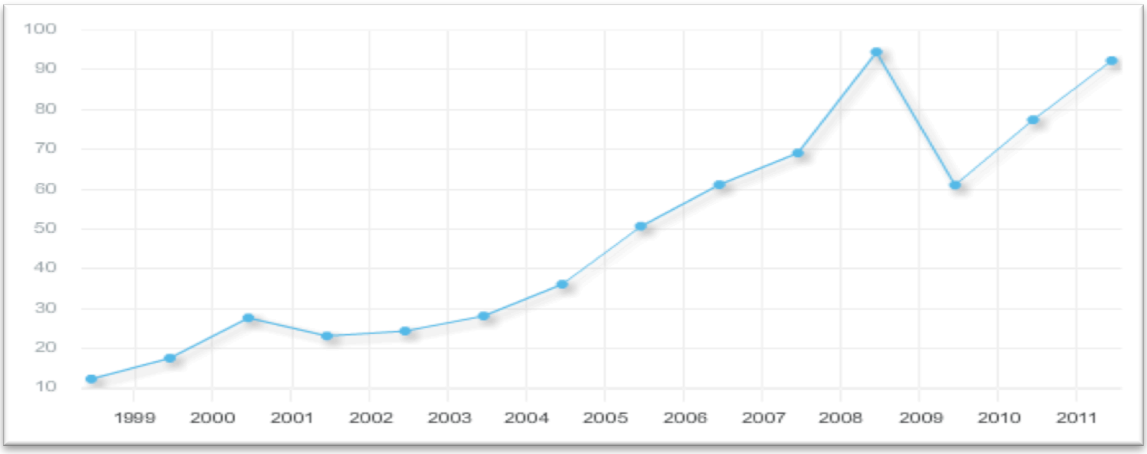


Diagram 1 Price per barrel crude oil (Opec, 2011b)

In many cities such as San Francisco, Lyon and Riga the buses, called trolleybuses, are already powered by electricity through overhead wires above the vehicles and works similarly to the trams in Gothenburg but with rubber wheels. Comparable attempts have been tried several times all over the world with different steering mechanisms and powertrain setups with various degree of success (Björklund, Soop, Rosenqvist, & Ydstedt, 2000). Trolley buses previously used in Gothenburg are described in the attached information box. However, today in Gothenburg the conditions are

Trolleybuses in Gothenburg 1940-64

With trolley busses inhabiting the route between Jaegerdorffsplatsen and Lilla bommen in 1940 Gothenburg became the first city in Sweden with trolley busses (Spårvagnssälskapet Ringlingen, 2011). The bus fleet was expanded to a total of 19 buses touring the route before it was abandoned due to the introduction of right hand traffic in combination with the great need for restoration of the trams and network. The diesel buses were then seen as the cheaper option (Göteborgs stad, 2003).

different whereby previous methods are not applicable since a current return connection is not built into the overhead wires. Instead trams use iron wheels to close the circuit through the rails. Also the fact that the buses in Gothenburg need to be flexible and capable of transport passengers outside the tram network calls for a new solution, where a dual-mode bus could be the answer. It combines an electric machine supplied by power from an external electric power source with a traditional combustion engine, both capable of driving the vehicle at full speed separately. This master thesis has emerged in order to investigate the cost and possibilities for dual-mode buses that utilizes both the Gothenburg tram network to power an electric machine and an alternative power source when the overhead wire is not available.

1.1 Purpose

The purpose of this master thesis is to investigate the feasibility of implementing dual-mode buses in Gothenburg's public transport with electricity from the existing tram network.

1.2 Research questions

In order to fulfil the purpose, the following questions have to be answered:

- What will possible technical concepts for current collection and return look like?
- What infrastructural and vehicle solutions are required for this investment to be profitable?
- How are the stakeholders affected by this solution?
- What are the risks and practical feasibilities to realize this solution?

1.2.1 Question clarifications

Existing buses have no possibilities to connect to a tram network and technical concepts for how this problem could be solved have to be generated.

An investigation of the effects of switching between different powertrains and how the infrastructure is utilized needs to be done. The total costs for different solutions that combine the option results with the technical concepts have to be presented and compared to a diesel bus. Also the costs for and effects of extending parts of the road have to be analysed. In order to give comparable and measurable figures of profitability compared to today's diesel buses, the cost resulting from driving one distance with electricity respectively with diesel have to be calculated.

In order to understand the prerequisites, risks and possibilities attached to an implementation of dual-mode buses the stakeholders involved, existing comparable solutions as well as the tram network capabilities have to be investigated.

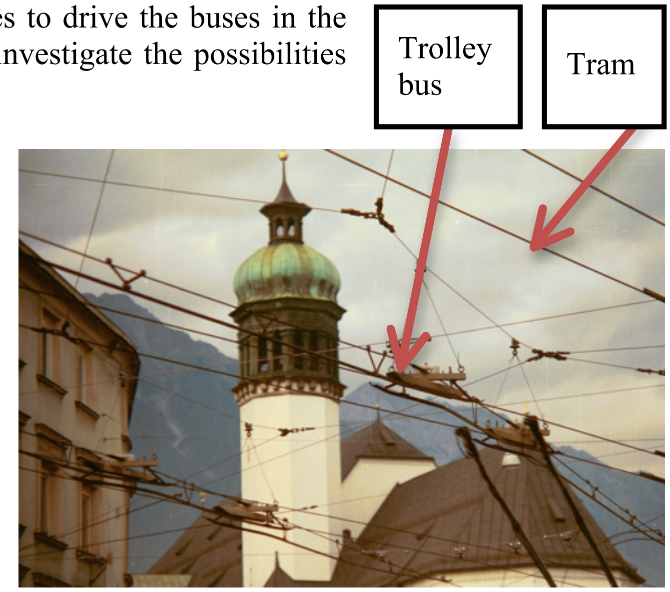
Technical complexities and resistances that could jeopardize the project need to be further examined. These have to be outlined and compared with the economical calculations to be able to give a total view of the risks and possibilities.

1.3 Delimitations

This research focus on buses and does not include other vehicles since it is believed that buses have the greatest potential for profitability because they represent the majority of the heavy combustion engine vehicles in the urban regions of the city.

The report only considers the possibilities to drive the buses in the Gothenburg tram network and does not investigate the possibilities in other cities.

Another delimitation of the study is to preserve the existing infrastructure to a great extent in order to minimize the costs. If necessary to extend some routes, the costs for adding asphalt to shorter distances will although be investigated. This decision also includes an aesthetical significance, more overhead wires and tramways would affect the whole cityscape. An example of how it could look like is from Innsbruck where trams and trolley buses use separate overhead wires, which means there are three overhead wires in each direction and the intersections (see Picture 1) look like vipers' nests. Other options such as inductive charging are not investigated since it requires great infrastructural changes and are considered to have too low efficiency (Thiringer & Zelaya, 2011).



Picture 1 Overhead wires in Innsbruck (Photo by Roger W Haworth)

The economical analysis and environmental comparison will only include diesel buses and dual-mode buses, and exclude others such as gas buses, since diesel buses today represent about 90 percent of the total bus fleet in Gothenburg (Sweco VBB, 2007).

The energy consumption for each vehicle will be measured in the amount of energy that needs to be supplied to the vehicle and will not include energy needed to produce the energy.

No prototype of the buses will be made and thereby neither a full product solution developed. Instead possible sustainable concepts are generated and discussed with technical experts.

No effort will be given to investigate the optimal routes for the buses, but instead the existing routes will be used for calculating the possibilities of realising the idea.

The idea is not to rebuild the existing bus fleet, but instead replace the diesel buses when they are old to new dual-mode buses.

Finally, the scope does not include making a full life cycle or emission analysis.

2 Methodology

This chapter presents the research strategy, design, process and methods. Furthermore, the reliability and validity of the report is discussed before the report structure and guidance will direct the reader through the report.

2.1 Research strategy

The research strategy gives direction to enable research in a systematic and methodical way. A qualitative strategy was used for this research since most of the input came from interviews and the data gathered is of qualitative nature. Although the qualitative approach gives the ability to study a phenomenon more in detail, it has the drawback of not always generate results that are generalizable (Bryman & Bell, 2007).

Within the qualitative research strategy an inductive approach was used which means that data collected from different sources, such as observations and interviews, were put together in order to identify patterns that provided a general understanding of the problem (Burney, 2008). Furthermore the research follows the epistemological position of interpretivism, which means the data was interpreted, and differences between opinions was respected and considered. The study thereby tried grasp a subjective meaning of social action and how this change would affect people and organisations. Since social actors are involved in the study the ontological position used is called constructionism. This means the study unlikely gets the same results if it is done twice, since the social phenomena and categories are in a constant state of revision (Bryman & Bell, 2007).

2.2 Research design

A case study research design is used since it narrows the very broad field of investigation from a single case into researchable topics (Bryman & Bell, 2007). As in the nature of a case study, the research questions are difficult to answer completely according to Shuttleworth (2008) since it would require a full-scale test, nor will a case study be generalizable due to the narrow focus (Denscombe, 2007). It will thus generate indications that could be used for predictions or as a hypothesis for future investigations. The case study in this report is also combined with a pilot-study that aims to simulate the settings in an attempt to be able to give preliminary estimations without conducting a full-scale test (Shuttleworth, 2008). The estimations based on the collected data are further used in the case study as a foundation for the technical and economic analysis, which in turn affects the stakeholders and the risks. Since the result of the report and the answer to the feasibility study is not only be based on whether it is economically sustainable but also include more long term intangible aspects from the stakeholders perspective, a case study is favoured since it gives the ability to study the settings in detail. Furthermore it also enabled the possibility to understand interrelations and how things are connected in a more holistic view (Denscombe, 2007).

2.3 Research process and research methods

During the research process different data collection and generation methods were used. Most of the work was performed in parallel, see Table 1, due to time limit and dependencies between the outcomes from the different activities.

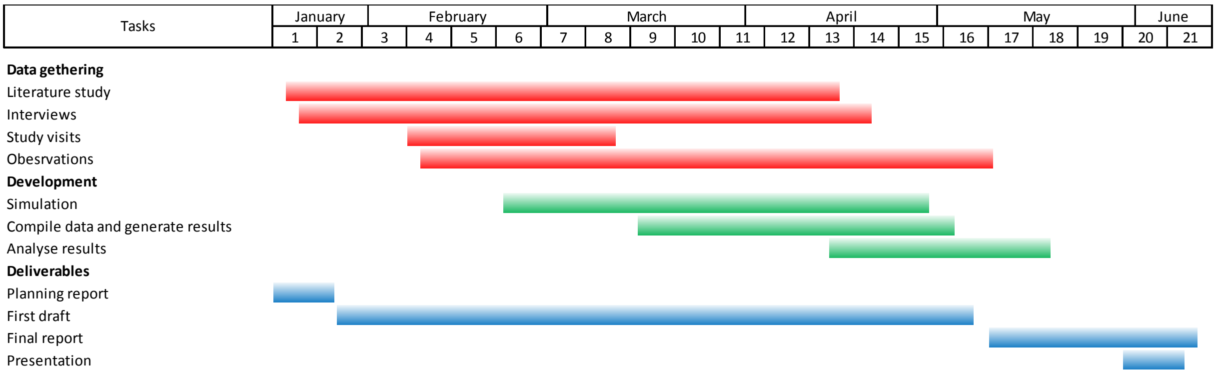


Table 1 Gantt chart illustrating the sequence and time period for the different tasks

The stages completed during the research process will be outlined in chronological order following the structure of the report. In all stages the aim, research method as well as its outcome is briefly described in the Table 2 below in order to provide an overview of the report. A more descriptive explanation of the stages follows later in the forthcoming sub headings.

To a great extent has similar data been found several times using many different research methods and sources such as interviews, literature study and sometimes also through simulation. It has then been compared and verified if any differences were identified. This method is called triangulation (Denscombe, 2007) and the underlying reason is to the greatest extent confirm the validity of the data and make sure the investigation has covered as many possible aspects of the complexity as possible.

Stage	Literature study	Empirical data collection			Technical concepts	Analysis				Conclusion and Discussion
		Social	Eco-nomic	Environ-mental		Simulation	Infrastructural and traffic	Economic	Risk	
Aims	Create an overall understanding for the techniques and prerequisites Create the theoretical framework for the report	Understand the fundamentals of tram network, buses and the usage of electricity as propulsion Comprehend the price trends for propellants and technical components and the environmental impact Structure the stakeholders involvement Structure the infrastructural prerequisites and the future plans for Gothenburg's public transport			Generate the technical concepts Understand the underlying costs tied to each technical concept	Investigate the different powertrains to find the most profitable option Generate data applicable to formulate the economic analysis and conclusion	Describe the capabilities and limitations of Gothenburg's tram network. Understand how the illustrated example is comparable with the average bus route in Gothenburg.	Comparing the total costs for dual-mode buses with a diesel bus	Statute the risks occurring from both technical and stakeholders involvement	Give general conclusions Present future areas of investigation
Research methods	Literature study	Interviews, Observations, Documentation and Email conversations			Applying empirical findings on environ-mental pre-requisites	Combining the literature and the empirical findings	Using databases and maps for bus routes provided by Västtrafik in combination with results from simulations	Combing the results from the simulation and technical concepts with findings from the empirical and literature research	Compare effects from the qualitative study with economic analysis	Combine the analysis with the findings from the qualitative study into the product solutions
Outcomes	A frame-work required to analyse the results	Underlying knowledge for generating the technical concepts as well as conducting the simulation Ability to outline how stakeholders was affected by the solution			Confirm feasibility and create underlying results to the economic analysis and conclusions	Underlying results to the economic analysis Generate requirements comparable with infrastructural prerequisites	Highlighting possible obstacles and limitations to dual-mode buses in Gothenburg	Guidelines for future investments	Give the ability to describe the result from different point of views	Conclusions accounting for the many point of views. Stating future areas for investigation

Table 2 Research process and research methods used during the report

2.3.1 *Literature study*

The literature study resulted in two major chapters, Principles and Theory, and Contemporary social and economic prerequisites. The general purposes of these chapters are to provide a spanning framework for the report and the underlying reasoning to the final conclusions. The Principles and Theory chapter aims to cover the basic technology and economy that is used throughout the report and give the reader the fundamental understanding to capture the analysis and discussion. Furthermore it includes some facts regarding sustainable development and the environmental impact of discussed alternatives. In the Contemporary social and economic prerequisites chapter the reader will be guided through an overview of the different propellants as well as bus component prices, which are essential in the following economic calculations. After describing the stakeholders' involvement the chapter follows with a short description of the future plans for Gothenburg's public transport as well as how it is perceived today. A brief description of the different alternatives of dual-mode buses is then presented with their pros and cons. Finally, how the city and in the end the stakeholders are affected by the solutions presented as well as the risks attached are important aspects that are further considered in the conclusion.

The main information sources have been the books from the library, reports and pre-studies covering the relevant topics. Also qualitative homepages has been scanned such as those connected to the stakeholders involved.

2.3.2 Empirical data collection

The empirical data collected is mostly based on experts' knowledge and should not be confused with the Principals and Theory chapter, which mainly consists of common understandings and facts. However, the empirical data continues to build upon the theoretical framework created through the literature study and is the primary input to the answers of the research questions. They also formed the basis for both the simulation and how the technical solutions should be designed. The three areas that formed the basis for the inquiries were Social, Economic and Environmental development. Due to the wide area covered and the many stakeholders involved the empirical data collection period was set to be long and extensive.

The methods used were both secondary sources such as interviews and also primary sources such as observations. Since information from one source could require further investigation within another area or that the information needed to be verified through observations the methods alternated throughout the whole collection period. When prices in different currencies occurred during the data gathering, a currency converter was used to convert to SEK in order to create coherence throughout the report. This is marked with footnotes.

Interviews

The interviewees selected were the ones perceived to have the best knowledge within the specific area. An initial contact where often taken through email and continued with a follow-up interview, performed either by a physical meeting or by telephone depending on the questions and the distance to the interviewee. If the questions were extensive or required pre investigation they were sent to the interviewee in advance. All interviews held were semi structured with the intention to let the interviewee speak freely around the areas that should be answered or discussed. The questions were always customized to the interviewee and when further questions arose during the interview they were subsequently asked. Similar questions were asked to different people with different backgrounds several times in order to broaden the perspective and understand the problem from different views.

Both authors participated at all interviews where one was leading the discussion and took notes and the other focused on taking extensive digital notes on computer. Furthermore, long interviews and interviews with high complexity were also recorded. After the interviews, the notes were transcribed on computer and if something was unclear the audio file was examined, or follow-up questions were sent to the interviewee. Initially the interviews focused on experts with information within relevant areas to gather their opinions and view regarding if the project seemed possible to conduct at all regarding infrastructural limitations and technical possibilities. When the project was deemed possible the interviews evolved to deepen within mainly the areas of product concept development, existing bus technologies, infrastructural capabilities and finally economical estimations. A list of the interviews performed can be seen in Appendix II in order for the reader to better understand the process.

The interviewees often shared information about other people to contact for further information about the specific topic.

Observations

Observations were made in order to connect to and verify the data that was collected through the literature study and during the interviews. Furthermore, data that could not be transferred verbally or written, often called tacit knowledge, were collected through the observations. Observations were made both in Gothenburg where both the regular trams and buses movement and positions were examined in relation to the rails and overhead wires. A hybrid bus was also tested to understand the passengers' perspective. In Landskrona trolley buses where tested and investigated in order to understand how a fully electric bus behaves and works while in traffic, see Picture 2.


Picture 2 Trolley bus in Landskrona

Also trunk bus 16 in Gothenburg was of particular interest since a significant distance was within the tram network and its route was thereby used as references during the simulations. With a GPS receiver, data including position and time was recorded both during movement and when standing still which was used as reference points in the simulations. Also the total distance where the bus is underneath the overhead wires were measured.

2.3.3 Technical concepts

With the literature study and the empirical analysis as foundations, the technical concepts were developed. The principles they describe are how to collect the current from the overhead wires and how to complete the circuit with the rail, not unlike the way a tram works. The assumptions possible to draw from the outcome of the technical concepts should be weather or not it is possible to use the electricity from the tram network and also what a price estimation would be for these solutions. The process started with collecting experts' ideas, which were then transformed into models. These were brought to meetings and discussed with other experts in order to verify their feasibility, develop their functions and to discuss their respective pros and cons. Since the concepts should not present the ultimate solution, two different feasible concepts were generated both for the current collector and for the grounding solution. After the models have been finally designed, their respective costs were estimated based on experts' advice, similar existing solutions and comparable development costs. In order to visualize the concepts they were also drawn using CAD.

2.3.4 Analyses

In order to analyse the data it was first processed using simulation. The results in combination with the literature and empirical findings were then analysed. Both an economical-, infrastructural and traffic- and risk- analysis were then applied.

Simulation of energy consumption and powertrain setup

In order to understand the energy consumption and how it was affected by the usage of overhead wires, batteries and the combination of two engines working together, simulations were performed. Another outcome was to predict the most useful combination and sizes of the parts contributing to the powertrain setup and understand which variations gave the larger affects. The simulations that were performed mostly in excel, but also in combination with Matlab. While the fixed parameters were set, the bus parameters were adjusted in order to understand how they affected each other and the final result.

Three different options were performed where the variables such as battery size, priorities for the energy supply and electrified distance were alternated. Both the theoretical framework and the empirical findings were used as input data and parameters for the model. Some of them in combination with observations were also used as reference data to ensure the results were reasonable. The design of the simulation was also reviewed several times by the supervisor to ensure nothing had been overlooked. Parameters used in the simulations, for example regarding the batteries, may not be optimized since data gathered could be deficient and divergent due to company secrecy. Instead only data that could be confirmed were used in order to increase the credibility.

From the outcome of the simulations could important assumptions be made such as among other things, the consumed energy per driven kilometre inside and outside the tram network as well as a reasonable size and cost for the battery. Although the estimations are somewhat specific to the vehicle and the setup used, the intention of the simulations were also to give estimations that can be used in future feasibility studies.

Infrastructural and traffic analysis

To present how the results from the simulation could be translated to the actual settings in Gothenburg the public transport was described and analysed as comparison. This was done using maps with bus routes, tram routes, tram stops and the municipality borders for Gothenburg provided by Västtrafik. The data was used to calculate the distances between each bus' end stations within Gothenburg and the distance when buses are driving parallel to the tram network.

Also the traffic and tram network was analysed in order to find risks that could reduce the possibilities of using dual-mode buses in the tram network. Both results from the simulation and data from the empirical data collection were used and compared.

Economical analysis

Within the economic analysis all the data gathered from literature study, empirical data collection, concept generation and simulation are merged into costs for the final solutions. The data were combined in an investment calculation considering mainly the costs, since the incomes will mainly be stable. The future development for the electricity price and the diesel price was estimated based on the figures and the discussions found in Contemporary social and economic prerequisites chapter. The development costs together with the concept costs were also estimated based on interviews. A comparison was then made between the regular diesel bus and the final solutions for the dual-mode buses to be able to evaluate the differences between the alternatives. The calculation method Net Present Value was used to estimate the present value of the total investment costs for the different solutions, but since the economic life-time is different between a regular diesel bus and a dual-mode bus another calculation method called Equivalent annual costs was used to be able to compare the different alternatives on an annual basis. The figures were then discussed with a professor in Engineering economic analysis (Löfsten, 2011) to validate the investment calculations.

Risk analysis

The risk analysis is the connection between the analysis and the conclusion as a way to highlight the risks attached to the project that needs further attention. Both the risks occurring from the technical concepts and the stakeholder's involvement were included as well as the author's own gathered opinions. The risks were clustered into four causes that all has the possible impact that dual-mode vehicles are not realizable in Gothenburg. An Ishikawa diagram was also used to further visualize the many point of views and how the risks were grouped. The risk analysis gives the conclusion the ability to describe the results from different points of views.

2.4 Reliability and validity

Reliability is in short an estimation of how well the data gathered is possible to regenerate using the same methods at a later stage. Tests and retests is one method, although somewhat questioned, to see if the results are similar (Golafshani, 2003). Throughout the data gathering triangulation has been used, which means that similar questions have been asked to different persons for verification, also literature have been treated in the same way. What is further highlighted by Befring (1994), and has also been seen as important, is that the sources used, especially those involving technical details, are fresh and are close to the source of information or topic. Some detailed technical data has been limited due to company secrecy and somewhat divergent whereby only data that could be verified has been used in favour of presenting the most optimal solution. A branch of reliability is the internal reliability, which is the degree the observers agree about what was heard or seen (Bryman & Bell, 2007). This has been verified by using dual set of notes from each interview with audio recordings as backup as foundations for the discussions that followed after the interviews that ensured everything were understood, also follow-up questions and emails have been used. The degree to which a study can be replicated called external reliability, is according to Bryman & Bell (2007) hard to ensure since every situation cannot be frozen. One example is the personality of the researchers and the way they are met by an interviewee or other person with information, which will be hard to replicate. However a diary was written on a daily basis during the literature and empirical research in order for the authors to remember and thus able to express the method used to the reader. Furthermore the simulations have been compared with measurements from reality as to ensure reliability. The reliability can therefore be seen as high as long as the environmental settings do not change.

To keep on track and stay focused on the very research questions can be very hard, especially over a long time when side tracks are everywhere. Therefore validity is of the greatest importance. Validity is that you are observing what you say that you are observing and that the means of measurement are accurate (Golafshani, 2003). It does not really matter how good the results are if they measure irrelevant things. Like reliability, there are two types of validity, internal and external. Internal validity means that there should be a good match between the researchers' observations and the ideas they develop. The results and answers gained through observations and interviews will be validated with different experts and people knowledge within the area. When required, questions have been brought up to the supervisors both at Chalmers or the Viktoria Institute for discussion. Others with concrete knowledge has also read and commented on the results and methods used. The way of working is confirmed by Bryman & Bell (2007) who reports that qualitative researchers have the possibility to establish a close connection to the "social life" and therefore also ensure a good connection between the concepts and the report. The external validity is to what extent the findings could be generalized across a social setting. In this report this is not of great importance since only Gothenburg will be the area investigated. Also the usage of environmental settings in Gothenburg will make it hard to replicate the findings elsewhere but where similar trams and tram network are used the findings might be applicable.

2.5 Report structure and guidance

The Principals and Theory chapter will give the reader the basic understanding for the different bus types with various engine combinations and a brief description of the economical calculations used. Some electricity science can also be found in Appendix III, which could be useful to grasp the simulations. Following is the Contemporary social and economic prerequisites chapter, which explains features of the different components in the bus and their specific costs as well as the social settings in Gothenburg that affects and is affected by the presented solutions. These chapters will be necessary for the newly devoted reader in order to understand the simulations and findings later presented. They will also create the foundation for the economical write-up and the conclusions. However the authors recommend the reader with experience within the area to continue from chapter 5 Technical concepts in order to capture the essential findings of the report. Furthermore the report does not include all the data in and from the simulations, but only a presentation of how they were conducted and the relevant results.

Due to the wide area covered and the limited time, all possible scenarios could not be foreseen and examined. The discussion chapter therefore presents areas that needs further attention that the interested reader are more than welcome to further investigate.

3 Principles and Theory

The Theory chapter aims to aid the reader in understanding the analysis and the conclusions. It initially explains some basic differences between electric, hybrid and dual-mode buses followed by a powertrain comparison before it briefly describes some environmental impact for all the alternatives and ends with some investment calculation methods.

3.1 Electric, hybrid and dual-mode buses

How the different types of buses are defined and used throughout the report will be further described in order to ease the reading and understanding. Also advantages and disadvantages will be brought up.

3.1.1 Electric buses

A fully electric bus is powered exclusively on electricity, which means it is without any internal combustion engine (ICE). Different types of electric buses exist and could either be propelled with continuous external power or through an energy storage system (ESS), usually battery (Larminie & Lowry, 2003). The most commonly used is the trolley bus, which like a tram mostly is connected to overhead wires during movement. Another type of external power supply is achieved through inductive charging where energy magnetically is transferred to the bus through wires in the road.

Other types of electric buses contain batteries and supercapacitors to store energy obtained from charging. Different types of charging exist such as at each bus stop or replacing the battery at the end of the route (Larminie & Lowry, 2003). Many of these types of buses are still in concept stage or newly presented to the market (Green Car Congress, 2010), (Green Car Congress, 2011).

A problem for these types of electric buses that does not have a continuous external power supply is that the batteries still are very heavy, have high volume and are expensive in comparison to the amount of energy they can store compared to conventional fuel (Larminie & Lowry, 2003). For a brief comparative calculation of the weight for diesel and batteries see Appendix IV.

When the electric vehicle is braking, the electric machine (EM) can often be reversed and used as a generator to capture the kinetic energy that could be stored and used when needed. This energy is lost in conventional vehicles only using ICE (Nelson, 2000).

3.1.2 Hybrid buses

A hybrid bus combines an EM with at least one additional engine, commonly an ICE. There are generally two types of setups for the hybrid buses called either a series or parallel hybrid. If a battery is used it can, in either case, often be charged through regenerative braking power but can also be charged directly by the ICE and does therefore not need to be as large as if it were the only energy source as in the electric buses (Rahman, Butler, & Ehsani, 1999).

In the series hybrid the driving force comes solely from the EM where the ICE is only running to produce electricity. A good thing with this setup is that the ICE is always running at is optimum engine speed regardless of the load of the vehicle and its speed and can therefore have a better fuel economy compared to regular ICE which has less good fuel economy during low and high engine speeds. The disadvantage is that the energy needs to pass through a generator and often a battery that both reduces the efficacy and adds costs (Rahman, Butler, & Ehsani, 1999) (Larminie & Lowry, 2003).

The parallel hybrid can, on the other hand use either engine solely to propel the vehicle or combined for maximum strength, for example during acceleration. This setup is more commonly used since it generally requires smaller engines. Here no propelling energy is lost due to energy conversion in the generator but the ICE cannot be used constantly for optimized efficiency (Larminie & Lowry, 2003) (Rahman, Butler, & Ehsani, 1999).

3.1.3 Dual-mode buses

A dual-mode vehicle has many similarities with a parallel hybrid vehicle as it uses two different engines; both strong enough to alone provide the propulsive power needed to propel the vehicle. The main difference is that at least one of the energy sources should come from external power supply and the vehicle could therefore in theory run indefinitely long time without recharge or refuel (Dual-mode vehicle, 2011). Dual-mode buses have been designed in many different shapes and some of them are combined with guide-ways dedicated to these vehicles where conventional steering is not necessary (Hanlon, 2011) (Silvertip design, 2010). A drawback with these guide-ways is that they usually come with high initial infrastructural costs. Since the dual-mode vehicle has an electric machine it has the possibility to benefit from regenerative braking power like electric and hybrid buses, but has also the possibility to send the energy back to the network for other vehicles to use.

3.2 Powertrain comparison

The two engine types used and their benefits and drawbacks are further discussed but also how they can be combined into a hybrid engine and what that could entail.

3.2.1 Diesel

The diesel engine converts the chemical energy in diesel to mechanical energy through small controlled explosions when mixed with air, moving the pistons in the cylinders (U.S. Department of Energy, 2003). Compared to an EM the torque is usually lower at low revs but it has higher pulling power at higher revs, see the blue line in Figure 1 (Volvo bus corporation, 2011). Since the diesel engine tends to have a peak torque quite low, a transmission is used. Emissions from the diesel engine are higher during non-optimum revs (Shi, Mark, & Harrison, 2000), which often occur during acceleration after standing still.

According to Haraldsson (2010) the diesel consumption for a heavy-duty vehicle is on average 0,43 litre/km and the equivalent figure for a bus in city traffic is 0,45 litre/km according to Andersson & Johansson (2005) and Spartalis (2011). Since the efficiency in the diesel engine is only between 30 percent (Andersson & Andersson, 2011) to 35 percent (Haraldsson, 2010) it means that about 1,69 kWh/km reaches the road from the original 4,83 kWh/km with the diesel energy of 38,6 MJ/litre (Austrailian Institute of Energy, 2011).

$$\left(\frac{0{,}45 * 38600000}{3600}\right) * 0{,}35 = 1{,}688 kWh/km$$

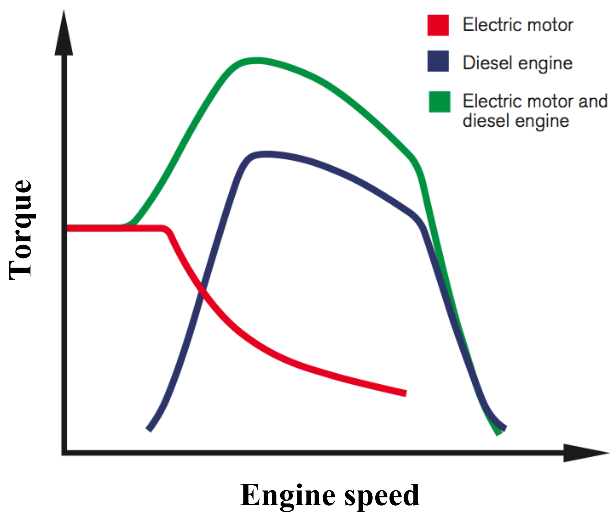


Figure 1 Combined diesel – electric propulsion (Volvo bus corporation, 2011)

3.2.2 Electricity

The most common EM converts electrical energy into mechanical energy through electricity that generates a magnetic field close to permanent magnets, which forces an axle to turn (Larminie & Lowry, 2003). Different from the diesel engine is that the EM produces the maximum torque right from the start which later declines and is therefore very suitable in vehicles designed for frequent start and stop (Volvo bus corporation, 2011), see the red line in Figure 1.

Comparable energy consumption for the electric bus is according to Andersson & Johansson (2005) 1,8 kWh/km with an efficiency of 90 percent in the EM (Andersson & Andersson, 2011) (Haraldsson, 2010). Also the EM is very silent and has less energy consumption compared to the diesel engine when no force is applied. As previously mentioned it also has the ability of regenerative charging, which will further reduce the energy consumption (Volvo bus corporation, 2011). However, if not connected to external power supply, the energy storage capacity in the ESS limits the range of the electric vehicle, which is further discussed in chapter 4.1.2 Batteries.

3.2.3 Hybrid

The hybrid powertrain can combine the benefits from both the EM and the diesel engine and allow the most appropriate engine to work at peak levels. Since the engines can be used together for maximum power the sizes could also be reduced, see the green line in Figure 1. Figures around a total of 30 percent lower fuel consumption has been shown for buses using the EM during acceleration from standing still and when braking (Volvo bus corporation, 2011).

3.3 Environmental impact

Although the main questions regard practicability and economical feasibility, sustainable development was one of the main factors initiating this report since it was thought that electric propulsion would have less environmental impact compared to diesel. The total environmental impact of a bus is not very easy to estimate since it depends on many different variables and since the focus of this report is the feasibility study, more attention will be given to sustainable development and to the energy sources' environmental impact.

3.3.1 Sustainable development

Sustainable development considers three dimensions namely social, economical and environmental development. They do all affect each other and could benefit from one another's loss and are therefore essential to coordinate (Ammenberg, 2004). These have different views of the world whereby the decision making is very tough. Environmentalists claim that the world's ecological limits should create the constraints for both economy and society. Economists argue that market solutions and substitution are available for all ecological and social problems and deny any real or immediate global limits. Sociologists insist that social justice or equity could be addressed by either ecology or economics (Schnurr & Holtz, 1998). The sustainable development is reached in equilibrium of the three when human needs are fulfilled without affecting generations to come (Ammenberg, 2004).

The usage of electric vehicles would address three important facts the three have in common. First of all, since the efficiency is higher in electric machines compared to diesel engines the energy need could be reduced. Less energy needed could reduce the pollution, especially if combined with the third fact that the electricity could be generated from renewable energy sources (Svenska Elfordonsföreningen SWEVA, 2007). A list of energy sources and their pollution can be seen in Appendix V.

Moving the emissions from the bus to power plants outside the city would directly reduce the local emissions (Svenska Elfordonsföreningen SWEVA, 2007). Since the trams in Gothenburg, and in a possible future also dual-mode buses, are powered only from renewable energy sources (Norrman, Arnell, Belhaj, & Flodström, 2005) both local and global emissions is further reduced.

3.3.2 Diesel

Compared to other combustion engines the diesel engine generally has lower CO_2 emissions due to its higher efficiency. The efficiency for new diesel engines is around 35 percent as mentioned earlier in the report (Haraldsson, 2010). The downside is that it emits higher levels of NO_X and is therefore worse from a local pollution aspect (Environmental Protection UK, 2011). The NO_X particles are the main ingredient in smog (EFD, 2003) and when these small particles are breathed in it can cause diseases such as lung and other types of cancers as well as asthma (ALAW, 2003). The diesel engines also cause a noise level around 80 decibel (Heinen, 2011), which can cause disturbance and even diseases to pedestrians or citizens living close to the road (Magnå & Sahlman, 2011).

3.3.3 Electricity

Considering only the local impact, the EM produces almost no emission where it is used if the electrical power initially comes from power plants. The environmental impact from that energy source depends on if it comes from renewable energy sources or fossil fuels, once again look at Appendix V for further details. Also electric powered vehicles combined with an ICE to charge the batteries have proven to be a good alternative to regular combustion vehicles from both a cost and environmental aspect (Granovskii, Dincer, & Rosen, 2006). On the other hand the noise level of electric vehicles is low, in fact so low that some car manufacturers have agreed to add noise for pedestrian safety (CNN Money, 2010) approximately 62 decibel which is comparable to normal a conversation (Heinen, 2011).

3.4 Investment calculation methods

The theoretical understanding for the investment calculations is presented in this section. The different methods used are Net Present Value (NPV) and Equivalent Annual Cost (EAC). Furthermore, there is a short description presented about how to set a discount rate and how tax is handled in an investment calculation.

3.4.1 Net present value

The basic idea of the method is to discount the future cash flows, to get a present value of the costs each year. It is also common to add the discounted residual value of the investment to the sum of the present values. The difference between the initial investment and the sum of the present values is the NPV. If the sum of the present values is higher than the initial investment, the investment is profitable (Skärvad & Olsson, 2006).

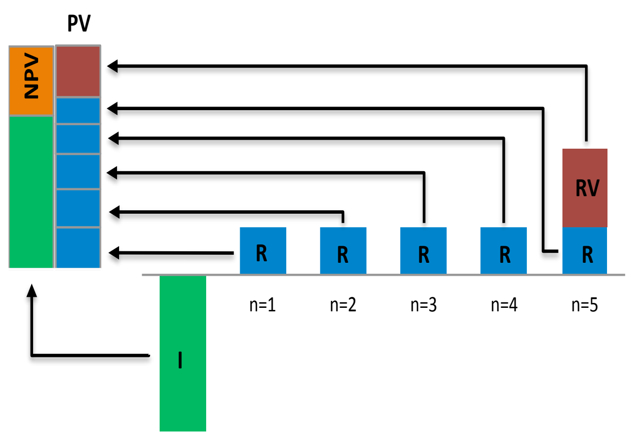


Diagram 2 The basic idea of NPV

The basic discount equation is as follows:

$$PV = \frac{FV * (1-t)}{(1+d)^n}$$

PV = Present value

d = Discount rate

n = Number of years in the future

FV = the value in the future
R = Net cash flow, RV = Residual value

I = Initial investment

t = tax rate

3.4.2 Equivalent annual cost

The equivalent annual cost is based on the NPV, but the outcome is the cost per year of owning and operating an asset over its entire lifespan. This investment calculation method is used to compare investments with unequal life spans (Götze, Northcott, & Schuster, 2008) (Davis Langdon Management Consulting, 2007). The EAC equation showed in Diagram 3 is the NPV multiplied by a factor A, which is based on the lifespan and discount rate.

$$EAC = NPV * A_{n,d}$$

$$A_{n,d} = \frac{d}{1-(1+d)^{-n}} = \frac{(1+d)^n * d}{(1+d)^n - 1}$$

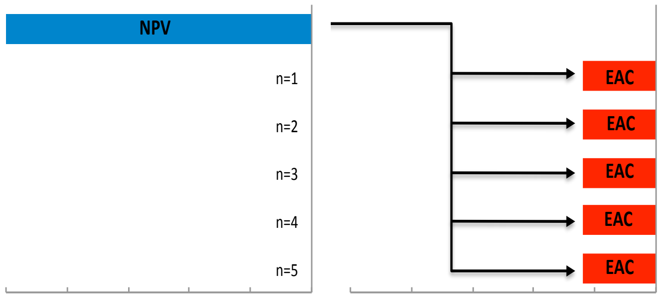


Diagram 3 The basic idea of EAC

3.4.3 Description of how to set the discount rate

The discount rate is a difficult figure to set and could depend on what yield another investment in something else could generate. Public corporations normally have lower discount rate than private corporations. Normal rate for public investments is between 2-5 percent excluding inflation, while the private sector uses a discount rate between 2-14 percent excluding inflation. The discount rate also depends on many different things, like the length and size of the investment, risk, required rate of return, inflation etc (Davis Langdon Management Consulting, 2007). When deciding about the discount rate, considerations about tax also have to be made. The discount rate after tax is 70 percent of the discount rate before tax if the tax rate is 30 percent, i.e. d_{at} = (1-tax rate)*d_{bt} (Wetter, 2011).

3.4.4 Taxation

Taxation is important to consider in order to get a better picture of the profit of an investment. An important condition is that the company has to be profitable; otherwise no tax payments are required.

Annual depreciations on capital assets, i.e. in this case the acquisition, are deductible due to the Swedish regulations. The annual costs, i.e. the electricity cost, diesel cost and maintenance cost are also deductible. Furthermore, the residual value is taxable if the investment is completely written off and then capital gains tax has to be paid (Wetter, 2011). The value added tax (VAT) is paid when you as a company buy a product, but you get this money back from the government. This is called VAT receivable (Ekonomikonsulter, 2010).

3.5 Chapter summary

The EM has advantages such as high efficiency and low pollution compared to the ICE. However, if not connected to internal energy sources such as in combination with a diesel engine in a hybrid or to external power sources such as dual-mode buses the battery will limit the range. Also the noise of the electric bus is significantly lower and can be compared with normal talking levels, which will enhance the milieu for the passenger as well as for the driver. Table 3 illustrates the three types of buses compared to each other from low to high in order to give a comparable overview of the buses discussed. As stated in the delimitations, the energy consumption only includes the energy that is needed to propel the vehicle and does not include the production of the energy or fuel.

	Electric bus	Diesel bus	Hybrid bus
Energy consumption	Low	High	Medium
Local pollution	Low	High	Medium
Range	Low to High*	High	High
Noise level	Low	High	Low to High**

Table 3 Comparable summary of electric, diesel and hybrid buses

* If connected to external power supply
** Low noise when solely using the EM

In order to further compare the diesel and electric bus against each other economic calculations will be used including the net present value and the equivalent annual cost. These methods discount the future cash flows and make it possible to compare their relative investment in present values even though they do not have the same life span.

4 Prerequisites

This chapter attends to the social and economic prerequisites for implementing dual-mode buses in Gothenburg’s public transport. The chapter includes the historical figures for propellant prices and some thoughts about the future prices for the diesel and electricity. Furthermore, facts about the bus components will be presented as well as the stakeholders’ involvement probably affecting the possibility of realizing this idea. The chapter will conclude in a SWOT analysis in order to grasp an overview and to be able to compare benefits with drawbacks.

4.1 Bus specifications and prices

In order to further enable the comparison between the solutions presented later in the report and the diesel bus, prices for the buses and its components were investigated.

4.1.1 Buses

To estimate the price of the entire bus specifying a number of parameters is initially required, which is problematic since they can change on a daily basis. The economic analysis is based on an existing hybrid bus that will be modified for the purpose of occasionally drive solely on electricity. The hybrid bus was chosen since it contained both a diesel engine and an EM. A diesel or trolley bus would require fitting an additional engine and battery, which would require great initial costs since the available area in the buses are limited whereby the final calculations would be skewed. Also in the hybrid bus, both engines can be strong enough to independently propel the bus (Forsberg, 2011). Furthermore the electric components in the hybrid bus such as the DC/DC converter, which is described later, are also capable of handling the current from the overhead wires and does thus not need to be replaced (Andersson & Andersson, 2011). The price for a 12 meter diesel bus is set to 2 million SEK and 2,7 million SEK for a hybrid bus with the same size (Andersson & Andersson, 2011). Also the buses needs to be modified in order to suit Gothenburg’s city traffic with air condition, low floor, interior set up and communication systems etc. Göteborgs Spårvägar pays around 2,5 million SEK for a smaller bus of 12 meter (Spartalis, 2011). The depreciation time is up to 12 years for a diesel bus and 20 years for a trolley bus according to Andersson & Johansson (2005). Hybrid buses has a lifetime calculated to be 15 years in heavy city traffic according to (NyTeknik, 2007) but the maximum lifetime for a bus used by Västtrafik is set to be 10 years (Spartalis, 2011) (Lorentzon, 2011). The second hand value for a smaller diesel bus depends on its condition but can be estimated to somewhere between 50 000-100 000 SEK (Spartalis, 2011). P-G Andersson (2011) estimates the second hand value for a trolley bus to be 5 percent of the initial investment.

The yearly maintenance cost for a diesel bus travelling 80000 km per year is 280 000 SEK which is calculated based on 3,50 SEK per kilometre (Spartalis, 2011). The equivalent yearly maintenance cost for a trolley bus is similar to the diesel bus (Andersson P. , 2011). The cost for maintaining the EM is lower than the ICE, but the total maintenance cost for the trolley bus also includes maintaining the current collector as well as the battery (Andersson & Johansson, 2005). In the final calculations a total of ten buses will be bought at the same time in order to make the initial costs more realistic and the expenses for the buses are scaled up from a 12 meter bus to an 18 meter articulated bus.

4.1.2 Batteries

The battery in an electric car is still the single most expensive piece of equipment, even though the development is very rapid (Gas 2.0, 2010). Reliable data is hard to find since battery properties are changing on a daily basis and are considered company secrets. Also batteries can be developed with different usage in mind whereby the characteristics of the "average" battery is hard to find and small changes can have immense price effects since the cost for about 70 percent of the battery are volume dependent (BCG, 2010).

There are also many different types of batteries using special components and with diverse features such as weight, price and energy density. This report focuses on Lithium-ion batteries due to the lightweight and relative high energy density, which makes it suitable for usage in vehicles (Axeon, 2011). However they can still be considered rather expensive.

The price for a battery pack can range between an estimated 2250 SEK/kWh[1] (Gas 2.0, 2010) and 3600 SEK/kWh[2] (Valentine-Urbschat & Bernhart, 2009) and up to 7320[1] SEK/kWh (BCG, 2010). In 2020 the same battery pack has an expected price tag of between 1800 SEK/kWh[2] (Valentine-Urbschat & Bernhart, 2009) and 2160 SEK/kWh[1](BCG, 2010).

Usually when batteries are compared for electric vehicles the energy density is of greatest concern since distance per charge is what is asked for. The energy density for lithium-ion batteries is obscure since figures from different sources differ on cell level compared to a total battery pack. Also these figures are very time dependent and hard to compare but somewhere between 80-120 Wh/kg (BCG, 2010), 140 Wh/kg in Nissan Leaf (Weissler, 2010) and between 100-200 Wh/kg (Axeon, 2011). Battery pack has in general 30-40 percent lower energy density compared to the same battery at cell level (BCG, 2010). According to Andersson & Andersson (2011) the weight of the battery pack is approximately 50 percent higher than the weight of the battery at cell level, which mean one third of the weight of the battery pack do not consist of the battery cell. This means the energy density of the battery pack is 33 percent lower than for the cells. However in this report the energy density is not a major concern since the buses will not be driven with energy from long-term charge but instead mostly charged from the regenerative braking, whereby the power density is of greater importance.

Also of interest is the expected lifetime for a battery. This is hard to describe without exactly knowing the composition of the battery, how it is used in the vehicle as well as the travelled route and environment. According to Axeon (2011) more than 2000 full cycles before the battery has dropped below 80 percent of its original capacity could give an indication, but Diagram 4 Battery lifetime below might indicate further the difficulty of prediction where above 100 000 cycles could be reached depending on how the battery is used. The greater the discharge cycles are, Depth Of Discharge (DOD), the fewer cycles the battery will last (Electropedia, 2005). Some manufacturers today guarantee a battery lifetime warranty of between 8-15 years (Scania press release, 2009) (Toyota, 2011).

[1] 1 USD = 6 SEK
[2] 1 Euro = 9 SEK

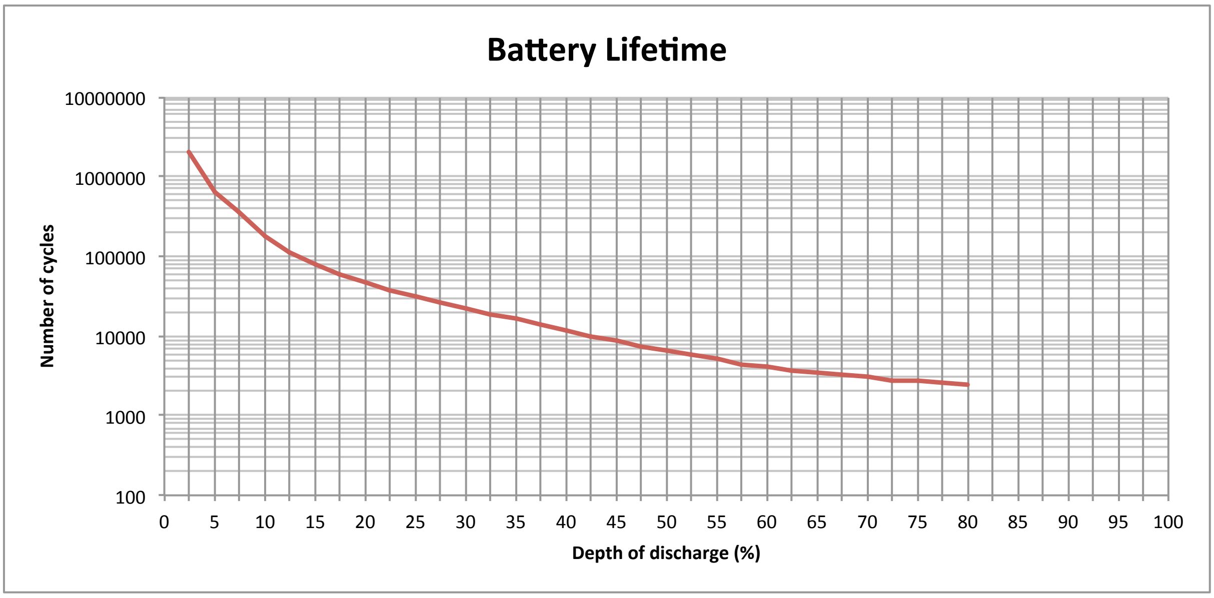


Diagram 4 Battery lifetime (Alaküla, Swedish hybrid vehicle centre, 2010)

The battery with the highest lifetime, energy density or lowest price might however not be the optimal but to further highlight the complexity the Figure 2 indicates that there are several more parameters to consider. There is a trade-off between all parameters and therefore the battery needs to be adapted for its specific purpose.

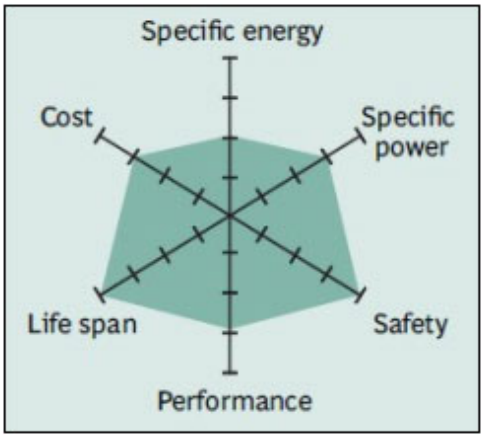


Figure 2 Battery parameters (BCG, 2010)

4.1.3 Additional electronics usable in dual-mode buses

DC/DC converters are commonly used in portable devices when the voltage from the battery needs to be regulated to fit the components in the device. Also if the voltage in the power supply fluctuates the DC/DC converter can maintain a constant voltage to the components by regulating the current (Fink & Beaty, 2006). If the resistance in the converter is constant, according to Ohm's law in Appendix III, the current will be increased or decreased. The same principle is used in trolley buses when the voltage in the overhead wires differs from what is used in the power components and battery (Andersson & Johansson, 2005). DC/AC converter is also commonly used in electric vehicles since most engines used to propel vehicles require AC current. Compared to a DC/DC converter where the voltage is changed the DC/AC converter also changes the direction of the current. (Fink & Beaty, 2006)

The properties of the other electronics will not be further dealt with since it is considered to be outside the scope of the report and also that they are already accounted for in the hybrid bus price (Andersson & Andersson, 2011). However an approximation of 10 percent of the total battery cost could be a good indication of the cost for wiring and converters (Thiringer & Zelaya, 2011). Added costs for changes related to these components will further be dealt with in the Economical analysis chapter.

4.2 Propellant prices

The main propellant used by the buses in Gothenburg's public transportation system is diesel and as mentioned in the delimitation chapter, gas will not be considered since it represents only a limited amount of the total bus fleet used by Västtrafik. The diesel prices will thereby be compared to the electricity price, which is a new propellant possible for buses. Historical figures for the diesel and electricity price and some of the issues affecting the prices are presented to illustrate the difficulty of anticipating the future prices.

4.2.1 Diesel

As described in the introduction the diesel price has increased rapidly the last couple of years. It is unclear for how long the oil will last for a reasonable price. The price change over the years can be found below and describes the last 10 years. The product cost, tax, gross margin, and value added tax is included. The sum of the figures is the selling price for the diesel for private customers.

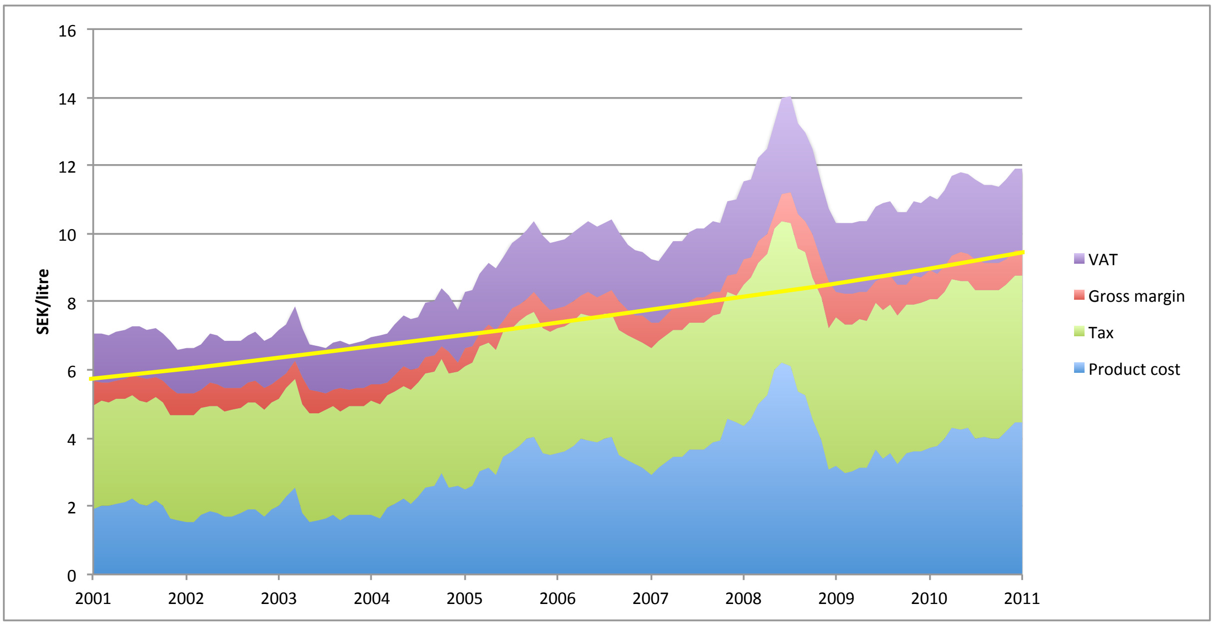


Diagram 5 Historical diesel price (Svenska petrolium institutet, 2011b)

For companies the value added tax is excluded as described earlier in the report. If the product cost, tax and gross margin are summed up the cost is 9,52 SEK/litre in December 2010. This means the price has increased around 68 percent or 5,33 percent per year from 5,66 SEK/litre, the last 10 years, which is the yellow line in Diagram 5.

4.2.2 Electricity

The electricity price has like the diesel price increased in recent years. The deregulation of the electricity market in 1996 made neighbour countries with higher prices export electricity to Sweden, which increased the market price. But the deregulation is not the only reason for higher prices; also political decisions both at a national level as well as international level have contributed. Higher governmental taxes and EU decisions about the claim for certificates of emission, have inflated the electricity prices. Furthermore, the dry year in 2002 caused low levels in the water reservoirs, which increased the electricity prices (Brännlund, 2006). Nuclear power is used for half of Sweden's electricity consumption. In the last years some of the nuclear reactors have had some disruptions due to inadequate maintenance, which also led to big fluctuations in the electricity price, especially during the two winters of 2009-2011 as can be seen in Diagram 6 (Sveriges Television, 2011).

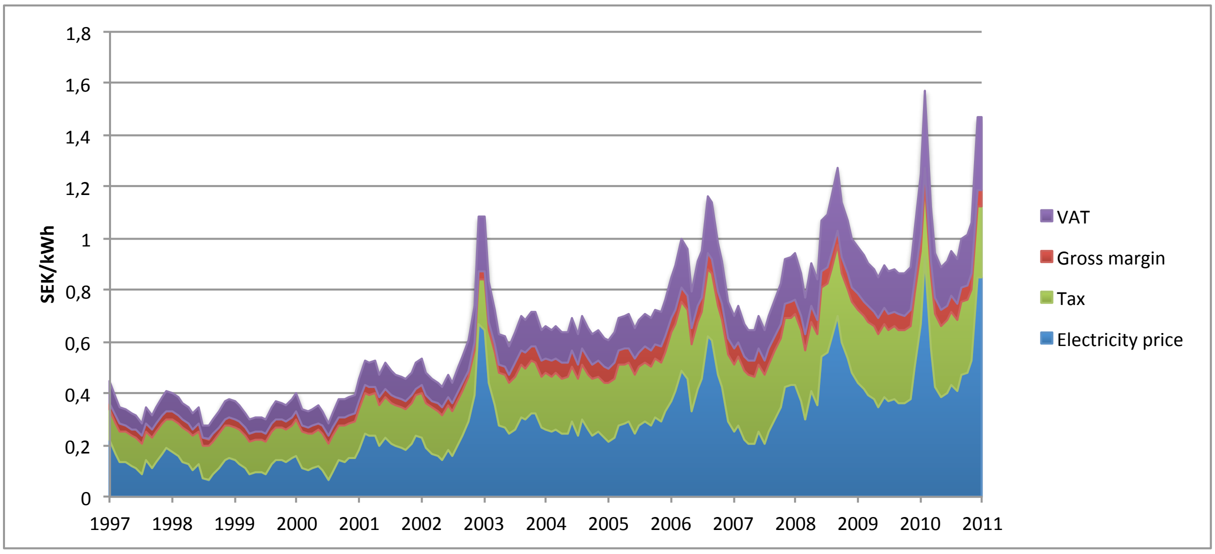


Diagram 6 Historical electricity price (Kundkraft, 2011)

The future electricity price is hard to estimate partly due to these fluctuations but Svensk Energi (2011) predicts the price to be relatively stable around 0,45 SEK/kWh[3] excluding tax, gross margin and value added tax. The forecast for the electricity price is also discussed in the report European Energy Pathways (Odenberger, Unger, & Johnsson, 2011) from Chalmers University of Technology. They separate a market scenario, which is the supply side, from a policy scenario as is more demand side oriented that promotes energy efficiency and the result is shown in Diagram 7. The diagram shows that the electricity price in the market scenario will be around 60 Euro/MWh which is around 0,66 SEK/kWh[3] while the policy scenario is more like the scenario presented by Svensk Energi above, 0,60 SEK/kWh[3].

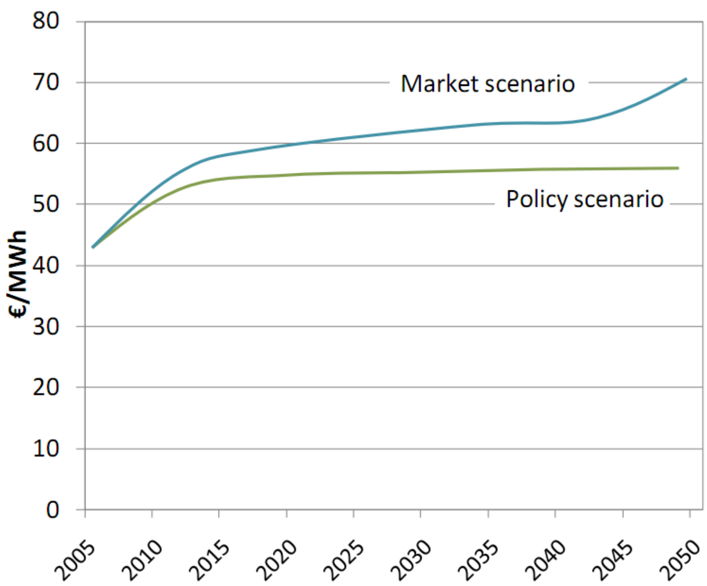


Diagram 7 Forecast of the electricity prices (Odenberger, Unger, & Johnsson, 2011)

Dieter Weise (2011) at Göteborgs Spårvägar, states that they are paying the price similar to the Nordic power exchange price from Nord Pool, which the figures presented above in Diagram 6 is based on. An additional power outtake will not change the existing price per kWh mentioned by Weise. As mentioned earlier companies can exclude VAT.

[3] 1 Euro = 9 SEK

4.3 Stakeholders' involvement

The large investment will not only be visible to the investor but will have further effects on the many subcontractors and also to those who in the end will make use of the bus. However there will also be other non-monetary effects such as an initial shift towards a more sustainable environment and advertisement for the city of Gothenburg. In order to understand the effects, the stakeholders involved and their connections will be outlined.

4.3.1 Public transport responsible and suppliers

Trafikkontoret is responsible for all the traffic in Gothenburg, which includes the public transportation and maintaining roads and tramways. They have no execution resources but instead hire entrepreneurs to perform the assignments (Trafikkontoret, 2011).

Västtrafik is hired by Trafikkontoret as the public transportation entrepreneur and is to fifty percent owned by Västra Götalandsregionen and the remaining is shared between the 49 municipalities within the region where they operate. Their mission is to coordinate all the public transport within the region. Timetables, tickets, routes and information systems are their responsibilities, while the actual traffic of the vehicles is outsourced. The traffic is attained with entrepreneurs responsible to drive the trams, trains, boats and buses. Among others are Göteborgs spårvägar and Veolia in turn hired by Västtrafik to drive the buses and the procurement takes place in competition between all bus companies (Västtrafik, 2009). It is also the bus companies who own the buses and are responsible for the maintenance.

The bus manufactures in Sweden such as Volvo and Scania have both offered hybrid buses since a few years back. However a certain resistance to rail bound transport has previously been found (Alatalo, 2011). Other bus manufacturers such as Ganz Solaris, Bombardier and Vossloh Kiepe has a longer track record of producing trolley buses mainly using electricity as a power source. In order to produce the parts necessary for buses to collect electricity from the tram network and also to return it to the rail other sub contractors with knowledge within the area such as Lucchini and SRS Sjölanders will be affected who are both leading in Scandinavia within their area of expertise (Lucchini Sweden, 2011) (SRS sjölanders, 2011).

4.3.2 Energy suppliers

Göteborg Energi is the electricity grid owner in Gothenburg and also serves all the trams in Gothenburg with electricity. If the dual-mode buses would use the same electricity Göteborg Energi could have an advantage since more electricity would be consumed and possibly more evenly distributed over time due to that electricity stored in batteries could be used during short peak outtakes (Sköldborg, 2011). For the same reason the diesel supplier would be negatively affected since less diesel would be consumed in the event of electrified vehicles.

4.3.3 Citizens

If no external funds will be provided as support for the investment will the passengers be the ones who will ultimately pay the price if the buses are not profitable compared to the existing transport solutions. However the citizens of Gothenburg will benefit from the lower noise levels, something that the authors noticed in Landskrona and onboard a hybrid bus in Gothenburg, along with better comfort due to lower vibrations. Also there will be lower local emission with the lesser usage of diesel.

4.4 Infrastructural and traffic prerequisites

Gothenburg's public transport hosts among other vehicles over 230 trams and additionally 450 buses (Gustafsson, 2011). Within the municipality there are 83 bus routes that have both end stations within the borders shown from the database acquired from Björck Laursen (2011). Four of these lines are trunk bus lines, which are mostly operating the very local parts of Gothenburg with 18 to 24 meter buses and frequent departures not unlike the trams. One of the trunk bus lines is included even though the end station is in Mölndal, since the bus drives a significant distance within the tram network. Many of these routes and especially the trunk bus routes share the same lanes as the trams on several distances, see Table 4. These trunk buses are therefore suitable for further investigation if dual-mode buses could be a profitable substitute (Spartalis, 2011) but also other buses with a high percentage or distance within the tram network.

Line	Route	Distance	In tram network
16	Högsbohöjd - City - Eketrägatan	16 km	3 km
17	Tuve - City - Östra Sjukhuset	17 km	2,5 km
18	Skälltorpsvägen - Backa - City - Johanneberg	15,5 km	1 km
19	Backa - City - Fredriksdal - Mölndal	17,5 km	2 km

Table 4 Trunk bus lines in Gothenburg

The tram network has a voltage of 750 V and the limit of usable current is set to 2500 A supplied by current distributors with about 600-800 meters in between. Trams in Gothenburg use at maximum between 300 - 1200 A per vehicle during acceleration. Other vehicles capable of connecting to the tram network could also share the benefits of using electricity. However, a number of dual-mode buses in the tram network will not overload the overhead wires since the limiting factor will be the traffic density with other vehicles in between those using the electricity. If the power outtake limit is reached it results in slower acceleration for the vehicles. Also by changing the overhead wires and increase the conducting area the maximum limit could be raised to 4000 A (Sköldborg, 2011).

As previously mentioned is this report based on that no infrastructural changes will be made in order to realize the solutions presented. However the traffic in the tram lane will cause wear on the asphalt and on the overhead wires. The cost for replacing the asphalt close to the tram rail is 2 million SEK per year (Sköldborg, 2011). Sköldborg although declares that the difference in maintenance cost is almost negligible since the buses, both diesel and dual-mode will drive most of the time on the rails in any occasion and the average life time for the overhead wires is 20 and sometimes even 40 years with a replacing cost of 250 SEK per meter.

Another interesting aspect is that roads previously only trafficked by trams could be asphalted. In this case the electrified distance for buses could be as much as doubled in length according to maps and the authors' observations. The cost for laying asphalt on an already pre-prepared surface is 150 SEK/m^2 (Olsson, 2011).

Since the hybrid buses are capable of accumulate energy when braking, as earlier described, there is a possibility to return energy to the overhead wires if there are no possibilities to store it in the bus. This requires the network grid to be capable of transmitting this power which should be possible since it is done today on the newer trams used in Gothenburg (Sköldborg, 2011).

4.5 Future plans for Gothenburg public transport

In 2013 congestion charges will be introduced in Gothenburg where people who drive a vehicle have to pay a certain amount of money when they pass through toll stations, which are located around the urban area. This is introduced to decrease the congestion and finance new infrastructural investments. The increase of passengers using public transportation in the urban area is planned to be 3 percent every year except for when the congestion charges are introduced 2013, that year the increase of passenger is estimated to 8 percent (Västtrafik, 2010) (Lorentzon, 2011).

The owners of Västtrafik have also stated a goal of twice as many passengers in the public transportation system 2025 as it was 2006 (Västtrafik, 2009). This will, among other things, require increased number of departures and faster transportation. Therefore, the plans for 2013 are that the express buses will not drive in the city centre of Gothenburg and instead should the number of trams and the trunk buses be increased (Förbundsstyrelsen vid Göteborgsregionens kommunalförbund et.al, 2009). For the trunk bus lines 16 and 17 is the plan is to only use 24 meter buses and the frequency of trips will be increased for all trunk bus lines including 17, 18 and 19 (Lorentzon, 2011).

There have been some speculations regarding an underground or tramway partly under the ground in Gothenburg, but these ideas are currently not close to realisation. However today plans exist about extending the tram network, for example the manager of public transportation at Trafikkontoret (Engström, 2011) thinks that an expansion to Lindholmen and Eriksberg will be reality in approximately a decade. Replacing the existing overhead wires with thicker in order to increase the capacity in the tram network is also on the wish list but it is expensive (Sköldborg, 2011).

4.6 Competing public transportation solutions

In order to describe the different transportation solutions available for the stakeholders these are further briefly presented with their pros and cons and summarized in Table 5.

4.6.1 Buses

Buses are a very common public transportation solution that often requires almost no changes in the infrastructure used by cars and is therefore a relatively cheap investment. There are many different kinds of buses where the diesel bus is the most common, but other more environmentally friendly solutions such as gas, hybrids, trolley, plug-in and inductive charged also exists. Due to the low infrastructure requirements the buses are often very flexible but has often less space compared to other public transportation solutions. If propelled by diesel the pollution per passenger kilometre is significantly higher compared to other alternatives with electricity (Lenner, 1999).

4.6.2 Trams

Trams are more expensive with an approximate investment cost of 25 million per tram, which is five to ten times as expensive compared to the bus (Gustafsson, 2011). Trams also have the drawback of being dependent on the infrastructure, which makes them very inflexible. This infrastructure is also very expensive and therefore requires thorough planning. On the other hand the trams have a much greater capacity compared to the buses and a possible lifetime exceeding 50 years (Gustafsson, 2011). Also since the trams run solely on electricity the local pollution is very limited per passenger kilometre even with electricity production included (Lenner, 1999).

4.6.3 Subway

Underground subway is in many aspects similar to trams but has even greater capacity but comes with a very high cost for building the needed infrastructure. A benefit with subways is that they are never affected by surrounding traffic conditions or pedestrians and can therefore have a greater average travelling speed, above 37 km/h (Gustafsson, 2011). In order to take advantage of the high speed and limit the costs the distance between stops are longer which makes the subway even less flexible. Regarding the environmental impact it is comparable with the tram since it uses similar technology. A big difference is that the subway is underneath the ground and does therefore not affect the cityscape.

4.6.4 Existing public transportation solutions comparison

	Bus	Tram	Subway
Initial investment	*	**	***
Infrastructure required	*(*)	**	***
Flexibility	**(*)	**	*
Environmental impact	(*)**	*	**

Table 5 Summarizing table for buses, trams and subway

Stars within brackets () consider buses connected to an electric power supply.

4.7 Chapter conclusion and summary

The SWOT, see Figure 3, analysis summarizes the strengths, weaknesses, opportunities and threats for dual-mode buses from a perspective beneficial for Gothenburg. The strengths and weaknesses are internal factors while opportunities and threats represent external factors (Kottler, 2000). No weight is given to either of the arguments since they are all subjects of personal opinions where some might be more important than others. What is common to all is that they do all share the importance to create or remove the need for dual-mode buses.

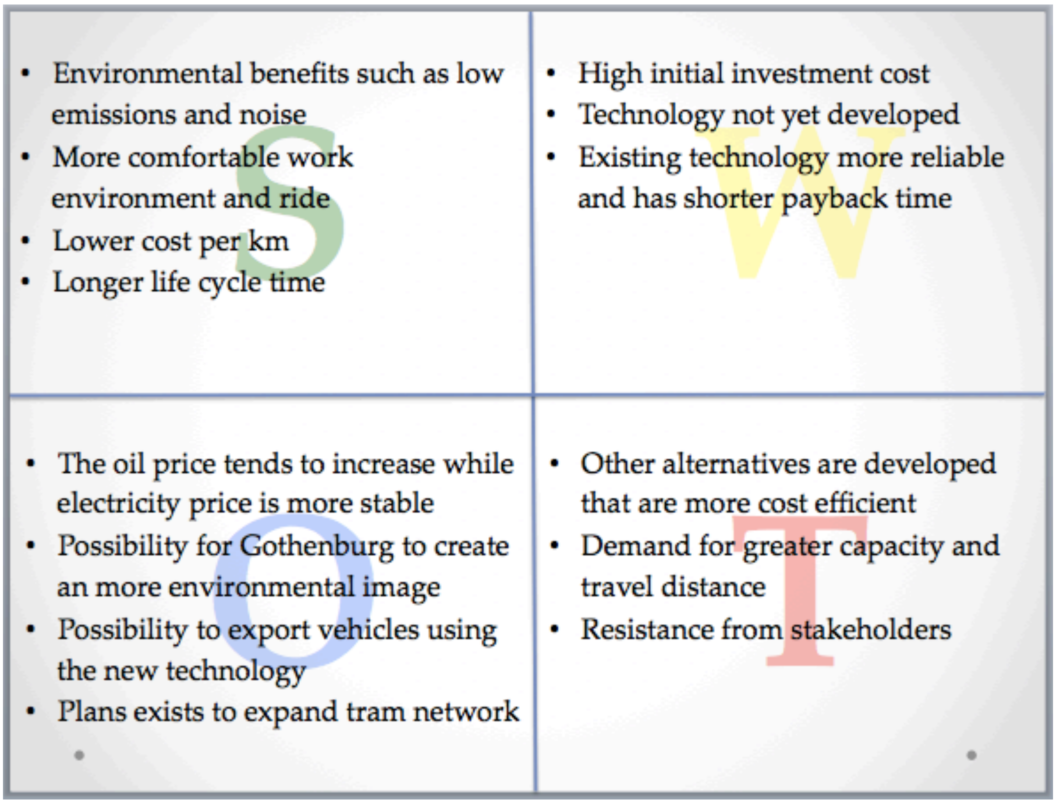


Figure 3 SWOT analysis for Dual-mode buses in Gothenburg

5 Technical concepts

Even though batteries today are still expensive, the increased environmental awareness makes emission free alternatives becoming more popular. A dual-mode bus has, as mentioned before, the advantage of being flexible compared to trams, but still take the advantage of propel the bus with the help of electricity.

Normal for today's dual-mode buses and trolley buses is that they have two overhead wires, one that acts as a positive pole, while the other returns the electricity to close the circuit. A conversion of the overhead wires in Gothenburg's tram network to suit this solution would affect the whole infrastructure. Changes that would be required includes both that the existing trams have to be rebuilt, the switches and intersections in the overhead wires would need a lot of costly changes not to mention that new wires need to be drawn. This is why, as described in delimitations, the infrastructure should be kept intact, only with minor changes if necessary.

Since no major changes of the infrastructure are considered, two focus areas are paid attention to in order to find endurable concepts. The first is how to connect to the overhead wires while the second issue is the grounding connection in order to close the circuit.

The concepts presented below will indicate that using the electricity from the tram network and return it to the rail is possible but should not be considered optimal solutions. Further development is needed in order to refine the concepts before they are implemented and used. Before the concepts are presented the prerequisites and the product requirements is specified.

5.1 Prerequisites

The concepts need to be constructed to be able to connect to the tram network and ensure connectivity as long as the dual-mode bus stays within the network. It is also of importance that the new functions do not add additional work tasks for the driver that takes the focus off the road or takes time that could delay the time schedule. Neither will concepts that points out from the bus be accepted from the Swedish Transportstyrelsen since it might cause damage to pedestrians and other vehicles (Göingberg, 2011).

The concepts also need to be reliable and ensure safety of operation. That includes functionality in any weather condition common in Gothenburg such as low temperature, rain, wind and snow. It should also be resistant to leaf and other objects that could occur in the rails. Furthermore it is important that the concepts works in any place operated by both trams and buses such as around tight corners, with switches, signal systems or where trees are growing close to the overhead wires. One of the closest tram turns in Gothenburg is in the crossing of Vasagatan and Viktoriagatan with a radius of 19 meters (Englund, 2011).

Also since the pedestrians and other road users as well as the passengers' safety have the first priority these should not be jeopardised in any case. If the buses, while using the electricity, have the capability of avoid an accident or overturn a bicycler, unlike trams bound to the rails, that is an advantage.

5.2 Current collector concepts


Picture 3 Suspension attachment in Gothenburg

Several solutions to reach the current exits and are in use today on trains, trams and other vehicles such as trolleybuses. Even though the vehicles have roughly the same height, their solutions are all developed to work in their particular circumstances and do therefore not exactly fit the purpose of dual-mode buses. What differs in the requirements for dual-mode buses are the need of connecting fast, if possible also during movement and to be flexible enough to reach the overhead wires even if the bus is not always following the tram rails exactly. Also the overhead wires in Gothenburg are suspended with attachments; see Picture 3, adjusted to pantographs that are not mechanically guided by the wire. Therefore trolley poles as a solution as used in trolleybuses are not combinable with the existing infrastructure (Andersson P. , 2011).

5.2.1 Modified pantograph


Picture 4 Modified pantograph (Niklas Dyverfors)

A pantograph similar to the one used on trams was the first obvious concept, see Picture 4. It is both well used and therefore durable and reliable. Since it is the same technology as used on the trams it can be considered possible to mount on a bus as well without a too great effort. The technical solution for how to create the pressure needed in order to get a good connection could also be the same as for pantographs used by trams. Approximately 50N (Spartalis, 2011) is needed to get a good connection for trams and could be generated, either with regular springs as used today in trams or hydraulic springs, which are both reliable. However since buses are moving more vertically due to road bumps etc. compared to trams, additional pressure needs to be applied. 120-130N is used for the trolley buses in Landskrona to create a connection and to guide the trolley poles along the overhead wires (Andersson & Johansson, 2005) whereby some 100N could be reasonable for this modified pantograph.

The downside with this concept is that it is fixed and very inflexible since it was developed for vehicles that are permanently travelling the exact route every time. The overhead wires are therefore drawn to maximise the usage of pantograph and always take the shortest route, see Figure 4. Since the buses are steered by the driver it can take different turns compared to trams and it can therefore accidently miss the overhead wires. The width of the pantograph therefore needs to be increased to allow for greater turns for the driver. The width of the pantograph should be the same as the grounding solution is capable to move horizontally which is almost the width of the bus. It will also make the driver able to avoid accidents or objects in the traffic. When the connection is lost the pantograph should automatically lower to avoid damage to the wires. The time it takes to higher or lower a pantograph on a tram is about five seconds (Spartalis, 2011) (Andersson P. , 2011). A sensor at each end of the pantograph will warn when the driver moves away from the wires and the battery will supply electricity to the electric machine if the connection to the overhead wires is lost. If the battery is depleted before the driver drives back under the overhead wires the diesel engine will automatically start. A suggested modification is that the driver could be alerted with warning lights built into the windscreen if the vehicle is close to lose connection (Alaküla, 2011). This would ease the driving for the driver without taking necessary attention from the road but would need further investigation regarding road safety, technology and price.

Figure 4 Illustration of a bus turning in the tram network

A reasonable placement of the pantograph is just behind the articulation, unless the rear wheels turn the opposite direction to the driver. In that case it should be mounted close to above the rear axle (Östlund, 2011). It is all in all a relatively inexpensive concept since a normal pantograph has an approximate price of 60-80 thousand SEK (Eriksson, 2011).

5.2.2 Intelligent current collector

Picture 5 Intelligent current collector (Niklas Dyverfors)

An intelligent current collector has the design that reminds of the pantograph in Picture 4 although rail on top is shorter, see Picture 5. Since the overhead wire is always above the rail and the intelligent current collector is connected to the grounding solution it knows where the overhead wire is. It then has the ability to move sideways according to the grounding solution as the bus turns. It is therefore a more flexible concept than the pantograph and allows the driver to take greater turns or to avoid objects. It also has the ability to connect and disconnect automatically on the fly given that a connection to the rail is secured. An existing current collector of this kind does not exist today but a prototype has been developed by Svenska Elvägar AB (2010). It is designed to be mounted on transport vehicles travelling most of the time on highways but could most likely be attached to a bus driving a distance in the tram network. The design allows vehicles to leave and attach to the overhead wires at highway speed, which is far more than the 70 km/h allowed for city buses. Ilsoe (2011) suggests that hydraulic springs should be used since they add the possibility to manoeuvre the collector with the precision needed. Also since the collector manoeuvres automatically it does not need to call for the driver's attention when it connects or disconnects to the overhead wires more than with an indication.

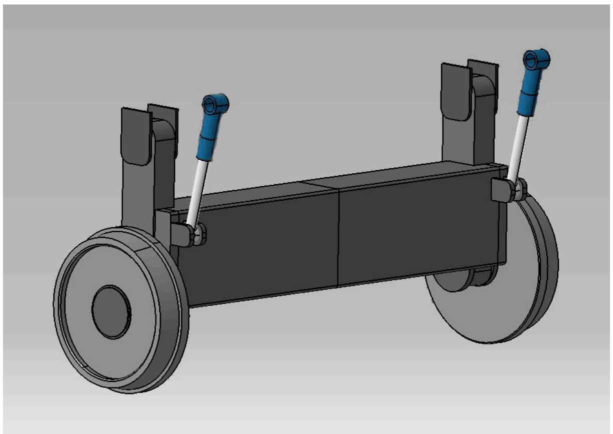
Other parameters will in many aspects look like those specified in the previous concept with a pressure of 100N and with a diesel engine that starts immediately when there is no connection or battery energy. However the placement is not as sensitive due to that it can move sideways but a reasonable estimation is at the same place for maximum reach and conducting capabilities. What is unknown in this alterative is the durability in weather and with the wind speed that is generated but according to a report presented by Svenska Elvägar (2010) is this technically feasible.

The ability to move will not only ease the driving but the size can also be smaller which may make it more visually attractive. However it is 2-3 times as complex as the usual pantograph, which increases its cost (Ranch, 2011).

5.3 Current return concepts

This is what differs the most from other vehicles with similar engine setup. There are no vehicles known to the authors that use both current from the overhead wires in combination with rubber tires and also returns the current to the tram rail. In order not to make the vehicle live the concepts presented needs to guarantee that there is always a connection to the ground. It also needs to have enough pressure not to give origin to electric arcs within the prerequisites described.

5.3.1 Tram wheels



Picture 6 Concept Tram wheels (Niklas Dyverfors)

To have an additional wheel axel with tram wheels in the front of the bus that could be lowered into the rails is the first current return concept, see Picture 6. The concept reminds on tram wheels (Sandström, 2011). When lowered, the pressure between the front rubber wheels and the ground is reduced and, like a tram, the vehicle will be guided by the rail instead of steered by the driver who only regulates the speed. Spartalis (2011) estimates the pressure required to be between 4-5 tons per wheel axle which is confirmed by Östlund (2011) who says that the majority of the weight from the front should be applied on the axle to reduce the risk of derailment and the possibility to steer from the driver seat. With this amount of pressure the contact to the rail is also guaranteed and additionally since the vehicle will drive the exact route every time the technical solution to connect to the overhead wires will be easier to develop (Östlund, 2011). It is also as resistant as trams against weather conditions and all types of junk in the rails, but it still maintains similar braking abilities as a bus.

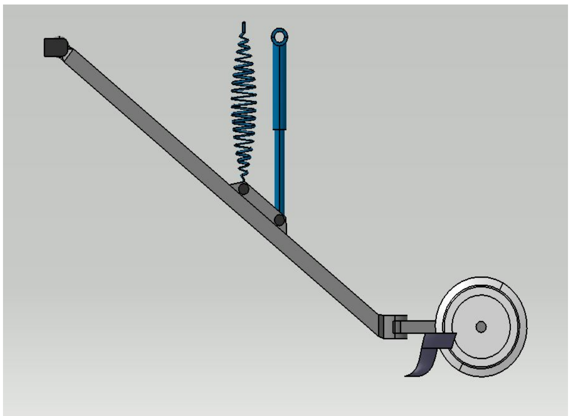
The placement in front of the bus is important since there will be no room underneath the low floor used today in most city buses or in combination with the steering attached to the front axle. It is also important that the rubber wheels has the ability to be risen when the tram wheels lowers otherwise it would not be possible to offer the same low floor solution (SRS Sjölanders AB, 2010).

With hydraulics and a camera it could take about four seconds to lower the wheels into the rails and raise the rubber wheels (Sandström, 2011). The drawback with this concept is that it probably would require that the vehicle is standing still while the tram wheels are lowered since it requires great precision not to miss the rails or great damage could be dealt to either the road or the rail (Ilsoe, 2011). This could however be done while the passengers are entering the vehicle but would require the drivers attention and without an automatic solution the general interest and also chances of realisation would be lowered (Alaküla, 2011). The concept is also heavy and the whole design could therefore be questioned but similar attempts both in maintenance vehicles as well as on trolley buses have been tried and used with success (Ranch, 2011). A price estimation is 90 000 SEK for the wheel axle and additionally 9 000 SEK for the camera (Sandström, 2011).

5.3.2 Current return arm

In some trains used today the grounding through the wheels are complemented with a metal "brush" that glides along the rail in order to ensure maximum connection (Östlund, 2011). Also in the subway in Stockholm a "third rail" is used to connect to a rail when no overhead current is available (Söderberg, 2011). The second possible identified concept for returning the current to the ground reminds both of these concepts and of the intelligent current collector previously described. This report has focused on two different designs for the current return arm. The first consists of an arm sliding along an axel that gives the ability to move both in sideways as the bus turns and also be flexible vertically to allow for bumps, see Picture 7. The second arm is fixed to the bus but has two joints that allow movement both horizontally and vertically, see Picture 8. In both cases, when the bus enters the rail from the left, the right arm should be lowered first in order for the left arm to reach the left rail, the opposite should be done if entering from the right. The connection to the rail could either be created through a wheel or with a metal plate. Both in Stockholm's subway (Söderberg, 2011) and in Ansaldo Stream concept (Ansaldobreda, 2004) metal plates are used since they are very durable. It could also be fitted with a metal braid as connection shaped like the side of the rail since it then would allow for good connection even if the rail is not entirely flat (Thiringer & Zelaya, 2011).

Picture 7 Sliding current return on axle (Niklas Dyverfors)



Picture 8 Rolling current return arm with joints (Niklas Dyverfors)

The other alternative consists of a metal wheel with an edge that fits into the rail. This enables good connection to the rail since pressure could be applied from two ways at the same time as less wearing of the rail will occur and therefore also quieter. The size of the wheel is a problem when approaching a road bump since most buses have low floor and the diameter needs to be around 150 mm (Ekberg, 2011). Therefore it must be space underneath the bus for the wheel to fit in to. Since the high current would wear out the roller bearing, slip rings are needed to transfer the current (Sköldborg, 2011) (Sandström, 2011)(Thiringer & Zelaya, 2011). In either of the concepts a sensor is needed for the arm to find the rail but also to indicate when to raise the arm as the bus leaves the rail (Thiringer & Zelaya, 2011). An inductive sensor does not work here since the current could be too low (Alatalo, 2011). Instead an analogue proximity capacitive sensor should be used since it is capable of both measuring the distance to the rail while also being resistive to dirt (Thunell, 2011). It is important that the connection to the ground is secured before the current collector connects to the overhead wires in order to reduce the possibility of making the bus conductive. The opposite should be done when leaving the tram network. The connection should be made on top of the rail since that is where the trams cleans the rail from ice and dirt and that cross sections, see Picture 9, otherwise could become a problem (Söderberg, 2011). According to Sköldborg (2011) four arms will be needed in order to ensure that there is at least one arm connecting to the ground, which is also confirmed by the authors' own investigation. The arms should be placed behind the articulation underneath the current collector (Östlund, 2011). As described for the modified pantograph, the sensors could give guidance for the driver in the windshield to ease the drive along the rail.

Picture 9 Tram crossing in Gothenburg

Kihlberg (2011) says that it is of importance that the arm is both light but also resistant to rust and therefore suggest aluminium. An approximate price for one arm was estimated to be 10 000 SEK. He further suggests that a brush or plough should be mounted to remove objects from the rails. Ekberg (2011) approximates that an hydraulic spring will create the pressure of 1000 N needed to get a good connection in the bumpy bus, which is generous compared to the 140+- 20N used in the subway system in Stockholm (Söderberg, 2011). Additionally 10 N vertically should also be applied to ensure that it is always following the rail (Ekberg, 2011). If no other hydraulic system is used in the bus, the springs could be controlled with pneumatics as used in the bus doors to reduce the cost (Ilsoe, 2011). In either case the surface area needed to conduct the current should at least be 250 mm^2 on each arm as that is used in the subways third rail in Stockholm (Söderberg, 2011). In Gothenburg 90 mm^2 is currently used on each tram wheel (Sköldborg, 2011).

5.4 Concept combinations

From the concepts presented, three different combinations were seen as relevant. Firstly, if the tram wheels were chosen, only a normal pantograph was needed since it would always take exactly the same route as trams. Both of the current return arms could be fitted with either a modified pantograph or an intelligent current collector, which are the other two combinations. The wider modified pantograph requires increased attention and driver skills but it is less expensive and probably durable since it is already used today apart from the extensions. The intelligent current collector allows the driver to do greater turns without losing the connection but it is at the same time more expensive.

6 Simulation of energy consumption and powertrain setup

The simulations combine the data from the literature study with the empirical research. Three different options were simulated in order to investigate how the different settings affected the possible energy consumption.

6.1 Input data

Before the simulations were initialized the settings and parameters needed to be determined. Initially the route data needed to be generated and verified against local measurements before a framework of powertrain parameters was constructed.

6.1.1 Route setup

The simulation is based on the drive cycle Cbr85, which was a City Bus Route number 85 in Gothenburg. The buses were operating the distance back and forth between Körkarlens gata to Masthugget but it was disused in 2004 due to the narrow streets which were hard to drive with articulated buses (Västtrafik, 2004). It is nevertheless still used by Volvo to simulate Gothenburg's city traffic. Some key figures from the recordings are presented in Table 6 below in order to enable comparisons.

Cbr85					
Total distance two ways	Altitude variation	Total duration two ways	Average unload time	Maximum speed	Average speed
23,13 km	0,5 - 69 m	4302 s	15,7 s	69 km/h	19,35 km/h

Table 6 Key figures for Cbr85

The equipment used when these figures were recorded was calibrated to record only when the vehicle was either accelerating or decelerate whereby the timestamps between each logged distance varies. In order to give good enough accuracy in the results, the simulations later performed required that the distance travelled was measured with one second intervals. Therefore Matlab was used to estimate this distance between each measurement using interpolation. The complete data set was exported from Matlab into Microsoft Excel where the actual simulation was performed. A fraction of the data is shown as illustrating example in the Appendix VI.

In order to increase the validity and make sure that Cbr85 could indeed be used as a good measurement; additional measurements were done at trunk bus number 16 since it was perceived as a bus line with potential of exchanging the diesel buses to dual-mode buses. The distance, altitude and time for this bus line were thereby recorded between the end stations using a GPS and stop watches. Additionally the time and distance when bus 16 was travelling under overhead wires were recorded as well as the average time it took to load and unload passengers at each stop. The figures are presented in Table 7.

Bus 16					
Total distance	Altitude variation	Average speed	Load and unload time	Average unload time	Distance with overhead wires
16,47 km	1 – 71 m	23 km/h	0 – 74 s	16,9 s	3 km

Table 7 Key figures for the trunk bus 16 in Gothenburg

However due to a lack of accuracy in the GPS signal, the recorded data could not be validated good enough to be used as the sole input data for the whole simulation even though the distance was travelled back and forth twice. The inaccuracy in the GPS signal resulted in unreasonable accelerations for a bus, but the total distance as well as speed could be validated using Google maps, see Appendix VII, and the provided bus timetable, see Appendix VIII. Also the average unload time were comparable and similar even though the maximum and minimum values varied between 0 and above 74 seconds and were therefore considered outliers and removed in both cases. The recorded 0 occurred when the driver did not stop at all and 74 was due to a road maintenance work. The average speed also proved to be quite similar in the two cases and the difference in altitude variation is almost identical. Although the data from the GPS source gave false maximum and minimum speed it is known that the bus cannot travel faster than 70 km/h (Spartalis, 2011) and is therefore also matching. Also known from the maps in Appendix VII that displays the track trafficked by trunk bus 16 was that roughly 3000 m or 19 % were underneath overhead wires and when applied to the Cbr85 it corresponded to two times 2100 meters. With the above figures in mind the Cbr85 was considered a good cycle that could be compared to the trunk bus 16. Also 600 meter was set as the distance between the current distributors since it was considered that the shortest distance between was needed in the city centre. This distance affects the maximum power output per kilometre, which affects the number of trams provided with energy per kilometre, which is used later in the simulations.

6.1.2 Powertrain setup

As previously mentioned, the powertrain setup is based on an existing hybrid bus modified with the technical concepts presented for collecting and returning the energy in the tram network. Since this bus contained all other electric and technical equipment (Andersson & Andersson, 2011), the development cost could be kept lower which was seen as important since it will only be shared between the few buses produced.

What was further seen as important was that these hybrid buses has been field tested and perceived as a functional solution (Svenska bussbraschens riksförbund, 2010) which were considered to increase the interest from the stakeholders. Plug-in hybrid buses with batteries as main source of energy are not very common but are field-tested in Umeå among others. Although the energy consumption will be lower for buses only relying on battery compared to other alternatives with ICE, they need to be standing still for 5-10 minutes in order to charge when the battery is empty (Green Car Congress, 2011).

The simulations use an 18 meter long articulated hybrid bus weighing 17 tonnes and has the maximum capacity of 118 passengers (Spartalis, 2011). The average number of passengers on a bus in Gothenburg is 27 according to Lorentzon (2011) but since a larger 18 meter articulated bus is used, 41 passengers per vehicle are assumed to be a more accurate figure. The total weight will further include a battery with variable weight and an estimated 0,5 tonnes of electronics. The average weight was used when calculating the average fuel and energy consumption while highest load gave the maximum start energy needed.

The two engines is each set to providing 240 hp or 180 kW which is an up scaled version of an existing 12 meter hybrid bus (Volvo bus corporation, 2011). This is estimated to be enough to power the vehicle with the maximum load to reasonable accelerations and speed. When the electric machine is used as a brake and at the same time generating electricity, the 180 kW is set as the charge limit unless the energy storage is capable of retrieving a lesser amount.

Further parameters used in the simulations are data regarding how the mechanical power from both the diesel engine and the electric machine is transmitted to the wheels and which losses that needs to be taken into consideration. The electric and mechanical overview scheme is presented in Appendix IX. The EM is set to have an efficiency of 90 percent (Andersson &

Andersson, 2011) (Svenska elvägar AB, 2011) and the transmission 95 percent. The current used in the overhead wires as well as possibly stored in the battery is DC but the electric machine requires AC to be run whereby the DC/AC and DC/DC converters are needed. These have an efficiency of 90 percent (Andersson & Andersson, 2011). The total efficiency from overhead wire to the end of powertrain is at best 0,77 percent, which can be seen from the green line in Appendix IX. Comparably has the diesel powertrain a total efficiency of only approximately 28,5 percent including clutch and generator. When a battery is used it is set to have an efficiency of 90 percent in and also 90 percent out (Andersson & Andersson, 2011) although this is not optimistic according to (Alatalo, 2011) who instead points at figures as high as 93 percent in and out. The summary of these figures for easy access is presented in Table 8 below. The minimum energy efficiency if a battery is used is 56 percent; see the red line in Appendix IX.

Efficiencies, energy content and losses	
Electric machine efficiency	90 %
Transmission	95 %
DC/AC converters	90 %
Energy storage system in	90 %
Energy storage system out	90 %
Diesel powertrain efficiency	28,5 %
Fuel energy content	38,6 MJ/l
Average mechanical auxiliary load	5 kW
Average electric auxiliary load	5 kW

Table 8 Used parameters in the simulation

An average auxiliary load of 5 kW was also added to the energy consumption to simulate the energy needed for the lights, engine cooling, pneumatics, air condition and other electrical equipment (Andersson & Andersson, 2011). The volumetric energy content for diesel was set to be 38,6 MJ/l (Austrailian Institute of Energy, 2011). This estimation was needed in order to compare diesel and electricity.

6.2 Option generation and selection

Before the simulations were performed the different vehicle combinations needed to be chosen that affected the energy consumption. What differed between the options was if and how the regenerative braking charge should be stored, which affected the size of the battery, but also how and if the electric machine should be used in combination with the diesel engine outside the tram network. Table 9 below illustrates the different options that were available. Not all options were considered applicable due to combination constraints. For example all alternatives including storing the regenerative charging in batteries but without using batteries were excluded. These are marked with dark grey in the figure. The options marked with light grey were plausible but were rejected due to limitations or that other options had the same or slightly the same functions achieved but with less means. This included options that did not capture regenerative charge inside the tram network, which were considered easy since the technology already exists in trams (Alatalo, 2011) or when batteries were available. Other would require fast charging supercapacitors which are not only a rather expensive addition to the batteries, but would also generate a great peaking electric load, see Appendix X, on the already loaded overhead wires (Sköldborg, 2011). Three different options were performed in order to investigate which option will be the cheapest to drive when the fuel and electricity costs per kilometre were summarized. Options only using battery as energy source outside the tram network were not studied since it was not considered reliable to provide energy for the whole trip. Also the batteries would be too big and the load on the overhead wires too great (Andersson & Andersson, 2011). The technical concepts earlier presented were not accounted for in these simulations since they were considered not to affect the results. Finally three options were selected which will be presented later. The evaluation considered the options that were either seen as the least complex while still maintain benefits, using electricity without overloading the overhead wires or using maximum available energy.

Battery charging and/or return energy to overhead wires	Propellant inside and outside the tram network											
	Outside TN	TN	Outside TN	TN	Outside TN	TN	Outside TN	TN	Outside TN	TN	Outside TN	TN
	Diesel	Electricity	Battery	Electricity	Diesel + battery	Electricity	Diesel	Electricity + Battery	Battery	Electricity + battery	Diesel + battery	Electricity + Battery
No regenerative charging												
Regenerative energy from breaking returned to overhead wires	1											
Regenerative energy from breaking returned to battery											2	
Regenerative energy from breaking returned to battery + wires												
Regenerative energy from breaking returned to battery + Battery charge from overhead wires											3	

TN = Tram network
Not applicable
Deleted alternatives
Not possible to combine with todays infrastructure
Chosen alternatives

Table 9 The options available and chosen

6.3 Performing the simulations

In the data acquired from the Matlab interpolation, only seconds and the momentary speed at that time were recorded. The simulations were all done using Microsoft Excel and the data that were in common between both options were calculated first. Since the time distance between each measurement was constantly one second, the distance at the time was first of all calculated as the speed plus the covered distance and then the acceleration as the difference between two time measurements. The connection between all parameters can be seen in the parameter relations in Appendix XI.

The mechanical power needed to accelerate the vehicle to a given speed needs to include the kinetic energy but also overcoming rolling resistance and drag resistance at any given second. The formulas that were used are presented below. The rolling and drag resistance were summarised and multiplied with the momentary speed before summarized with the kinetic energy in order to convert the power to energy that could be translated to the amount of fuel or electric power needed.

Kinetic energy

$$E_k = \frac{1}{2}mv^2$$

Rolling resistance

$$F_r = c_r \cdot mg$$

Drag resistance

$$F_a = \frac{1}{2} \cdot \rho_a \cdot A \cdot c_d \cdot v^2$$

The formulas are acquired from Guzella & Sciarretta (2007) where c_r is the rolling friction coefficient estimated to 0,0055 (Lomaeus, 2011) (Iven, 2011) and mostly based on the speed and tire pressure. However this figure varies between type of tyres and manufacturers. A is the front area of the bus and is set to 2,55 x 3,2 m^2 (Volvo bus corporation, 2011). The air density, ρ_a, is 1,23 kg/m^3 at 10 degrees Celsius (Hellsten, 1992) and c_d is the air drag coefficient, set to 0,79 (O'Keefe & Vertin, 2002) that is an individual figure for each vehicle.

The timetable for trunk bus 16, Appendix VIII, was used to calculate the total number of departures per year which was used to estimate the average number of drive cycles per day for Cbr85 which resulted in 9,2 drive cycles.

6.3.1 Option 1

The first option chosen uses a pure diesel engine outside the tram network and an EM inside the tram network to propel the vehicle. In this option no battery is included and therefore also no regenerative braking will be possible outside the tram network. However, inside the tram network it will return power through the overhead wires during braking as long as there is another vehicle consuming it simultaneously (Sörensson, 2011). In order for other vehicles to be able to receive all the current they need to be consuming the same amount and between the same current providers as the transmitting vehicle (Andersson, 2011). The rest of the braking energy is transformed into heat and wasted by using ordinary disk brakes. Also the size of the EM used to retrieve energy when braking limits the maximum amount of energy possible to regain (Volvo bus corporation, 2008). The total amount of energy needed to propel the bus was simulated to be 2,24 kWh/km when using the power from the overhead wires. However in the simulation the energy regenerated through braking summed up to 0,40 kWh/km, which could be returned back to the overhead wires whereby only 1,84 kWh/km was actually used by the bus. In the simulation, account was also taken to the possibility of no other vehicle being close enough to retrieve the energy by limit the maximum power returned to the average energy consumed by trams. The simulated 18 percent returned energy could be compared with 16 percent which are actual figures measured in trolley buses used in Landskrona (Sörensson, 2011) (Andersson, 2011). While inside the tram network the maximum power needed to accelerate the 26 tonnes fully loaded bus was 335 kW and an average of 42,5 kW was used for an average vehicle of 20,5 tonnes including 41 passengers. For the rest of the drive cycle, where the diesel engine were used, an average 0,56 litre/km was needed for the 20,5 tonnes vehicle. The summary of key figures from the simulation of Option 1 is seen below in Table 10 for easy comparison.

Option 1			
Electricity usage	Maximum 26 tonnes	Average 20,5 tonnes	Diesel usage
1,84 kWh/km	335 kW	42,5 kW	0,56 l/km

Table 10 Key figures for Option 1

6.3.2 Option 2

In Option 2, the EM collaborates with the diesel engine outside the tram network. The energy comes from regenerative charging when the vehicle is braking, stored in the battery, and used during the forthcoming acceleration. Inside the tram network the electric machine will be used in the same way for braking and acceleration as in Option 1 but the braking energy generated will be stored in a battery, which is optimized for fast charging and high output. If the battery becomes fully charged or the energy is too great for the battery to handle, the energy will be returned to the overhead wires for other electric vehicles to use. The battery will be seen as the main source of energy in favour of the overhead wires in order to ease during maximum power outtake. The use of battery reduces the risk of no tram available to receive the energy whereby the energy is wasted. A drawback is though that the battery as well as the converters has less efficiency compared to the overhead wires and some energy is therefore lost in the transformation.

It is the size of the battery and its configuration that limits the maximum power possible to store in the battery rather than the size of the electric machine. The power density of the battery used in the simulation is 200 W/kg and with an energy density of 60 Wh/kg. A diagram giving an overview of the performances at cell levels for different batteries can be seen in Appendix XII. According to Andersson & Andersson (2011) a bus will become hard to drive properly if a weight greater than 1000 kg is loaded on the roof of the bus, which often is the only space available. The maximum size of the battery is therefore limited not to affect the driving capabilities. These limitations combined with the simulation of optimal charge limit which is dependent on the size of the battery as displayed in Figure 5, resulted in an optimum 90 kW which meant a weight of 500 kg when fuel consumption and battery cost was included. This is enough to create a discharge limit of 100 kW. An increased weight would increase the amount of energy possible to charge and also increases the maximum output but would at the same time also increase the energy consumption due to its weight.

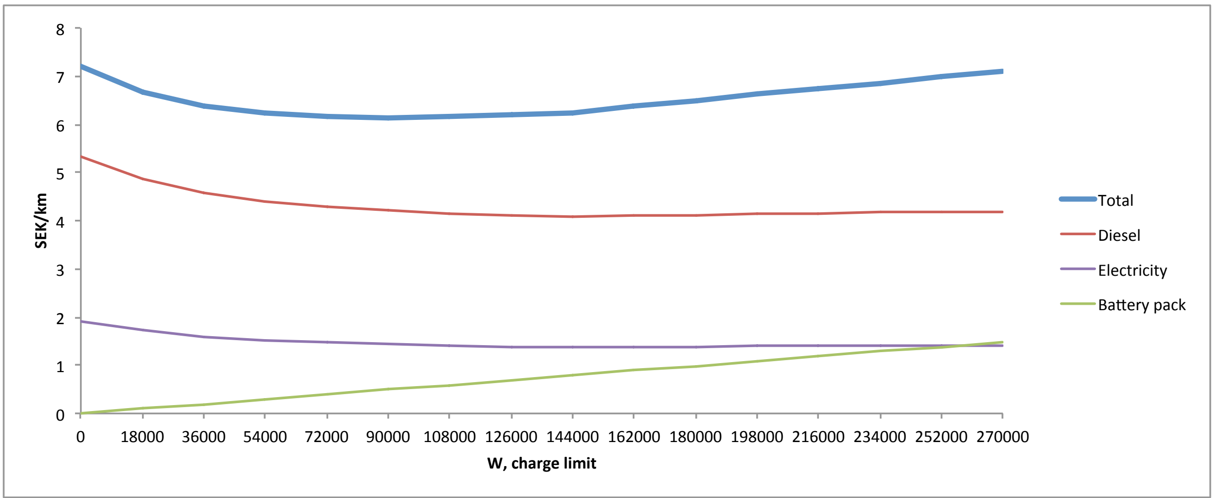


Figure 5 SEK/km depending on charge capacity in Option 2 with battery only used for regenerative charge

The total amount of energy needed to propel the bus was simulated to be 1,68 kWh/km when inside the tram system and includes the energy harnessed from braking. The maximum power needed to be applied inside the tram network was slightly higher at 341 kW due to the increased weight of the battery, which summed up a total of 26,5 tonnes. However due to the battery, the energy is stored within the vehicle and therefore was the average power outtake simulated to be reduced to 31,9 kW for the 21 tonnes bus. Also the energy needed to propel the vehicle outside the tram network is reduced due to the combined use of electric and diesel engine and ended up being an average of 0,44 litre/km, as can be seen in Table 11. The reutilization of braking energy and more efficient ICE usage generates a reduction of used fuel with about 20 percent compared to the Option 1.

Option 2			
Electricity usage	Maximum 27,5 tonnes	Average 21,5 tonnes	Diesel usage
1,68 kWh/km	341 kW	31,9 kW	0,44 l/km

Table 11 Key figures for Option 2

6.3.3 Option 3

Option 3 is similar to the Option 2 but has a different battery that is capable of charging from the overhead wires. This option is therefore the one using the most power from the tram network but it also has the possibility of propelling the vehicle longer distances outside the tram network using the energy from battery. The other advantage is the possibility to limit the brief maximum power outtake from the overhead wires since the battery and the overhead wires can be used together to reach the power needed during acceleration, see Appendix XIII.

A drawback with this option that (Sköldborg, 2011) points out is that there are many losses that occur when the battery is used as energy source compared to using the energy directly from the overhead wires.

The battery is optimized for high capacity in order to extend the range outside the tram network. It is also adjusted to be capable to obtain most of the energy generated from braking whereby no additional equipment is needed to transmit the power back to the overhead wires. The power density of the battery used in the simulation is 110 W/kg and with an energy density of 100 Wh/kg taken from the BCG report (2010). When the optimal battery was weighted against the price per driven kilometre it resulted in a 400 kg battery was chosen, see Figure 6 with a charge capacity of 39,6 kW.

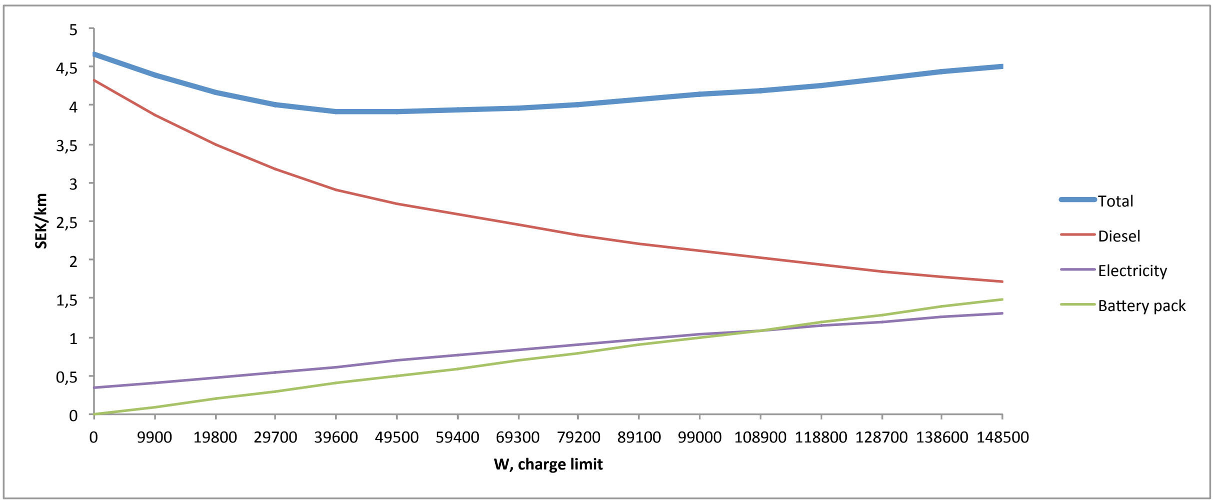


Figure 6 SEK/km depending on charge capacity in Option 3 with charging from the overhead wire.

In the simulation of Option 3, the overhead wires were always prioritized as the main source for propulsion. Since the battery is almost constantly being charged while in the tram network, it would only be a source of waste if that energy had been used. The battery was only used to reduce the peak power outtake during the greatest accelerations, see Appendix XIII. However outside the tram network it is the core energy source and provides the EM with energy equal to the discharge limit of the battery, which was set to 44 kW. The rest of the energy comes from the ICE.

As previously mentioned the capacity in the tram network is limited, especially when larger trams are accelerating and thereby also the amount of current available for charging. From the recordings it was seen that the bus was accelerating 51 percent of the time and from the calculations in Appendix XIV the authors estimate that at least two trams were accelerating within the 600 meter half of the time. During these accelerations no energy could be charged at all. In order to ease the simulation the network capacity, i.e. the ESS charge limit, was set to be 74,5 percent of the original 39,6 kW all the time. Although the charging capacity of the battery is small compared to the maximum capability in the overhead wires the bus needs to be able to stop the charging when other vehicles are accelerating not to overload the current providers. This is possible to do since a distinct loss of voltage can be recognized during other vehicles acceleration. However the effect of a power need greater than the capability will only result in slower acceleration (Weise, 2011). Furthermore, when the bus is braking, no charging will be taken from the tram network.

Compared to the previous two options the energy usage per kilometre is hard to simulate since the energy retrieved is used both inside and outside the tram network and the amount of energy that is stored depends on the amount of time spent connected. The most accurate figure is therefore the total amount of energy used, split by the total distance. The distance normally driven by trunk bus 16 has been used to give an indication. Furthermore, when the bus has finished the drive cycle and there is additional power left in the battery, this energy has been added as initial energy to the forthcoming drive cycle so that no energy is wasted. All together the electric usage reduced the diesel usage with 44 percent compared to Option 1.

Option 3			
Electricity usage	Maximum 27,4 tonnes	Average 21,4 tonnes	Diesel usage
0,73 kWh/km	300 kW	42 kW	0,31 l/km

Table 12 Key figures for Option 3

The tram network between Wavrinskys plats and Marklandsgatan is partly not asphalted which makes the buses not capable of using the tram lane. If these would have been asphalted the distance underneath the overhead wires could be increased by additionally 3000 meters. The more it drives in the tram network, the less power it has to use to charge the battery. Only around 11 kW instead of 40,5 kW charge power is necessary for the cbr85 route with trunk bus 16 and still maintaining the same distance travelled outside the tram network on electricity. However the ICE is simultaneously used as the ESS discharge limit is reached since it limits the EM.

7 Infrastructural and traffic analysis

With the gathered empirical data tested with the results from the simulations and observations the infrastructural capabilities for handling increased traffic from dual-mode buses could be analysed. Also the public transport in Gothenburg is analysed to describe an overview that is comparative with the settings for the trunk bus 16 in order to present the possible scaling capabilities for this investment.

7.1 Infrastructural analysis

Through the empirical data collection it was discovered that the possibilities for connecting a dual-mode bus to the tram network exists without changing the existing infrastructure. What was further said was that the capacity available was not depending on the number of trams using the wires but was instead limited by the traffic density. The authors own investigations, as can be seen in Appendix XIV, also shows that there are in average 1,3 trams are within 600 meters which is the distance between the current distributors. If two of the largest trams happen to be accelerating simultaneously, the current needed would be 2400 A, and the network would not be overloaded in theory. If also a dual mode bus is added to the network with the maximum amount of passengers, additionally 400-450 A would be needed which could overload the network. It is important to remember that this will only result in a slower acceleration and that the average consumption for the dual-mode bus in motion is 56 A, which is similar to the average tram.

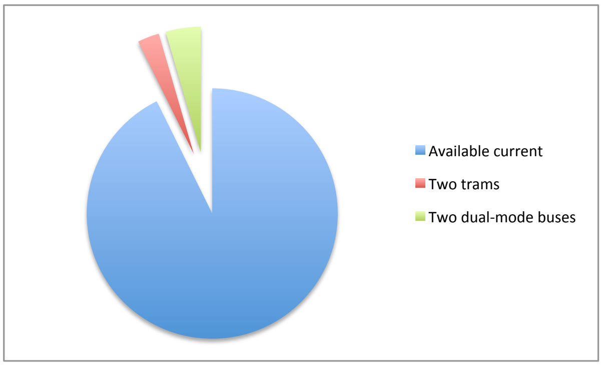


Diagram 8 Remaining current when four vehicles maintain their speed

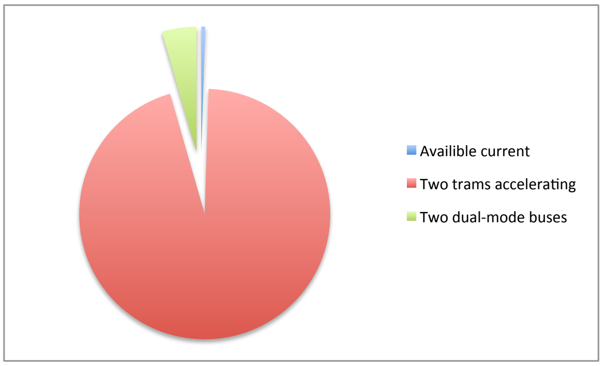


Diagram 9 Remaining current when two trams accelerate

As can be seen in Diagram 8 and Diagram 9,
there is a great difference in current needed for two trams accelerating compared to another two only maintaining their speed. If the peak power outtake from the tram network could be reduced then the capability would be increased. The battery in the dual-mode bus could be used as an additional power reserve and could therefore increase the capacity in the network. This is especially useful in combination with integrated intelligence in the dual-mode buses that recognizes when there are current available for charging, when to stop charge and when to send current to other vehicles. Battery usage in this way does however mean losses compared to using the tram network and should therefore be used sparsely.

In a future where dual-mode buses have replaced diesel buses on some routes, the capacity in the tram network probably needs to be increased. This is partly due to that the increased traffic requires more power but also that the diesel bus no longer will limit the minimum distance between the electricity usage vehicles.

7.2 Traffic analysis

The total distance for trunk bus 16 is confirmed to be 16 km by the data from Västtrafik's database provided by Björck Laursen (2011) and it also showed that roughly 3 km was inside the tram network as was used in the simulation. These figures will also be further used in the following economic calculation. Comparable figures for the other trunk buses that are travelling a very similar total distance are between 1 and 2,5 km within the tram network. This is not the same distance but with a few hundred meters of asphalt where overhead wires already exists the distance could be increased with additionally 2 to 3 km for each line which makes them suitable options, see Table 13.

		Distance	In tram network	Possible extension
16	Högsbohöjd - City - Eketrägatan	16 km	3 km	3 km
17	Tuve - City - Östra Sjukhuset	17 km	2,5 km	3 km
18	Skälltorpsvägen - Backa - City - Johanneberg	15,5 km	1 km	2 km
19	Backa - City - Fredriksdal - Mölndal	17,5 km	2 km	2 km

Table 13 Existing and possible distances within the tram network for the trunk buses

Another suitable measurement for identifying suitable lines is to measure the number of stops the bus shares with the tram lane. For the trunk buses the number was between 3 and 8. Three other lines 42, 52 and 58 were identified with more than 6 stops and possibility to extend up to 12 common stops. With asphalt extensions also lines 21, 129, 141 and 159 could get more than 8 common stops within the tram network also making them possible for future investigation. The total number of suitable buses, including the trunk buses, adds up to be 11 lines. As comparison this is 13,2 percent of the lines in Gothenburg or almost as many as the number of tram lines.

An additional benefit occurring from buses using the tram network is that the traffic density would be decreased both for the buses and for the general traffic and therefore also shorter travelling time. A risk is although that bottlenecks could occur at tram stops, which needs further attention in order to be avoided. If the width of the road is estimated to two times three meters the cost per km would be 900 000 SEK.

8 Economical analysis

In this chapter the costs of the different solutions will be analysed and the final investment calculation will be presented. Included in the solutions are both the concepts and the results from the simulations. The economic analysis will give a price indication for the total costs for the investor. The figures used in the calculation are set at lower levels with the intention not to get too good results, but instead try to make careful and realistic estimations of the figures to get a reliable result. Thereby, the actual result can instead hopefully be slightly better than the result we conclude.

8.1 Capital investment costs

Since the solutions presented require no additional cost for adapting the infrastructure to the vehicles, the bus itself carries the single greatest cost. The costs calculation for the dual-mode bus is based on the three different options and three combinations of technical concepts, resulting in nine different solutions.

8.1.1 Bus and battery cost

The dual-mode bus has almost the same electrical components as a hybrid bus (Andersson & Andersson, 2011), why the acquisition cost for the dual-mode bus is based on the price for a hybrid bus. A total cost of 3,575 million SEK is the estimated cost for a 18 meter articulated bus based a 50 % addition to the 2 million SEK price for a 12 meter diesel bus given by Andersson & Andersson (2011) and 2,1 million SEK given by Andersson & Johansson (2005) including additional 0,5 million SEK for adapting the vehicle to the Gothenburg's public transportation (Spartalis, 2011). The 4,55 million SEK cost for the dual mode bus is estimated using the same principles as for the diesel bus, but is based on 2,7 million SEK for a 12 meter hybrid bus with similar additions for length and public transportation adaptation (Andersson & Andersson, 2011).

The major difference for the dual-mode bus in the simulated Option 1 is the exclusion of the battery, why the cost for the battery in this option is removed. In Option 2 and 3 there is instead a need of replace the battery after 8 years based on the findings in the chapter Contemporary social and economic prerequisites about the battery lifetime. The cost for the battery is based on the figures from the chapter about battery prices mentioned earlier in the report, and is set to 6000 SEK/kWh[4]. As discussed earlier in this chapter the battery cost is constantly decreasing since a lot of research is going on in this field. As mentioned in the (BCG, 2010), the price will probably decrease to around 2400 SEK/kWh[4] in 2020. This cost is used in Option 2 and 3 since the battery will be replaced for these options due to the limited lifetime. In Option 3 the battery is assumed to weigh 400 kg and have an energy density of 100 Wh/kg. These figures are multiplied and the cost of the battery is then 96 000 SEK. 96 000 SEK is then discounted 8 years, since this is the time where the battery have to be replaced. The present value for the battery cost in Option 3 is then 60 232 SEK. The same calculations are performed for Option 2 with the difference of the weight which is 500 kg. Since the battery in Option 2 is more power optimized and thereby has a lower energy density than Option 3 the cost of 2400 SEK/kWh cannot be used. Instead the weight of the battery is used as the changing parameter and since the mass of the battery in Option 2 is 500 kg the battery cost is set to 5/4 of the cost for the battery in Option 3. The cost for the replacement battery is then 120 000 SEK and the present value is 75 289 SEK. The battery cost is unlike Option 2 and 3 removed in Option 1 since there is no battery. The assumption of the weight in

[4] 1 USD = 6 SEK

this option is 500 kg and price used for this battery is then 6000 SEK/kWh since the battery is removed in the initial phase of the investment. The cost saving is then 300 000 SEK with the same present value for the battery as can be seen in Table 14.

	Option 1	Option 2	Option 3
For a hybrid bus	4 550 000 SEK	4 550 000 SEK	4 550 000 SEK
Battery	-300 000 SEK	75 289 SEK	60 232 SEK

Table 14 The bus and battery cost

8.1.2 Current collector concepts

Furthermore the costs for the current collector concepts are added. According to Eriksson (2011) the price for a normal tram pantograph is 60-80 000 SEK whereby 70 000 SEK is used together with the current return wheel axle described earlier, since the tram wheels will guarantee the vehicles position under the overhead wires. Together with the current return arm the width of the pantograph has to be increased and is thereby estimated to a cost of 100 000 SEK which also includes the connection with the current return arms alerting when the vehicle leaves the tram network. The other alternative with an intelligent current collector were considered by (Ranch, 2011) to be two to three times as complex compared to an normal pantograph and were therefore thought to carry the cost of 150 000 SEK.

The development cost of these three current collector concepts is based on estimations made by Tomas Forsberg (2011). According to Tomas, it is important to look at the number of already existing parts as well as number of common parts which both lower the cost if used. For a widened pantograph a big number of already existing parts can be used and 200 hours is therefore set for design modifications and 80 hours is set for strength calculations. The strength calculations are according to Tomas hard to estimate since it depends on the dimensions and mechanical complexity, which he has no deeper information about in this case. The man-hour costs approximately 820 SEK according to Tomas, which means 164 000 SEK for the design modifications and 65 600 SEK for the strength calculations. Furthermore the cost for a prototype of the modified pantograph built for testing and evaluation used to be around 4-5 times the price for the original construction. Of course these costs can decrease depending on the contact with the suppliers and size of order according to Tomas. He also mentioned the possibility of getting it cheaper by buying an original pantograph and then modifier it. The cost is set to 4 times 70 000 SEK for building a prototype. The last part of the development cost is the cost for production tools. Moulding is more expensive than welding, but in this case welding is most likely enough. Tomas suggests a cost of 60 000 SEK or maximum 100 000 SEK. The cost is therefore set to 80 000 SEK. All these costs are divided by the number of buses ordered, which is estimated to ten. The development cost for a modified pantograph averaged over 10 buses is 58 960 SEK/bus. All the above mentioned figures are adapted to the other two current collector concepts. The first is simply an ordinary pantograph that only need some design modifications and is therefore set to the same number mentioned above, 164 000 SEK for 10 buses and consequently, the development cost for one bus is 16 400 SEK. For the intelligent current collector which does not exist today, the development cost is based on the above reasoning, but the construction cost is set to 150 000 SEK as mentioned above and the outcome is then doubled. The development cost for the intelligent current collector is then 181 920 SEK per bus. The final figures are summarised in Table 15.

	Pantograph	Mod. pantograph	Int. cur. coll.
Pantograph	100 000 SEK	70 000 SEK	N/A
Intelligent current collector	N/A	N/A	150 000 SEK
Development costs	58 960 SEK	16 400 SEK	181 920 SEK

Table 15 The costs for the current collector concepts

8.1.3 Current return concepts

In order to return the current to the rail the different current return concepts also needs to be accounted for. A setup of tram wheels on an axle, which reminds on maintenance vehicles used today in Gothenburg, costs 90 000 SEK including springs and additionally 9 000 SEK for a camera needed for deployment (Sandström, 2011). The development cost for this concept is based on the same reasoning as when calculated the development cost for the current collector concepts in the previous section. In this case design modifications and strength calculations is assumed to be necessary to develop this component. The development cost for one bus is then 22 960 SEK.

In the second alternative 40 000 SEK is the approximate price given by (Kihlberg, 2011) for the four arms and additionally 40 000 SEK for sensors and hydraulic/spring components. The cost is difficult to evaluate since these concepts have never been tested before known to the authors. Either a wider pantograph or an intelligent current collector is available with this option. The development cost is also difficult to estimate since the product does not exist. The total cost for the product, 80 000 SEK, is multiplied by 4 to build a prototype and the cost for design modification, strength calculation and production tools are added similar to the description in the previous section. Finally the result is multiplied by 2 due to the new construction and the complexity of the product. The final development cost is then set to 125 920 SEK per bus for the current return arms and also these figures are shown below in Table 16.

	Wheel axle	Return arms
- 4 Aluminium arms with wheel or slide rail	N/A	40 000 SEK
- Wheel axel in front of the cabine	90 000 SEK	N/A
- Springs	included above	4 000 SEK
- Sensor	9 000 SEK	36 000 SEK
Development costs	22 960 SEK	125 920 SEK

Table 16 The costs for the current return concepts

8.1.4 Planning and contingency costs

The planning cost for this investment is set to 250 000 SEK since (Jonsson, 2011) at Hybricon estimated this figure after a description of the project. Another reference is (Andersson P. , 2011) from the traffic consulting firm Trivector who mention they invoiced 400 000 SEK, but then the infrastructure was also investigated and planned for while this investigation only includes to develop the vehicles, not the whole system. For each bus the cost is then 25 000 SEK for the planning process. Furthermore, the cost for unforeseen events which can occur during the process is set to 5 percent of the acquisition cost for the bus including the development costs and is thereby between 222 918 - 258 156 SEK for the different dual-mode buses.

8.1.5 Residual value

The residual value for the diesel bus is set to 100 000 SEK after the 10 years, since Paul Spartalis mentioned the buses in their bus fleet normally sell their buses for between 50 000-

100 000 SEK and this is an articulated 18 meter bus. Since the investment is assumed to be completely written-off, tax has to be paid of the capital gained. After the value is discounted 10 years, the present value of the residual value for the diesel bus is 39 088 SEK. For the dual-mode buses (Andersson P. , 2011) claims the residual value for trolley buses is 5 percent or more of the acquisition cost. The residual value in this case is therefore set to 5 percent of the acquisition cost and the present value for the dual-mode buses after the tax is paid is then between 68 732 – 79 308 SEK after 15 years.

8.2 Annual costs

The annual costs are divided into fixed costs and variable costs that depend on the distance driven each year.

8.2.1 Fixed annual costs

The only fixed annual cost accounted for in the calculation is the cost for maintenance. The annual maintenance cost for the diesel bus is set to 280 000 SEK based on the figures of normal bus distance 80 000 km/year and the cost 3,50 SEK/km from (Spartalis, 2011). The 80 000 km is also verified by looking at the timetable for bus line 16 which also shows around 80 000 km/year for 16 buses in the bus fleet, see Appendix XV. The maintenance cost for a dual-mode bus is difficult to estimate. The electric machine need less maintenance than a diesel engine, but the estimation of the maintenance cost is 10 percent higher than for a diesel bus due to the fact that a dual-mode bus has more components and a more complex system.

The road tax for a diesel bus is 18 000 SEK/year for a diesel bus (Spartalis, 2011). In 2004 the annual road tax for trolley buses was 930 SEK (Andersson & Johansson, Trådbuss Landskrona, 2005). Since no dual-mode buses are driving on Swedish roads there is no indication of the road tax for these kinds of vehicles. In the calculation the cost for this is not included neither for the diesel bus nor the dual-mode bus even though the cost probably should have been less for the dual-mode bus.

8.2.2 Variable annual costs

The variable costs are further based on the expected diesel price and the electricity price since there relative increase depends on a number of factors.

Diesel price

Based on the diesel price in December 2010 in the chapter Contemporary social and economic prerequisites the diesel price in the calculation is set to 9,52 SEK/litre excluding VAT. The price trend is difficult to estimate because of the big fluctuations of the diesel price the last years. The diesel price will most likely not decrease or even abate due to the reduced oil resources and thereby harder and more costly to extract oil. During the last ten years the price for diesel has a percentage increase as shown in the diagram in the chapter Contemporary social and economic prerequisites. In the calculation the diesel price annually increase with 5,33 percent per year since this is the price trend from the last ten years. The cash flow for a diesel bus is shown in Appendix XVI. The diesel cost per year for each Option 1 to 3 selected can be seen in the Appendix XVII to XIX.

Electricity price

During the last couple of years it has been big fluctuations in the electricity price as described earlier in the chapter Contemporary social and economic prerequisites. The electricity price is affected by many parameters which sometimes cause big variations and makes it hard to predict. Political decisions, stakeholders and the nature itself are all affecting the prices.

Västtrafik has many bus entrepreneurs, but Göteborgs Spårvägar is today one of the two bigger parties taking care of the public transportation in the city centre of Gothenburg. The other party is Veolia Transport. The price the tram entrepreneurs have to pay for the electricity is according to Weise (2011) at Göteborgs Spårvägar the same as the Nord Pool spot prices mentioned in Chapter 3. This will most likely also be the price the bus entrepreneurs will have to pay for the electricity. Nord Pool's spot price is today (April, 2011) around 0,49 SEK/kWh which also is a valid figure if the development of the spot price is studied. On top of this tax and gross margin is added, and the initial electricity price is therefore set to 0,86 SEK/kWh in the calculations.

The change of the electricity price in the future is assumed to abate but not decrease the coming years. The increase is expected to 0,02 SEK/year, close to the increase Odenberger, Unger, & Johnsson (2011) expect. This increase is somewhere between the historical increase which have been 0,045 SEK/kWh over the past 14 years if a linear function is assumed, and the policy scenario from Odenberger, Unger, & Johnsson (2011) and the price expected by (Svensk Energi, 2011) which assume the price to be stable around 0,50-0,55 SEK in the future. Based on this price estimation and increase the electricity costs per year for each Option selected can be seen in the Appendix XVII to XIX.

8.3 Investment calculations

The calculation method used for this investment is NPV and EAC to be able to compare the different solutions of dual-mode buses with a diesel bus. The EAC calculation method is used since it is different depreciation times for a diesel bus compared to a dual-mode bus. To be able to use the EAC method the NPV has to be calculated first since the annual costs varies over time.

The nominal calculation is made for the buyer and a discount rate is set to 6 percent after tax. The incomes are considered the same for the diesel bus and a dual-mode bus and can thereby be set off against each other. Therefore, only the costs are considered in the calculation except for the residual value that varies between the solutions. Costs not tied to the bus, like personnel costs, are not included since these are the same and do not depend on the bus. The figures in the calculation seen in Table 17 are for one bus even though the development costs are apportioned to ten buses.

Parameters

Number of dual-mode buses	10	buses	Initial diesel cost	9,52	SEK/litre
Depreciation time diesel bus	10	years	Increase of diesel cost each year	5,33%	
Depreciation time duo bus	15	years			
			Initial electricity cost	0,84	SEK/kWh
Discount rate	6%	(after tax)	Increase of electricity cost each year	0,02	SEK/kWh
Tax rate	30%				

Summary of the investment calculation

	Acquisition cost for one bus	PV of reduction in tax payments through depreciations	PV of annual costs	PV of residual value	Net present value	Equivalent annual cost	Annual savings (+) / losses (-)
Regular diesel bus	-3 575 000 SEK	789 369 SEK	-4 750 266 SEK	39 088 SEK	-7 496 809 SEK	-1 018 576 SEK	0 SEK
Solution 1.1	-4 706 278 SEK	914 171 SEK	-6 328 128 SEK	68 732 SEK	-10 051 503 SEK	-1 034 931 SEK	-16 354 SEK
Solution 1.2	-4 870 624 SEK	946 094 SEK	-6 328 128 SEK	71 132 SEK	-10 181 526 SEK	-1 048 318 SEK	-29 742 SEK
Solution 1.3	-5 052 232 SEK	981 371 SEK	-6 328 128 SEK	73 784 SEK	-10 325 205 SEK	-1 063 112 SEK	-44 536 SEK
Solution 2.1	-5 100 332 SEK	990 714 SEK	-5 652 277 SEK	74 487 SEK	-9 687 408 SEK	-997 442 SEK	21 134 SEK
Solution 2.2	-5 264 678 SEK	1 022 637 SEK	-5 652 277 SEK	76 887 SEK	-9 817 431 SEK	-1 010 830 SEK	7 746 SEK
Solution 2.3	-5 446 286 SEK	1 057 914 SEK	-5 652 277 SEK	79 539 SEK	-9 961 110 SEK	-1 025 623 SEK	-7 047 SEK
Solution 3.1	-5 084 521 SEK	987 643 SEK	-5 546 796 SEK	74 256 SEK	-9 569 419 SEK	-985 294 SEK	33 282 SEK
Solution 3.2	-5 248 867 SEK	1 019 566 SEK	-5 546 796 SEK	76 656 SEK	-9 699 441 SEK	-998 681 SEK	19 895 SEK
Solution 3.3	-5 430 475 SEK	1 054 843 SEK	-5 546 796 SEK	79 308 SEK	-9 843 120 SEK	-1 013 475 SEK	5 101 SEK

Table 17 Parameters and cost for the different solutions

The initial acquisition cost ranges between about 3,58 million SEK for the diesel bus, up to 5,43 million SEK for the most expensive same sized dual-mode bus. That is 36 percent more, which also includes a greater risk. However when following the calculation process in Appendix XX and the figures above in Table 17 which adds the cost for propellants and maintenance for each year into the equivalent annual cost it is shown that the difference is no longer significant and actually in favour for some dual-mode vehicle setups. Up to 33 000 SEK after tax can be saved annually for Solution 3. Since the savings are not so substantial it can however be questioned if it is worth the initial risk. This is further investigated in the sensitivity analysis. The importance of the calculations is also shown when analysing Solution 1. This alternative does not use a battery and could therefore be interesting for those not willing to take the risk of an expensive battery failure but the downside is that no electricity can be used or generated outside the tram network and results in losses of up to around 45 000 annually. It is important to keep in mind that these calculations and the development costs are for 10 buses. If 10 diesel buses are replaced by 10 dual-mode buses all the figures are 10 times higher, both the losses and the savings.

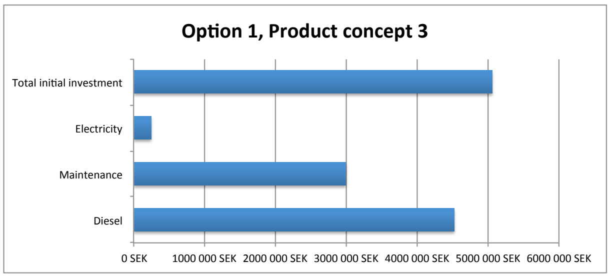


Diagram 10 Cost comparisons for Option 1

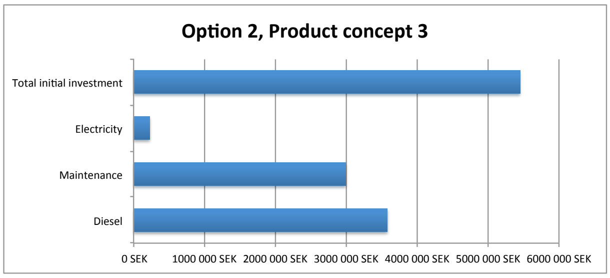


Diagram 11 Cost comparisons for Option 2

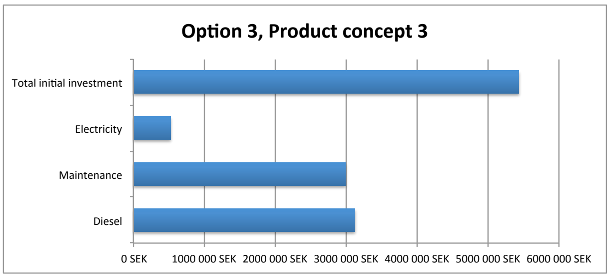


Diagram 12 Cost comparisons for Option 3

The different EAC for the different technical concepts are around 28 000 SEK between the first and the third technical concept. The second concept is in between, with 13 400 SEK more expensive than concept 1, but 14 800 SEK less expensive than concept 3 annually. The biggest difference is nevertheless for the different propulsion options calculated in the simulation, which can be seen in the Diagram 10, Diagram 11 and Diagram 12. Between simulation option 1 and option 2 the difference is 37 500 SEK benefit for option 2. Furthermore, the difference between Option 2 and 3 was not as big as expected, only 12 000 SEK annually, even though the battery is continuously charged when driving in the tram network. The reason why the benefit is limited is the efficiency from the overhead wires into the battery and then further to the driving wheels. But still it is more profitable.

The simulations show that the cost for driving one kilometre with electricity in Option 1 is 1,54 SEK/km and 1,41 SEK/km for Option 2. An equivalent figure for Option 3 is difficult to present since it depends on the amount of time, within each route, where charging the battery is possible. In the simulation 18,8 percent of the route distance is within the tram network, while 81,2 percent is outside the tram network.

The diesel cost for the diesel bus and Option 1 should be almost the same but differ depending on the input data, the bus consume more inside than outside the tram network. This is natural, since it is more stops and brakes closer to the city centre where most of the tram network is found, than a bit outside. For Option 2 the hybrid powertrain makes the bus consume less both when driving on diesel and electricity because of the regenerative braking. The total propulsion cost, see Table 18, illustrates the big difference of using electricity even though the percentage of driving within the tram network is limited to 18,8 percent of the route,

	Diesel bus	Option 1	Option 2	Option 3
Diesel	5,65 SEK/km	5,32 SEK/km	4,21 SEK/km	-
Electricity	-	1,54 SEK/km	1,41 SEK/km	-
Propulsion cost	5,65 SEK/km	4,60 SEK/km	3,68 SEK/km	3,60 SEK/km

Table 18 Price comparison for the different options

By using these figures, an equation of the propulsion cost for Option 1 and 2 is possible and will look like below.

$$\begin{aligned} &\mathit{Propulsion\ cost\ for\ Option}\ 1 \\ &\qquad = 5{,}32 * \mathit{percentage\ outside\ the\ tram\ network} + 1{,}54 \\ &\qquad * \mathit{percentage\ within\ the\ tram\ network} \end{aligned}$$

$$\begin{aligned} &\mathit{Propulsion\ cost\ for\ Option}\ 2 \\ &\qquad = 4{,}21 * \mathit{percentage\ outside\ the\ tram\ network} + 1{,}41 \\ &\qquad * \mathit{percentage\ within\ the\ tram\ network} \end{aligned}$$

If the bus drives 80 000 km per year, which is common for these buses, the savings for Option 1 is 84 000 SEK per year, and for Option 2 is it 158 000 SEK per year and for Option 3 is it 164 000 SEK considering the propulsion costs.

Important to keep in mind is that all the figures about SEK/km is based on today's prices, which means it will in the future most likely be even more profitable to drive on electricity compare to diesel. An important aspect partly mentioned earlier is also that the diesel and electricity prices increases continuously which means the dual-mode buses with longer life time gets higher prices in the end of the economic life.

The difference between the regular diesel bus and Option 1 with electricity propulsion, with regenerative braking back to the overhead wires in the tram network and diesel propulsion outside the tram network saves around 15,5 percent in propulsion cost based on the present value. For Option 2 the savings are 32,5 percent compared to a regular diesel bus. In Option 3 the savings of the propulsion cost is instead 35 percent compared to a regular diesel bus. The savings is even greater if the figures above about the cost per kilometre are compared. These savings can be taken into account when a decision about the acquisition cost for the bus is made.

When only considering the propulsion difference, the acquisition cost in Option 1 have to be at most 4,5 million SEK to be profitable compared to a diesel bus. For Option 2 the dual-mode bus can cost at most 5,3 million SEK and still be more profitable than a diesel bus. Finally, for Option 3 the acquisition cost for an 18 meter articulated dual-mode bus can be 5,4 million SEK and be profitable compare to an 18 meter articulated diesel bus.

8.4 Sensitivity analysis

All the comparisons in the sensitivity analysis are based on the EAC for the different solutions. If the number of dual-mode buses developed is halved from 10 to 5, the results for the technical options is decreased between 5 000 – 28 000 SEK annually. Concept 3 is the concept with the biggest change since it has the biggest development cost, while Concept 1 uses more existing parts and is therefore not that expensive to develop. If the buses developed instead are doubled to 20 buses the gain is only between 2 000 – 14 000 SEK annually. But it is important to keep in mind that the figures are for each bus. The total gain is much higher.

The lifetime of the dual-mode bus is of significant value for the final result. It is also hard to predict the lifetime of the dual-mode bus. In Option 1 it is a need of an economic lifetime of 21-22 years in order to be profitable compared to the diesel bus. The same figure for Option 2 is instead 14-16 years in order to be profitable and 13-15 years for Option 3. If the life time instead is set to the same, i.e. 10 years, the losses for Option 1 should be between 80 000 – 120 000 SEK, for Option 2 60 000 – 100 000 SEK and for Option 3 50 000 – 90 000 SEK annually.

The discount rate is different for different actors, but in previous calculations the discount rate was set to 6 percent after tax. If this figure instead is set to 2 percent after tax the results are significantly better. The first option shows between 10 000 SEK loss and 9 000 SEK profit. Option 2 is then much better with a profit between 38 000 SEK and 58 000 SEK. Option 3 is of cause even better with a profit between 51 000 SEK and 71 000 SEK. On the other hand, if the discount rate is raised to 10 percent after tax all the options are making losses between 12 000 SEK and 88 000 SEK annually.

During the last years it has been big fluctuations in the electricity price as described earlier. It could then be interesting to look into what effect different developments of the electricity price could have on the outcome. If the price is going to be stable around 0,84 SEK/kWh, the different options would gain only between 2 000 – 4 700 SEK annually, while it would loss between 2 500 – 5 900 SEK if the electricity price increase in the same pace as the last 14 years, i.e. 0,045 SEK/kWh per year. This low affect on the outcome is because the cost of electricity is very small compare to all the other costs (see Diagram 10-12).

The diesel price is also hard to predict because of reasons described earlier in the report. The problem with comparing a big increase of the diesel price is the fact that the dual-mode buses have longer lifetime and the increased price mostly affect the dual-mode buses between year 11-15 even though these buses are consuming less amount of diesel. No increase of the diesel price is therefore better for the dual-mode buses in this calculation, even though an increased diesel price also affect the diesel bus in the future. This is why no figures are shown which would otherwise mislead the reader.

If the distance is extended 3 km with new asphalt between Wavrinskys plats and Marklandsgatan, the energy costs will look like below.

$$Propulsion\ cost\ for\ Option\ 1\ (6\ km\ within\ the\ tram\ network) = 5{,}32 * 0{,}624 + 1{,}54 * 0{,}376 = 3{,}90$$

$$Propulsion\ cost\ for\ Option\ 2\ (6\ km\ within\ the\ tram\ network) = 4{,}21 * 0{,}624 + 1{,}41 * 0{,}376 = 3{,}16$$

The propulsion cost is then 3,90 SEK/km instead of 4,60 SEK/km for Option 1. For Option 2 the propulsion cost is then 3,16 SEK/km instead of 3,68 SEK/km. For Option 3 the propulsion cost is around 3.53 SEK/km instead of 3,60 SEK/km from this change, since it depends on how much the bus charges the battery. In general, if the percentage within the tram network increases with 10 percent the propulsion costs will decrease with 0,38 SEK/km for each bus in Option 1 and 0,28 SEK/km for each bus in Option 2.

If all the parameters, i.e. number of buses, life time for dual-mode buses, discount rate and the electricity price, would be set to the worst for dual-mode buses the worst case scenario should have been losses between 106 000 – 208 00 SEK annually for each bus. If the parameters instead is set to the best case scenario the profit should have been between 2 000 – 78 000 SEK annually.

9 Risk analysis

In a project with many new technical solutions, intended to be combined with an infrastructure that was initially built for a different purpose, there will be many risks involved. Throughout the report the intention has been to describe and overcome most of these but still some are not possible to predict or influence. The causes and affects from the risks further presented are visualized in an Ishikawa diagram, see Diagram 13, in order to see their interconnections. Forthcoming are the different effects presented that could result in Dual-mode buses not realizable in Gothenburg.

Increased price

Many of the risks associated with the project come with economical assumptions more or less predictable and with a great impact. Examples are the increasing price trends earlier described in the sensitivity analysis for electricity and diesel fuel, which has the single greatest affect on the increased cost per kilometre. Also the efficiencies parameters set in the simulations could have been misinterpreted although verified with different sources. In order not to prettify any of the simulated options the action has been, as previously described, to make figures worse instead of setting an unsure value. The assumption was to eliminate the risks and that actual results from a field test should indicate even superior values for the options. The information regarding batteries were however very diverse and lifetime, price and properties depends very much on type and manufacturer whereby this is still seen as a risk.

Technical difficulties

The investigation of the technical possibilities is an important part of the feasibility study, which includes the development of the technical concepts and investigations of the tram network capabilities. Much effort has been given to gathering different opinions from experts with wide knowledge and experience within the areas. However no models have been created to practically test the theories and nor has any full-scale tests been made with the same conditions as in Gothenburg. Therefore, even if the solutions do seem to be realizable in theory could additional field test prove contradictory results. Also even one dual-mode bus cope well with the infrastructure there is a risk that an increased number could have affects not previously thought of.

Stakeholder resistance

The dual-mode buses will have some major impacts on the stakeholders as indicated earlier, which might cause negative views. Although many of the impacts are positive there will also be negative effects that could delay or even put a stop to the project. Resistance from the bus owner could occur due to sheer complexity with new technology and routines compared to regular diesel buses. This would require additional education both for the drivers that should know how to drive with the new buses but also for the service personnel responsible for the maintenance. Also the economic motives such as longer payback time and higher initial investments presents risks to the bus owner that could result in resistance, something that could be reduced if funds were given to pilot projects. For the citizens of Gothenburg the new appearance of the buses with current collectors on the roof and with the sound of the current return arm dragging along the rail could cause negative opinions. It is also of great importance that the new vehicle proves to be very reliable, something that the dual independent engines might indicate, otherwise the existing solutions such as trams and buses will continue to be used.

Dual-mode buses not a compatible product on the market

More or less unpredictable events on the market that could change the way public transport is recognized could generate a great risk regarding dual-mode buses. These could be disruptive technologies that lead to changed demands for the typical public transport user but it could also be the results of change in city size or inhabitants. Smaller breakthroughs in the battery technology, which are plausible within the forthcoming decade, could make the dual mode bus more affordable while greater breakthroughs could totally reduce the need of an additional ICE engine. Furthermore the tram infrastructure could for unimaginable reasons be changed or revised making trams and dual-mode buses as they are created today not working together.

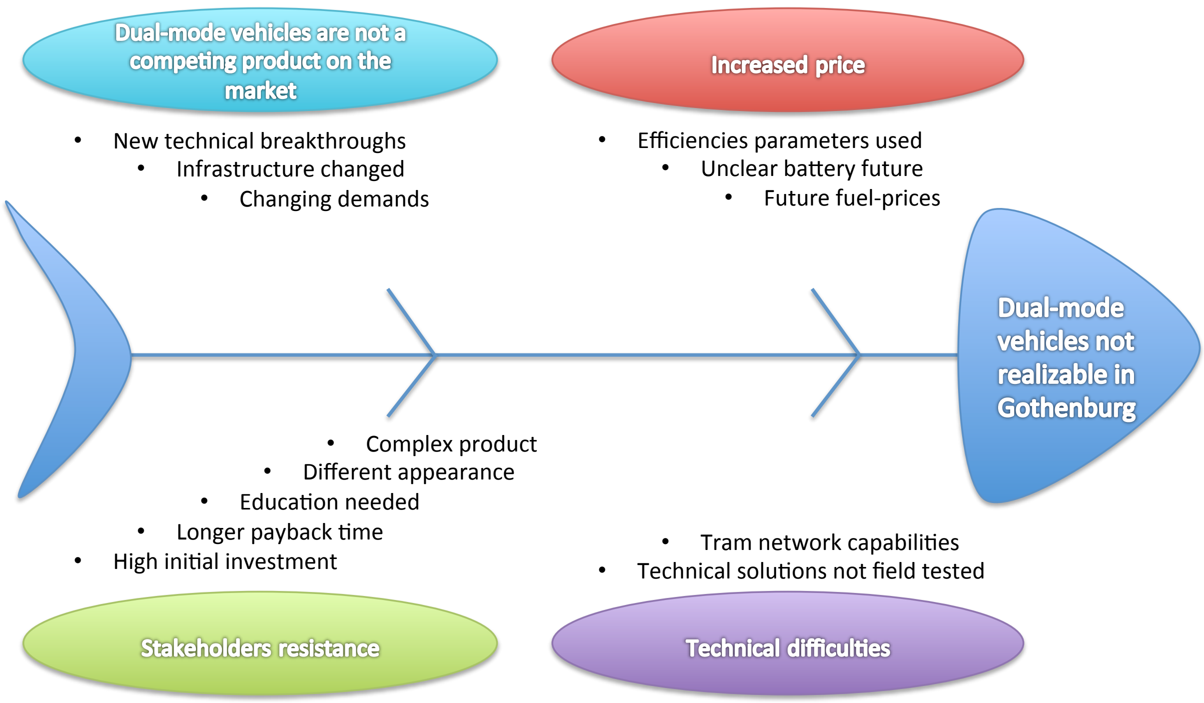


Diagram 13 Ishikawa - or "Fish bone" - diagram for dual mode vehicles in Gothenburg

10 Conclusion

One of the research questions of the report was to investigate possible concepts how to connect to the overhead wires and close the circuit through the rails. The results from the interviews and the observations indicated that there actually were possibilities, as long as they used the same technique as pantographs, whereby the technical concepts were developed. Two new types of current collectors and two types of current return concepts were presented and could be combined into three suitable combinations. They do all have their pros and cons, commonly that the solutions with increased technical complexity come with increased driving possibilities and user-friendliness for the driver but also with an increased investment and development cost. The costs for the different technical concepts is between 170 000 – 230 000 SEK per bus apportioned on 10 buses, i.e. it is not a big difference. The big difference is instead the development costs for the technical concepts which varies from 40 000 SEK for the less expensive solution with a regular pantograph and a wheel axle in the front to 308 000 SEK per bus for an intelligent current collector and return arms. Less expensive are the alternatives that use many existing design solutions with high reliability, however these require the dual-mode bus to be fixed to the rail and does therefore make it less flexible. The many different combinations presented indicate in theory an increased possibility for realization, but it is a matter of costs. Further models and field tests are required in order to guarantee functionality in practice. Also the concepts do most likely not conclude an optimal design but focuses instead on technical practicability. An increased investment cost also comes with the bus mounted with dual engines. The acquisition cost for a regular articulated 18 metre diesel bus is 3,6 million SEK while a dual-mode bus with the same length is estimated to cost between 4,7-5,3 million SEK.

Throughout the report the argument has been that the dual-mode buses should not affect the infrastructure. Also the empirical study shows that this actually is feasible since increased electrified traffic might not increase the peak power usage due to traffic limitations, which is a requirement since the tram network capacity is already utilized to a great extent. In a future scenario with increased trams and dual-mode buses in combination with fewer diesel buses probably although require increased network capacity. This upgrade does not entirely depend on the dual-mode buses and might be necessary also without this introduction. The usage of the batteries in the vehicles as backup capacity could actually reduce the load on the overhead wires during short peak demands.

An increased distance with asphalt along the tram rails is considered as a possible investment in order to increase the usage of electricity and the distance where the EM could be used continuously and where the battery could be charged. This would reduce both the costs and emissions. These benefits would though depend on the number of dual-mode buses planned to be taken into traffic. Some of the places possible to asphalt are along the trunk buses routes, which could more than double the distance driven on electricity. For trunk bus 16 it would imply that at least 37 percent of the distance could be driven on electricity, instead of 19 percent of the total route distance i.e. 16 km. Other bus lines where it is possible to use dual-mode buses are the other trunk bus lines 17, 18 and 19. Furthermore, bus lines 42, 52 and 58 also have potential of driving dual-mode buses on their routes. In all the cases the distance in the tram network can be increased by adding asphalt, especially if a small distance, less than 500 meters, close to Hjalmar Brantingsplatsen is asphalted because then the connection between Lilla Bommen/Nordstan and Hjalmar Brantingsplatsen will give 2 km longer distance in the tram network for bus lines 17, 18, 19, 42 and 52. However trunk bus 16 seems to have the greatest advantage due to the percentage of its route within the tram network, but it is closely followed by the other bus lines mentioned above.

An implementation of dual-mode buses will have some major impacts for the many stakeholders partly due to the several users affected. Some of these are negative and could lead to stakeholder resistance. For the bus owner are examples the high initial investment, unsure reliability of the technical concepts, increased complexity and a need for education. Also the increased usage and wear of the infrastructure as well as an increased population of the tram network are further discussions that need to be dealt with although it is shown not to be an immediate problem.

There will also be many optimistic features as well and many of them are also positive from an environmental perspective. With decreased usage of diesel fuel and the efficiency of the EM will have a direct impact on the operating cost and reduced local pollution. The total propulsion costs for the different options driving as trunk bus 16 are described in Table 19. Furthermore, the table also includes the annual savings with today's propellant prices of a dual-mode bus 16 compared to a diesel bus driving 80 000 km per year. If the diesel price increase more than the electricity price, as expected in our calculations, the difference between the options will be even greater in the future.

	Propulsion cost	Annual savings
Diesel bus	5,65 SEK/km	
Option 1	4,60 SEK/km	84 000 SEK
Option 2	3,68 SEK/km	157 600 SEK
Option 3	3,60 SEK/km	164 000 SEK

Table 19 Propulsion costs and annual savings compared to a diesel bus

Even though the cost difference between Option 2, where the battery was only charged with regenerative braking energy, and 3 is not substantial, Option 3 uses a higher percentage of electricity since it also charges from the tram network, which makes it less dependent on oil price fluctuations and more environmentally friendly assuming that the electricity is generated in a green way. Especially compared to the Option 1 without a battery that shown to be the least profitable solution. The usage of electricity is seen by many as the future propellant and the knowledge gained from the usage can also be an important future asset. Another benefit from the EM is that it also produces less noise that will disturb the environment and at the same time give the passengers and driver a more comfortable ride and working conditions. Further benefits for the Gothenburg city could be a more environmental image with increased tourism and inhabitant satisfaction.

The drawbacks for the dual-mode vehicle is that it is relatively expensive, heavy and that it is unsure how long the battery will last since it depends on how it is designed and used. Although many manufacturers guarantee the battery to last between 5-10 years these are in combination with the long-term investment up to 15 years creating some risks for the buyers that new breakthrough alternatives could evolve. The choice of dual-mode bus setup without a battery could seem to reduce the risks and in a worst-case scenario without electricity be used as a regular diesel bus. However the greater possibilities come with a battery that allows harnessing the regenerative braking energy and also to charge while inside the tram network, which could result in greater savings. An investment in a dual-mode bus without batteries has actually shown to be a negative investment in this report despite the lower propellant cost.

A parallel hybrid bus is seen possible and suitable to rebuild for the purpose of connecting to the tram network since it has the engine capacity; most electrical equipment needed and is proven to be reliable. The battery design has however great impact on the buses capabilities, complexities and price and should therefore be designed with the intended purpose and risks in mind. It has been ascertain that these technologies regarding both the bus and the battery do exist and are technologies that to a great extent are mastered. Therefore, the feasibility of the dual-mode bus is considered good regarding these possibilities.

Other risks are attached to the technical concepts that have not yet been tested in practice and that also the tram network behaviour with increased usage despite the thorough empirical investigation. Also if the predicted lifetime of 15 years for the dual-mode vehicle is too long and instead turns out to be 10 years that would result in losses between 50 000 – 120 000 SEK annually for the solutions. The Option 1 would even need an economic lifetime of 21-22 years in order to be profitable if all the parameters are set. Option 2 should need an economic lifetime of 14-16 years, while the similar figure for Option 3 is 13-15 years in order to be profitable compared to a regular diesel bus. In these calculations the benefits from reduced emissions, noise, better working conditions and a smoother ride is not included which can be as important.

From a technical point of view this investigation indicates a possible future for the dual-mode bus in Gothenburg's tram network. The economical benefits do not create any major disadvantages although some solutions show minor negative figures. The annual losses or savings are between -44 000 SEK and 33 000 SEK compared to a regular diesel bus depending on what solution is chosen. If 15 buses are implemented which represent the total bus fleet for the trunk bus line 16, also comparable to the other trunk bus lines, total savings of up to 495 000 SEK annually could be reached. It is important to highlight the reduced dependency on diesel and increased knowledge gained in a future transport field. Furthermore, the infrastructure does already exist today in Gothenburg and provides green energy so why not use it to the greatest extent? Since the results show an economic possibility of implementing dual-mode buses in Gothenburg's public transport it is a trade-off between the risks presented and the positive environmental and social benefits.

11 Discussion

A dual-mode bus might not the ultimate solution to solve the energy and environmental problems that exists. The diesel engine used will still be as bad to the environment but an increased usage of electricity will hopefully guide the future development in the right direction. A possible outcome from further investigation that has already been mentioned is that with an increased tram network capability and better battery capacity could routes be fully electrified. A serial hybrid bus in combination with a bigger battery could also be a future scenario that would admit longer distances travelled on electricity. Similarly could a future usage of improved supercapacitors, which has been set-aside in this report for several reasons, possibly in combination with batteries be a potential scenario since it would deliver an even greater power output and increased energy regeneration.

The focus of this report has been to investigate the feasibility of dual-mode buses and therefore have no extensive optimisation of the buses or bus components been made. Further research would probably indicate that great improvements could be made especially within the battery field, which could lower the cost for the bus. With real experiments could other benefits that can be hard to measure in monetary terms, such as increased passenger satisfaction and lower disturbance, be additionally visualized. This is crucial due to the limited economical benefits presented in this report and as a part of the effort to further highlight the importance of environmental and social benefits. Since money often is the driving force it is also vital to minimize the risks attached which is weighted against these benefits. A close relationship and collaboration between the bus entrepreneur and the manufacturer is thus essential to understand the needs and reduce the risks for both parties.

The target to increase the number of passengers, partly due to the implementation of congestion charges, in combination with reducing non trunk bus traffic could be a good opportunity to electrify all public transport in Gothenburg city centre. This could be valuable to the image of Gothenburg as an environmentally friendly city. Furthermore this research is narrowed to indicate possible usefulness in Gothenburg, an investigation to realise dual-mode buses in other cities with similar infrastructure could show even further usefulness. Especially in cities with a larger tram network where the distance travelled by bus parallel to the tram network are even longer and where the traffic pollution is even more severe.

By showing that there are actually possibilities to use the tram network as a power source also for buses and that the social and environmental benefits are measurable for dual-mode buses we hope that the interest for this solution has been increased. We do also hope that this could be the start for an increased research within this field and that it could be a valuable asset to the future of Gothenburg.

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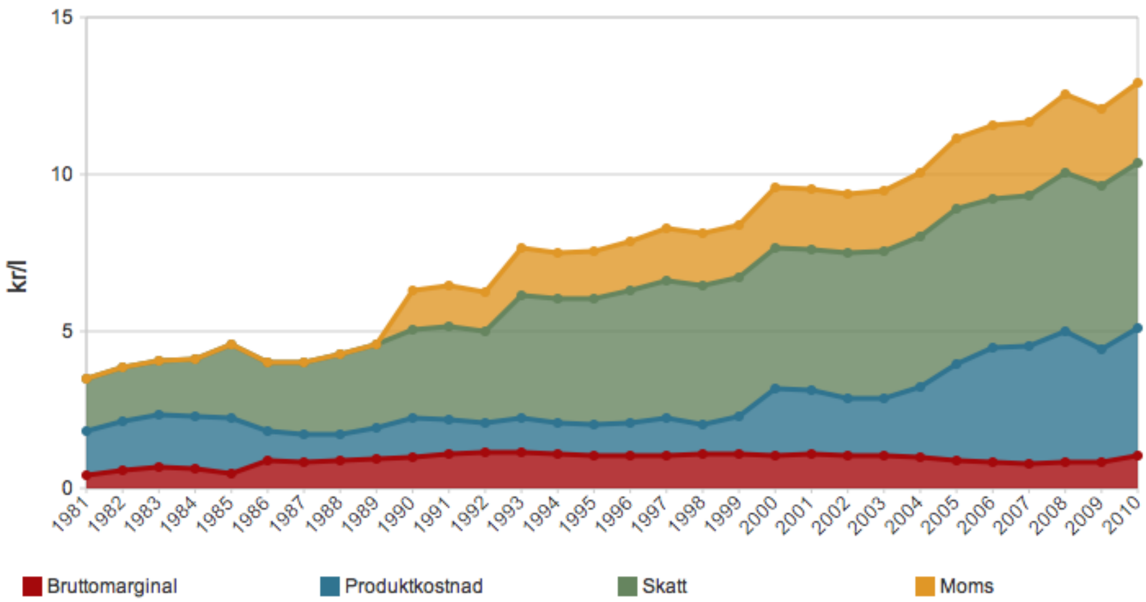
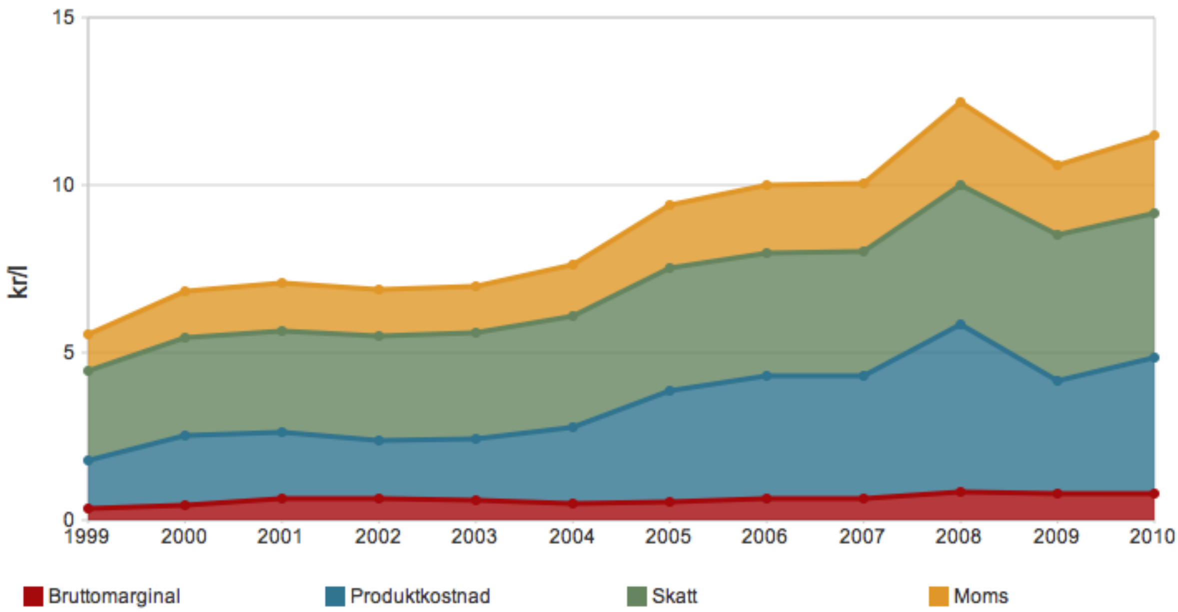
13 List of illustrations

Appendices

Appendix I - Gas and diesel prices including taxes



Gas price from 1981-2010 (Svenska petrolium institutet, 2011a)



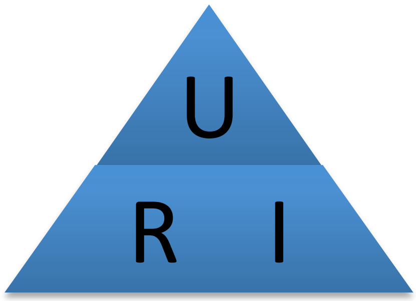
Diesel price 1999-2010 (Svenska petrolium institutet, 2011b)

Appendix II – List of interviews

Interviewee	Position and knowledge area	Information areas discussed
Anders Ekberg	Chalmers - PhD, Docent Charmec	Technical concept for collecting and return the electricity to the tram network
Anders Thunell	Robotdalen - Research Engineer	Sensors for technical concept
Christian Andersson	Volvo buses	Batteries, Existing hybrid buses, Dual-mode bus requirements including batteries, engine, functions, pricing and efficiencies
Dennis Sköldborg	Banteknik, Göteborgs Spårvägar - Cheif operating officer, Overhead wires	Trams and tram network prerequisites including electricity and economics. Concept ideas
Dieter Weise	GS Spårvagn - Local Manager	Energy consumption for trams and tram network capabilities
Erik Kihlberg	Lucchini Sweden - CEO	Technical concept for collecting and return the electricity to the tram network including prices
Hector Zelaya	Chalmers - Professor, Electric Power	Batteries, technical concept for collecting and return the electricity to the tram network and prices for the above. Electrical components and technologies used today.
Jan Söderberg	SL – Group manager	Technical concept for collecting and return the electricity to the tram network including prices
Jan-Olof Eriksson	GS Spårvagn - Purchaser	Prices for technical concept for collecting the electricity from the tram network
Kent M Andersson	Volvo buses	Batteries, Existing hybrid buses, Dual-mode bus requirements including batteries, engine, functions, pricing and efficiencies
Klas Sörensson	Skånetrafiken - Responsible transportation developer	Trolley buses in Landskrona in general. Focus on energy consumption and prices.
Lars Ilsöe	Kiepe Elektriska AB	Technical concept for collecting and return the electricity to the tram network
Leif Olsson	Skanska	Prices for asphalt

Lennart Englund	Göteborgs stad Trafikkontoret - ITS drift	Contacts to people with expert knowledge within specific areas
Magnus Lorentzon	Västtrafik - Project leader	Future plans for Gothenburg's public transport, tram features
Mats Allaküla	Professor LTH, Senior Scientific Advisor Volvo Powertrain Hybrid Technology	Simulation of energy consumption, engine facts, technical concept for collecting and return the electricity to the tram network
Mikael Alatalo	Chalmers - Researcher, Electric Power	Technical concept for collecting and return the electricity to the tram network
Paul Spartalis	GS Buss AB – Personnel planning	Bus and tram data including prices, lifetime, travel distances and weight.
Per Ranch	Svenska elvägar AB – Project leader	Technical concept for collecting and return the electricity to the tram network including prices
Pär Jonsson	Hybricon - Sales manager	Development costs, planning expenses, batteries and specifically about Hybricon's project in Umeå
Peter Sandström	SRS Sjölanders AB	Technical concept for collecting and return the electricity to the tram network including prices
PG Andersson	Trivector traffic AB – Executive Vice President	Trolley buses in Landskrona in general. Focus on energy prerequisites, energy consumption, and investment calculations and technical concept.
Stefan Östlund	KTH Royal Institute of technology - Professor, Electric power engineering	Technical concept for collecting and return the electricity to the tram network including prices
Tomas Forsberg	Volvo buses AB – Consultant Powertrain systems	Technical concept for collecting and return the electricity to the tram network, development costs for technical solutions.
Torbjörn Thiringer	Chalmers - Professor, Electric Power	Batteries, technical concept for collecting and return the electricity to the tram network and prices for the above. Electrical components and technologies used today.

Appendix III - Basic electricity science



Electricity is created through a surplus of positive charge and a shortage of negative charge. These need to be connected in order for the electrons to be able to create equilibrium, which when happening will create an electric current. The electric current is measured in Ampere and with the capital letter I. The difference between the positive and negative charge is called voltage and is measured in volts (V). When the electricity is conducted a resistance is present, Ohm (Ω). The relationship between these is described with Ohm's law $U = R * I$ (Lenning, 2006) see figure.

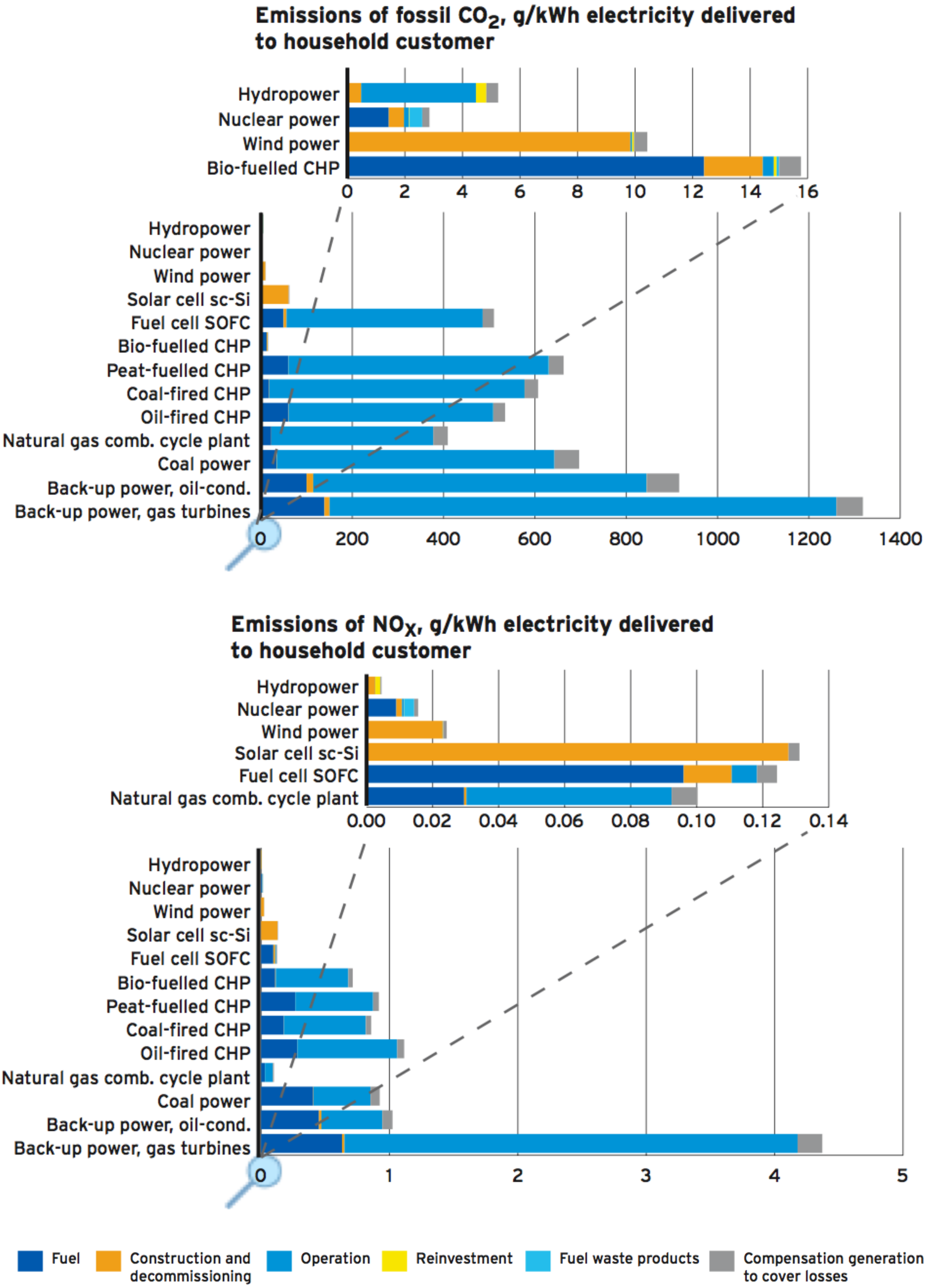
The power is the amount of current times the voltage measured in watts (W). In a car battery the voltage is usually 12V, which is created by connecting six 2V cells in series. The size determines the current and the amount of energy possibly to store. When quantifying the energy in a battery, (Wh) is often used as a measurement. (Lenning, 2006)

There are two types of currents, the Direct Current DC where electrons travels constantly from the positive charge to the negative pole. Another type of current is the Alternating Current AC when the current is changing direction many times per second which is commonly used in house power outlets. (Lenning, 2006)

Appendix IV – Comparison of a diesel tank and a battery

Fuel energy content	38,6	MJ/litre
Diesel tank capacity	300	litre
Diesel density	0,8	kg/litre
Weight of a diesel tank in a bus	240	kg
Volume of a diesel tank in a bus	0,3	m^3
Energy content in a fuel tank	11580	MJ
Energy content in a fuel tank	3217	kWh
Energy/weight for a battery pack	100	Wh/kg
Energy/volume for a battery pack	250	Wh/litre
Weight of the battery needed to replace the energy in the fuel tank	32 167	kg
Volume of the battery needed to replace the energy in the fuel tank	12,9	m^3
Efficiency from battery to the wheels (incl. Battery charge losses)	62,3	%
Efficiency from fueltank to the wheels	27,1	%
Times higher efficiency with electricity compare to diesel	2,3	
Weight of battery	13 973	kg
Volume of battery	5,6	m^3

Appendix V - Emission from energy sources



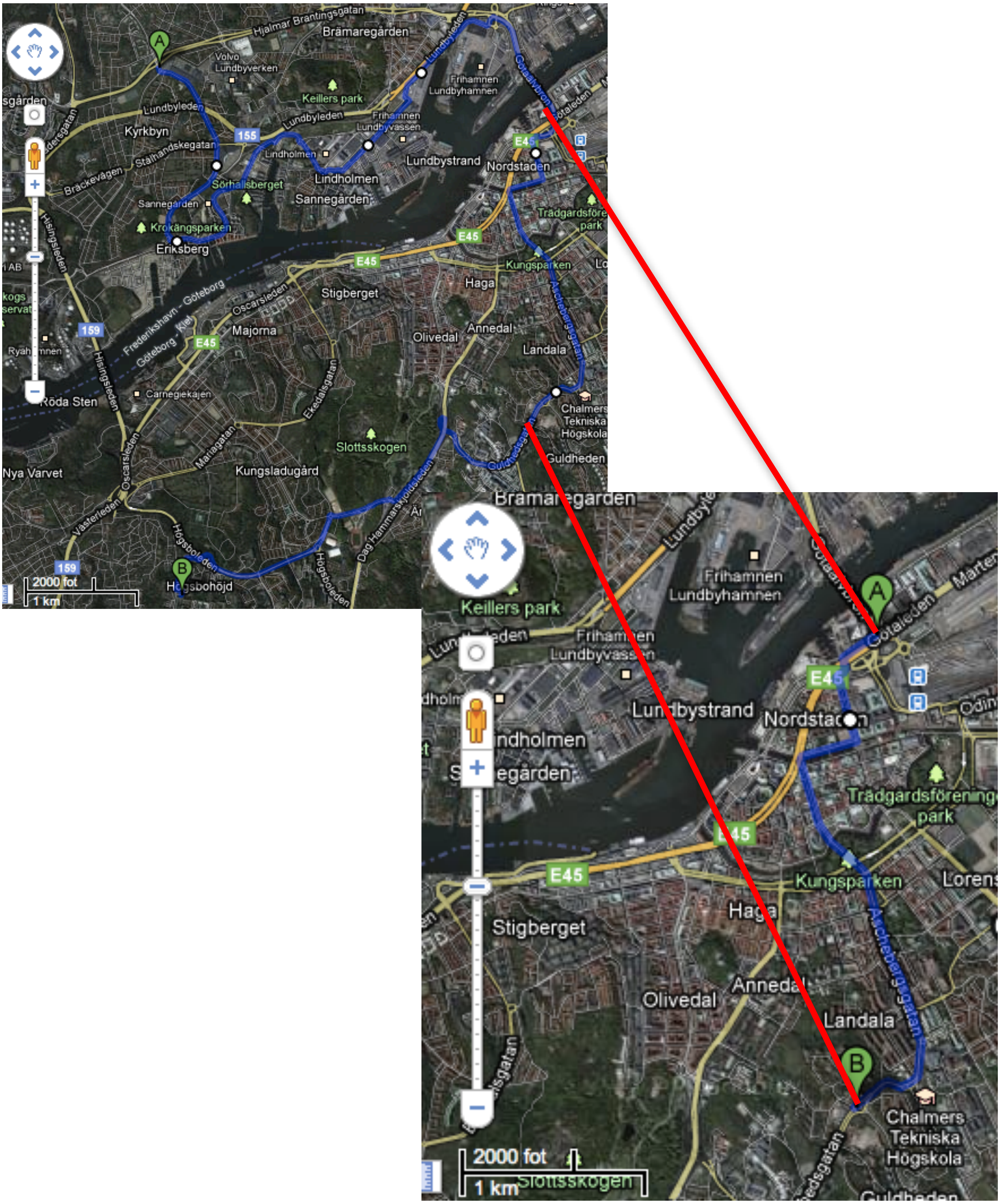
(Vattenfall, 2005)

Appendix VI - Illustrative data from the simulation

Time (s)	Speed (m/s)	Position (m)	Acceleration (m/s^2)	Kinetic Energy (J) (Ws)	Rolling resistance & drag (W)	Mech Power (W)	EM electric generated power (W)	Overhead wires charge power (W)	ESS Charge power (W)	ESS Energy content (J) (Ws)
487	5,27	3550	1,14	290612	6534	118358	0		0	6162287
488	6,16	3556	0,88	396197	7876	113460	0		0	6118287
489	7,09	3563	0,93	524709	9409	137922	0		0	6074287
490	8,05	3572	0,97	677792	11162	164245	0		0	6030287
491	8,88	3580	0,83	824121	12801	159130	0		0	5986287
492	9,51	3590	0,63	945139	14145	135163	0		0	5942287
493	10,19	3600	0,68	1085726	15704	156292	0		0	5898287
494	10,88	3611	0,69	1237695	17395	169364	0		0	5854287
495	11,61	3623	0,72	1407364	19296	188966	0		0	5810287
496	12,25	3635	0,64	1567129	21104	180869	0		0	5766287
497	12,87	3648	0,62	1729830	22967	185667	0	0	0	5722287
498	13,46	3661	0,59	1891837	24845	186852	0	0	0	5703785
499	13,64	3675	0,19	1945074	25468	78705	0	40469	29502	5683571
500	13,55	3688	-0,09	1919496	25168	-410	0	40469	29502	5713073
501	13,37	3702	-0,19	1867451	24561	-27484	18499	33767	39600	5742575
502	13,22	3715	-0,15	1826882	24089	-16479	9090	40469	36865	5782175
503	13,20	3728	-0,02	1820532	24015	17665	0	40469	29502	5819040
504	13,15	3741	-0,04	1808140	23872	11479	0	40469	29502	5848542
505	13,14	3754	-0,02	1803744	23821	19425	0	40469	29502	5878044
506	13,13	3768	-0,01	1800724	23786	20767	0	40469	29502	5907546
507	13,10	3781	-0,03	1793051	23697	16023	0	40469	29502	5937048
508	13,07	3794	-0,03	1785667	23611	16227	0	40469	29502	5966550
509	12,87	3807	-0,20	1731175	22982	-31510	21941	29942	39600	5996052
510	12,39	3819	-0,48	1604719	21532	-104923	84709	0	39600	6035652
511	11,77	3831	-0,62	1448161	19756	-136803	111966	0	39600	6075252
512	11,19	3842	-0,58	1309444	18197	-120520	98045	0	39600	6114852
513	10,78	3853	-0,41	1214378	17135	-77931	61631	0	39600	6154452
514	10,20	3863	-0,58	1086152	15709	-112516	91201	0	39600	6194052
515	9,41	3872	-0,78	925898	13932	-146322	120106	0	39600	6233652
516	8,49	3881	-0,92	753574	12014	-160310	132065	0	39600	6273252
517	7,70	3889	-0,80	618792	10493	-124289	101267	0	39600	6312852
518	7,20	3896	-0,49	541894	9609	-67290	52533	0	39600	6352452
519	7,16	3903	-0,04	535531	9535	3173	0	40469	29502	6392052
520	7,32	3910	0,16	559385	9812	33666	0	40469	29502	6421554
521	7,34	3918	0,03	563706	9861	14182	0	40469	29502	6451056
522	7,08	3925	-0,26	524443	9406	-29857	20528	31512	39600	6480558
523	6,09	3931	-0,99	388144	7777	-128522	104886	0	39600	6520158

ESS discharge power (W)	External Power supply (W)	EM electric power in (W)	EM propulsive power (W)	ICE propulsive power (W)	ICE energy generated	Consumed fuel hybrid (l)	Conv ICE propulsive power (W)	Conv ICE energy generated (J)	Consumed fuel conventional (l)
44000		35640	30472	87886	342144	0,01	118358	454692	0,01
44000		35640	30472	82988	324056	0,01	113460	436604	0,01
44000		35640	30472	107449	414402	0,01	137922	526949	0,01
44000		35640	30472	133773	511625	0,01	164245	624173	0,02
44000		35640	30472	128658	492735	0,01	159130	605283	0,02
44000		35640	30472	104691	404213	0,01	135163	516760	0,01
44000		35640	30472	125820	482252	0,01	156292	594799	0,02
44000		35640	30472	138891	530531	0,01	169364	643079	0,02
44000		35640	30472	158494	602931	0,02	188966	715478	0,02
44000		35640	30472	150397	573026	0,01	180869	685573	0,02
18503	230186	217155	185667	0		0,00	185667	703296	0,02
20213	230186	218541	186852	0		0,00	186852	707672	0,02
0	107836	92052	78705	0		0,00	78705	308235	0,01
0	5167	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	28512	20661	17665	0		0,00	17665	82789	0,00
0	20473	13426	11479	0		0,00	11479	59942	0,00
0	30799	22719	19425	0		0,00	19425	89288	0,00
0	32543	24288	20767	0		0,00	20767	94244	0,00
0	26378	18741	16023	0		0,00	16023	76724	0,00
0	26644	18979	16227	0		0,00	16227	77478	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	0	0	0	0		0,00	0	17544	0,00
0	9679	3711	3173	0		0,00	3173	29262	0,00
0	49306	39375	33666	0		0,00	33666	141887	0,00

Appendix VII – Route for Tram bus 16



Appendix VIII – Trunk bus 16

16

FRÅN EKETRÄGATAN
TILL HÖGSBOHÖJD

MÅNDAG TILL FREDAG

4	46											
5	06	21	36	46	56							
6	06	16	26	36	46	56						
7	01A	06	11A	16	21A	26	31A	36	41A	46	51A	56
8	01A	06	11A	16	26	36	47	58				
9	08	18	28	38	48	58						
10	08	18	28	38	48	58						
11	08	18	28	38	48	58						
12	08	18	28	38	48	58						
13	08	18	28	38	48	58						
14	08	18	28	38	47	56						
15	02A	06	12A	16	22A	26	32A	36	42A	46	52A	56
16	02A	06	12A	16	22A	26	32A	36	42A	46	52A	56
17	02A	06	16	26	36	47	58					
18	09	19	29	39	49							
19	04	20	36	51								
20	10	30	50									
21	10	30	50									
22	10	30	50									
23	10	30										
0	00	30										
1	00F	35F										
2	05F	35F										
3	05F											

LÖRDAG

5	15	45		
6	15	45		
7	15	45		
8	05	25	45	
9	05	25	45	
10	05	20	35	50
11	05	20	35	50
12	05	20	35	50
13	05	20	35	50
14	05	20	35	50
15	05	20	35	50
16	05	20	35	50
17	05	20	35	50
18	10	30	50	
19	10	30	50	
20	10	30	50	
21	10	30	50	
22	10	30	50	
23	10	30		
0	00	30		
1	00	35		
2	05	35		
3	05			

SÖNDAG OCH HELGDAG

5	15	45		
6	15	45		
7	15	45		
8	05	25	45	
9	05	25	45	
10	05	20	35	50
11	05	20	35	50
12	05	20	35	50
13	05	20	35	50
14	05	20	35	50
15	05	20	35	50
16	05	20	35	50
17	05	20	35	50
18	10	30	50	
19	10	30	50	
20	10	30	50	
21	10	30	50	
22	10	30	50	
23	10	30		
0	00	30		

RESTID & HÅLLPLATSER

0	**Eketrägatan**
1	Lundby Gamla Kyrka
2	Säterigatan
3	Danaplatsen
5	Eriksbergstorget
6	Sörhallstorget
7	Nordviksgatan
9	Sannegårdshamnen
11	Lindholmen
11	Regnbågsgatan
12	Pumpgatan
18	Nordstan
20	Brunnsparken
21	Domkyrkan
22	Grönsakstorget
25	Vasaplatsen
26	Kapellplatsen
27	Chalmers
28	Wavrinskys Plats
31	Sahlgrenska Huvudentré
31	Annedalskyrkan
36	Marklandsgatan
39	Tolvskillingsgatan
41	Fyrktorget

A = Kör endast till Marklandsgatan.
F = Kör endast fredag.

Obs! Nattaxa gäller på skuggade turer.

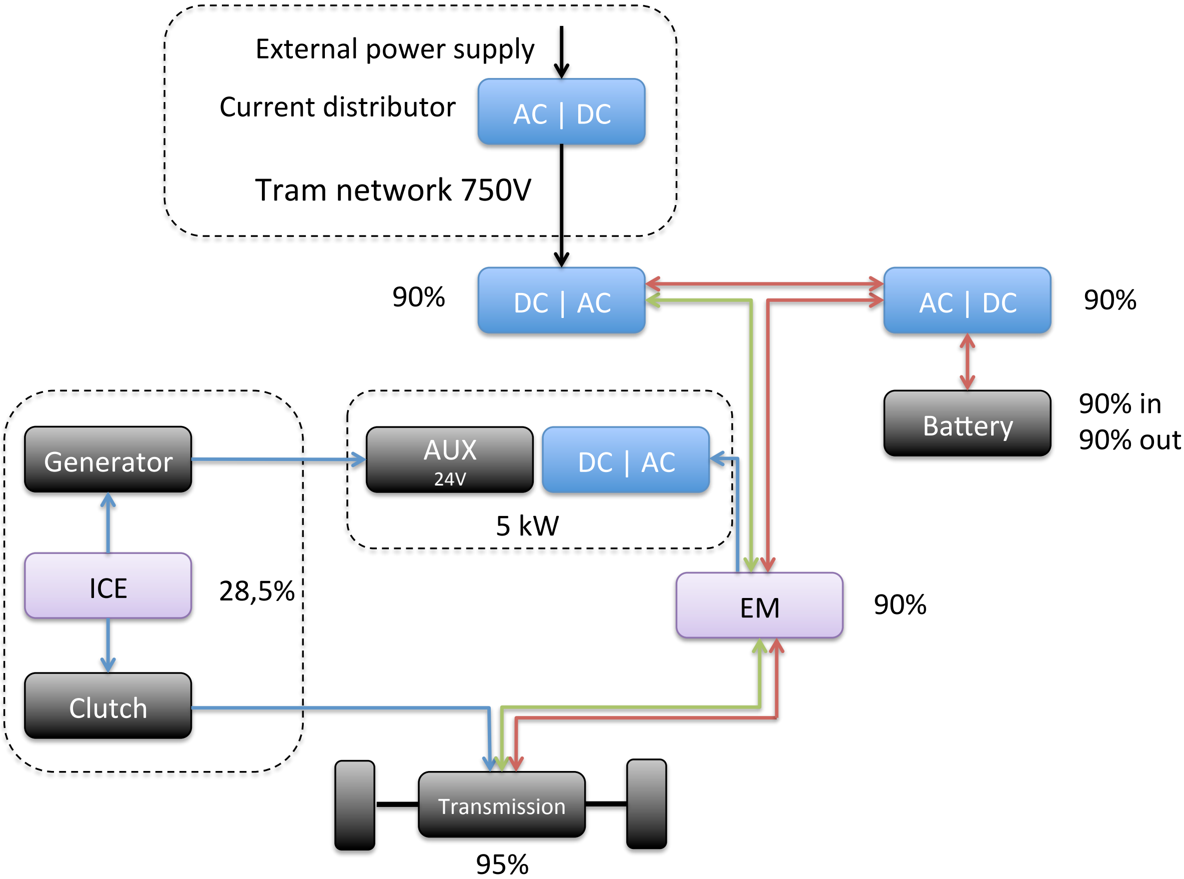
Gäller 2010-12-12 - 2011-06-18

Tiderna i tabellen är ungefärliga.

Västtrafik: 0771 - 41 43 00

(Västtrafik, 2011)

Appendix IX – Powertrain scheme



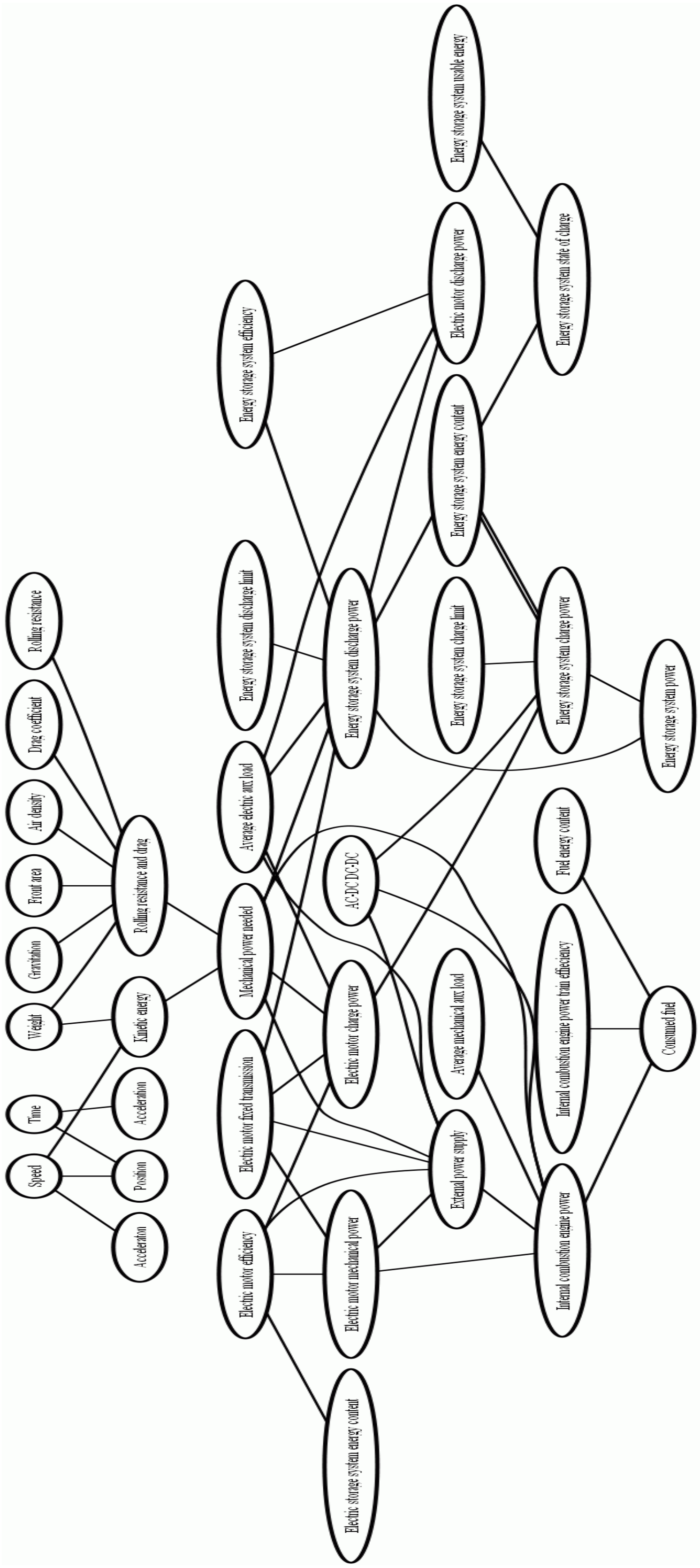
Appendix X – Current needed to charge at each stop

	Distance	Time	Average speed	Energy/Distance	Energy consumption	Average power	Round trip
Tram network	3 km	12 min	15 km/h	1,8 kWh/km	5,4 kWh	27 kW	
Outside tram network (towards Eketrägatan)	8 km	19,5 min	25 km/h	1,8 kWh/km	14,4 kWh	44 kW	28,8 kWh
Outside tram network (towards Fyrktorget)	5 km	12,5 min	24 km/h	1,8 kWh/km	9 kWh	43 kW	18 kWh

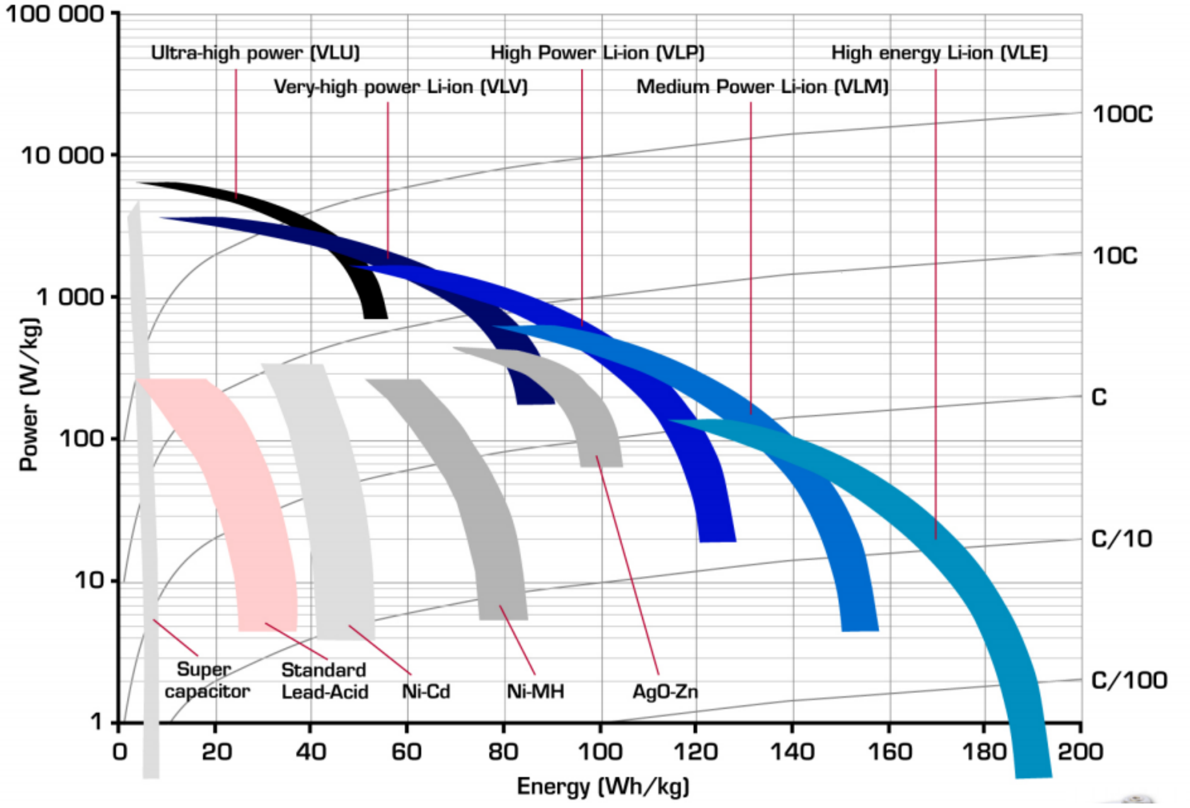
Charging at tram stops		
Voltage	750	V
Average stoptime at each tram stop	0,42	min
Time availible for charging at each tram stop	0,33	min
Number of tram stops on route	8	#
Total time available for charging	2,67	min
Power needed	770	kW
Current needed	>1	kA

1 kA is almost as much as an accelerating tram of the newest type in Gothenburg uses for a short period of time. The total possible power output is 2,5 kA. If the battery is charged in this way, this peak load would be required for more than 15 seconds at each bus stop.

Appendix XI – Parameter relations

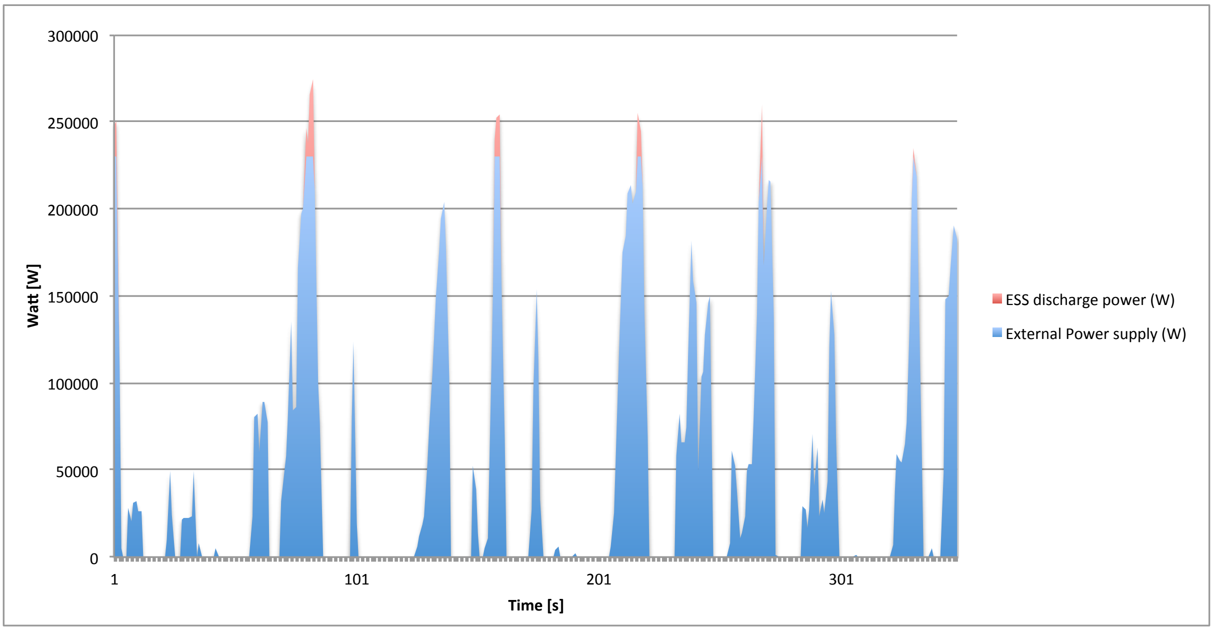


Appendix XII - Battery comparison at cell level



(Saft, 2008)

Appendix XIII - External power supply plus ESS



Appendix XIV – Calculated tram parameters

Lines	16	1	2	3	6	7	8	9	10	11	13
Monday-Friday	122	95	82	99	99	97	83	95	95	101	22
Monday-Thursday	0	9	0	9	6	5	0	6	9	9	6
Friday	5	21	0	20	14	7	0	8	19	22	10
Departures weekdays	123,0	106,4	82	110,2	106,6	102,4	83	101,4	106	112,6	28,8
Saturday	68	88	51	94	89	81	52	83	96	100	32
Sunday	63	70	44	76	72	68	44	71	76	77	25
Departures per week	746	690	505	721	694	661	511	661	702	740	201
Number of tram stops where bus 16 also stops		3	4	1	6	4	2	2	4	2	5
Number of departures from stops used by bus 16		2070	2020	721	4164	2644	1022	1322	2808	1480	1005

19256 departures/from all bus 16 stops/week
0,26 departures/tram stop/min

Average tram speed in city centre	2	m/s
Distance between current distributors	600	m
Travelling time for a tram between two current distributors	5	min
Number of trams per 600 meter	**1,3**	**#**
Average power/tram	26,1	kW

Average power posible to send back to the tram network 33948 W

Appendix XV –Route information for bus 16

Number of departures (two ways)	1492	Departures/week
	211,8	Departures on average per day (
Number of buses in the bus fleet	16	buses
Travelling distance/route (one way)	16	km
Distance for each bus each day	212	km/bus/day
Drive cycles per day	6,62	# of round trips
Distance for each bus each year	77290	km/bus/year
	6441	km/bus/month
Travelling time/route (one way)	41	min
Travelling time/route (one way) + margin	47	min
Travelling time	622,03	min/day
	10,37	h/day
Average speed	20,43	km/h

Appendix XVI - Propulsion cost for diesel bus

Diesel

Year	Diesel cost	Consumed fuel	Total cost	Present value
1	9,52	44 010	418 977 SEK	395 261 SEK
2	10,03	44 010	441 308 SEK	392 763 SEK
3	10,56	44 010	464 830 SEK	390 280 SEK
4	11,12	44 010	489 605 SEK	387 813 SEK
5	11,72	44 010	515 701 SEK	385 362 SEK
6	12,34	44 010	543 188 SEK	382 926 SEK
7	13,00	44 010	572 140 SEK	380 506 SEK
8	13,69	44 010	602 635 SEK	378 101 SEK
9	14,42	44 010	634 756 SEK	375 711 SEK
10	15,19	44 010	668 588 SEK	373 336 SEK
11	16,00	44 010	704 224 SEK	- SEK
12	16,85	44 010	741 759 SEK	- SEK
13	17,75	44 010	781 295 SEK	- SEK
14	18,70	44 010	822 938 SEK	- SEK
15	19,70	44 010	866 800 SEK	- SEK
16	20,75	44 010	913 001 SEK	- SEK
17	21,85	44 010	961 664 SEK	- SEK
18	23,02	44 010	1 012 920 SEK	- SEK
19	24,24	44 010	1 066 909 SEK	- SEK
20	25,53	44 010	1 123 775 SEK	- SEK
			Diesel cost	3 842 059 SEK

Total propulsion cost
3 842 059 SEK

Appendix XVII Propulsion cost for Option 1

Diesel					Electricity					
Year	Diesel cost	Consumed fuel	Cash flow	Present value	Year	Diesel cost	Consumed fuel	Cash flow	Present value	Annual propulsion cost
1	9,52	35 059	333 766 SEK	314 874 SEK	1	0,83	26 593	22 125 SEK	20 873 SEK	335 747 SEK
2	10,03	35 059	351 556 SEK	312 883 SEK	2	0,86	26 593	22 923 SEK	20 402 SEK	333 285 SEK
3	10,56	35 059	370 294 SEK	310 906 SEK	3	0,89	26 593	23 721 SEK	19 917 SEK	330 822 SEK
4	11,12	35 059	390 030 SEK	308 940 SEK	4	0,92	26 593	24 519 SEK	19 421 SEK	328 362 SEK
5	11,72	35 059	410 819 SEK	306 988 SEK	5	0,95	26 593	25 317 SEK	18 918 SEK	325 906 SEK
6	12,34	35 059	432 715 SEK	305 047 SEK	6	0,98	26 593	26 114 SEK	18 410 SEK	323 457 SEK
7	13,00	35 059	455 779 SEK	303 119 SEK	7	1,01	26 593	26 912 SEK	17 898 SEK	321 017 SEK
8	13,69	35 059	480 072 SEK	301 203 SEK	8	1,04	26 593	27 710 SEK	17 386 SEK	318 589 SEK
9	14,42	35 059	505 660 SEK	299 299 SEK	9	1,07	26 593	28 508 SEK	16 874 SEK	316 173 SEK
10	15,19	35 059	532 612 SEK	297 408 SEK	10	1,10	26 593	29 306 SEK	16 364 SEK	313 772 SEK
11	16,00	35 059	561 000 SEK	295 528 SEK	11	1,13	26 593	30 103 SEK	15 858 SEK	311 386 SEK
12	16,85	35 059	590 901 SEK	293 660 SEK	12	1,16	26 593	30 901 SEK	15 357 SEK	309 017 SEK
13	17,75	35 059	622 396 SEK	291 804 SEK	13	1,19	26 593	31 699 SEK	14 862 SEK	306 665 SEK
14	18,70	35 059	655 570 SEK	289 959 SEK	14	1,22	26 593	32 497 SEK	14 373 SEK	304 333 SEK
15	19,70	35 059	690 512 SEK	288 126 SEK	15	1,25	26 593	33 295 SEK	13 893 SEK	302 019 SEK
16	20,75	35 059	727 316 SEK	- SEK	16	1,28	26 593	34 092 SEK	- SEK	- SEK
17	21,85	35 059	766 082 SEK	- SEK	17	1,31	26 593	34 890 SEK	- SEK	- SEK
18	23,02	35 059	806 914 SEK	- SEK	18	1,34	26 593	35 688 SEK	- SEK	- SEK
19	24,24	35 059	849 923 SEK	- SEK	19	1,37	26 593	36 486 SEK	- SEK	- SEK
20	25,53	35 059	895 224 SEK	- SEK	20	1,40	26 593	37 284 SEK	- SEK	- SEK
										Total propulsion cost
			Diesel cost	4 519 745 SEK				Electricxity cost	260 805 SEK	**4 780 549 SEK**

Appendix XVIII Propulsion cost for Option 2

Diesel					Electricity					
Year	Diesel cost	Consumed fuel	Total cost	Present value	Year	Diesel cost	Consumed fuel	Total cost	Present value	Annual propulsion cost
1	9,52	27 729	263 980 SEK	249 038 SEK	1	0,83	24 388	20 291 SEK	19 142 SEK	268 180 SEK
2	10,03	27 729	278 050 SEK	247 464 SEK	2	0,86	24 388	21 022 SEK	18 710 SEK	266 174 SEK
3	10,56	27 729	292 870 SEK	245 900 SEK	3	0,89	24 388	21 754 SEK	18 265 SEK	264 165 SEK
4	11,12	27 729	308 480 SEK	244 345 SEK	4	0,92	24 388	22 486 SEK	17 811 SEK	262 156 SEK
5	11,72	27 729	324 922 SEK	242 801 SEK	5	0,95	24 388	23 217 SEK	17 349 SEK	260 150 SEK
6	12,34	27 729	342 241 SEK	241 266 SEK	6	0,98	24 388	23 949 SEK	16 883 SEK	258 149 SEK
7	13,00	27 729	360 482 SEK	239 741 SEK	7	1,01	24 388	24 681 SEK	16 414 SEK	256 155 SEK
8	13,69	27 729	379 696 SEK	238 226 SEK	8	1,04	24 388	25 412 SEK	15 944 SEK	254 170 SEK
9	14,42	27 729	399 934 SEK	236 720 SEK	9	1,07	24 388	26 144 SEK	15 475 SEK	252 195 SEK
10	15,19	27 729	421 250 SEK	235 224 SEK	10	1,10	24 388	26 876 SEK	15 007 SEK	250 231 SEK
11	16,00	27 729	443 703 SEK	233 737 SEK	11	1,13	24 388	27 607 SEK	14 543 SEK	248 280 SEK
12	16,85	27 729	467 352 SEK	232 260 SEK	12	1,16	24 388	28 339 SEK	14 084 SEK	246 343 SEK
13	17,75	27 729	492 262 SEK	230 792 SEK	13	1,19	24 388	29 070 SEK	13 629 SEK	244 421 SEK
14	18,70	27 729	518 499 SEK	229 333 SEK	14	1,22	24 388	29 802 SEK	13 182 SEK	242 514 SEK
15	19,70	27 729	546 135 SEK	227 883 SEK	15	1,25	24 388	30 534 SEK	12 741 SEK	240 624 SEK
16	20,75	27 729	575 244 SEK	- SEK	16	1,28	24 388	31 265 SEK	- SEK	- SEK
17	21,85	27 729	605 905 SEK	- SEK	17	1,31	24 388	31 997 SEK	- SEK	- SEK
18	23,02	27 729	638 200 SEK	- SEK	18	1,34	24 388	32 729 SEK	- SEK	- SEK
19	24,24	27 729	672 216 SEK	- SEK	19	1,37	24 388	33 460 SEK	- SEK	- SEK
20	25,53	27 729	708 045 SEK	- SEK	20	1,40	24 388	34 192 SEK	- SEK	- SEK
										Total propulsion cost
			Diesel cost	3 574 728 SEK				Electricxity cost	239 179 SEK	**3 813 907 SEK**

Appendix XIX Propulsion cost for Option 3

Diesel					Electricity					
Year	Diesel cost	Consumed fuel	Total cost	Present value	Year	Diesel cost	Consumed fuel	Total cost	Present value	Annual propulsion cost
1	9,52	24 235	230 718 SEK	217 659 SEK	1	0,83	56 652	47 134 SEK	44 466 SEK	262 125 SEK
2	10,03	24 235	243 016 SEK	216 283 SEK	2	0,86	56 652	48 834 SEK	43 462 SEK	259 745 SEK
3	10,56	24 235	255 968 SEK	214 916 SEK	3	0,89	56 652	50 534 SEK	42 429 SEK	257 345 SEK
4	11,12	24 235	269 612 SEK	213 558 SEK	4	0,92	56 652	52 233 SEK	41 374 SEK	254 931 SEK
5	11,72	24 235	283 982 SEK	212 208 SEK	5	0,95	56 652	53 933 SEK	40 302 SEK	252 509 SEK
6	12,34	24 235	299 118 SEK	210 866 SEK	6	0,98	56 652	55 632 SEK	39 219 SEK	250 085 SEK
7	13,00	24 235	315 061 SEK	209 534 SEK	7	1,01	56 652	57 332 SEK	38 129 SEK	247 663 SEK
8	13,69	24 235	331 854 SEK	208 209 SEK	8	1,04	56 652	59 031 SEK	37 037 SEK	245 246 SEK
9	14,42	24 235	349 542 SEK	206 893 SEK	9	1,07	56 652	60 731 SEK	35 947 SEK	242 840 SEK
10	15,19	24 235	368 172 SEK	205 585 SEK	10	1,10	56 652	62 431 SEK	34 861 SEK	240 446 SEK
11	16,00	24 235	387 796 SEK	204 286 SEK	11	1,13	56 652	64 130 SEK	33 783 SEK	238 069 SEK
12	16,85	24 235	408 465 SEK	202 995 SEK	12	1,16	56 652	65 830 SEK	32 715 SEK	235 710 SEK
13	17,75	24 235	430 236 SEK	201 712 SEK	13	1,19	56 652	67 529 SEK	31 660 SEK	233 372 SEK
14	18,70	24 235	453 168 SEK	200 437 SEK	14	1,22	56 652	69 229 SEK	30 620 SEK	231 057 SEK
15	19,70	24 235	477 322 SEK	199 170 SEK	15	1,25	56 652	70 928 SEK	29 596 SEK	228 766 SEK
16	20,75	24 235	502 763 SEK	- SEK	16	1,28	56 652	72 628 SEK	- SEK	- SEK
17	21,85	24 235	529 561 SEK	- SEK	17	1,31	56 652	74 327 SEK	- SEK	- SEK
18	23,02	24 235	557 786 SEK	- SEK	18	1,34	56 652	76 027 SEK	- SEK	- SEK
19	24,24	24 235	587 516 SEK	- SEK	19	1,37	56 652	77 727 SEK	- SEK	- SEK
20	25,53	24 235	618 831 SEK	- SEK	20	1,40	56 652	79 426 SEK	- SEK	- SEK
										Total propulsion cost
			Diesel cost	3 124 310 SEK				Electricxity cost	555 599 SEK	**3 679 909 SEK**

Appendix XX – Investment calculation process

$$I * \frac{1}{n} * t * \left(\frac{1}{d} - \frac{1}{d*(1+d)^n}\right)$$

$$\sum_{i=1}^{n} \frac{FV_i*(1-t)}{(1+d)^i}$$

$$\frac{RV*(1-t)}{(1+d)^n}$$

$$\frac{d}{1-(a+d)^{-n}}$$