

Cost optimized electrification of Lund city bus traffic using Elonroad electric road system

A simulative study



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MASTER THESIS

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– A simulative study –

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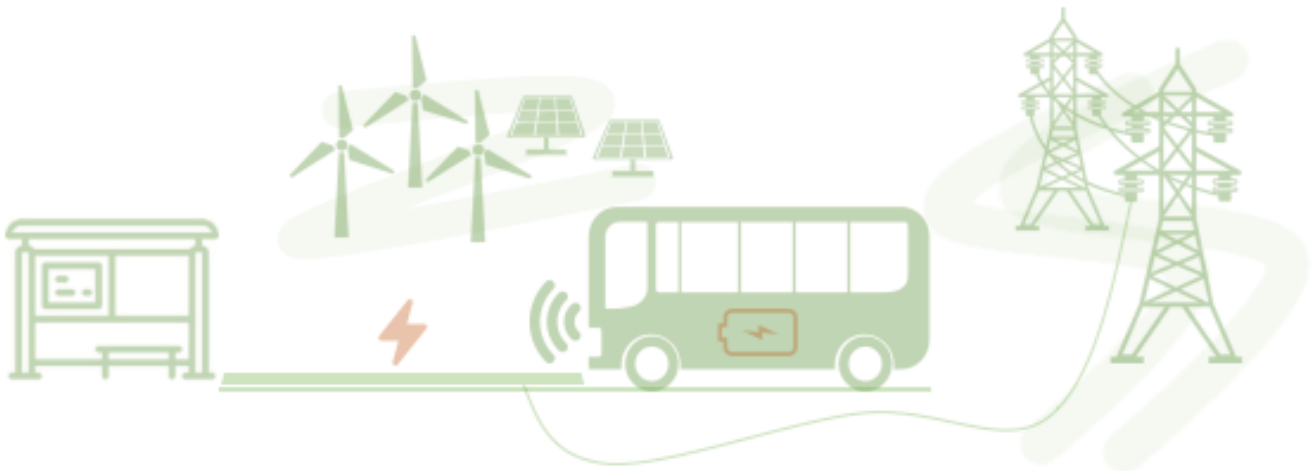
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ABSTRACT

The Swedish government issues aggressive regulations to meet national environmental objectives like zero net emissions of green house gases by 2045. With the transport sector in Sweden being almost exclusively operated on fossil fuels, the current focus on turning this sector more sustainable is high. This thesis examines future possibilities of a promising technique, electric roads, that could possibly be a part of the sustainability transition. Present charging techniques are generally limited to static charging, meaning that vehicles are stationary during some time to get sufficient electric supply. Electric roads have the opportunity to offer dynamic charging, meaning that vehicles can instead charge while driving.

This thesis aims to answer how a new specific electric road technique called Elonroad should be installed to operate an electric bus fleet in the city of Lund at lowest possible cost. Elonroad is currently at development state for their first serious tests in real traffic and Lund municipality is at the same time interested in changing the present gas-fueled bus fleet into electric by 2023, a favorable concurrence.

An algorithm is written in MATLAB to obtain the optimal locations for installing electric road sections. Real time measurements of bus movements, dwelling times, velocities and more are obtained from Skånetrafiken (local bus operator) and used as inputs to the optimization algorithm. Lund municipality and involved bus system operators have proposed a rearrangement of many bus routes in conjunction with the possible transition to an electric fleet. Thus the real time measurements are modified to create a simplified model based on average velocities and stop times for various zones in the city. Results show that the algorithm come to similar conclusions using real and simplified data. Furthermore, a combined set of practical limitations like roundabouts, road intersections and pedestrian crossings are added to the algorithm to make sure that any final propositions are realistic.

A bus system needs to be robust in order to operate during traffic congestions, bad weather and other factors. Important inputs such as end terminal time, average velocity and charging power are varied and put into the optimization algorithm in order to mimic different scenarios. The results show that a system with 3.4 km of electric road together with 9 end stop chargers (consisting of a short Elonroad strip) with a charge power of 180 kW is the most economic option if the buses are allowed to charge during 5 minutes at end terminal stations. This alternative is slightly cheaper than the present gas bus system regarding pure operational costs (but more expensive when including vehicle investments). Less end terminal time and higher velocities result in optimized systems with longer road segments and thus higher costs. These systems would however withstand irregularities in the movement of the buses which should be highly appreciated by the company in charge of the bus system.

Key words: ERS, Elonroad, charging infrastructure, optimization algorithm, bus electrification, dynamic charging, Lund

PREFACE AND ACKNOWLEDGEMENTS

This thesis is the last piece of a five year long puzzle, being the engineering program at LTH. Hampus Alfredsson from environmental engineering and Erik von Essen from mechanical engineering will both get their masters degree within energy systems. The thesis work has been performed at the IEA (Industrial Electrical engineering and Automation) institution together with stakeholders from Elonroad, Skånetrafiken, Krafringen Nät AB and Lund municipality.

Special thanks to our supervisor, Lars Lindgren, for giving input and information about electric road systems and optimization programming. A valuable engineer with lots of innovative ideas.

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LIST OF ABBREVIATIONS

CCPI	climate change performance index
EV	electric vehicle
V2G	vehicle-to-grid
V2V	vehicle-to-vehicle
ERS	electric road system
SoC	state of charge
DoD	depth of discharge
NoC	number of cycles
GTFS	General Transit Feed Specification
SMHI	Sveriges meteorologiska och hydrologiska institut
NPV	net present value
EBR	ElnätsBranschens Riktlinjer

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1 INTRODUCTION

1.1 Background

World population is constantly increasing, creating a larger energy demand than ever before. At the same time, incentives and laws regarding energy management are constantly updated to meet climate change requirements. In 2015, the 21st Conference of the Parties was held in Paris, adopting the goal to limit global warming to "well below" 2°C. During year 2017, Sweden has moved to fifth place of the climate change performance index (CCPI) ranking with low emission levels in energy supply and national goals of 100% renewable electricity by 2040. (Burck, Marten, & Bals, 2017)

Even though many nations are effectively working towards a more renewable society, certain sectors are still highly dependent on fossil fuels. The transport sector is generally dominated by petroleum and diesel fuels where Sweden makes no exception (*Figure 1.1*). Electricity occupies merely 3% of the total energy use, meaning that the national goal of 100% renewable electricity by 2040 won't significantly affect the transport sector (Energimyndigheten, 2017). However, there is another goal connected to green house gases saying that Sweden must have zero net emissions by 2045 (Naturvårdsverket, 2018). Consequently, the combination of less emissions and 100% renewable electricity make key factors in the quest for a more sustainable future with transport electrification as one efficient solution.

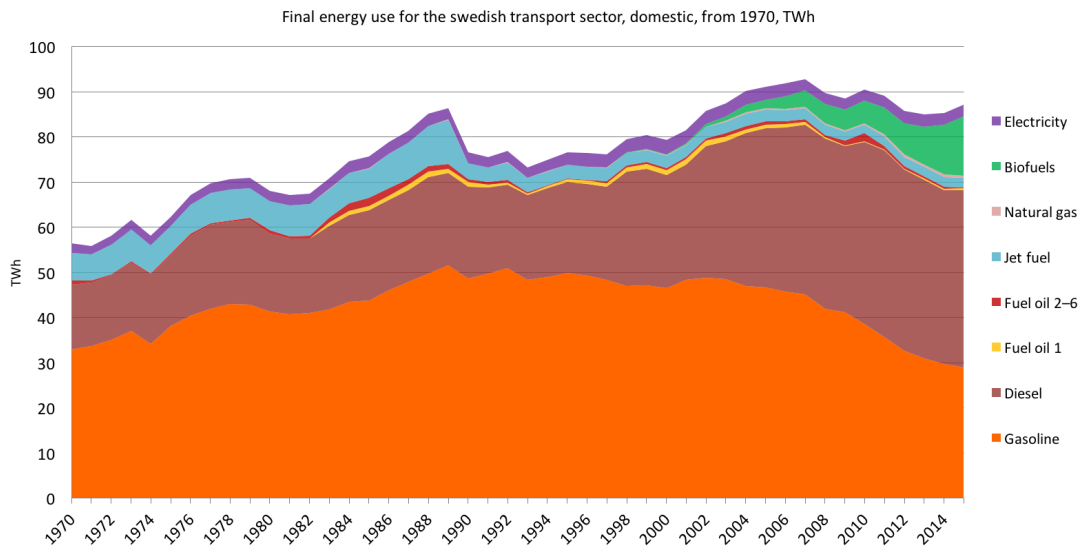


Figure 1.1: Energy use by fuel type in the transport sector of Sweden from 1970 to 2015 (Energimyndigheten, 2017).

According to present statistics, the latest years indicate a clear upward trend for electricity powered transport. Total share of rechargeable vehicles has increased by 60% during the last 12

months in Sweden. (Elbilsstatistik, 2017)

There are some factors which needs to be taken into consideration before fully converting from today’s fossil fueled transport. Using Sweden as an example, Figure 1.1 present that domestic vehicles are filled with approximately 70 TWh of gasoline and diesel every year. It is of importance to assure whether today’s electric power system will be able to support a full conversion. Firstly, electricity is roughly three times more efficient, meaning that 70 TWh of fossil fuels would be replaced by 20-25 TWh electric energy (Gustafsson & Johansson, 2015). Since Sweden generate 140-160 TWh of electricity every year (Figure 1.2), energy would probably not be a problem (Energimyndigheten, 2017).

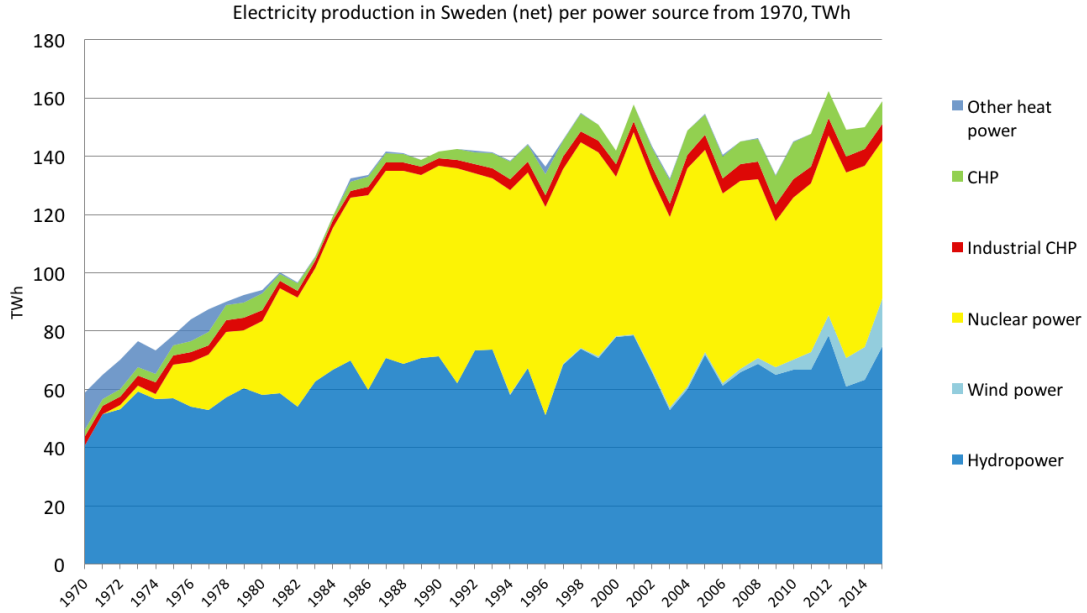


Figure 1.2: Electricity production measured in TWh by power source from 1970 to 2015 (Energimyndigheten, 2017).

So energy might not be a problem, but what about power? Since power is momentarily for each load, the total power level is highly dependent on the amount of simultaneous loads. For instance if 25 TWh of electric energy were to be evenly distributed over 365 days per year, power capacity could be simply calculated according to *Equations 1.1* and *1.2*. If all charging were to be done during 8 hours(i.e. night time) or 16 hours(distributed charging), the total power load would be approximately 8.5 GW or 4.5 GW respectively.

$$P = \frac{E}{t} = \frac{25 \cdot 10^{12}}{365 \cdot 8} \left[\frac{Wh}{h} \right] \approx 8.5 \text{ GW} \tag{1.1}$$

$$P = \frac{E}{t} = \frac{25 \cdot 10^{12}}{365 \cdot 16} \left[\frac{Wh}{h} \right] \approx 4.5 \text{ GW} \tag{1.2}$$

Unlike the case for energy use, these results are far more difficult to reach. Today, the total installed capacity on the Swedish electric power grid is some 40 GW. Consequently, charging every vehicle during same 8 hours per day according to *Equation 1.1* above would occupy more than 20% of the total available power. (Svenska Kraftnät, 2017)

Undoubtedly it would be hard to supply enough power at all times to meet the total national load and hence some distributive solution is required. Also, as more renewable power sources are introduced to our energy systems, spreading and scheduling of charging behavior become more important. One favorable feature with an electric vehicle (EV) is its ability to store energy, enabling flexibility for scheduling of charging infrastructure. Consistent with these statements, there are lots of ongoing research regarding for example vehicle-to-grid (V2G) or vehicle-to-vehicle (V2V) where the main goal is to distribute or assist the power grid load. (You, Yang, Chow, & Sun, 2016)

Another frequently discussed factor regarding EV's is the driving distance provided by the batteries. Research and development of improved battery technology (mainly lower costs and specific energy content) is crucial in order to compete with today's fossil fueled vehicles (Young, Wang, Wang, & Strunz, 2017). For example, the latest EV by Tesla (Model 3) offer 350-500 km driving range with a reasonably small battery of some 50-75 kWh starting at a price of 35 000 USD. Evidently, pricing and drive range is starting to become competitive with many of today's conventional vehicles. Further, recharging is becoming faster as the EV's are designed to handle higher charge powers. Tesla's supercharger network provide approximately 120 kW, enabling full recharge in some 30-40 minutes. (Tesla Inc., 2018a)

Still, the battery technology of today is being widely discussed and meet a lot of opposition. Continued research and smart solutions are still required. Longer driving range can of course be accomplished by battery enlargement, but with today's battery techniques it would risk too high costs (Watanabe, 2017). Furthermore the Lithium batteries that are mostly used today are comprised of materials that can be found in finite quantities in the earths crust. The scarceness of resources could be a problem for future battery production. Recycling of the Lithium and other materials is being investigated (Tesla Inc., 2018b) but to the authors knowledge there is no such recycling practice being performed in big scale today.

Whilst research is in the quest for better battery capacity, development of other possible solutions is of importance, e.g. charging infrastructure techniques.

Today it is possible to charge an electrical vehicle at many different locations with various properties. At home, charging can be performed through 120V or 240V outlets. They provide relatively small powers and hence charging is generally taking place over night or during times when the vehicle is not needed. Another alternative is to use public charging. These stations enable much higher power output, making charging times faster as described with the Tesla supercharger above. (ChargeHub, 2017)

Private car drivers generally has the advantage of flexibility. Exact times of departure and arrival can often be determined to suit the schedule of a single driver, a family, a small group of people etc. As information technology and communication are developing, its becoming easy to plan private journeys ahead, including recharging times. However, the flexibility is not as adjustable when discussing public transport, for instance city bus traffic. Operators should be able to follow predetermined schedules whilst all commuters rely on buses to arrive and departure accordingly. Consequently, infrastructure logistics and planning are important when adopting electrified bus traffic systems. The original idea regarding electrification of bus systems rely on static charging, and many publications treat optimization as a location planning of these stations. As the name static implies, the charging has to be performed when the EV is stationary.(Wirges, Linder, & Kessler, 2012)

However, city bus systems present upsides that might allow other solutions since each vehicle is continuously repeating a specified route. This enables the possibility of good estimations regarding fuel consumption, traffic behavior and thus also resulting cost analyses of the required infrastructure. During recent times the potential of dynamic charging (charging while driving) technologies, so called electric road system (ERS), are being widely researched. The three main ERS-technologies

existing today are conductive power transfer from overhead lines, conductive power transfer from rails or inductive power transfer from road-embedded inductive coils (see *Figure 1.3* below). (S. Andersson & Edfeldt, 2013)



Figure 1.3: The three main ERS strategies marked in yellow. Conductive charging from roof receiver or road rails and inductive charging through the road.

Collaboration between Dan Zethraeus (CEO at Elonroad) and professors at Lund University has lately resulted in a new electric road technology, called Elonroad. It involves a conductive rail with a electric pick-up underneath vehicles, like the one in *Figure 1.3*. Considering city bus traffic, many of the features linked to Elonroad indicated that it might be a preferable technique in a near future (Elonroad, 2017). The Swedish transport administration (Trafikverket) have recently posted a national plan for testing and evaluation of electric roads where Elonroad is proposed as one possible solution (Trafikverket, 2018).

1.2 Purpose and goals

This master thesis intend to,

- evaluate the possibilities of introducing electric roads to electrify all city bus traffic owned by Skånetrafiken in Lund, Sweden.
- economically optimized and realistic propositions of where to place the electric road segments should be presented to stakeholders. It will include routes between bus stations and stationary road segments at bus stations.
- all system designs will be created from an algorithm written by the thesis authors in MATLAB.
- the analysis should include a transition between the present bus system and a future possible system with electric infrastructure.

- important parameters such as connection to the local power grid and practical implications of high power chargers in city environment should be analyzed in order to validate a proposed infrastructure.

1.2.1 Engineering questions

1. How could a future electric road network be designed and cost optimized to cover the energy demand of an electrified city bus fleet in Lund?
2. Is full electrification of Lund city bus traffic using electric roads economically defensible compared to conventional techniques?
3. What advantages does Elonroad have compared to other dynamic or static charging techniques?
4. What additional components and services are required to make reality of an ERS like this one?
5. What site specific infrastructural limitations are present in Lund that might infer with the implementation of an ERS?
6. Could other traffic in Lund be included in the electric road system and how would this affect the economical results?

1.3 Limitations and assumptions

Extensive planning and computational projects like this one meet obstacles related to time duration. Since the initial goal is to produce somewhat realistic propositions, it is important to locate which parameters that have big impact and which does not affect the final result to any great extent.

First, one need to set system boundaries which can be motivated as reasonable simplifications or sectioning of reality. Even though the actual task is limited to bus city traffic, there are several systems existing within Lund. It is considered that the most profitable approach is to design the ERS for buses only operating withing the city area. However, there are some regional bus lines connecting Lund with Malmö and other nearby cities. This regional traffic is not included in the main analysis since it would aggravate the problem. They differ a lot in driving distances and might require a whole other approach regarding charging infrastructure design. Though a rough estimation example is presented in the appendix where regional traffic is accounted for.

Evidently, there are a lot of charging methods and solutions existing today. It is possible that a combination of techniques is optimal for a project like this one. But to examine the possibilities and future prospects of Elonroad, this specific technique is used throughout the simulations.

Skånetrafiken has provided good information and real time data measurements for the present bus system whilst the future system obviously demands extensive estimations of data inputs. Therefore, present measurements are processed to gain as good estimations as possible for any analysis of a future design. This procedure is explained later in the *Chapter 4 – Data collection and use*.

It should be added that Elonroad is still in a prototype state, thus various parameters concerning its functionality and economics are uncertain. Qualified assumptions about the price for electric road segments and some key parameters like power transfer capacity, infrastructure lifetime and maintenance are built on discussions with Elonroad representatives and comparisons with other related reports.

Regarding energy storage, the thesis authors have chosen to use solely Lithium-ion batteries for all buses. Pricing and lifetime of batteries are always difficult to predict since they depend on factors like surrounding climate and usage patterns (Arcus, 2016). Estimations are made using other reports and available charging/discharging profile algorithms.

Precise costs of electric hardware is always hard to determine before a project is actually implemented. The authors have communicated with local electric grid operators and used online database services to gain a fair picture of the real situation. All projects that demand restructuring of city areas will not only draw larger expenditure, but also meet political obstacles and public opinions. Such issues are not considered to have influence on any final results.

The present bus system operates on gas. Estimations about these vehicles, i.e costs and energy consumption is taken from a previous report about the Lund bus system (Lindgren, 2015). Prices and consumption related to electrical buses are also taken from the same report. However, the authors have cross referenced these facts with other reports as well.

By obvious reasons the future bus system is more difficult to model than the present one. Current constructions of a new tram system through the city of Lund further complicates comparisons between present and future layouts. Thus assumptions about how the future system will operate have been made to complete available prospects about its design.

To summarize, the main limitations and assumptions are those regarding,

- Overall time scope of the thesis project which will limit the possibility of reaching a global optimum.
- The system boundaries drawn to only include bus traffic operating within Lund city.
- The use of one single charging technique.
- Information about the future bus system.
- Battery lifetime and costs.
- Vehicle, charging infrastructure and electric hardware costs, lifetime and maintenance.

1.4 Thesis outline

Chapter 1 contains a short introduction to the importance of creating a more efficient and sustainable transport sector. The concept of electric vehicles and their current challenges are mentioned as well as purpose, goals and limitations of this specific thesis. Several engineering questions are formulated to help both the reader and the authors to understand and draw any final conclusions.

Chapter 2 is a description of the present and future bus systems in Lund. Operational paths, route lengths, departure frequencies and other important information is given for each bus line. A comparison of fuel consumption and emission rates is presented to motivate the conversion from gas-fueled to electrified vehicles.

Chapter 3 states all components that are needed to create a functioning electric road system. Some sections include information required for implementation in Lund. Economics is discussed in most sections which is a crucial input to the optimization algorithm.

Chapter 4 clarifies the sources from which the optimization model collect bus-data regarding stoptimes, velocities, distances and geographic locations. Furthermore, the main working principle of the optimization algorithm as well as limitations of some data use is presented.

Chapter 5 explains step by step how the optimization algorithm functions, what parameters that are used and lastly a description of the "rainflow counting" method which is included in the optimization process.

Chapter 6 presents all results from the algorithm as well as manually added costs for electric components and grid connections. Chapter 7 is a discussion of results, limitations, possibilities and other important system aspects.

2 BUS SYSTEM DESCRIPTION

This chapter initially describes how the present bus system is managed and what paths that each line operates. A recent proposition of the future bus line network design in Lund is also presented.

Since the public transport organizer in Lund has shown interest in electrification, a section on present and possibly future vehicle techniques and their fuel consumption follows.

2.1 Present fleet and bus line network

The public transportation system in Lund is organized by *Skånetrafiken* which is a part of the administration of Skåne county in the south of Sweden. Skånetrafiken is responsible for organizing the bus fleet, procuring bus services, customer contact and marketing (Skånetrafiken, 2018).

Concordant with Swedish laws, the bus service contract is made public for companies to bid on. The present bus fleet in Lund is chauffeured by Nettbuss Sverige AB, but in year 2023 there will be a new round of bidding. Several investigations have been performed in conjunction with this new round regarding possibilities of an electric system instead of today's gas-fueled bus fleet. Though Skånetrafiken has stated that in-depth analyses of different alternatives are required before any agreements, thus creating an opportunity for Elonroad to join the competition. (Tyréns, 2018) There are currently 64 vehicles operating in Lund of which 59 are serving the different bus lines and 5 are additional (Sörensson, 2018). The decision of bus vehicle size is in general dependent on factors like route length and traveler intensity which may differ within one system. Lund is however a small city with fairly short bus routes, enabling operation with only one bus dimension of 12 meters. The buses are made by the bus manufacturer Man and where procured by Nettbuss in between 2013-2015. (Jansson, 2018)

The Lund city bus system consists of lines 1 through 6, 9, 20, 752 and 753. The two latter lines are only operating during certain nights of the week and are not following a specified route. Consequently they are not included in the analysis since their patterns are hard to predict. An overview of the present bus system in *Figure 2.1* shows how the city center is connected with its peripheral parts in north, south, east and west.

The densely operated city center area is divided into two major sub routes (*Figure 2.2*) where most of the bus lines pass. The larger quadrangle connects *Lund central* station in the west with *Lundagård* in the east. The smaller quadrangle represents a regulatory stop called *Botulfsplatsen* where chauffeur changes and lunch breaks often are made (Jansson, 2018). A more detailed map showing the central parts of Lund including station names can be seen in *Appendix B* for easier understanding.



Figure 2.1: Present bus routes in Lund city (Tyréns, 2018).

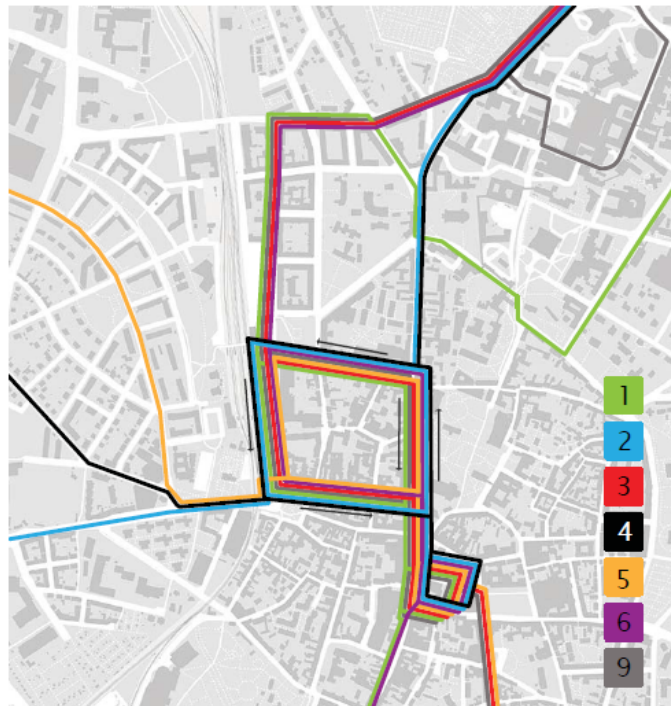


Figure 2.2: Present bus routes in the center of Lund city (Tyréns, 2018).

Like most other public transportation systems, there are time schedules deciding from where and when departures and arrivals will occur. These schedules changes from weekday to weekend and also between summer months and rest of the year due to the difference in traveler patterns. *Table 2.1* presents round-trip lengths of each bus line and extractions of their departure amounts during a weekday with normal conditions. With route lengths and departures combined, Skånetrafiken need to organize approximately 12 500 km of operational service during every weekday, evenly spread out over their 64 vehicles.

Table 2.1: *Relevant bus lines with corresponding round-trip route lengths and departure frequencies during a normal weekday. Distances and departures are calculated using data from Skånetrafiken database.*

Line	Route length (km)	Departures per day
1	18,6	65
2	15,6	64
3	22,2	135
4	22,6	134
5	19,0	66
6	21,6	98
9	13,8	5
20	13,2	75

2.2 Future fleet and changes

The city of Lund is currently seeing a lot of construction due to a new electric tram system being installed. The tram, which will bring passengers from Lund central station to the future residential area of *Brunnshög* situated in the north east of Lund is planned into operation around year 2020. As a result, it will force redirections of several existing bus routes. Further, since the tram will start operating within a few years, the design of an ERS must be constructed with regards to future system boundaries. Otherwise any results might become too uncertain or possibly even misleading.

Lund municipality together with Skånetrafiken and Nettbuss recently published a proposal of a new bus line network that will fit the introduction of a tram line. They present a number of changes regarding existing paths, departure frequencies and bus station extensions to cover heavier bus traffic. There are two major solutions being discussed, one "**Lund C option**" and one "**Botulfsplatsen option**". The Lund C option seems to be more attractive and more in line with future visions regarding development of Lund city and therefore work as an outset for optimization inputs throughout this thesis. The main improvements found in this option are stated below. All changes are proposed in order to increase the number of bus passengers and to accommodate the needs of a growing city. (Tyréns, 2018)

- Lund central station will have increased traffic and importance as a hub for the city buses as well as the regional transportations system such as the regional buses and trains.
- The area around *Botulfsplatsen* will see a 30-50% decrease in traffic.
- The departure frequency (departure every n^{th} minute) will change for a number of lines according to *Table 2.2*.

- Average velocity within the city bus system should increase to 22 km/h (earlier average velocity is some 18-19 km/h gained from real time measurements).
- As can be seen if comparing the future proposal in *Figure 2.3* with the present from *Figure 2.2*, line 4 and line 2 will be redirected to not traffic the inner city areas. This is an important move to reach the desired decrease of traffic around *Botulfsplatsen*.
- Line 20 is canceled and replaced by the new tram that is marked as a black dashed line in *Figure 2.3*.
- Line 1 at *Klostergården* in the south will run in both directions which will bring some infrastructural changes.
- Line 6 will be altered to also cover the Ideon area in the north of Lund which is a gathering point for many established companies.

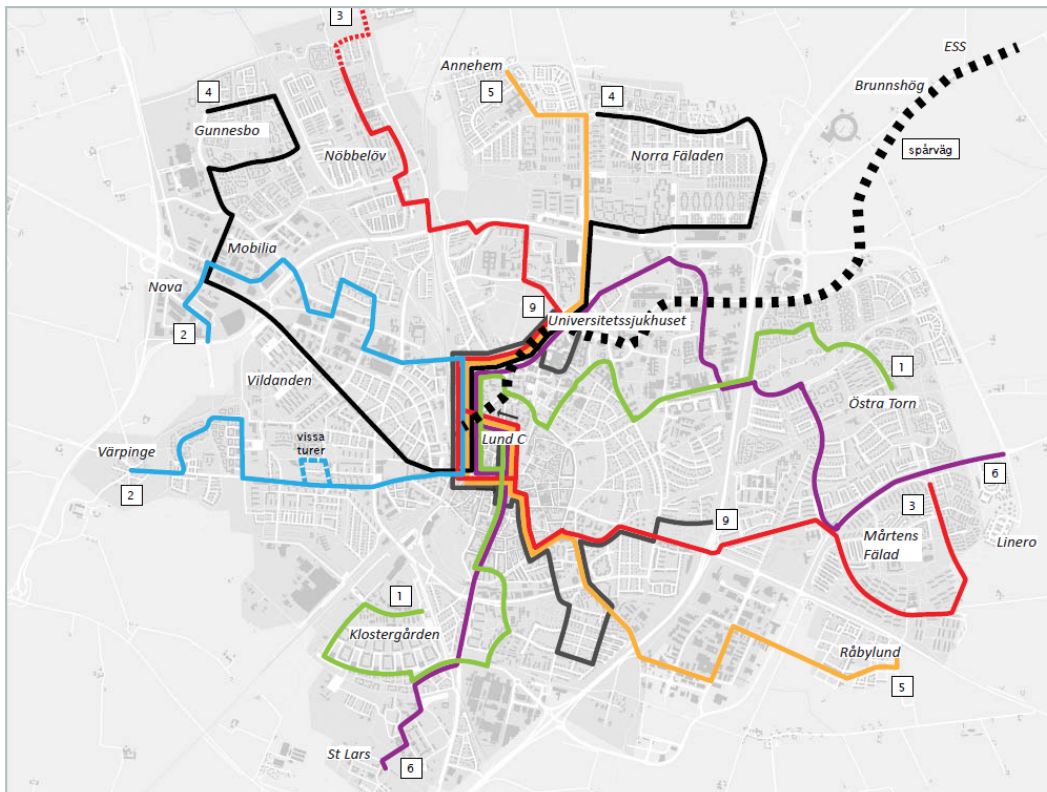


Figure 2.3: Proposed future bus system with Lund C as main hub. This "Lund C option" seem to be the most preferred (Tyréns, 2018).

New round-trip route lengths and departure frequencies are presented in *Table 2.2* where distances are gained from manual measurements or approximations of part-stretches whilst frequencies are given in the recent publication. Even though some rearrangements are included, each route length seems to not change more than 5–10%. However, since some lines will be modified or rearranged in the proposed future system, there might be uncertainties regarding these percentages.

Table 2.2: *New round-trip route lengths in km as well as present and future departure frequencies. Frequencies are expressed as departure every n^{th} minutes (Tyréns, 2018).*

Line	Route length (km)	Present dep. freq.	Proposed dep. freq.
1	19.5	15	10
2	13.8	15	15
3	20.5	6	5
4	21.2	6	5
5	17.7	15	15
6	19.8	10	10
9	13.8	60	60

The ratio between present and future departure frequencies together with number of departures per day from *Table 2.1* were used to estimate future departure frequencies according to *Equation 2.1* below.

$$\text{No. departures} = \frac{\text{Present dep. freq.}}{\text{Future dep. freq.}} \cdot (\text{Present dep. per day}) \quad (2.1)$$

2.3 Fuel consumption electric vs. gas

The energy consumption of electric vehicles depends on various factors where some are more decisive than others. One need to account for *propulsion, heating systems, air conditioning systems* and other loads like compressors and lighting to obtain the total consumption. Earlier studies and real measurements have rated the electric propulsion of a 12 meter bus to 0.9–1.2 kWh/km (Borén et al., 2015). The authors have chosen a consumption of 2 kWh/km to cover some extra loads like air conditioning and other auxiliaries, similar to other studies. This should also leave some margins which is good for the credibility of any final results. Though earlier studies have chosen the same consumption for 18 meter buses, which create even more marginals for this thesis results since they are based on 12 meter buses (Lindgren, 2017).

One considerably large load is the heating system of buses, especially during winters months. In an earlier study from Lund, values of up to 2.5 kWh/km were used for extremely cold days to include both propulsion and heating (Lindgren, 2015). Lindgren argues that the energy for the heating should be provided by a different source than electricity to gain profitability, for instance by using a fuel based heat source of some kind. A suggestion is using a small biofueled combustion engine which is well isolated. It can be connected to a generator to charge the vehicle batteries if needed while the lost heat (due to some 30% efficiency) could be recirculated as comfort heat.

Increased energy consumption due to uphill driving is a question that might appear and thought to be significant. The energy content needed to propel one vehicle a certain number of meters in a vertical direction is depending on the mass of the vehicle, the gravitational constant and the vertical rise. GPS tracking of routes in Lund shows that the lowest parts of the city, around *Lund C*, are situated about 35 meters above sea level whilst higher elevations in the northern parts of Lund are situated around 90 meters above sea level.

With an estimated bus vehicle weight of 20 000 kg and a vertical rise of 55 m (90 – 35), the potential energy demand can be calculated according to *Equation 2.2*. (Byggnadsmekanik, 2018)

$$E = m \cdot g \cdot h = 20\,000 \cdot 9.81 \cdot 55 \left[\text{kg} \cdot \frac{\text{m}}{\text{s}^2} \cdot \text{m} \right] = 3.0 \text{ kWh} \text{ (10.8 MJ)} \quad (2.2)$$

Consequently, the maximum energy required to propel a bus due to elevation differences is approximately 3 kWh in Lund. However, since electric vehicles often have the ability to recover some of this energy when returning downhill, this figure is smaller for round-trip calculations. According to a study on electric buses and energy consumption (J. Zhang, Lu, Xue, & Li, 2008), around 50 % of the potential energy can be regenerated into the battery when the bus is braking. Thus the net extra energy consumption due to elevation differences in Lund should at maximum reach around 1.5 kWh during one round-trip. With an average consumption of 2 kWh/km and most route lengths being above 15 km (*Table 2.1*), the extra 1.5 kWh will make up for less than 5 % of its total energy consumption. This fraction is regarded as insignificant and covered by the chosen margin of the 2 kWh/km electric energy consumption.

Economic performance comparison between the present gas-fueled and an electrified bus fleet is important in order to get a clear view of future possibilities. For instance, purchase of one electric bus vehicle is considered more expensive by a factor close to 1.5 according to earlier studies (Olsson, Grauers, & Pettersson, 2016). However, they bring low fuel costs and high powertrain efficiency. A gas bus consumes approximately 0.35 kg/km at a price of 16 SEK/kg, about three times more expensive than an electric bus consuming 2 kWh/km at a price of 0.85 SEK/kWh. (Lindgren, 2015)

3 ELECTRIC ROAD SYSTEM COMPONENTS

This chapter introduces the main aspects of an electric road system including the electric road technique, charging philosophies, batteries and connection to the power grid. All sections are analyzed with Elonroad in mind to clarify some parameters and costs used through an optimization algorithm which is explained in a later chapter.

3.1 The Elonroad technique

The electric roads developed by Elonroad use a conductive charging technique from rails on top of the street whilst a future objective is to also design slightly dug down Elonroad. Both possibilities present positive as well as negative effects depending on purpose of use. Fully dug down, the electric road is more suitable for highway driving where laws and restrictions concerning the road surface are more stringent. However, putting the electric road on top of the street surface enables fast and easy installation whereas other techniques might require much digging or construction for stability and operation. Less digging and construction is coherent with shorter installation time, less service and maintenance, thus creating room for reduced costs. This latter on-top version of Elonroad is especially suited for inner city areas where speed limits are low and quick installations are of greater interest. Consequently the authors choose to focus exclusively on this technique which will result in less digging costs and hopefully become more competitive. (Elonroad, 2017)

Elonroad is produced as short separate rail segments, easily connected into desired lengths of electric road. A unique design allows for only specific segments of the road to be active simultaneously leading to safe power transmission and electric environments in cities (Stuart & Alexéus, 2016). Elonroad is approximately 5 cm high and 30 cm wide with inclined sides to make lane changes over the rail safe.

Incoming EV's signal the charging infrastructure and if authorized they are provided with power, segment by segment. Each vehicle decides what power to receive as long as the maximum installed power is not exceeded. An EV that uses the ERS has to be equipped with a pick-up that is mounted underneath the vehicle (see *Figure 3.1*). When the vehicle passes over a specific segment, this pick-up automatically locates the metallic rail strip and connects to it. The idea is that a pick-up should be able to connect to both on-top laying ERS and submerged ERS. (Elonroad, 2017)

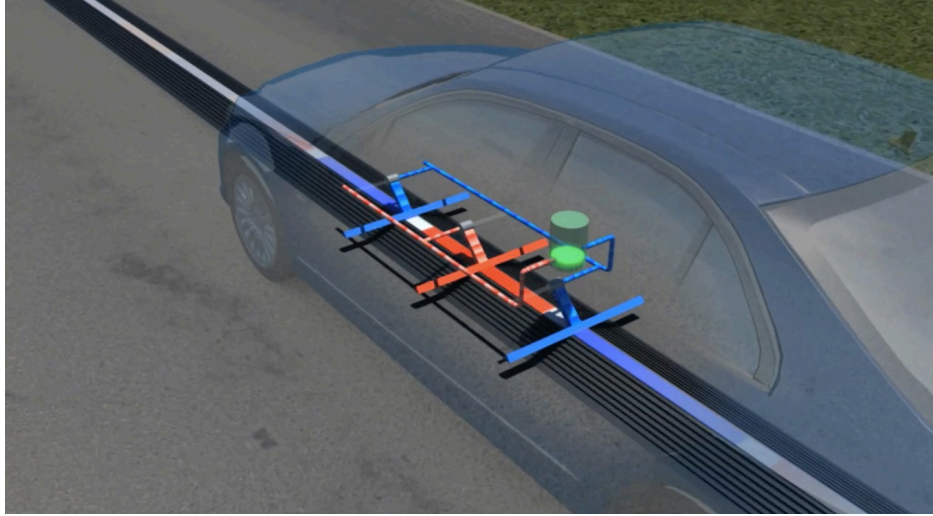


Figure 3.1: Connection to the Elonroad segment is done using a pick-up that is mounted underneath each vehicle (Stoica & Nybom, 2017).

The maximum power that can be transferred to each vehicle pick-up from the conductive metal strip is currently estimated to 180 kW. With two pick-up receivers one might accept up to 360 kW. A higher power enables faster charging times and hence less electric road demand. However, it is important to discuss the possibilities of utilizing these powers fully. End terminal stations are usually not occupied by more than one vehicle at a time and could therefore be assumed to always provide 360 kW. On the contrary, electric road segments might be long (several hundred meters) and occupied by many buses simultaneously requesting power. In these situations, the Elonroad technique could need to partition less than 360 kW to each vehicle depending on the total grid connection capacity. (Lindgren, 2018)

There are a number of other examples of ERS that are under development today. Alstom and Elways are two companies who also use conductive charging techniques. Both these companies uses designs where the electric roads are dug down in the road (Elways, 2011). Furthermore, the company Siemens is implementing a conductive system located in the air with the main difference that it can only be used by heavy vehicles (i.e. trucks or buses) (Siemens AG, 2015). There are also many companies worldwide currently developing inductive ERS, (Tongur & Sundelin, 2016) though a main drawback with inductive systems is a considerably higher costs combined with lower capability of transferring power. However, an advantage with such a system is its possibility to be completely hidden underneath the road surface (Singh, 2016).

3.2 Charging possibilities

As proposed earlier, the thesis considers exclusively use of the dynamic charging system Elonroad. Though when profitable, this technique may also be used similarly to existing static chargers by simply adding a small segment on the road at a bus stop. Whilst existing static charging methods require an overhead pantograph (M. Andersson, 2016) or similar for power transfer, Elonroad is perhaps easier or less expensive to install at bus stops. Furthermore, as the ERS segments can be connected to form optional lengths, they are easily dimensioned to provide power to numerous vehicles at the same location. This could be the most important feature compared to the other methods regarding static charging. When applied to bus stops the minimum length of electric road

is assumed to be 10 meters, long enough to enable sectioning into smaller parts for multiple vehicle use according to the authors.

3.2.1 Dynamic charging

The main advantage with ERS is the ability to charge while driving, decreasing the extra waiting time standing at stationary locations. A security is also created since bus drivers get less dependent on reaching every station in time to sufficiently fill the batteries. A system with electric roads can be designed with consideration to current speed limits, ensuring that enough electricity will be provided during each dynamic charging segment. If a vehicle is running late to a station due to heavy traffic, it could still cover its needs along the way. Furthermore, the vehicle's on-board batteries may be considerably smaller due to frequent dynamic refill and hence cheaper.

3.2.2 Depot charging

Depot charging is a useful technique. The bus fleet will be stationary at its depot, often for several hours during night time. Therefore, they can easily recharge using low power supply which is less costly than fast charging with high power. Also, the depot charging creates a possibility to daily "reset" every bus to its starting battery level. In the optimization algorithm written by the thesis authors, each bus line is designed to regain this starting level after every round-trip, but no solutions are proposed regarding how they get to their "starting points" with enough battery content. The answer might be depot charging at some joint location close enough for every vehicle to reach their desired starting content. Alternatively, one could include some high-power charging time at each end terminal station before beginning a day of driving. But that obviously require enough battery capacity to cover the distance to the bus depot at night and back in the morning. If analyzing city bus traffic like in this thesis, the depot is usually located within the city and furthermore Lund is not very large. Hence the round-trip consumption to and from the depot should not be a problem.

3.3 Batteries

Today, lithium-ion (Li-ion) is the most used battery technology in electric vehicles and buses makes no exception. They have high volumetric- and specific energy and power densities compared to other conventional batteries, thus well suited as energy storage in EV's. For instance, more energy and power per unit means prolonged range with less battery. Typical values for energy density today is 100-180 Wh/kg. Though, there are new promising lithium technologies under development which promise a significant raise in energy density, up to 2500 Wh/kg. (Mahmoud, Garnett, Ferguson, & Kanaroglou, 2016)

With what power and how deep batteries are either charged or discharged will affect their lifespan. A commonly used term when discussing maximum manageable charging power of a battery is C-rate (or charge-rate), expressed as kW/kWh. Depending on operational priorities, batteries are either energy- or power optimized. Vehicles that consume much electric energy or are supposed to drive far will usually be equipped with energy optimized batteries to manage longer discharge time periods. The opposite applies for vehicles that are not exposed to deep cycles and can thus be power optimized to manage higher charging rates, usually up to 6 kW/kWh. (Lindgren, 2017)

The possibilities when designing electric power infrastructure for bus systems are today often limited to static charging at end terminal stations. Discharge periods are consequently long and require energy optimized batteries for effective and profitable operation. An opening for use of more power optimized batteries might occur if charging was possible more frequently, for instance

along dynamic electric road segments whilst driving. This thesis will despite dynamic charging possibilities initially assume energy optimized batteries with a C-rate of 2 kW/kWh, but a power optimized scenario is discussed shortly in *Chapter 7 – Discussion*. Buses are supposed to drive long distances every day for several years and might therefore not make profitable use of power optimized batteries, even though discharge levels are low. (E. Karlsson, 2016)

In order to evaluate charging patterns it is of importance to know state of charge (SoC) levels. State of charge is a measure of how much energy content that is left in a battery expressed as percentage, where 100% means fully charged. Since batteries last longer whilst kept within "normal" and small SoC intervals, it is advantageous to start the day with them recharged to some level within efficient limits. Though these normal limits vary between different battery models and are therefore hard to predict (E. Karlsson, 2016). The initial level is easily modified in the resulting optimization model, though the authors have chosen a desired starting SoC of 75% (the resulting charging patterns have shown to consist of very small fluctuations and hence 75% is enough to maintain a battery buffer which is explained later).

Figure 3.2 shows an approximated relationship between depth of discharge (DoD) (how much the battery content is decreased between recharges expressed in percentage, or $1 - SoC$) and corresponding number of cycles (NoC) before the battery is unusable. These curves are technique-specific, but the figure below is considered a good approximation and is used for battery wear calculations in the optimization model. It is obvious that one should seek to lower DoD. (P. Zhang, Liang, & Zhang, 2017)

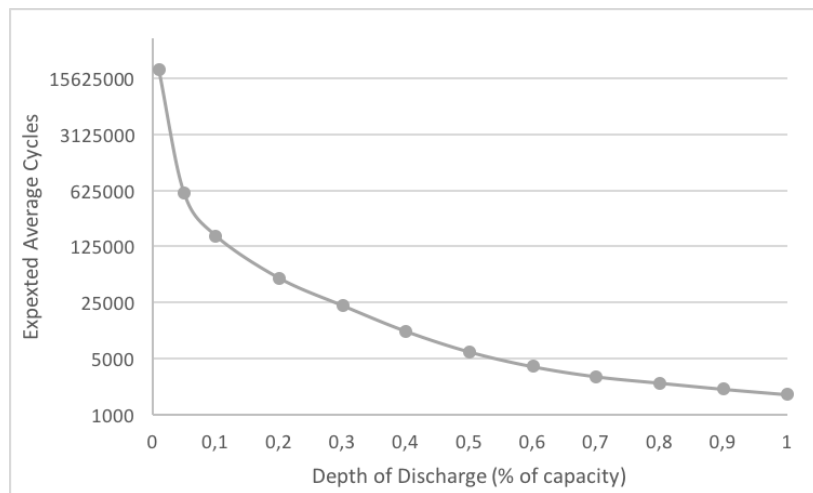


Figure 3.2: An approximate relation between DoD and NoC which proves the importance of lower discharge (Lindgren, 2018).

The price and weight for the battery increases with increasing energy content. Current prices for Li-ion batteries can be approximated to 3000 SEK/kWh (Lindgren, 2017). Any final economic results might be reduced depending on the actual cost of batteries. According to forecasts for years 2020 & 2030 in *Figure 3.3*, prices are expected to decrease a lot (Lambert, 2017). A price of 3000 SEK/kWh is used in this thesis to rather over- than underestimate any results. Hence any final cost will probably be lower or decrease in a near future.

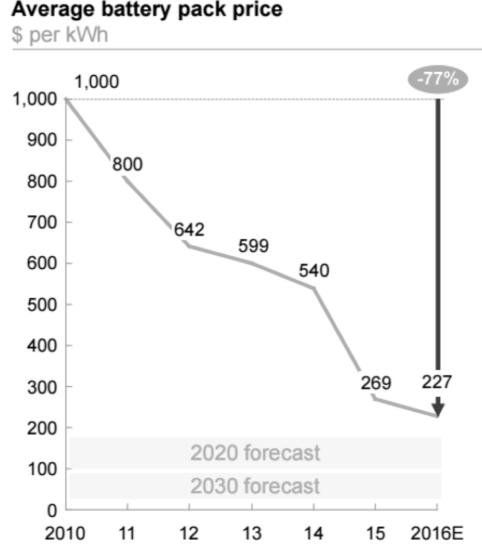


Figure 3.3: Today the prices of Li-ion batteries is somewhere around 220-300 /kWh. But according to forecast the prices will decrease even further (Lambert, 2017).

If disregarding the fact that larger batteries occupy more space and are heavier, they do contribute to lower DoD (1kWh discharge results in a lower percentage for a 100kWh battery than for a 10kWh battery). Hence there is less need for replacements, but the capital expenditure is considerably larger. It is crucial to examine what battery size and discharge that is most profitable in each case. Consider the following example of DoD control techniques to confirm this theory. A battery of 100 kWh and a daily electricity consumption of 10 kWh is used for simplicity.

Charge-strategy 1: Charge the battery every 8th day

$$DoD = \frac{8 \cdot 10}{100} \left[\frac{kWh}{kWh} \right] = 0.80 \text{ (80\%)} \quad (3.1)$$

Charge-strategy 2: Charge the battery every 2nd day

$$DoD = \frac{2 \cdot 10}{100} \left[\frac{kWh}{kWh} \right] = 0.20 \text{ (20\%)} \quad (3.2)$$

Provided that discharge values are given, it is possible to estimate the total battery NoC from a relationship like the one in *Figure 3.2*. A DoD of 80 % and 20 % results in 2 500 and 50 000 NoC respectively. Thus, the total energy need of each battery may be calculated as *Equations 3.3* and *3.4* below.

$$2\,500 \cdot 80 \left[\frac{cycle \cdot kWh}{cycle} \right] = 200\,000 \text{ kWh} \quad (3.3)$$

$$50\,000 \cdot 20 \left[\frac{cycle \cdot kWh}{cycle} \right] = 1\,000\,000 \text{ kWh} \quad (3.4)$$

$$\frac{3\,000 \cdot 100}{200\,000} \left[\frac{\frac{SEK}{kWh} \cdot kWh}{kWh} \right] = 1.5 \frac{SEK}{kWh} \quad (3.5)$$

$$\frac{3\,000 \cdot 100}{1\,000\,000} \left[\frac{\frac{SEK}{kWh} \cdot kWh}{kWh} \right] = 0.3 \frac{SEK}{kWh} \quad (3.6)$$

Apparently, by charging the battery more often and hence retaining lower DoD, the capital expenditure can be spread over many more kWh's of electric energy. Though at some point it becomes impossible to charge more often. One can as mentioned achieve lower depth of discharge with the same energy use by increasing battery size, but likewise this also becomes non-profitable at some point. Summarized, one needs to combine charging possibilities with choice of battery size to achieve an economic optimum.

Furthermore, the examples above are only simplified reasoning for understanding the importance of DoD. In a realistic case, each cycle between charges might be completely different from the others. A bus system like the one investigated in this thesis will undergo charging cycles with irregular amplitudes. *Figure 3.4* gives an example of how SoC might differ over time. Every event depends on driving distance before an Elonroad segment, driving distance while connected to Elonroad and the charging power transfer magnitude.

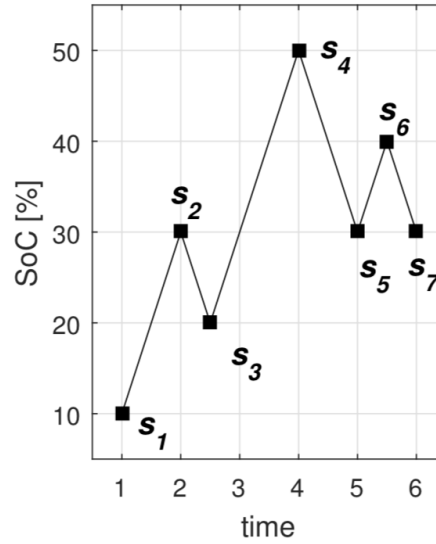


Figure 3.4: An example of how SOC might differ over time. This is probably the case when discussing EV battery use. Variables s_1 – s_7 is the local extreme values of SOC through this charging event array (Shi et al., 2017).

Unlike the simplified *equations 3.1–3.6*, some detailed model describing the combined effect of these events on the battery lifetime and cost is required. The most widely used semi-empirical method for these calculations is the *rainflow counting algorithm* which is further described in the optimization process description. (Shi et al., 2017)

3.4 Electric power grid

Since EV batteries are portable and dependent on electricity storage for propulsion, they require DC supply. The Elonroad technique is estimated to supply a voltage of 600 V and a maximum amperage of 300 A. This gives a power supply to the EV of about 180 kW. (Stuart & Alexéus, 2016) High power supply is crucial due to relatively short periods of time that each vehicle remains connected. Consider a bus traveling over a 100 meters long (s) electric road segment in 20 km/h (v). "Level 2" charging of some 10 kW (P) would bring much less electric energy (E) than "Level 3" charging of >100 kW during that distance and time according to Equation 3.7 and 3.8 below. (ChargeHub, 2017)

$$E = \frac{P \cdot s}{v} = \frac{10\,000 \cdot 0.100}{20} \left[\frac{W \cdot km}{\frac{km}{h}} \right] = 50 \text{ Wh} \quad (3.7)$$

$$E = \frac{P \cdot s}{v} = \frac{100\,000 \cdot 0.100}{20} \left[\frac{kW \cdot km}{\frac{km}{h}} \right] = 500 \text{ Wh} \quad (3.8)$$

Bus traffic is generally time limited and hence high charging power is the preferred option. Furthermore, the overall system must have an installed capacity large enough to satisfy an average demand of the combined bus fleet. As many Elonroad stretches might become shared between different bus lines, a single segment might need to have an installed capacity that covers the possibility of all bus lines requesting power simultaneously. This is further discussed in following subsections.

3.4.1 Lund power grid configuration

Kraftringen Nät AB is the appointed local grid owner in Lund city area. They are responsible for the physical grid of cables with surrounding equipment and distribution of electrical power from the regional grid.

The power supply to the city of Lund goes through two main entry points, being *Värpingemottagningen*(VPE) and *Östra mottagningen*(ÖM). In a broader perspective, these stations are directly connected to the regional power grid of 130 kV. E.ON is responsible for operation and maintenance of the regional grid, meaning that Kraftringen has to agree with E.ON regarding maximum power supply at each connection. Consequently, introducing electric roads with enough power to supply a city bus fleet requires assurance that the capacities of regional connection points are not exceeded. In general this applies to the average hourly value of supplied current.

At the consumer side of VPE and ÖM entry points there are several substations, either transforming to a lower voltage or transferring the current forward to other stations. For safety precautions, Lund municipality has chosen to connect two more 130 kV stations (*Södra mottagningen* (SM) and *Västra mottagningen* (VM)) directly to VPE and ÖM. In case of electric power failure on regional level distribution to one entry point, Lund city will still retain power supply from the other entry point. (Frennesson & Sporre, 2014)

Depending on power requirements and other factors like distance and safety, each customer is connected to a specific substation as in *Figure 3.5*. For instance, regular homes need 400/230 V supply whilst industries and other applications like Elonroad might demand higher voltages.

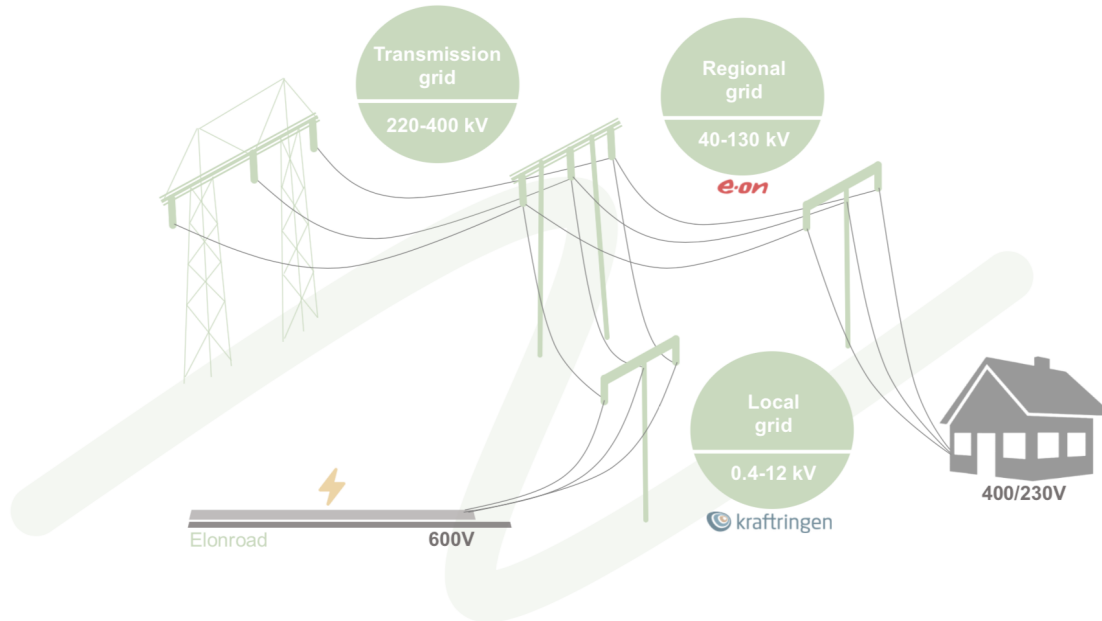


Figure 3.5: The regional grid owned by E:ON supplies power to the local grid owned by Kraftringen where it is transformed in several substations. Different users connect to different substations depending on its specific demands.

In the case where several bus vehicles request charging simultaneously from the same road stretch, there might be a need for medium voltage grid connection (meaning 11-22 kV). According to Kraftringen there are plenty of 12 kV cables running across the center of Lund and power supply of up to 2 MW should be possible at most of them. All costs related to both low- and medium voltage grid connections are presented in *Table 3.1*.

The subscription tariff is based on the highest power consumption averaged during one hour over the year. For values over 1 MW, a maximum power has to be decided in advance and using more power than this will render in penalties. The power tariff is based on an average of the top two consumption hours during the time period November-March. The rest of the costs are either constants or dependent on the total electricity consumption during a certain period. (Kraftringen, 2018)

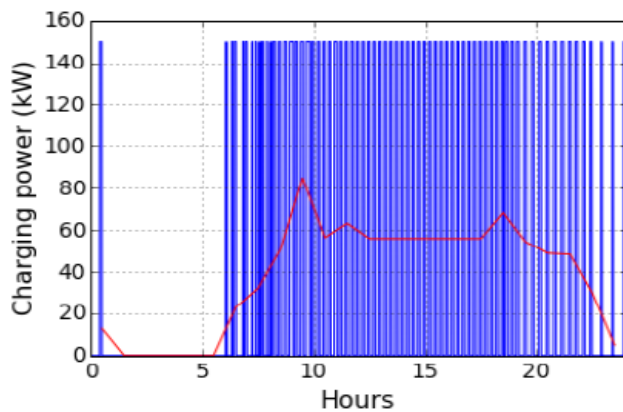
Table 3.1: Costs related to connection to electric grid. All costs excluding VAT and energy tax (Kraftringen, 2018).

Cost	11-22 kV	0.4 kV	Unit
Fixed tariff	12 000	6 000	SEK/yr
Subscription tariff	155	193	SEK/kW/yr
Power tariff	373	453	SEK/kW/yr
Net compensation tariff	0,055	0,075	SEK/kWh
Connection fee (0-200m, 200A)	82 500	82 500	SEK

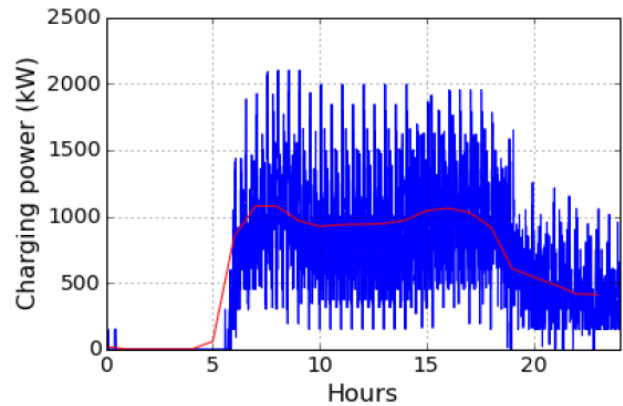
3.4.2 Electric road grid requirements

The main components associated with power transfer to electric roads are rectifiers, transformers and cables. Many vehicles charging at the same time from an interconnected segment increase the power accordingly. Therefore calculations has to be made with respect to the combined power magnitude that a certain number of buses might simultaneously request. Generally the costs of associated components are functions of installed power which needs to be taken into consideration throughout any economic calculation.

Current design of the local grid with its substations and different voltage levels will effect the connection points for electric roads. A segment with high power capacity might not be suitable to place in an area where the grid is weak. Weak grids can usually be found on the country side where long low voltage cables are used. If connected to such a sub-grid there would be problems with the voltage level at the households on the same sub-grid. In cities, however, the grid is usually strong and has better capabilities of delivering the power needed to propel various vehicles (Alaküla, Gertmar, & Samuelsson, 2011). The earlier study by Lars Lindgren on installation of electric charging infrastructure in Lund (Lindgren, 2015) included a simulation of bus traffic during one day to obtain estimations of instantaneous and average load in a system with both static and dynamic charging possibilities. *Figure 3.6a* shows average load on a typical single bus station whilst *Figure 3.6b* shows average load in the system. Individual charging powers are limited to 150 kW in the earlier study and hence the values in *Figure 3.6* will be increased slightly. Due to time limits, the authors use Lindgren’s results to draw conclusions about grid connections and other related electrical components.



(a) Instantaneous and average power drawn from a charging station during 24 hours.



(b) Instantaneous and average power drawn from the entire system during 24 hours.

Figure 3.6: Results from simulation of bus traffic in Lund during one day (Lindgren, 2015).

Another requirement for grid connection of electric roads is a transformer. The negative pole of the electric road segments is connected to earth, but so is the local grid side. Using a transformer is an effective way to allow for this setup.

Table 3.2 presents all relevant charging infrastructural components and their corresponding costs. Net station, transformer and cable costs are obtained from the ElnätsBranschens Riktlinjer (EBR) system provided by Svensk Energi (Svensk Energi, 2018). Both cables and net stations are potentially more expensive to place in the city center compared to the outskirts. The three

different types of additions to the bigger net stations are due to local requirements. In the very center of Lund it could be necessary to dig down a station entirely in order to maintain the visual appearance of the city. Apparently this raises the price of the installation with more than 3 million SEK compared to a simple net station. Apart from external equipment, each vehicle also requires some on-board pick up and DC/DC converter to manage the supply of electricity. These internal components are estimated to cost 250 000 SEK for 180 kW charging and 500 000 SEK for 360 kW (Lindgren, 2018).

Table 3.2: All costs related to components of the full electric road system from Svensk Energi (Svensk Energi, 2018) and earlier studies.

Component	Cost	Unit
Net stations		
Net station 315 kW	170 020	SEK/qty
Net station 800 kW	202 022	SEK/qty
Net station 1.25 MW	373 149	SEK/qty
Added cost net station in center \geq 800 kW	902 282	SEK/qty
Transformers		
12/0,4kV Trafo 315 kW	51 380	SEK/qty
12/0,4kV Trafo 500 kW	63 942	SEK/qty
12/0,4kV Trafo 1.25 MW	165 000	SEK/qty
Cables		
PEX 3x240 12 kV center	1 076 322	SEK/km
PEX 3x240 12 kV urban	737 452	SEK/km
PEX 3x240 12 kV rural	416 183	SEK/km
On-board equipment		SEK/qty
180 kW	250 000	SEK/qty
360 kW	500 000	SEK/qty

3.4.3 Realistic connection points

Consultations with Krafrtingen has been iterative throughout the thesis process to gain somewhat realistic results on where to connect an ERS in Lund. In the end, a map that represents some average design of the results was brought to Krafrtingen to discuss possible solutions. They analyzed the design and came up with an effective and profitable solution based on,

- available power capacity
- distance to possible connection points
- distance from potential connections to the end of a connected Elonroad segment. The Elonroad company have stated that more than 500 m could be problematic (Zethraeus, 2018)

Apparently most results (see *Figure 6.5–6.9*) include segments of electric road around *Lund C*, *Bantorget* and *Universitetssjukhuset* which could be supplied with enough electricity using 3 central locations (see *Figure 3.7* black dots) according to Krafrtingen. Furthermore, they propose two options on how to utilize these three points. If all connection points should require more than 2 MW of installed power, one would need to draw cables to the VM substation outside Värpinge (see *Figure 3.7* red dot) in the west of Lund (described in *Section 3.4.1 – Lund power grid configuration*).

But as long as each location can settle with 1-2 MW, the 3 central locations are sufficient. Connection at VM would cost around 15 MSEK whereas connections at the 3 central points would cost around 0.5 MSEK each. These costs can be found in in *Table3.2*

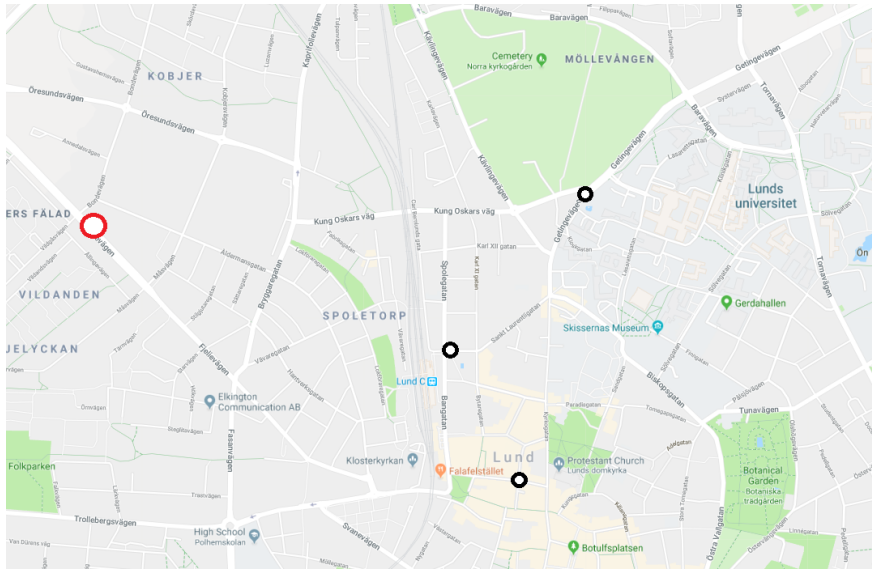


Figure 3.7: The three central connection points are marked as black circles near Lund C, Bantorget and Universitetssjukhuset. The VM substation is marked as a red circle (Skarrie, 2018).

For the end terminal stations – being too far from the central connection points – Kraftringen presented cable lengths needed to reach suitable locations at their low voltage grid for each individual station. This was done for both 180 kW and 360 kW charging power options and resulting costs include physical connection to the dug down cables of the grid, cables up to the electric road and electric meters. Yearly and energy consumption dependent costs from *Table 3.1* are added in the results section.

The simulated power requirements from *Figure 3.6b* by Lindgren are altered slightly to be valid for 180 kW individual charge power rather than 150 kW used throughout his study. A linear increase would be obtained by the ratio $\frac{180}{150}$ which equals 1.2. Though to create margins and reduce risks of an insufficient system, the authors use a factor of **1.5**. A quick recalculation gives that instantaneous power should now have its peak at approximately 3.2 MW whilst the average power should increase to around 1.5-1.7 MW depending on time of the day.

By utilizing 1.25 MW net stations from *Table 3.2* at all three central locations, the system power demand of most results would arguably be covered since $1.25 \text{ MW} \cdot 3$ equals 3.75 MW (which is larger than the estimated 3.2 MW peak). One might argue that utilization of two central locations with a combined power of 2.5 MW could as well be sufficient. It would easily cover the average power demand, and peak power is valid for the whole system including end terminal stations. The peak power demand from central dynamic and static charging loads is thus even less than 3.2 MW and will probably not add up to above 2.5 MW very often. Furthermore, the electrical components can most certainly withstand occasional "overloading" or else the Elonroad technique might deliver less than each vehicle require during some short periods. (Lindgren, 2018)

4 DATA COLLECTION AND USE

This chapter explains where data input for the optimization algorithm (explained in a later chapter) comes from. Real time measurements are available for the present system whilst good approximations of reality is the only option for the future system. Selection of specific time periods for data extraction is described and the use of data to calculate bus density is introduced.

In order to obtain an optimized proposition of where to place electric road segments from an economical point of view, some sets of informative data and processing software are crucial. Mainly, it is of interest to know and present,

- How the bus traffic is/will be organized and operated today/in the future regarding dwelling times, velocities and exact route geographic locations.
- What possibilities and limitations there are regarding power grid connections.
- A written algorithm which takes into account all the information above and optimizes costs.
- What restrictions there might be in the city area for implementation and construction of the electric road system.
- Other information that might influence the realism of the optimized design.

4.1 Bus system

As mentioned earlier, each route is assigned a specific schedule that might differ between weekdays or weekends. Also there might be several buses taking turns on operating one route during a day etc. At perfect conditions, these facts should create a somewhat predictable system. However the impact of things like of human delay, traffic jams and such will always affect the system continuity, complicating the process of optimizing any features.

4.1.1 Present system data

To gain a more realistic result of this thesis, it is crucial to use real time measurements. Fortunately the bus organizer Skånetrafiken could provide such information during any given time period including much of the desired real time information. It is considered as most significant for the validity of the results.

The authors were admitted access to Skånetrafiken's bus analysis tool called *Citrix Receiver* in order to retrieve the data from their portal. Arrival and departure times, average velocity between bus stops, number of trips per day and station sequences was essential data that could be collected for all lines and any period of time during the past two years. No measured distances were available

in the data base, and thus most of them have been estimated using time and average velocity between stations to avoid manual measurements of all routes.

In addition to measured data, the authors have used available General Transit Feed Specification (GTFS) data from *Samtrafiken* – a cooperation between 60 Swedish transportation companies – to get geographic locations of every bus station in Lund (Samtrafiken, 2018).

Finally there are always some errors in large quantities of data that have to be corrected. For instance, some distances might fail to be calculated and at the same time hard to detect. Therefore, an approximative function is used which calculated the shortest distance between two geographic locations. All data is organized in structures with specified dates, lines, directions and such to enable easy access to correct measurements.

4.1.2 Future system data

Due to the impossibility of real time measurements for a not yet tested bus system, one need to apply several approximations based on present operational patterns and information from the organizations in charge of the project. The authors use Citrix Reciever data valid for the present system combined with geographic locations from Samtrafiken to create a simplified model including average values of station dwelling times and velocities distributed over different zones. No specific geographic borders are available to divide Lund into these zones and hence they have been obtained as length from the city center (see *Figure 4.1* for principal sectioning). Each geographic point in Lund from GTFS-data is allocated to a specific zone and all points within this zone are found in Citrix Reciever to form average values of their dwelling times and velocities.



Figure 4.1: The city of Lund has been divided into several zones depending on length from the city center.

Regarding future geographic locations and distances, most of the bus station sequences are similar to present ones (compare *Figure 2.1* and *Figure 2.3*). Though some had to be manually

added, processed and measured using Google Maps online services.

It should be mentioned that testing of the simplified model on the present system is crucial to show validity and transferability to a future system.

4.1.3 Input data selection

When studying the Citrix Receiver database, it became clear that measured values differ between weekdays, weekends, summer and winter as suspected. Thus it is crucial to motivate any selection of data inputs to the optimization model since it might affect the final results. An important feature of a bus system is its robustness and flexibility, meaning it must be reliable even during "worst case scenarios". However due to Elonroad's ability to employ both static and dynamic charging, a definition of these scenarios becomes somewhat divided. A worst case for static charging would for instance be during periods of extreme traffic which could imply lots of delays, creating less charging time at each station and risk for "stranded vehicles" (Olsson et al., 2016). In comparison, electrical roads are generally less vulnerable to interruptions in the traffic since a bus can not skip any road stretches to make up for lost time. It will get charged regardless of when the trip is made. But the velocity could however have an impact. A worst case for dynamic charging would be during times with almost no travelers or traffic, meaning higher velocities and less "stops" along the electric roads due to queuing. Similar to the opposite case, this is instead favorable for full utilization of static charging times at every station. As the reasoning implies, a combination of both charging strategies is probably required to cover every possible scenario.

According to studied data, summer months generally mean lower frequency of departures, slightly higher velocities and shorter dwelling times at each station. The opposite case tends to be valid during rest of the year, especially at weekday mornings and afternoons. Dwelling times and departure frequencies become longer due to increased traveler activity whilst velocities decrease due to more traffic. Because of these differences, both summer and winter based data would be preferred. However, the electric tram construction work in Lund has forced significant changes in bus line driving routes. The authors gained information about how the bus system is designed today and could therefore not use data from earlier summer months. Instead, all data input were limited to the period January–April of year 2018. It was prioritized to locate a period with extreme weather which might infer a lot with the logistics stability. Using weather data from Sveriges meteorologiska och hydrologiska institut (SMHI) (SMHI, 2018), one particular week in the shift of February and March with plenty of snow and sub zero temperatures was located. This week work as basis for all optimization results and is further modified through the "*possible scenario results*" to resemble extreme conditions similar to mentioned worst case scenarios.

4.1.4 Bus density

A written algorithm requires some base philosophy for decision making of what it believes to be the optimal choice. The authors call this philosophy **bus density** which can be explained as,

"number of seconds that each road segment or station is occupied by bus traffic during a specified time period"

All costs can thence be divided over total density to guide the algorithm towards the cheapest locations of Elonroad installation. However, the definition "all costs" is a bit hard to cover. The theory of bus density has to be combined with limitations regarding surrounding power grid capacity. Power output increase linearly with the amount of simultaneous connected vehicles, hence altering the combined load on the grid along with investment costs for larger electrical components. It

requires lots of time and accuracy to correctly include these constantly changing parameters. The algorithm need to have some additional information regarding connection points in Lund and what power that is available in each point to make realistic implementable choices. The authors could not obtain this information, and due to time limits the costs are approximated from EBR numbers within the same zones mentioned in *Section 4.1.2 – Future system data* (inner city, urban and rural). The approach for grid connection points is to present an optimized electric road network design to Krafringen, without regards to available points and powers. They will analyze the design and propose how to connect the system in the most profitable way.

4.2 Lund possibilities and limitations

Consistent with the thesis purpose of presenting an optimized but yet realistic solution, there are some site specific limitations that need to be considered. Many of these limitations are difficult to point out unless you have knowledge about both technical performance and geographic obstacles.

A combination of digging costs and development state limit this thesis to the use of on-surface electric road segments. Although it might not result in any component damage or danger to road users, it is considered an unnecessary risk to position these segments in junctions, roundabouts and pedestrian crossings.

All central parts of Lund that are indicated by the dark purple color in *Figure 4.2*, the streets are covered with small cobblestone. Outside of this perimeter there are patches of cobblestone but mainly asphalt. Questions arise about how electric road segments should be installed where the road is covered with cobblestone and according to Anna Karlsson (A. Karlsson, 2018) the municipally has had previous problems with durability when material or paint is attached to to the cobblestone. This problem is due to the behavior of different materials when exposed to varying temperatures during the winter months. Furthermore it is evident that any digging will be more expensive where cobblestone is located compared to the figures in the EBR system for a city center. (A. Karlsson, 2018).

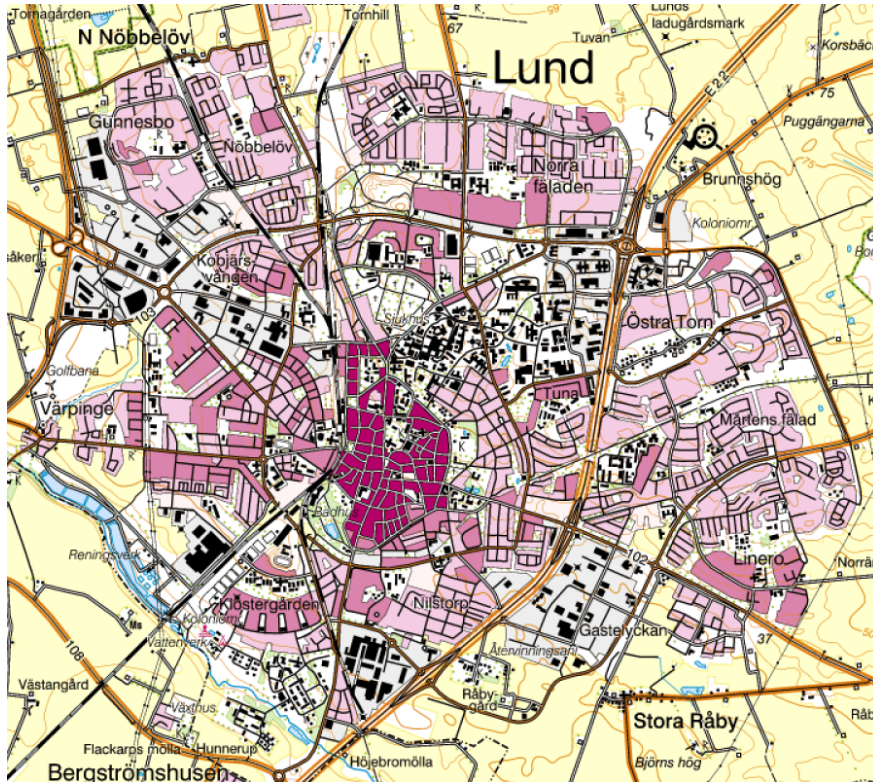


Figure 4.2: Lund city center in deep purple color, urban area in light purple color and rural area in yellow color (Lantmäteriet, 2018).

As a result, any optimized economic result might need some modifications to fit the current traffic situation in Lund (explained further in *Chapter 6 – Simulation results*). The *Google Maps* on-line service combined with personal experience of the authors work as sources for data collection regarding these restrictive areas.

5 THE OPTIMIZATION PROCESS

This chapter explains how the optimization process functions. Some important approaches and treated obstacles are mentioned together with their solutions. The process of selecting profitable Elonroad locations is described together with some included cost estimates. Lastly, a rainflow counting algorithm which estimates battery life time is explained

Optimization processes generally require management of large quantities of data. The amount of variables allowed to influence any final result decide the complexity of the problem. It is common that a complete optimization, meaning the quest for a global extreme, is too difficult and time consuming. By making good approximations of reality and choosing smart solution methods, one can end up with a simplified but surprisingly accurate model. A global extreme might not be reached, but in many cases a well motivated local optimum could be just as valuable.

A bus system will constantly undergo variations in how the fleet is managed depending on seasons, weather, city construction work and many other events. Hence finding the global cost minimum of implementing a new operational strategy like charging strategy for a future electrified bus fleet might not be possible. Retaining a constant minimum would very likely need the opportunity to rearrange a large part of the charging infrastructure over certain periods of time.

Since periodically rearranging a whole network of electric roads is not an alternative, one must dimension the system to at least sustain average operation patterns during a chosen period. Preferably this should be a period with harsh conditions to eliminate risks of failure.

Furthermore, one need to consider the importance of all involved parameters. In the case of this thesis, importance is directly connected with cost of each component or service. All costs correctly included in the optimization model would enable a global minimum calculation, but as suggested it could risk a very slow process. The main cost drivers have been chosen as electric road and batteries whereas grid connections and other electrical components are approximated by zone functions combined with the vicinity of other Elonroad segments (described further in next section).

5.1 MATLAB simulation model

The simulation model is written by the thesis authors in MATLAB and is programmed to work according to a set of suboptimized steps which are intelligibly explained through this chapter.

The basic approach is founded on the use of geolocation, i.e. latitude-longitude coordinate pairs, to track where bus lines intersect and share routes. If two lines share a coordinate pair and driving direction, the station or following road segment is considered shared. The result of this philosophy is described as bus density in *Section 4.1.4 – Bus density* and expressed as *bus seconds per time period* trough the simulation process. The amount of bus seconds (\mathbf{D}) in each road segment or at each station is defined as the sum of products of total vehicles (\mathbf{N}) and time duration (\mathbf{t}) as in *Equation 5.1*. Each bus route performs a specific amount of cycles and dwell some average seconds

at a specific point or road segment. Hence the combined traffic found in a specific point is obtained from simply analyzing shared geographic coordinates in the system, but time duration differ from many earlier works made within this topic. Whilst other similar projects often is limited to static charging time at bus stations or terminals (Worley, Klabjan, & Sweda, 2012), electric roads enable the possibility of dynamic charging time with its advantages mentioned in *Chapter 3*. Therefore the time contribution to bus density is not only expressed as station dwelling time, but also as distance and velocity between stationary points.

$$D = \sum_{n=1}^{\text{No. shared lines}} (N \cdot t) \tag{5.1}$$

One obstacle that require some manual work when analyzing dynamic charging possibilities is the lack of sufficient information regarding exact driving paths. It is relatively simple to communicate bus stations to determine density since each route either includes a specific station or not. However, the communication of shared roads are not always linked with bus stations. Consider the two cases in *Figure 5.1* where shared roads are accidentally ignored. The green points are stations where bus line A dwell whereas red points are stations where bus line B dwell. In the upper case, stations 1A and 1B are approaching a junction from different directions. Thus their station coordinates are not equal and the algorithm will not consider the stretch between the junction and station 2A/2B as shared. The lower case describes roads with several stations or positions used by different bus lines. Whilst bus line A uses stops 1A and 2A, bus line B uses stops 1B and 2B which are all separated. The algorithm will not detect any shared coordinates and hence no shared road segments here either. The authors have solved this problem by manually adding "imaginary" stations with zero dwelling time at motivated junctions and points shown as yellow dots in *Figure 5.1*. Every bus line passing these dots without actually stopping will still have them noted in their paths to allow density calculations.

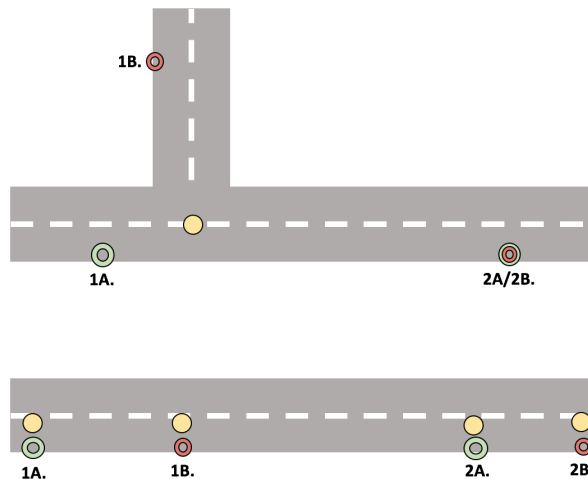


Figure 5.1: Some extra points have to be manually added to allow for density communication between shared road segments. In both cases above, these shared segments would be ignored without addition. Red and green points are bus stations, yellow dots are added "imaginary" stations.

The density approach is considered an efficient tool to interconnect the Lund city bus traffic system. The primary simulation goal is to analyze and fulfill the energy demand of a complete round-trip in each bus route, making them *charging neutral* and independent of individual vehicles. With this approach, any bus should be able to operate every single route without charging related issues provided that there is some predetermined battery buffer covering bus line changes and other energy-consuming short term maneuvers.

A correct application of the density tool will point towards certain stations and road segments which are more profitable to electrify from a system perspective. To prioritize economical results, the model is preferably built to minimize cost per charged kWh. A given density combined with charging power (P) will tell the amount of kWh's possible to allocate in each point (E_{pot}) during a specified time period (Equation 5.2).

$$E_{pot} = P \cdot D \text{ [kWh]} \quad (5.2)$$

Since the aim is to make every bus line charging neutral, i.e. supply a certain amount of energy, the charge potential above become crucial for locating the cheapest possible kWh's in the system. Consequently the optimization algorithm is designed to gradually pinpoint the cheapest units based on the most important system costs. However, there are some embedded charge level restrictions which might force the optimization model to choose less profitable locations. Further explanation follow below in the electrification selection process.

5.1.1 Electrification selection process

The MATLAB model requires multiple datasets to begin its selection process. Apart from the variables that define density and charging potential, one need to specify several cost related and system limiting factors. A complete set of necessary parameters is presented in Table 5.1. All parameters (except latitude-longitude coordinates that define the system) can be varied by the user to test the system response and analyze cost effectiveness.

Table 5.1: Parameters required to initiate the optimization process.

Parameters	Unit	Description
[lat _{drive} lon _{drive}]	°	Latitude-longitude sets along each bus line (including road intersections).
[lat _{stop} lon _{stop}]	°	Latitude-longitude sets for stations along each bus line.
s	m	Distance between pairs of coordinate sets.
v _{avg}	m/s	Average velocity between all bus stations.
t	s	Dwell time spent at every bus station.
NoC _{line}	qty	Number of cycles per line during specified period.
C-rate	h ⁻¹	The maximum allowed battery charge rate.
P	kW	Charging power.
P _{terminal}	kW	Charging power at end terminal stations.
W _{batt}	kWh	Battery size.
SoC _{start}	%	The SoC value that each line should have when starting every round-trip.
SoC _{max}	%	Maximum allowed SoC value during a round-trip.
SoC _{min}	%	Minimum allowed SoC value during a round-trip.
km _{cons}	kWh/km	Electricity consumption per km.
C _{elonroad}	SEK/km	Cost per km of Elonroad.
C _{batt}	SEK/kWh	Cost per kWh of battery.

Each bus line is gradually assigned electric road segments until its net round-trip energy use is neutral (meaning that $E_{\text{consumed}} - E_{\text{charged}} = 0$). The selection algorithm (*Figure 5.2*) is repeatedly locating the cheapest possible kWh's within the limits of SoC maximum and minimum limits. Some selections (like end terminal stations) generate large electricity quantities due to long dwelling times and might lead to addition of unnecessarily much charging. Therefore a first regulatory step of erasing possible electric road locations within an individual line is initiated. Every location is erased with a priority order of most expensive first to test the system response. If a deletion is possible (the line is still neutral), it is "accepted" by the algorithm which effectively deletes the position. When all bus lines are satisfied with enough charging infrastructure, a first sub-optimization is considered complete. Though since they have been designed individually with density as the only communicative tool, the total system might become over-dimensioned. A shared station or road segment could be selected in *Line A* but not in *Line B*, thus providing unnecessarily energy to *Line B* when the system is combined. The global optimum or some close approximation is considered as included in this system, but further processing is required to find and remove any unnecessary charging infrastructure, this time on a system level.

Again, every static and dynamic electric road segment is tested to be deleted from the system with priority order most expensive first. If the system response is positive, i.e. all lines remain charge neutral and become cheaper, this new system is saved. Having tested all deletions, an attempt for reaching optimum (or closely related) charging infrastructure design using the initial parameters is acquired. Its economical performance (costs of electric road and batteries) and design are presented which can be compared with other system results. The user can easily vary input parameters to compare economic results with other starting conditions. Results have shown to be competitive with the present bus system (*Chapter 6 – Simulation results*) and thus the algorithm is considered reliable.

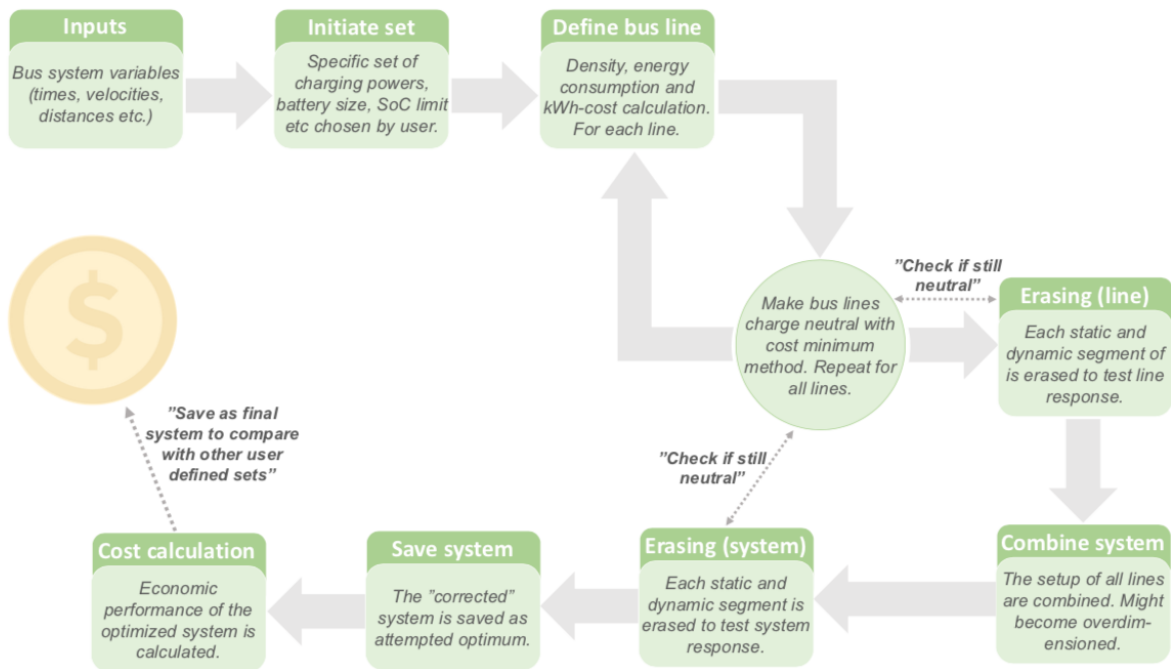


Figure 5.2: The algorithm works according to several different sub-optimizing steps. In the end, the cheapest system design will be saved for further analysis.

Economical performance is measured as cost for electric road system design and batteries at the end of each optimization. Costs related to power grid connection and other electrical hardware are regarded as either very difficult or not decisive enough for integration in the algorithm. Instead, they are added manually in a later stage to better suit the power grid configuration in Lund. But in order to force the algorithm to make sufficiently realistic assumptions of these costs, the authors felt that cost estimations for connections to the electrical grid were needed throughout the optimization.

From *Table 3.2* it is obvious that installation costs for electrical components like transformers and cables vary from most expensive in central areas to least expensive in rural areas. Furthermore, if two possible electric road locations are close to each other (this distance is estimated to 10 meters but can be changed if better information is available) they might share costs of a common grid connection including installation and electrical components. To prioritize interconnected segments and account for city areas, zone based costs are included in the calculation for each and every segment. This cost is not exact, it is merely a way of giving inputs to the algorithm that will favor a continuation of electric road segments and construction of single charging points in the outskirts of the city.

The connection cost includes estimations of all components from *Table 3.2* combined with connection fees from *Table 3.1*. If costs can be shared (i.e. the segments are closer than 10 meters), the cost for connecting a second segment to the first one equals 0 and hence the only costs driver is Elonroad. The map in *Figure 4.2* shows the center of Lund in purple color. In this area there is an added cost for installing larger net stations over 800 kVA. Furthermore this area is the most expensive zone for digging and cable laying as can be seen in *Table 3.2*. The light purple color in the map is considered to be urban area and the yellow color represents rural area where digging and cable laying is less costly.

Figure 5.3 shows how the authors choose to divide Lund into three zones (central, urban & rural) which are used in the algorithm for allocating estimated costs to every Elonroad segment. The reason for this somewhat strange arrangement of the zones is the fact that the very center of Lund is not geographical placed in the middle of the city. Furthermore, there are no exact definitions available for these areas in Lund and hence the estimations were the only solution (A. Karlsson, 2018). However, they are easily modified in the algorithm code if better information is gained.

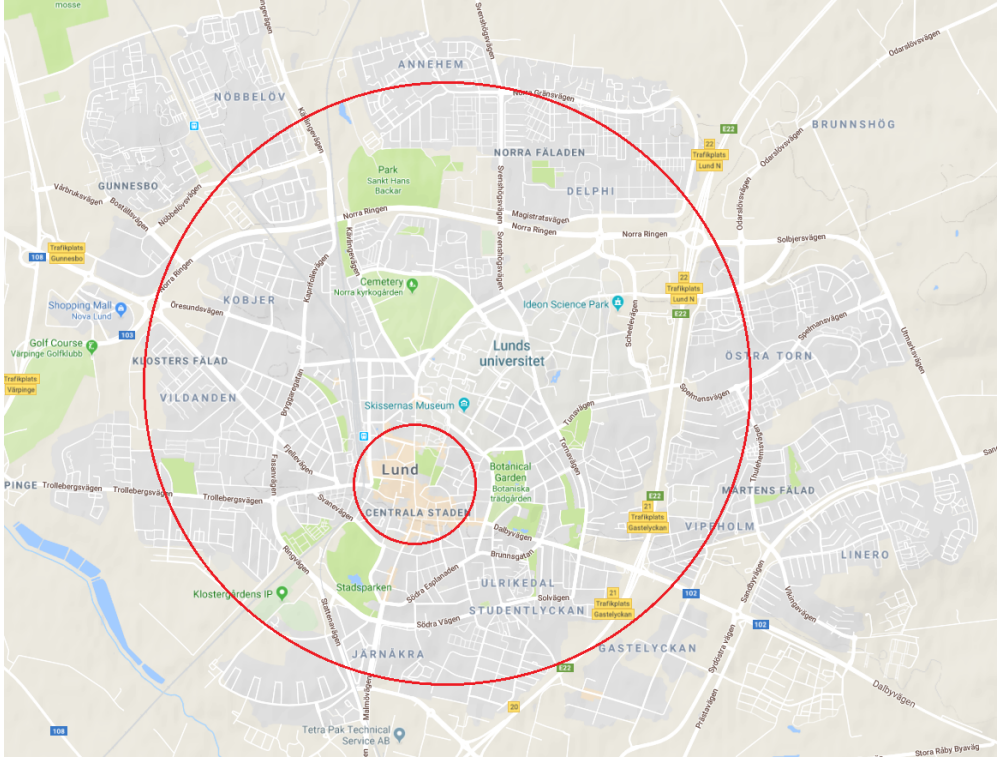


Figure 5.3: Lund city divided into three zones where the inner circle represents zone 1 and so on.

Table 5.2 shows the costs associated to the connection of a new segment of Elonroad in the three respective zones.

Table 5.2: Zone costs for a new connection used in the algorithm.

	SEK/new connection
Zone 1 (central)	1 447 000
Zone 2 (urban)	714 000
Zone 3 (rural)	582 000

To create a dynamic algorithm selection process, the cost for installing an electric road segment is constantly updated for every location. When initiating the process, all locations need a new grid connection along with new electrical components. Thus bus density and city area are sole decision makers regarding where to put the first dynamic or static charging segment. The system is instantly updated to reduce costs for electrification at roads or bus stations that are interconnected (or close) to the earlier selection.

Elonroad costs are calculated from knowing exact lengths of electrified segments and SEK/km of the hardware. Batteries are however more difficult to analyze as mentioned in *Section 3.3 - Batteries*. A rainflow counting-algorithm has been included for the charge and discharge events of every bus line to determine battery damage and lifetime. Its basics are explained below.

5.2 Rainflow counting-algorithm

When a material is exposed to enough repeated fatigue cycles (loading and unloading), it will eventually fail. If all loads are identical, it would be relatively easy to predict the number of fatigue cycles before failing. But since this is rarely the case, some method considering alternating stress is desirable. The rainflow counting-algorithm is a widely used method when analyzing the impact of stress loads on any material.

It has been noticed that stress behavior is transferable to the charging and discharging events of electric batteries. With a given SoC profile, one might use the rainflow method to estimate the degradation of batteries over time. (Xu, Zhao, Zheng, Litvinov, & Kirschen, 2017)

5.2.1 Working principle

In order to gain all important information and good results, the *four point counting method* is used. Four points are repeatedly selected and processed whenever the end points are local extremes. *Figure 5.4a* shows the first selection of values from the earlier example of how the SoC might vary over time. Here, s_1 and s_4 represent the local extremes. The algorithm picks the smaller charge and discharge events with a length equal to the distance between s_2 and s_3 (red markings), stores them in a matrix and erases them from the SoC profile. A new sequence is formed according to *Figure 5.4b* which is processed in the same way. Notice that s_1 is not included in *Step 2* since this would require s_6 (the fourth point) to be an end point and hence also a local extreme which it is not. Instead, the algorithm move the sequence one step ahead to see if the next four points are applicable. This procedure goes on, storing all charge and discharge depths until there is only one large cycle left, called residue (*Figure 5.4c to 5.4d*). Finally, this residue is also stored as a cycle. (Hiatt, 2016)

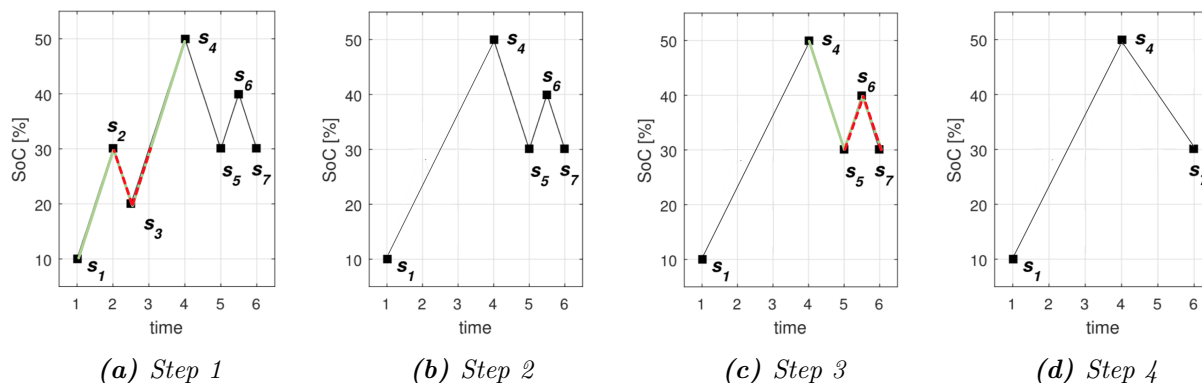


Figure 5.4: How the algorithm would work on this SoC profile example (Shi et al., 2017).

All extracted intervals are stored as sets of charge and discharge depths in vectors where all extreme values can be distinguished and stored. A final array of stored extreme values serve as input to the rainflow counting algorithm. Suitable counting methods are derived as MATLAB functions which in turn output all results as indexed arrays with amplitude, cycle depth and half or whole cycles connected to each charge-discharge-cycle. Examples of all outputs and their appearance are visualized using the same SoC profile as before for simplicity in *Figure 5.5*. The philosophy behind whole or half cycles is easiest shown by flipping the SoC profile 90°. Cycle numbers are detected by releasing "flows" from each valley, hence the expression rainflow counting.

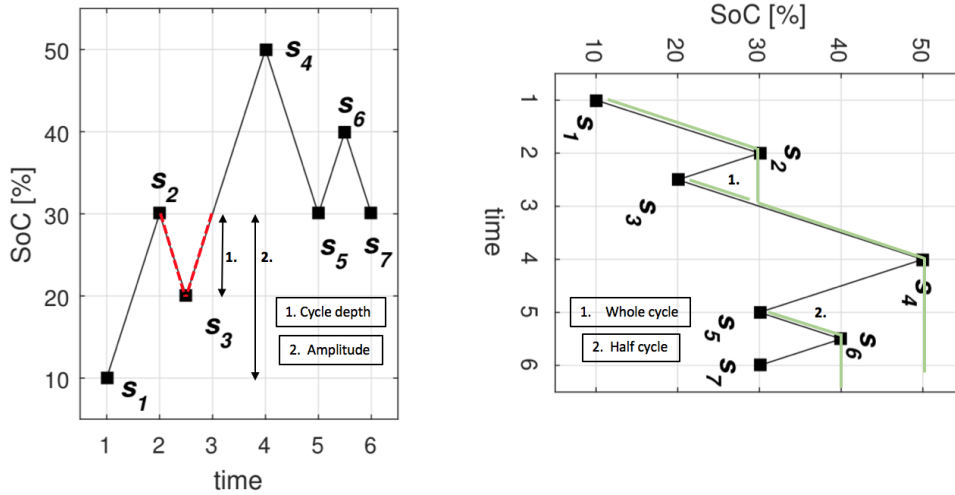


Figure 5.5: Outputs obtained through the rainflow counting algorithm. Cycle depth and amplitude are easily detected whereas cycle numbers have to be visualized with a "rainflow" (Shi et al., 2017).

Each cycle depth is connected to a given battery wear curve (like the one in *Figure 3.2*) to account for its specific number of fatigue cycles before failing. A total wear and thereby possible number of repeated charging-discharging profile before failure is estimated according to *Equation 5.3*. Each charge or discharge event corresponds to a specific NoC which is multiplied with either 1 or 0.5 cycles (whole or half). The inverse of that product becomes its individual wear which is summarized with the wear of all other cycles. Inverting that sum will generate an estimation of total NoC before battery failure.

$$NoC_{tot} = \frac{1}{\sum_{n=1}^{No. \ events} \left(\frac{1}{NoC_n} \right)} \quad (5.3)$$

This total NoC value is compared with the scheduled amount of bus cycles during a specified time period to verify whether one battery will be sufficient. If not, the ratio between scheduled cycles and possible battery cycles will tell the number of battery changes required. It should be added that 64 batteries (same amount as bus vehicles in the fleet) are always required as investment cost. If less than 64 batteries are required to cover NoC_{tot} according to the counting algorithm, it simply means that most of the 64 batteries have lifetime left after the investigated time period.

6 SIMULATION RESULTS

This chapter begins with a presentation of some parameter values chosen by the user as inputs to the optimization algorithm. Results for the present system are presented together with a simplified model which is used to estimate profitable designs in a future system. Several imaginable scenarios are tested and evaluated through a couple of sub-processes. The algorithm automatically gives some costs whereas the remaining economics is added manually

6.1 Input values

Any outcome of the optimization algorithm might be highly dependent on the user defined inputs. To mimic different kinds of realistic situations, one need to analyze the system response under various conditions. Decision makers within infrastructural planning projects must know that the system is robust and flexible before accepting any investments, therefore creating great importance of thorough testing. The authors have chosen multiple sets based on constants and intervals presented in *Table 6.1* which are regarded as sufficient basis for sensitivity analyses and to draw any final conclusions about an efficient and profitable system design.

The present bus system in Lund will not become equipped with an ERS and therefore it is not tested with all sets. It simply works as basis to evaluate accuracy of a simplified model with zones for dwelling time and velocity. As mentioned in *Section 4.1.2 – Future system data*, these simplifications are required since real time measurements are not possible to get for a future system.

Table 6.1: *These parameters, constants and intervals are chosen for a thorough analysis of possible conditions.*

Parameter	Used values	Unit
P	180	kW
P_terminal	[180 360]	kW
W _{batt}	[90 180]	kWh
SoC _{start}	75	%
SoC _{max}	90	%
SoC _{min}	[50 25]	%
km _{cons}	2	kWh/km
t _{terminal}	[0 90 180 300]	s
C _{batt}	3 000	SEK/kWh
C _{elonroad}	7 500 000	SEK/km
C-rate	2	h ⁻¹

As argued in *Section 3.1 – The Elonroad technique*, the use of dynamic segments involve risks of many vehicles requesting power simultaneously. Dynamic (or static at bus stops in city center) power supply (**P**) has therefore been limited to 180 kW per vehicle to avoid risks of infrastructural underestimation. This choice is further discussed in the next chapter.

The C-rate is initially set to 2 kW/kWh, meaning that a chosen battery is charge power limited by a factor of two in kW vs kWh capacity. Some of the combinations from *Table 6.1* are therefore not allowed, for instance a 100 kWh battery with 360 kW charge power. However, a C-rate of 6 kW/kWh is tested as an extreme scenario for analysis and discussion reasons.

Battery sizes are varied from small 90 kWh to large 180 kWh to investigate wear costs compared with investment costs. Small batteries will wear more, but they are at the same time cheaper.

A maximum SoC value of 90% is chosen with respect to earlier studies mentioned in *Section 3.3 – Batteries*.

The starting SoC value is chosen as below maximum but still with large marginal to minimum, creating some space for charge and discharge events.

Minimum SoC values are dependent on the tested battery size. They are modified to manage one round-trip of the longest bus line (Line 4 according to *Table 2.2* with $21.2 \text{ km} \cdot 2 \text{ kWh/km}$) in case of accidental electricity disruptions in the system. The longest is chosen to ensure that all vehicles can operate any line and always manage one round-trip without charging.

The electric road cost is set to 7 500 000 SEK/km after discussions with the Elonroad company. This cost applies to the exact distance of installed road segments. If Elonroad is installed in both directions at a 1 kilometer road strip, the total cost is therefore 15 000 000 (1 kilometer at both sides of the road).

It should be repeated that any algorithm cost results are based on required electric road and battery wear. These costs do not tell the whole story before being combined with grid connection costs and other components. A more expensive algorithm result might become cheaper after these additions and must therefore not be excluded in this first step.

6.2 Description of result presentation

All bus routes are plotted as straight black lines between every bus station latitudinal (y-axis) and longitudinal (x-axis) coordinates. Electric road segments are shown as lines whereas bus stations with static charging are shown as dots. A thicker line or a larger dot implicate more bus lines being dependent on charging in that exact location. This is connected with total possible load and thus installed power capacity. Furthermore some color coding is done to separate unidirectional from bidirectional dynamic or static charging locations. A light green line means unidirectional electric road whilst dark green lines imply bidirectional. Pink dots mean unidirectional static charging whilst red dots imply bidirectional. Final economic results for electric road costs and battery costs can be read in each figure.

Electric road costs (presented in *Figures 6.1–6.9*) are solely based on total investment costs for pure electric road components. The zone based costs used throughout the algorithm process is neglected and more precise costs for grid connection and other components are added in the next section. Pure electric road costs also enable calculations of total electric road distance installed for each system design. This distance is considered interesting and important to present to any decision maker.

Battery costs are presented in all result figures as total investment cost for purchasing 64 units (one for each bus vehicle (Sörensson, 2018)) and one "equivalent wear". Equivalent wear is defined as "how much battery lifetime that the system will demand over a specific time period" (in this

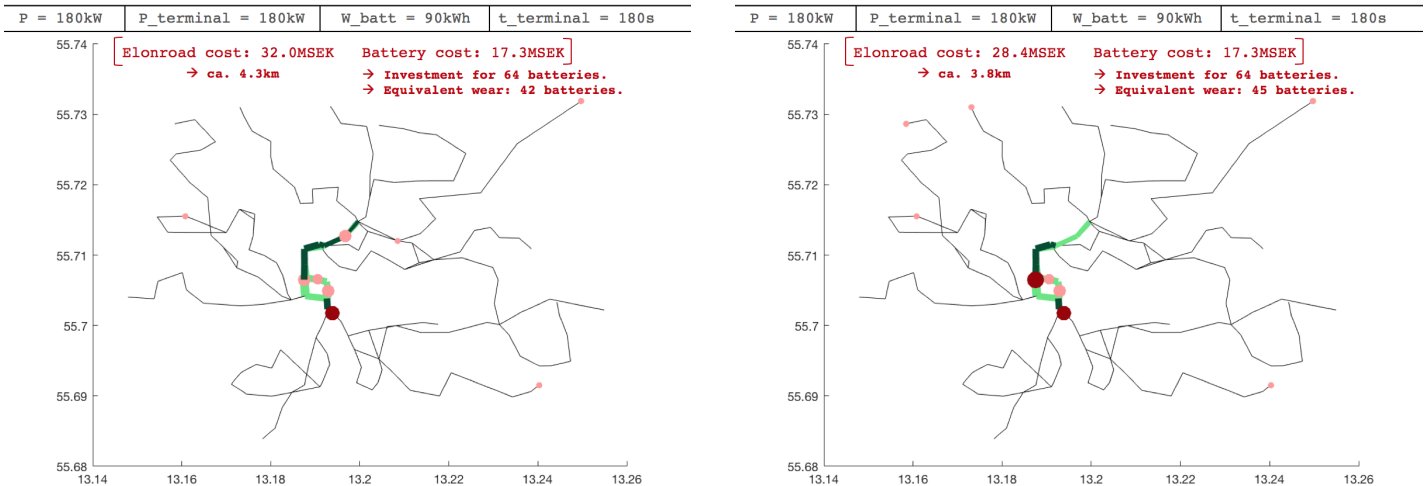
case 10 years) with a given battery size. If this value is **less** than 64, it implies that there will be battery lifetime left to use. If this value is instead **larger** than 64, it implies that some battery replacements will be required to manage operation during the specified time period.

6.3 Present system and simplification

Real time measurements result (to the left) and simplification result (to the right) are presented in *Figure 6.1*. Real time measurements means that the actual velocities and stoptimes from Skånetrafiken have been used. In the simplified model average values have been used as described in *Section 4.1.2 – Future system data*.

The parameter setup consists of exclusively 180 kW charging power, 90 kWh batteries and 180s (3 minutes) dwelling time at end terminals. The exact input values are not very important in this case, they are rather chosen as presentable for comparisons with a simplified model.

The battery investment cost for 64 vehicles is equal in the present system results, though less lifetime is required to cover total energy consumption during a 10 year period. Since all vehicles need to be equipped with individual batteries to manage logistics, this extra lifetime is "unnecessary" unless some resale value is accounted for. Electric road costs seem to be higher with real data than with the simplified model (32.0 and 28.4 million SEK). The simplified model uses mean values for velocity and stop times instead of real measurements as in the "real data result" to the left.



(a) Real data result for present system.

(b) Result from simplification model.

Figure 6.1: A comparison between the current real system and its simplified model. This is important for further analyzes. The x- and y-axis are longitude and latitude coordinate respective for plotting bus routes in correct geographic locations.

The most apparent difference is the bidirectional (dark green) stretch of electric road in the north of the real system being replaced with some extra bus stop chargers. This can be explained by the current construction work in Lund. The authors are aware of large traffic redirections in this northern area close to *Universitetssjukhuset* which probably means slower average velocities. Slower velocities has the opposite effect on density which increase due to more time spent across each segment. In a simplified case however, the velocity through this area is affected by all velocities within a certain zone. Consequently, site specific parameters will not have as strong decisive role

regarding where to place electric road. As a result, the high density road segment from *Figure 6.1a* become unidirectional in the simplified case where velocities are higher. It is instead more profitable to add some two extra end terminal stations and bidirectional charging at *Lund C*. These rearrangements are considered highly motivated and thus the simplified model is suitable for realistic approximations.

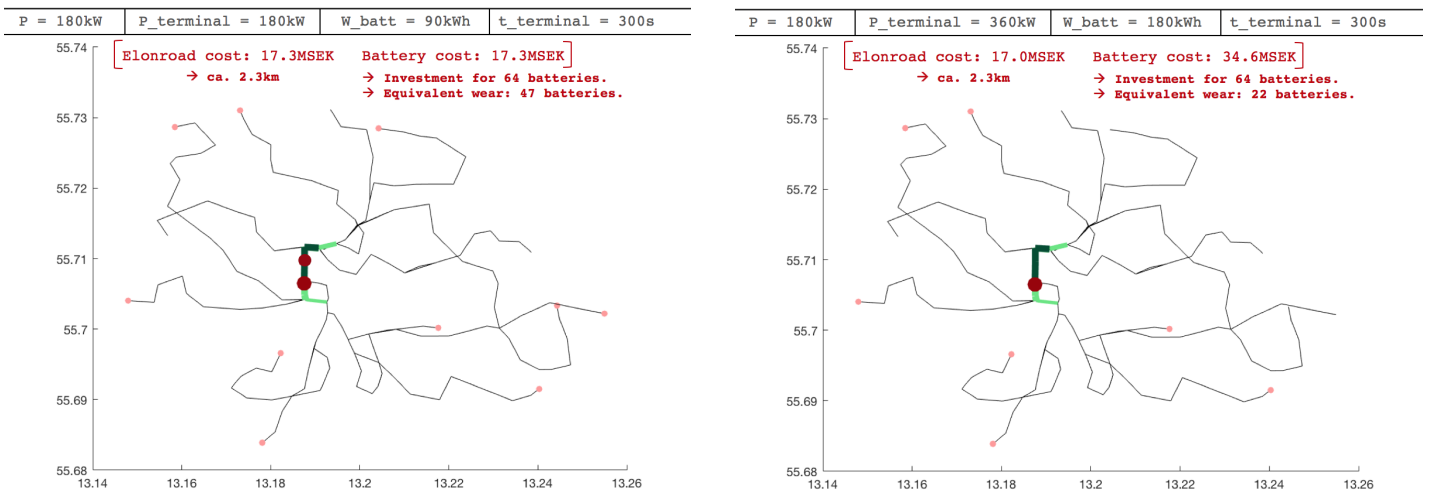
6.4 Future system results

Unlike the present case, the future system is to be designed for true implementation of an ERS. Hence different data setups are tested to analyze economic results and performance. A wider result perspective is advantageous for later discussion.

Initial dwelling time at end terminal stations is set to 300s (5 minutes) after communication with Nettbuss bus operator. Concordant with the collective agreements of hired bus drivers, Nettbuss try to maintain at least 8-10 minutes at one end station (where toilets and other necessities are available) and a few minutes at the other end (Jansson, 2018). The authors thence feel confident that 5 minutes in each end is a good estimation of a "perfectly working system".

6.4.1 No geographic limitations included

Two cases of charging power are presented below where *Figure 6.2a* is limited to 180 kW and *Figure 6.2b* has the possibility of 360 kW static charging at end terminal stations. Due to an assumed C-rate of 2 kW/kWh, the batteries in the latter case can not be smaller than 180 kWh whilst the first case can manage 90 kWh and above. All results are based on the simplified model. Even with higher charging power at end terminal stations, the most central parts of Lund seem important enough to become selected. As *Section 2.2 – Future fleet and changes* propose, the area around *Botulfsplatsen* will see a 30–50% decrease in traffic which is validated when comparing below results with *Figure 6.1*.



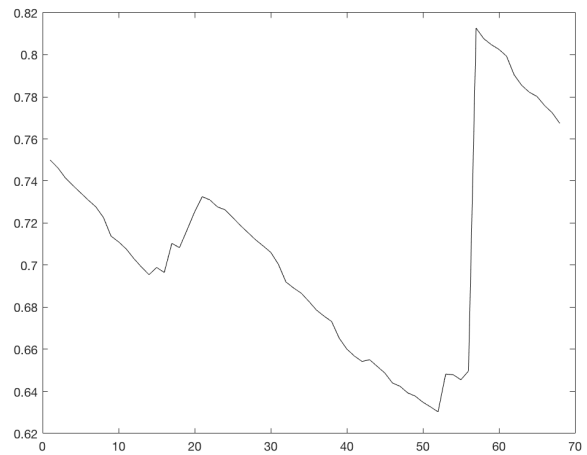
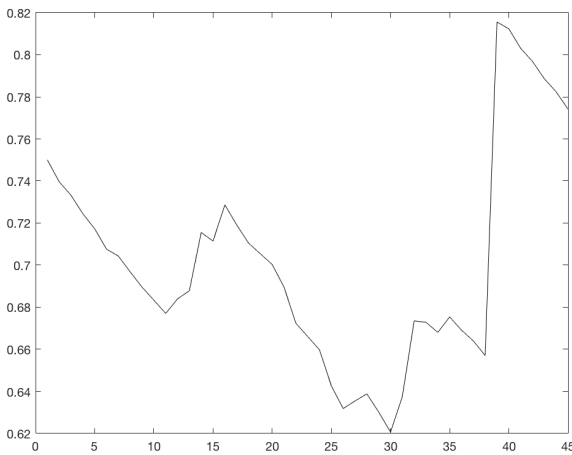
(a) Result with 180kW charging power throughout the whole system.

(b) Result with 360kW charging power at end terminal stations and 180 kW throughout rest of the system.

Figure 6.2: Two different charging power configurations for the future system are tested to get a flexible basis for further discussion. The x- and y-axis are longitude and latitude coordinate respective for plotting bus routes in correct geographic locations.

Several battery sizes were tested to find out that the least possible dimensions allowed by assumed C-rate is sufficient. Still, the total energy consumption require less than 64 batteries over a 10 year period (47 in case (a) and 22 in case (b)). Unless there is some resale value, one would argue for using even smaller batteries. *Figure 6.3* presents SoC-profiles for the most crucial lines in each of the two cases above. Most crucial meaning closest to reach the buffer level of one round-trip (of Line 4) without electricity supply. The minimum SoC-value is a crucial parameter if any smaller batteries should be motivated since they will suffer even higher discharge.

Both the present and this future system show that 360 kW charge power at end terminal stations become significantly more expensive due to the larger battery demand as a result of the C-rate limit being 2 kW/kWh. All electrical components that are added manually in a later stage are more expensive in order to manage higher power supply. The 360 kW alternative is hence always become unprofitable in relation to the 180 kW alternative (despite the possible need of less charging stations), unless there is some way to accept higher C-rates. This is further discussed in *Chapter 7 – Discussion*.



(a) Most crucial SoC-profile of the system with exclusively 180 kW charging power.

(b) Most crucial SoC-profile of the system with 360 kW at end terminal stations and 180 kW in rest of the system.

Figure 6.3: The x-axis is measured points (i.e. value at each geographic coordinate) and y-axis is the SoC level in percentage where 1 equals 100%. Evidently there are some space left for decreased battery size in both future cases. The buffer levels are 50% and 25% in case (a) and (b) respectively.

6.4.2 Geographic limitations included (Default scenario)

So far the model do not account for geographic obstacles which is a part-goal of this thesis. To avoid complications, the main obstacles – being **junctions**, **roundabouts** and **pedestrian crossings** – are regarded as unavailable charging locations. To cover these, every line is now made charge neutral by tricking the algorithm that sufficient electricity supply is reached at total round-trip consumption plus some extra value chosen by the user. To ensure that the whole system becomes neutral, this value is approximated by knowledge of bus routes combined with results from *Figure 6.2*. All obstacles that seem to become included in resulting system designs plus some extra additions (for pedestrian crossings and to ensure full coverage) are measured in *Figure 6.4* to obtain a total "unavailable distance".



Figure 6.4: Several obstacles are chosen and added to ensure full charging coverage for each bus line. The total unavailable distance is 500 meters which gives approximately 10 kWh extra charging marginal input to the algorithm.

An estimated sum of the distance covering all obstacles and extra additions for each line became 500 meters. This value is over-rated for many other lines, but enough to manage extremes. An assumption of 10 km/h average driving velocity (approximately half of the system average) through all limitations give a loss of energy supply (E_{loss}) according to *Equation 6.1*.

$$E_{\text{loss}} = 180 \cdot \frac{500}{10 \cdot 1000} \left[kW \cdot \frac{m}{h} \right] \approx 10 \text{ kWh} \quad (6.1)$$

The total consumption is hereby increased by 10 kWh for every bus line, forcing the algorithm to find a slightly different solution. New results including realistic limitations are presented below (Figure 6.5). Most resulting costs are probably too large due to 10 kWh extra being an overestimation. For instance, a decrease to 400 meter obstacle distance at an average velocity of 15 km/h would require only 5 kWh additional charge. It should be mentioned that the distance of electric road in all proceeding figures is too far by 500 meters which is unavailable charging. But if all obstacles are removed, one need to connect the remaining patches of electric road with cables, thus increasing costs. Therefore, the authors choose to see this extra cost as 500 meters of electric road instead of cables, to over-estimate rather than underestimate cost results.

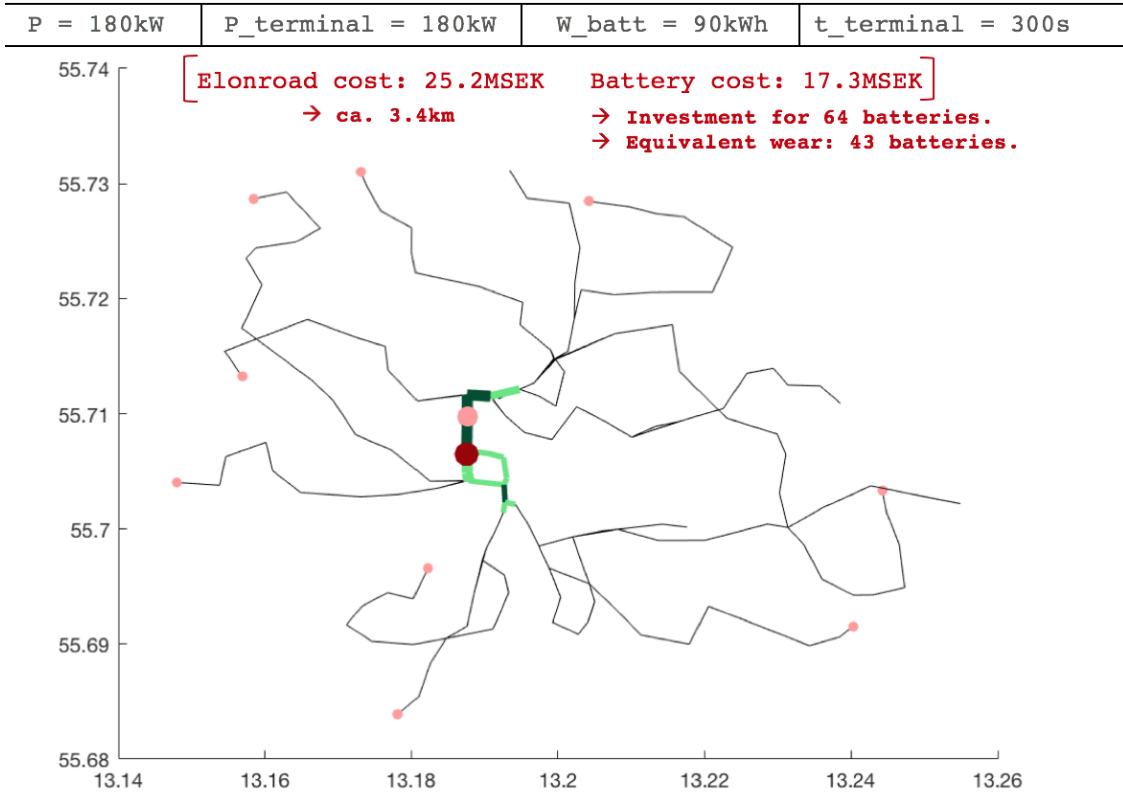


Figure 6.5: Addition of an estimated sum of limited distances to the future system force selection of more dynamic charging.

The new system design is as imagined similar to the ones without realistic limitations with the addition of some extra electric road segments, mainly from *Botulfsplatsen* to *Lund C* via *Lundagård* and *Stadsbiblioteket*.

6.5 Possible scenario results

Bus system logistics is as known dynamic, meaning that it changes depending on traffic situations. To cover more conditions and draw conclusions about robustness and flexibility for future designs, some scenarios are presented below.

6.5.1 Less time at end terminals

During days with lots of travelers and heavy traffic the bus drivers might arrive late to end terminal stations, meaning less time to recharge. A situation where only 90 seconds dwelling time (1.5 minutes) might be a recurrent problem during harsh periods, for instance during cold winter weekdays. *Figure 6.6* shows that the most profitable solution is installation of some extra electric road stretches (ca. 2 km extra with a resulting cost of 39.8 million SEK compared to 25.2 million SEK with 5 minutes end terminal charging).

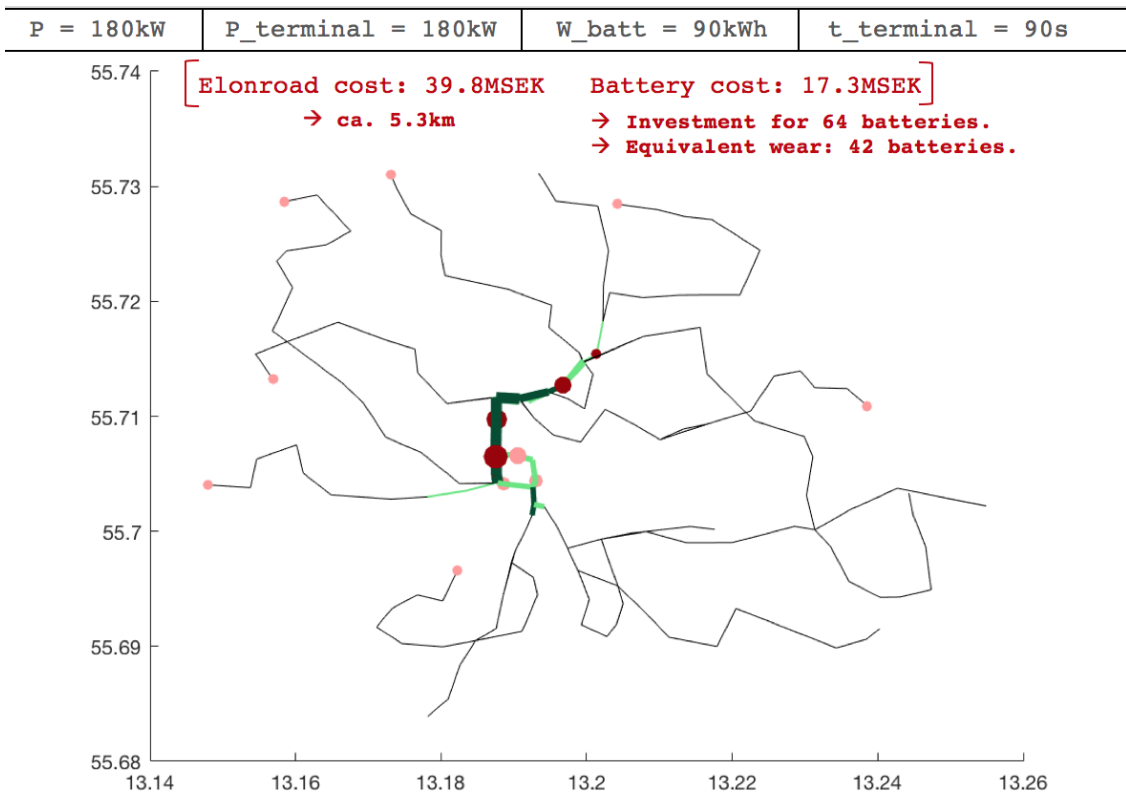


Figure 6.6: Less charging time and exclusively 180 kW charging power in the future system.

6.5.2 No charging time at end terminal stations

An extreme scenario where drivers must continue directly after reaching an end terminal station will result in several minutes loss of charge. As seen from SoC-profiles in *Figure 6.3*, the charging events at end terminals are generally very important to maintain a sought neutrality. Their absence might drain the battery in a few round-trips which is highly undesirable for a system that many people rely on. This is an interesting scenario to test since it should increase the importance of dynamic charging.

Results show that approximately twice as much dynamic electric road segments should be installed (7.1 km with a total cost of 53.4 million SEK compared to 25.2 million SEK with 5 minutes end terminal charging) together with a lot of extra static charging points (*Figure 6.7*).

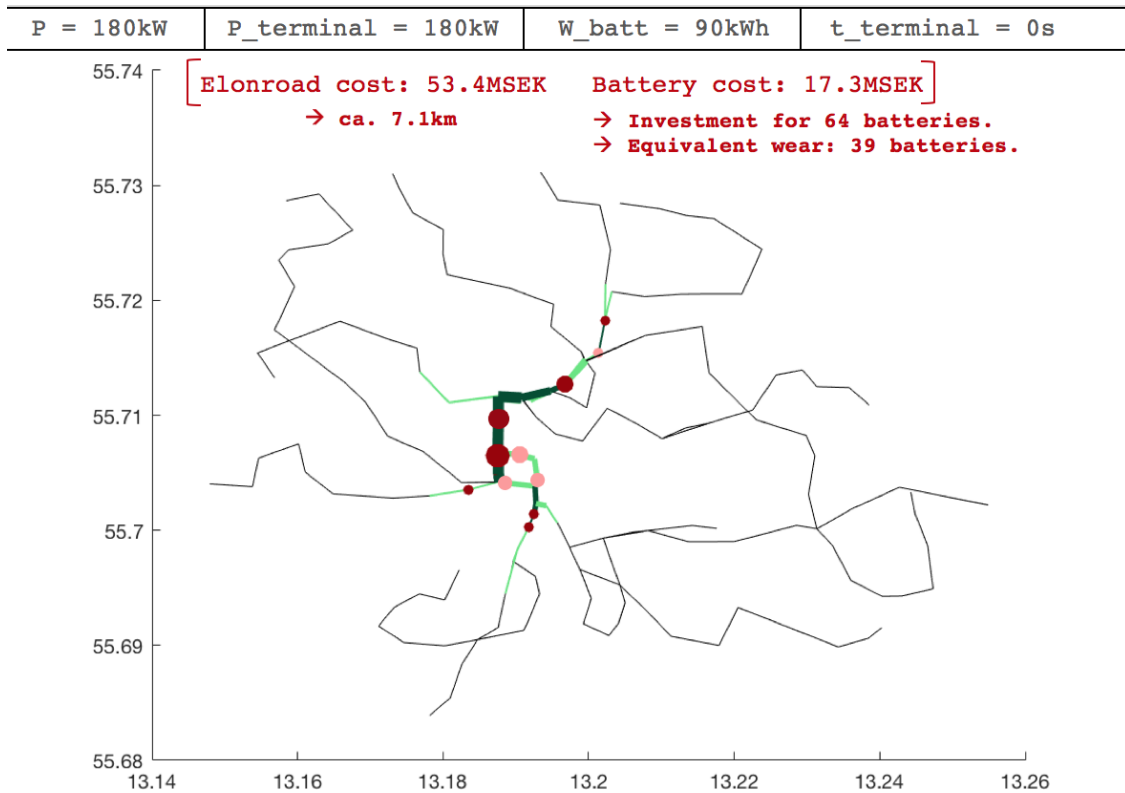


Figure 6.7: No end station charging time and 90 kWh batteries (i.e system designed for 180 kW charge power) in the future system.

All of the static points are located along dynamic stretches which is profitable due to a simple "branching" possibility. Other static points might require new grid connections if they are situated far from other electric road segments, making them significantly more expensive.

6.5.3 Higher average velocity

One improvement proposed in the published bus system rearrangement plan from *Section 2.2 – Future fleet and changes* is a higher average velocity, 22 km/h. Higher velocities imply shorter time spent connected to every dynamic segment and might therefore result in need of extra electric road. If comparing *Figure 6.8* with *Figure 6.5*, the system behaves as suspected. One stretch close to *Universitetssjukhuset* becomes bidirectional and an extra static charging position is added at *Stadsbiblioteket*.

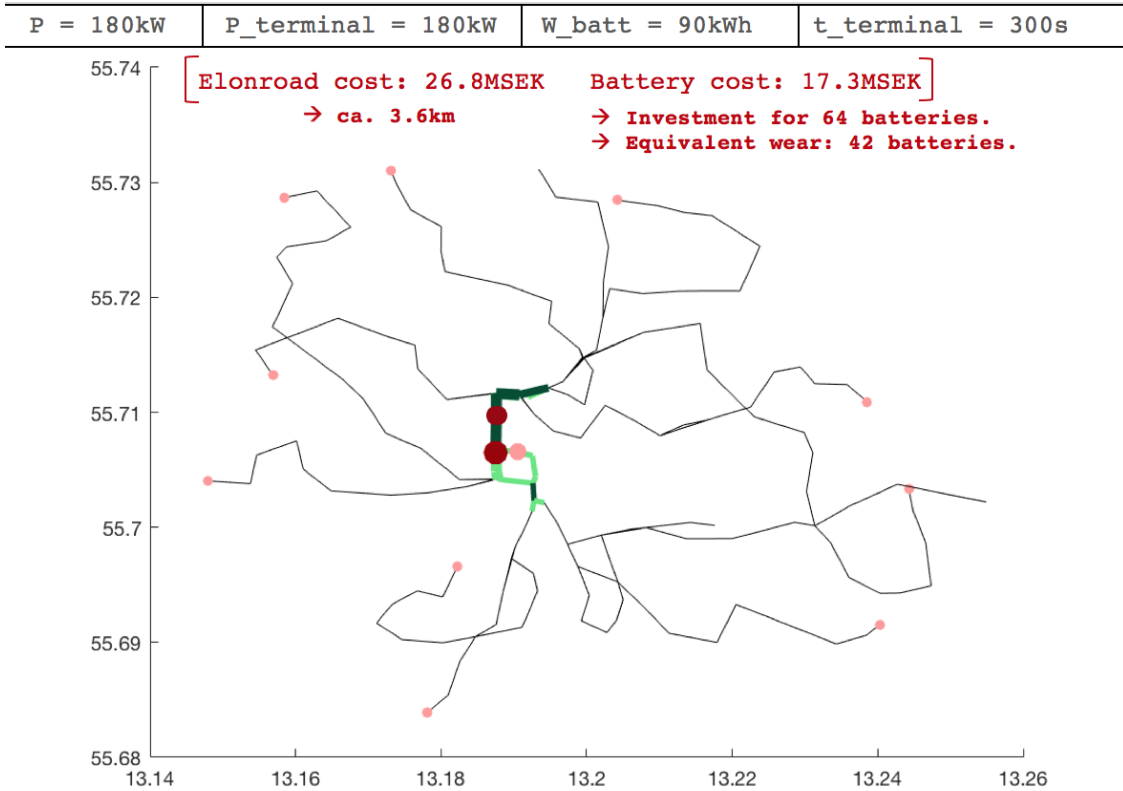


Figure 6.8: A scenario where the average velocity in the future system is increased to 22 km/h (from approximately 18.5 km/h before)

6.5.4 Only static charging at end terminal stations

Earlier studies and bus traffic electrification processes have generally only had the opportunity of static charging. Below is the result if only using this technique at end terminal stations of 300 seconds dwelling time. No geographic obstacles are included since no dynamic charging is possible.

A charging power of 360 kW is used as the only alternative at end terminal stations. Simple calculations show that 180 kW of end station charge power during 300 seconds provide 15 kWh per station (i.e. 30 kWh in total). Most bus lines in *Table 2.2* are longer than 15 km, meaning that 180 kW would generally not be sufficient with 2 kWh/km consumption.

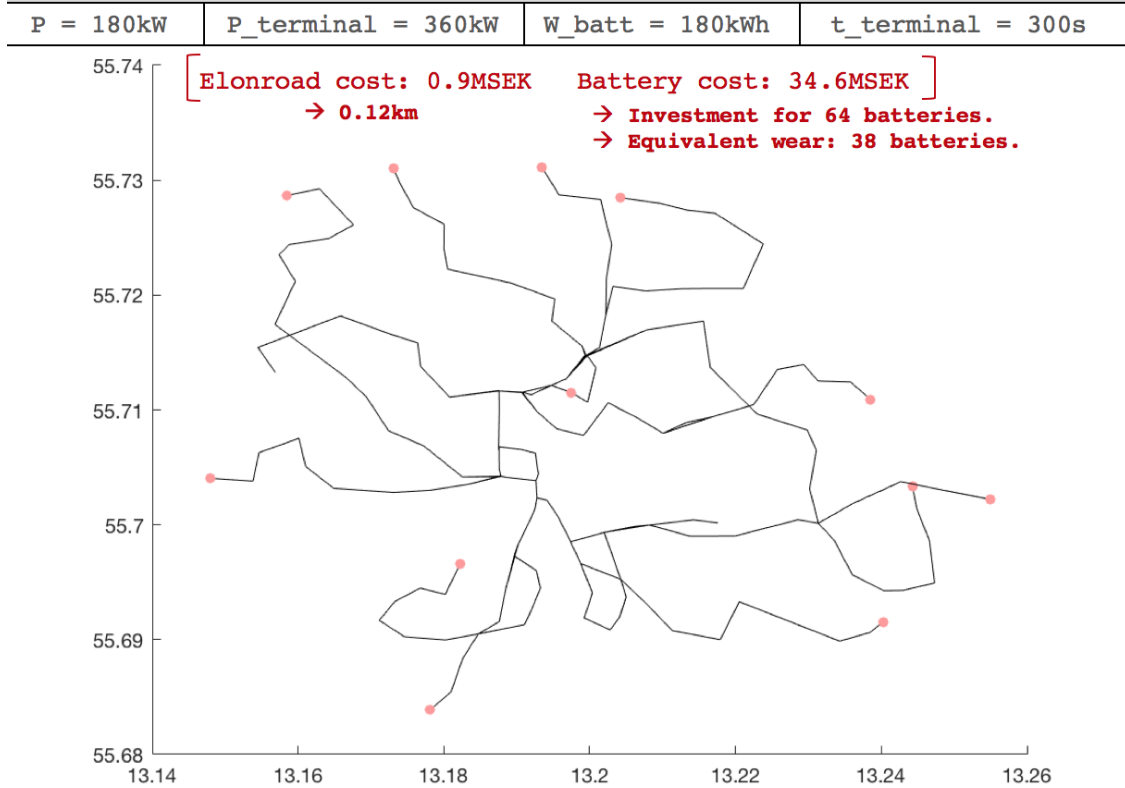


Figure 6.9: A future system scenario where the only charging option is static charging at end terminal stations with 360 kW power.

It is obvious that the algorithm result becomes considerably cheaper since no dynamic stretches are installed. The average round-trip distance of the future system is **18.0 km** (*Table 2.2*), which means that minimum dwelling time at each end terminal station must be,

$$\frac{18}{360} \cdot 2 \cdot 3600 \left[\frac{km}{kW} \cdot \frac{kWh}{km} \cdot \frac{s}{h} \right] = 360 s \quad (6.2)$$

In other words, the system needs an average of 180 seconds (3 minutes) at both end terminals to get sufficient electricity supply. Some lines need more than this whilst other need less. All in all, the system gets very dependent on keeping up with the time schedule.

6.6 System costs

As suggested, it is of great importance to examine all optimization algorithm results before drawing any conclusion about the most profitable system design. All items from *Section 3 - Electric road system components* need to be included and correctly treated to get a complete picture and good basis for further discussion. These include energy consumption, power grid connection fees, net stations, on-board charging equipment and other related system components.

Furthermore, both the electric infrastructure and the bus vehicles need maintenance. The annual cost for maintenance of infrastructure is assumed to be 5% of the investment cost for electric road plus electric infrastructure. For the buses, maintenance cost depends on the distance that each individual vehicle operate. Since an electric bus does not use much mechanical breaks and its engine being less complicated then a conventional one, costs for maintenance is considered to be slightly lower. However, since the electric bus has an on-board pick up and DC/DC converter the maintenance for both electric bus and gas bus is set to 2 SEK/km. (Olsson et al., 2016)

Grid connections and necessary cables are evaluated differently than the ones from *Table 3.2* which are estimations from Svensk Energi (Svensk Energi, 2018) and used as inputs to the optimization algorithm. Realistic connection points and their "package costs" are instead gained from consultation with Kraftringen (see *Section 3.4.3 - Realistic connection points*). All possibilities given by Kraftringen are presented in *Table 6.2* and the authors were free to use any connection dependent on analyzed system design. High voltage connections are given as a definite cost whereas low voltage connections are given as the alternatives 180 kW or 360 kW of installed power.

Table 6.2: Cost estimations of realistic connection points from Kraftringen (Skarrie, 2018).

Connection	Cost [SEK]
High voltage	
Central point < 2MW	500 000
VM(<i>Västra Mottagningen</i>) 15MW	15 000 000
Low voltage (end terminals)	
Gunnesbo Gård	220 000–370 000
Hubertusparken	130 000–230 000
Annehem	180 000–310 000
Jordabalksvägen	160 000–280 000
Företagsvägen	150 000–260 000
Univ-sjukhuset	300 000–490 000
Flygelvägen	180 000–310 000
Värpinge by	120 000–230 000
Galjevången	220 000–370 000
Drapavägen	180 000–320 000
Ringhornegränden	240 000–400 000
Arenan	200 000–340 000
Råbylund	200 000–340 000
S:t Lars	170 000–300 000

In order to make a fair comparison between the present system and a future electric system the cost for large infrastructural investments are spread over a depreciation period with the same costs occurring every year. A lifetime (**n**) of 15 years is used for all electric infrastructure whereas buses are supposed to last 10 years (coherent with total operative period used throughout the optimiza-

tion algorithm). (Olsson et al., 2016) Combined annual costs can then be calculated according to *Equation 6.3*.

$$\text{Annual cost} = \frac{NPV \cdot p}{(1 - (1 + p)^{-n})} \quad (6.3)$$

Where p is the interest rate which is considered to be 5% and n is the lifetime (Olsson et al., 2016). Net present value (NPV) is the future value of a present investment with regards to inflation and interest rates.

To summarize, the authors have used Microsoft Excel to combine costs of **electric road, batteries, charging infrastructure, on-board equipment, fuel consumption, grid connection fees** and **maintenance**. They are translated to annual costs using net present value (NPV) in order to get more comparable results and *Table 6.3* shows final results for every future scenario tested. No costs for vehicle investments are included at this stage for a simplified understanding of pure operational and ERS costs. Bus driver salaries are not included in any results since the authors presume that they are equal in both cases.

Table 6.3: Annual costs for all scenarios where the default scenario has 5 minutes of terminal charge time. A depreciation time of 10 and 15 years is used for vehicle and infrastructure investments respectively in order to calculate the annual costs.

Annual cost	Gas	Electric [180/180 kW]	Electric [180/360 kW]
Gas alternative	28 500 000		
Default scenario		25 038 213	29 432 484
90 seconds terminal time		26 881 723	
0 seconds terminal time		29 415 122	
Higher velocity		25 272 178	
Only terminal charging			25 323 128

As shown, the alternative with 360 kW charging power at end terminal stations and 180 kW in the rest of the system become significantly more expensive in the default scenario. The ratio become slightly different for other scenarios (not shown) but still always in favor of the alternative with exclusively 180 kW. The economic results for both alternatives in the default scenario is fractionated (*Table 6.4*) to easier spot decisive cost drivers.

Table 6.4: Break down of annual costs in SEK for default electric options, one with exclusively 180 kW and one with 360 kW charging passibility at end terminal stations.

Annual cost drivers	Electric [180/180 kW]	Electric [180/360 kW]
Energy	6 375 000	6 375 000
Maintenance	9 152 243	9 094 036
Depreciation electric road	2 456 728	2 384 472
Depreciation electric infrastructure	991 830	1 076 212
Depreciation batteries	2 237 839	4 475 678
Depreciation bus equipment	2 072 073	4 144 146
Electric fees	1 752 500	1 882 940
Total	25 038 213	29 432 484

It is obvious that battery and bus equipment depreciation are the cost drivers that in the end disfavor use of 360 kW charging powers, even though infrastructure and its maintenance costs are

lower.

The least expensive scenario is compared with the present gas-fueled alternative in *Figure 6.10* to easier differentiate between cost drivers and to create support for any decision making. It is evident that the fuel consumption costs ("energy" in the figure) are far larger in the gas alternative. This is coherent with the three times higher kilometer price argued in *Section 2.3 – Fuel consumption electric vs. gas*.

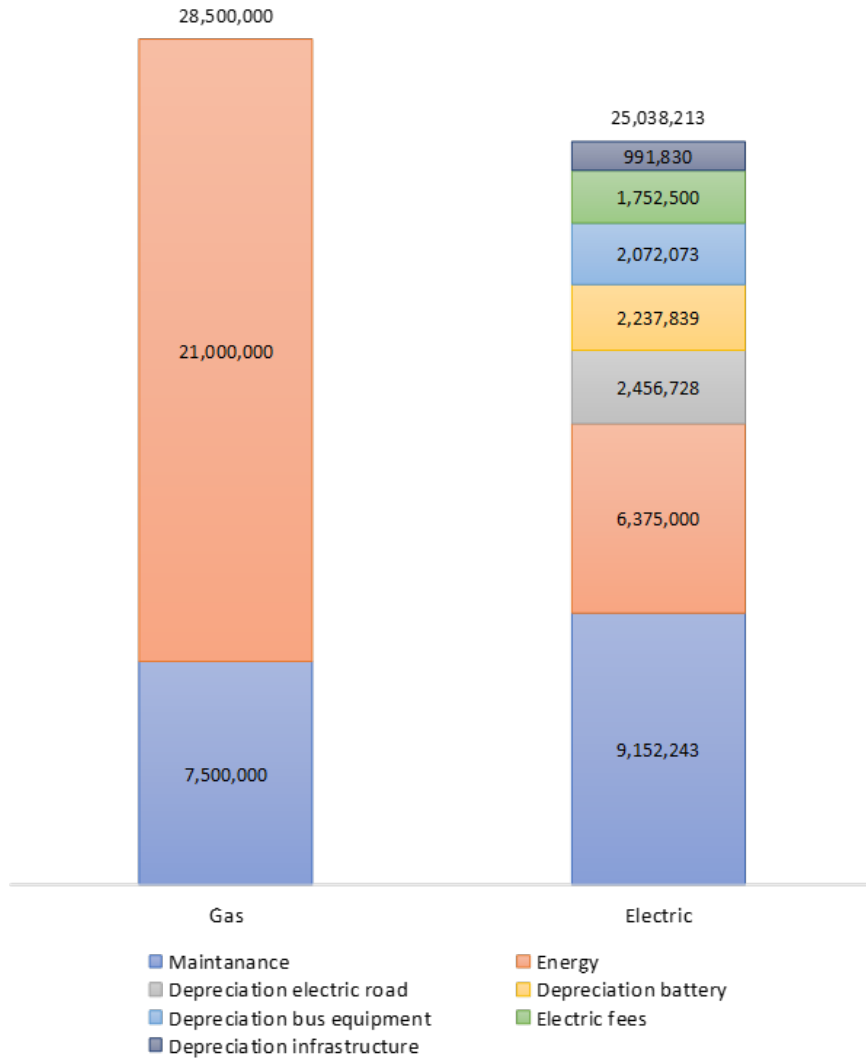


Figure 6.10: All annual costs for present gas driven system and the most economical electric option with 180 kW of charging power at end stations.

When adding the procurement of electric and gas buses the picture changes dramatically. *Figure 6.11* shows how the annual costs would be distributed in such a case. The 1.5 times larger cost for the electric bus in comparison to the gas alternative makes up for over half the annual costs rendering the electrical system 8 MSEK more expensive per year.

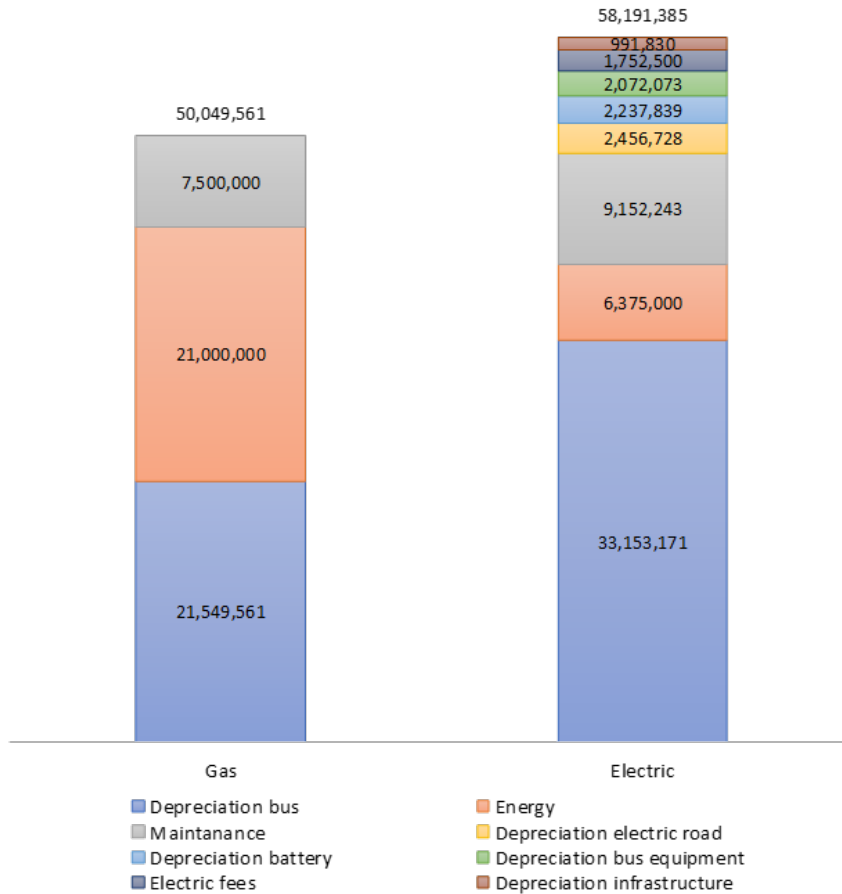


Figure 6.11: Annual costs of gas and optimal electric option when procurement of buses is also taken into consideration.

It seems like the performance of an electrified system might become competitive, and furthermore one scientific question from the initial thesis goals concern utilization of the ERS by other traffic. Increased traffic could reduce costs since some of them can be shared by more stakeholders and "divided" upon more vehicles. *Appendix A* describes a case where 10 present regional bus lines are included in the future ERS system to evaluate the impact of added traffic.

7 DISCUSSION

This chapter discuss and evaluate all results from last chapter. It compare advantages and disadvantages with the different scenarios and describe them in terms of flexibility and robustness and the total cost for the investments. There is also some discussion about uncertainties, possibilities and other important factors like safety issues and public opinion.

7.1 Result, flexibility and robustness

The default case with 300 seconds dwelling time at end terminal stations is the most profitable one from an economic perspective. Two alternatives are given with either 180 kW or 360 kW charging power at end terminals to examine the value of less static charging locations and possibly less Elonroad at the expense of larger batteries and higher grid connection fees. It seems like the 180 kW alternative is more profitable due to its significantly smaller battery depreciation costs (compare in *Table 6.4*).

It is also interesting and a bit surprising that the scenario with exclusively static charging at end stations become more expensive than the default scenario including electric roads. The importance of smaller batteries and economic performance of Elonroad become evident in this case. Overall, it is obvious that large batteries decrease profitability, which calls for discussions about higher charging rates. If somehow the energy optimized batteries could accept C-rates of 4 kW/kWh or if power optimized batteries could be used, one might find an even cheaper design with 360 kW charging power at end terminal stations. A halving of batteries to 90 kWh in the "static only scenario" could possibly result in a much more profitable system than the default one. Also, if the consumption per km become lower, more bus lines can manage a static only scenario with exclusively 180 kW charging power. That system is probably significantly cheaper than the default one, but at the same time very dependent on correct dwelling times.

Another solution that might create profitability for 360 kW supply is to also account for that power during dynamic charging. Since the vehicles are equipped with two pick-ups in this case anyway (to manage 360 kW at end terminals), they could electrically accept more than 180 kW. If more information become available regarding how many vehicles simultaneously requesting power supply at each location, the dynamic charging power to each individual vehicle could probably be increased and thus result in less installed Elonroad. The 180 kW limit is rather a computational approach to ensure coverage during dense bus traffic. In reality, Elonroad has the ability to divide its total available power upon a specified number of vehicles. If a decision maker were to have better information about bus traffic flows, the system design could therefore become more cost optimized by simple algorithm input modifications.

However, despite this pursuit of the cheapest system possible one must argue if it is flexible and robust enough to handle unexpected traffic situations. Systems optimized with 300 seconds at end terminals or the option with only static charging become highly dependent on perfect logistics and

time schedules. During harsh periods with lots of delay and unexpected traffic situations, these designs could result in vehicles being unable to operate due to battery drainage. It is therefore extremely important to optimize with input parameters that are representable for these scenarios. The operator can then feel confident that all vehicles get enough electricity supply even when traffic patterns differ from its original setup.

Table 6.3 offer cost estimations of some tested scenarios including less time at end stations and higher average velocities. The optimization algorithm is user friendly and can be used to modify other parameters, but the chosen ones are considered most important. If a bus administrator would like to cover an extreme case with constant delay and no time to charge at end stations, the system would cost approximately 29.5 MSEK per year without including vehicle investments. This is quite expensive if compared to the default case with 25.0 MSEK annual costs. With a depreciation time of 10 or 15 years (which is used through this thesis), that extreme design would result in initial investments of 45–65 MSEK more which might not be of interest for a buyer. Furthermore, the sole use of dynamic charging and some occasional static charging at bus stops is still sensitive to average velocity increase. Some solution that includes sufficient margin for both delay to end terminal stations and average velocity changes would undeniably be a preferred choice as long as economics are reasonable. The scenarios "*90 seconds terminal time*" and "*higher average velocity*" are approximately 1.8 MSEK more expensive and 0.2 MSEK more expensive respectively. A combination of these would hence add up to around 2 MSEK extra annual costs per year, resulting in some 20–30 MSEK more expensive than the default "perfect system". This combinational design might just be the recommended choice despite larger investment costs due to its higher flexibility and robustness.

7.2 Batteries

Batteries are evidently important when discussing economic performance. As mentioned it would be profitable to make use of smaller and more power optimized batteries. But public transportation systems are deemed to operate many cycles per day and during most days of the year. A fleet of electric vehicles will therefore be exposed to a lot of wear, possibly too much for small and power optimized batteries. The only other option to create true profitability is therefore a decrease in battery prices. An overestimation of 3000 SEK/kWh is used through this thesis, but forecasts (*Figure 3.3*) are predicting prices of less than 2000 SEK/kWh (200 \$/kWh). If this became reality, the public transport market could see huge disruption and electrification growth in a near future. Batteries represent approximately 10% of the annual operational costs for the 180/180 kW (with 90 kWh battery) alternative in *Table 6.4* but increases to around 15% in the 180/360 kW (with 180 kWh battery) alternative. Variable costs like maintenance and energy consumption are apparently much larger cost drivers than batteries since they are valid for a large system of 64 buses. Lower battery costs would of course benefit economic performance of public transport systems, but they are probably more important in the private transport sector where maintenance requirements and energy magnitudes are smaller.

7.3 Energy consumption

As mentioned in *Section 2.3 – Fuel consumption electric vs. gas*, the consumption might become significantly higher if accounting for heating, air conditioning and all other auxiliaries. The thesis results are all based on a consumption of 2 kWh/km which thereby could become an underestimation in some cases, mainly during cold winter days. It is easy to modify this parameter using the

optimization algorithm interface, but it has not been tested yet since earlier studies argue that it should be more profitable using additional heating from another source than electricity. It would be interesting to compare results using electricity for heating with other solutions, but the authors have found no useful studies on those economics. It is known that average length of each bus route is 18 km, meaning that average consumption with 2 kWh/km is 36 kWh. Earlier studies using a peak consumption of 2.5 kWh/km including electric heating for cold winter days would instead result in 45 kWh average demand, approximately 10 kWh difference. A 10 kWh increase is the same amount used to cover realistic obstacles like roundabouts and pedestrian crossings in *Figure 6.5* which compared to no obstacles included (*Figure 6.2a*) need 1 km extra Elonroad. Depreciation of electric road seem to occupy around 10% of the total annual operational costs in *Figure 6.10* and thus the extra electric heating might not affect the results very much. However, the 2 kWh/km used is as mentioned an overestimation made to ensure coverage of both propulsion and some extra auxiliaries. If the consumption in reality is closer to 1-1.5 kWh/km, an addition of electric heating to 2.5 kWh/km would imply double annual costs of electric road depreciation and hence become more decisive.

7.4 Future system uncertainties and possibilities

Optimized results throughout this thesis are based on estimations of a future system that has not yet been decided. Stakeholders seem to lean heavily towards the proposed "Lund C option" at this moment but nothing is guaranteed. Extensive construction work in Lund, further analysis or public opinion are just a few factors that might force redirections and other modifications of the current proposition. Even though there seem to be consent about the Lund C option, some uncertainties about new routes and stations are only vaguely mentioned and has thus forced the authors to make several assumptions. For now, all assumptions are yet considered to show a fair and somehow likely system which is sufficient and give a pointer on how to design a future ERS in Lund. The optimization algorithm and its interlinked functions are easily modified when a more detailed bus system is presented to generate an even more realistic solution.

An important question is how an ERS should be financed if introduced for public transport in a city like Lund and furthermore what will happen when more vehicles become electrified. The results of this thesis is presented as annual costs for a single bus operator, but one could argue that other traffic companies, municipality vehicles and such could come together for a joint venture in both utilization and financing of the ERS. Costs related to each vehicle (batteries, energy and maintenance) are naturally not affected, but external costs like electric infrastructure with maintenance and electric fees could be greatly reduced. Since these costs represent around 30% of the annual expenditure (see *Figure 6.10*), the economic results would certainly change drastically in favor of an electrified city traffic.

A fast analysis including some assumptions is presented in *Appendix A* where regional buses serving Lund are included in the analysis. The cost difference between a gas fueled and an electrified bus fleet seem to increase even more in favor of the electrified case, hence raising interest in the potential use of dynamic charging. It is crucial to notice the term **dynamic** when talking about possibilities for other traffic utilization. One can easily argue that static charging locations are harder to share due to limited space and the probability of them being placed at secluded areas like end terminal stations. With the bus density approach it seem obvious that dynamic segments should be installed in the most central parts where many lines operate. Fortunately these areas are also occupied by much other traffic that circulate or cut through the city area. With good logistics and power capacity coverage, lots of vehicles could utilize dynamic segments when driving through

Lund without having to stop at some distant location for recharge.

7.5 Power grid connection

Iterative communication with Krafringen has arguably created some realistic solution to functional and profitable grid connections. Though since the new bus fleet will be introduced by year 2023, the whole power grid situation might be different. The current tram construction will require electricity supply and other projects before year 2023 could also occupy some capacity. Thus the proposed solution will probably need some modifications and resumed discussions with Krafringen. However, the current solution is regarded as good for cost estimations. A future design of other connection points could change cable costs due to increased or decreased distances, but the combined power demand should be somewhat equal. If this is the case, all connection fees and costs of components like transformers and net stations would still be credible.

7.6 Margins

The authors have prioritized having extra margins in numerous calculations through the thesis to ensure that the system would function well in reality. Main overestimations that might result in a more expensive system are,

- use of 2 kWh/km consumption which is (in many cases) higher than values gathered from available research
- a set battery price of 3000 SEK/kWh which as argued most likely is significantly higher than current costs
- the extra 10 kWh assigned to cover geographic obstacles in each line. In some cases, this might be a large overestimation.
- costs for electric bus vehicles being a factor 1.5 larger than conventional vehicles. This is an estimation from earlier studies which most likely could decrease when buying a complete bus fleet.

More accurate information about these components and functions could create a more profitable system than the one presented in the results. If an electrified bus fleet in Lund was to become reality, the communication with for instance battery providers would give precise investment costs which can be used as input to the algorithm.

7.7 Safety and public opinion

Whether or not electric roads will be built in Lund does not only depend on how it can support the bus system and its financial outcome. Other factors like public opinion about building such infrastructure in the middle of a city with old history or security issues will probably play a big role in the future discussions. Resistance might arise because of the fact that a high voltage connected ERS is placed on top of the street in densely populated areas. Thus it is crucial to ensure and present safety precautions before proposing any complete solution. However, these concerns have not been included in this thesis any more than accounting for safety and accessibility limitations

like roundabouts or pedestrian crossings. There might be further issues with for example cyclists having to cross the electric road "bump", increasing the extent of a possible continued analysis.

The other issue of public opinion might not be connected to safety aspects but rather visual impact or doubt. It is important to do thorough testing and maintain frequent contact with people in the area to ensure that the ERS become publicly accepted. A solution to visual problems could be the use of inductive roads where charging infrastructure is placed underground. Though as mentioned these bring significantly higher costs and lower power capability together with time consuming and disruptive installation projects. One need to consider all aspects and use them to motivate the most appropriate system.

8 CONCLUSIONS

The definition of an optimal public transport system is highly dependent on flexibility and robustness requirements. Long dwelling times at end terminal stations seem to be preferable from an economic perspective, but the system gets very sensitive to disturbances that cause delay. A more expensive alternative that covers harsh scenarios might instead be the recommended choice to invest in. Dynamic charging is a possible solution to the flexibility problem since vehicles can charge while driving without falling behind schedule. Some scenarios have been tested through this thesis to evaluate their impact and assist any decision making. The authors recommend a combination of less dwelling time at end stations and increased average velocity to cover harsh conditions for both static and dynamic charging. A perfect system with long dwelling times would cost around 25 MSEK per year excluding vehicle investments whilst a more flexible system result in some 2 MSEK extra per year according to this thesis. An ERS seem to be competitive or maybe even cheaper than a gas-fueled system regarding operational costs. However, when adding vehicle investments the electrified solution become more expensive. Future reductions of electric vehicle prices are therefore crucial to create total profitability.

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A Future scenario with added traffic

In a future system with electric buses serving the center of Lund it is not a very far fetched idea that also regional buses could be electrified and utilize the same charging infrastructure. Most of the regional buses serving Lund travel the roads in between *Lund C* and *Universitetssjukhuset* (seen as yellow lines in *Figure A.1*) and this route is almost completely covered with electric road in the the cost optimized future system presented in *Figure 6.5* (180 kW dynamic and static charging). All flexible scenarios (less time and higher velocity) also include full coverage of the route, but the default system is used as template for regional traffic addition.

It is interesting to look at the amount of electric energy that could be transferred when regional buses enter and exit Lund, thus passing over electric road segments. Each vehicle might then drive a certain distance consuming this "free energy", possibly enough to cover their round-trips with some small additions of new charging locations.



Figure A.1: The area around Lund C with the regional buses represented by yellow lines (Skånetrafiken, 2017).

Above can be seen how ten regional bus lines enter the central parts of Lund from two different directions: *Universitetssjukhuset* in the north and *Bantorget* in the south.

- Five lines (108, 123, 159, 160 and 169) pass *Universitetssjukhuset* on their way to *Lund C*, rest, and then travel back in the same direction.
- Four lines (126, 137, 139 and 165) enter from *Bantorget*, stop at *Lund C*, travel to *Universitetssjukhuset* and rest before returning the same way.

- Line 155 enters from *Bantorget* and has *Lund C* as its final destination before returning the same way.

On their way through Lund the lines will pass a certain length of electric road that will provide them with electric energy. No information about regional bus consumption is available and therefore the same value used for city buses (2 kWh/km) has been assumed. It arguably includes fairly large margins and should therefore be in the same order of magnitude. Also, a velocity in central parts of 18 km/h has been set which is considered credible. Current average velocity in the system is some 18.5 km/h whilst a future increase to 22 km/h is desired, but central parts mean more traffic and thus lower velocities (coherent with zone based values from the simplified optimization model).

Furthermore it is assumed that the dwell time at the terminal stations *Lund C* and *Universitetssjukhuset* is five minutes and both the static and dynamic charging is set to 180 kW (since static charging is performed at central parts of Lund, 360 kW is considered too high). By using these inputs, one can calculate how many kilometers each bus line could drive with the charged energy provided by the infrastructure made for the city buses. *Table A.1* presents information about bus destinations when exiting Lund, round-trip lengths, available Elonroad length and resulting driving distance after utilizing of the charging infrastructure. A percentage of each line and complete system that can be covered with the electricity supply in Lund is also shown to easier understand the future potential of including regional buses.

Table A.1: Information about regional bus lines entering the city of Lund.

Bus line number	End destination	Route length [km]	Distance of Elonroad [km]	Distance on electric charge [km]	Route coverage [%]
108	Gårdstånga	29	2.6	21	72
123	Kävlinge	29	2.6	21	72
126	Hänkelstorp	43	3.1	23	53
137	Bjärred	23	3.1	23	100
139	Lomma	22	3.1	23	100
155	Harlösa	62	0.3	9	15
159	Skrylleskogen	29	2.6	21	72
160	Sjöbo	72	2.6	21	29
165	Svedala	54	3.1	23	43
169	Malmö	37	2.6	21	57
Total:	–	400	25.7	206	52

It is interesting to compare the total distance that the regional bus lines could run on the charged energy with the total length of all the routes. Around 52 % of the total distance would be covered in this case which has to be considered high. Two of the lines (137 and 139) would be able to charge in Lund, go to their other destination and then return purely on the energy charged from this electric road system. Three more lines (108, 123 and 159) are fairly close to achieve the same result with 72% coverage.

However in these cases there is no energy buffer to ensure coverage during electrical faults or shorter terminal charging time, and obviously some lines need additional charging infrastructure anyway. Introducing more vehicles to utilize the same electric infrastructure would probably also demand components (transformers, net stations etc) that can handle higher capacities and perhaps even new grid connections to not risk extreme loads. More vehicles will also occupy more space at bus stops, meaning that these (*Lund C* and *Universitetssjukhuset*) will have to be extended with more Elonroad segments to allow simultaneous charging.

In total, to include regional traffic would require some investments in new charging and electric infrastructure, but it could become very profitable to utilize "existing" Elonroad segments. Higher charging powers or addition of static and dynamic charging locations are possible solutions, but no economic analysis is performed at this stage since data and other information are insufficient.

B Lund city map with bus station names

