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- a simulation study based on data from Linköping

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2017

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Lindgren, L. (2017). *Electrification of city bus traffic: - a simulation study based on data from Linköping*. Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology. http://iea.lth.se/publications/Reports/LTH-IEA-7265.pdf

Total number of authors:
1

CODEN:LUTEDX/(TEIE-7265)/1-43/(2017)

Industrial Electrical Engineering and Automation

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- a simulation study based on data from Linköping

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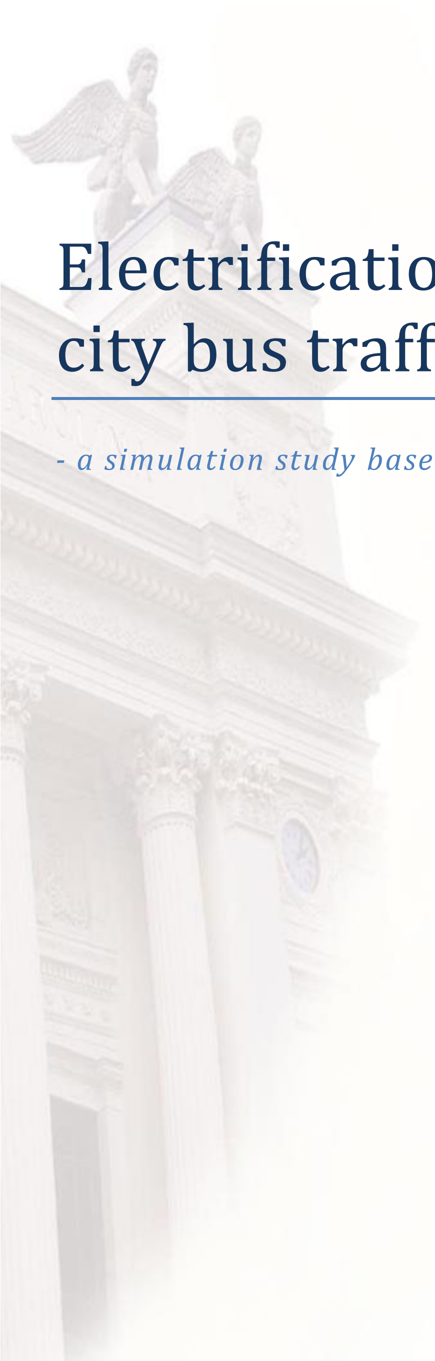

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- a simulation study based on data from Linköping

Lund 2017-07-14

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1 Preface

This report presents interim results from the project ”Vad är en miljöbuss egentligen? En socioteknisk scenariostudie” (”What is an environmental bus? A socio-technical scenario study”), which is funded by Vinnova (Dnr 2015-03536). The project, which runs 2016-2018, uses scenarios for a fossil-independent vehicle fleet in Sweden, outlined by the Swedish public investigation ”Fossilfritt på väg” (“Fossil-free on the road”, SOU 2013:84), as a starting point. These scenarios propose a significantly raised implementation of electric city buses in Sweden. According to the investigation, 83% of Swedish city bus traffic could be based on electric propulsion by 2030.

During recent years, several Swedish cities have invested in biogas-fuelled city buses. Linköping is an example of such a city. The project "Vad är en miljöbuss egentligen? En socioteknisk scenariostudie” starts with the proposals of a rapid implementation of electric buses from ”Fossilfritt på väg”, takes down these national proposals to a to a regional level and poses the question what implications these proposals can have in cities and regions which today have established biogas production and use a significant part of the biogas as a fuel for city buses. The project analyzes possibilities to implement electric buses, while continuing to stimulate a further development of the biogas production. A first step in such an analysis is to describe a possible electric bus system.

Thomas Magnusson, Linköpings universitet

2 Förord

Föreliggande rapport presenterar delresultat från projektet ”Vad är en miljöbuss egentligen? En socioteknisk scenariostudie” som finansieras av Vinnova (Dnr 2015-03536). Startpunkten för projektet, som löper 2016-2018, är de scenarios för en fossilberoende fordonsflotta i Sverige, som den statliga offentliga utredningen ”Fossilfritt på väg” (SOU 2013:84) presenterar. Dessa scenarios föreslår en omfattande elektrifiering av stadsbussarna i Sverige. Enligt utredningen skulle 83% av svenska stadsbussars trafikarbete kunna baseras på eldrift år 2030.

Sedan ett antal år tillbaka har man i flera svenska städer satsat på biogasdrivna stadsbussar. Projektet ”Vad är en miljöbuss egentligen? En socioteknisk scenariostudie” utgår från de förslag om en väsentligt uppskalad elektrifiering som ”Fossilfritt på väg” redovisar, lyfter ned dessa nationella förslag till en regional nivå och ställer frågan vad de kan innebära i städer och regioner där det finns en etablerad biogasproduktion och där en betydande andel av biogasen idag används som bränsle i stadsbussarna. Projektet analyserar hur det kan vara möjligt att implementera eldrivna stadsbussar och samtidigt stimulera en fortsatt utveckling av biogasverksamheten. Ett första steg i en sådan analys är att skapa en bild av hur ett system med eldrivna stadsbussar skulle kunna se ut.

Thomas Magnusson, Linköping university

3 Abstract

Flexible and economic systems for electric operation of road vehicles is an area of interest for research and development. This report applies such systems to the operation of city buses in Linköping. An LTH developed software for simulations and economic optimizations of such systems is used and a few system designs are presented. The tested systems differ in selection of bus lines and the type of charging system: bus stop charger, high power bus stop charger and electric road. An attempt to a realistic cost and performance estimate of the main components is presented. All buses are assumed to operate with the same time table as today. Under some of the assumptions these systems are shown to be cost competitive to diesel and gas buses in addition to being quieter and without local pollution. This result is however uncertain due to the difficulty in predicting the cost of new technologies and due to other sources of error such as error in assumed energy consumption.

4 Sammanfattning

Flexibla och ekonomiska system för eldrift av vägfordon är ett område med aktiv utveckling och forskning. Denna rapport tillämpar sådana system för drift av stadsbussar i Linköping. En programvara för simulering och ekonomisk optimering av sådana system har använts och några systemkonstruktioner presenteras. Programvaran utvecklades i ett tidigare projekt på LTH. De testade systemen skiljer sig i valet av busslinjer och typen av laddningssystem: busshållplatsladdare, hög effekt busshållplatsladdare och elväg. Ett försök till realistiska kostnader och resultat uppskattningar av de viktigaste komponenterna presenteras. Alla bussar antas köra enligt samma tidtabell som i dag. Under vissa antaganden visar det sig att dessa system är konkurrenskraftiga jämfört med diesel och gas bussar förutom att de är tystare och utan lokala föroreningar. Detta resultat är dock osäkert på grund av svårigheten att förutsäga kostnaden för ny teknik och på grund av andra felkällor som till exempel fel i antagen energiförbrukning.

5 Table of Contents

6 Introduction

This report presents a study on Linköping's city bus network and is a part of the larger research project "Vad är en miljöbuss egentligen? En socioteknisk scenariostudie" (in English "What is an eco-bus any-way? A socio-technical scenario study"). The study is similar to a prior work which analyzes the bus network in Lund. (1) However, this work focuses more on how different parts of the city bus network can be electrified in steps and less on different charging technologies and heating systems. The cost assumptions and modeling have been updated. The main author of this report Lars Lindgren is involved in a number of projects related to electrical roads. (2) (3) (4) (1)

6.1 Background and motivation for study

There is a general trend towards electrification of different transportation infrastructures. This is driven by an ambition to reduce exhaust gas and acoustic noise emissions, and to reduce the depend-ence on fuels suitable for vehicles. Most fuels suitable for vehicles have fossil origin and there are not enough sources of biofuel to replace all fossil fuel on a global scale. In addition to this, the electrifica-tion of transportation infrastructures also yields other benefits due to lower noise and emission levels such as the opportunity to operate commercial vehicles at early/ late hours (e.g. garbage holding) and/or in-doors (like having a bus terminal within a shopping mall).

The ability to run fully or partially electric city buses has in recent years been demonstrated through individual bus lines in cities around the world. The charging is controlled automatically by wireless inductive or automatic conductive energy transfer from the charging station to the bus. A city bus typically covers a distance of about 5 to 15 km between two end stops and uses about 1.5 kWh/km electric energy, i.e. from just below 10 kWh to just over 20 kWh depending on route distance, one way. The average speed is under 20 km/h, i.e. a single trip between two terminals takes 15 to 45 minutes' drive depending on distance. With aforementioned conditions, a charging station at each end of the bus line with a charging power of 200 kW can fully recharge the battery in 3 to 6 minutes. This is a reasonable rest time for the driver, seen in relation to the running time.

Apart from the end stop charging stations, it is also possible that charging at additional stations along the route is both technically and economically advantageous. With the extended charging infrastruc-ture, the cost of the stations is shared by the bus lines that use the same stops. Furthermore, additional stations lead to shorter charging times (3 to 6 min) which make it possible to use smaller batteries. The shorter charging times also lead to longer battery lifetime since the depth of discharge in the batteries de-creases. These arguments show the importance of a closer study on how an electric city bus service in Linköping urban area would best be supplied with energy with respect to the number and locations of charging stations, charging times, and so on.

6.2 Electric road systems and electric buses

In recent years several research and product development projects towards Electrical Road Systems (ERS) have started, and some products have already emerged. Conceptually such systems are similar to trolley bus systems in the sense that electric power is supplied to vehicles while moving. The main difference is that the new systems emerging are applicable to general traffic and can thus be used by more than only buses, e.g. by local goods distribution, taxis and cars. There exist three main categories of electric road systems:

1. Overhead wires (Limited to Buses, trucks and other high vehicles)
2. Electric tracks in the road surface
3. Inductive energy transfer from coils under the road surface

The main difference from trolley bus systems is that vehicles need to be able to connect and disconnect from the system automatically while driving at speed and those vehicles are assumed to have a battery on board that is charged from the ERS so that the vehicles can operate outside the ERS. Due to this, the charging infrastructure cost can be reduced since only specific selected roads need to be equipped with ERS.

Plug-In and Full Electric bus technologies work as a good platform for electro mobility technology. The dynamic driving pattern with intense start/stop operation benefits from hybridization and electrification. The repetitive driving pattern – repeating a particular bus line – facilitates the use of a dedicated charging infrastructure. These are reasons why public bus transport has emerged as the first adopter of new electro mobility technology, including the use of automatic bus stop charging systems and ERS technology.

In this study, both automatic bus stops charging systems and ERS technology are combined in the system optimization of the Linköping city bus network.

6.3 Limitations

Downwards follows a list of limitations, simplifications and considerations of this study.

- In this project the 2016-04-12 city bus traffic schedule is used as a test case. No alterations of the bus schedule and route network are made to better fit an electric operation. The requirement is that the system should operate fully electric with adequate reserves for missed charging opportunities. The reserves are handled by including margins in charging power and power consumptions. No detailed modeling of contingencies is made.
- When designing a new public transport system, predictions on future transport demands need to be taken into consideration. This is not done in this report as this concern is independent of energy source.
- The solutions in this report are optimized for minimal total cost. The different actors such as Östgötatrafiken, the Bus operator and Linköping municipality have incentives to optimize the economy of their part. This could potentially lead to a suboptimal total solution.
- The calculation is based on data for 18 meter articulated buses since that is what is used in Linköping today.

- The traffic schedule used is the published schedule. This schedule is only available with times rounded to whole minutes and rough approximations are used to generate more detailed timing.
- An automatic scheduling algorithm schedules the empty trips needed to get the buses to the start of each trip in the published schedule. This is not based on the current practice neither optimized especially for electric buses. The algorithm generated some problems since in some scenarios the scheduling algorithm found inefficient schedules that required more buses than are in operation today and hence more potential time for charging at end stops. This was partially solved by excluding bus lines with low traffic intensity since these were problematic for the scheduling algorithm.
- The stop times are adjusted based on the average recorded stop time for a particular bus line on a particular stop in real operation. Driving times and driving distances are adjusted similarly.
- Even through the data that were made available by Östgötatrafiken included the actual scheduling of the buses, that information was not used since it took too long time to develop the functionality to import that information in to the simulator.
- The battery costs and lifetime modeling that are included in the study are based on realistic assumptions. No detailed comparisons between different battery types are made.
- It is always hard to get accurate cost estimates of the different components and installations in this type of systems before you are able to ask for real quotations. We have tried to make realistic assumptions for early series production costs.
- No socioeconomic calculation of the value of reduced acoustic noise and cleaner air in the city are made.

7 Assumptions in this simulation study

A large number of assumptions and approximations are needed in a study like this. The most important ones are presented in this chapter.

7.1 Batteries

Batteries are the most limiting component in most electric road vehicles.

Many different combinations of battery performance can be produced for different applications; the main performance parameters are:

- Cost [SEK/kWh]. Estimations of current and future electric vehicle battery costs range from 1 500 SEK/kWh to 10 000 SEK/kWh. Battery cost can be given on cell level or at the system level including packaging cooling and control system. Battery costs have been steadily declining in recent years. (5) In this study a system cost of 3000 SEK/kWh is used as an estimate of the battery cost.

- Energy density [kWh/kg, kWh/litre]. A typical energy density in energy optimized battery packs are about 0.1 kWh/kg. The battery packs used in this study's simulations are in the range 100 to 300 kWh. Consequently, the mass of the batteries can be estimated to between 1000 kg and 3000 kg if energy optimized battery packs are considered. The mass of the batteries is not accounted for in the simulations but it is rather small compared to the total vehicle mass.

- Power density, charging/discharging [W/kg or kW/kWh]. Typical energy optimised batteries can be charged with maximum 1 to 2 kW per kWh battery capacity, but more power can be provided during short periods of time. Typical power optimized batteries can be charged with maximum 6 kW per kWh battery capacity. High charging power shortens the operational life of the battery. The battery packs used in this study's simulations are assumed to be energy optimized and therefore the charging rate is limited to 2 kW/kWh.

- Operating life, Number of cycles vs. cycle depth. The main parameter limiting battery life in this application is the cycling between charging and discharging.

  A method called Rain flow counting estimates the life of the battery given a simulated sequence of charging and discharging in a specific bus schedule and charging infrastructure.

Batteries in city bus applications are used with very many charging/discharging cycles at high power. The main concern is therefore battery lifetime in relation to cost given a charging/discharging cycle. The demands on energy density and power density are less stringent than in some other applications since the battery generally makes up a relatively small fraction of the bus mass. There are however potential problems with mounting large batteries in standard bus designs.

Most high performance batteries today are based on some lithium chemistry. In general, lithium batteries have much better life if only a small part of the capacity is used regularly. This means that either large batteries with low cycle life, or smaller high quality batteries with high cycle life, can be used to achieve a given lifetime. In this study the cycle life curve in Figure 1 is used. This curve is representative for normal lithium-ion batteries for vehicle applications. The batteries are sized so the expected operational life exceeds the assumed 10-year depreciation time of the buses.

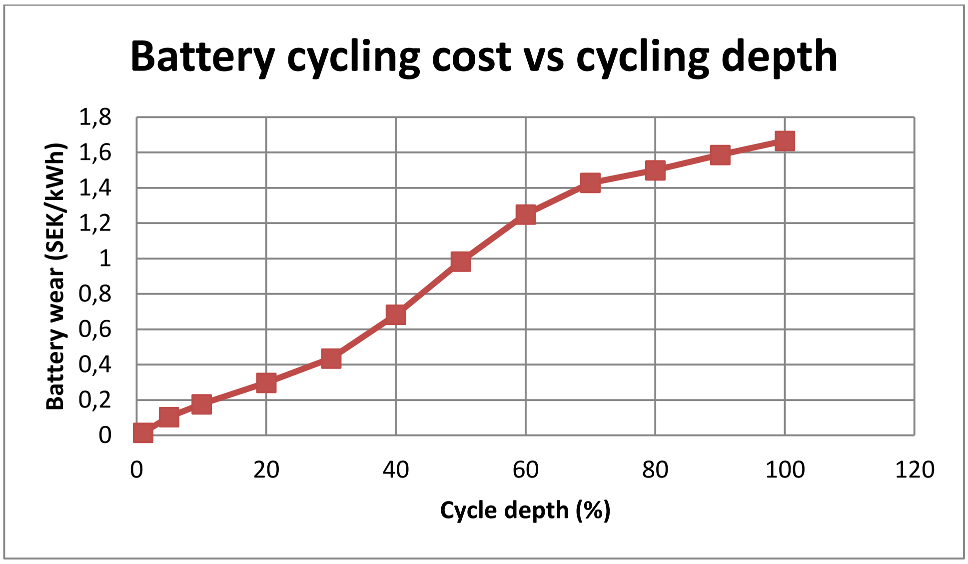

Figure 1 *Used relationship between battery cycle depth and battery damage cost. This curve is calculated using a battery price of 3000 SEK/kWh. The life time at 100% cycle depth is 1800 cycles.*

Batteries also tend to wear more when operated almost full or almost empty, this is not explicitly modelled in this study, but for this reason the batteries are never charged to more than 80 percent of their capacity in the simulations, and deep discharging is avoided in most cases.

In addition to the wear of the batteries due to cycling it is assumed that the batteries have a calendar life of 10 years and that the cost for these degradation modes can be added directly.

For each of the simulated cases it is assumed that all buses in the bus-fleet have the same battery size.

7.2 Reference cases

The cost calculations in this report are mainly intended to compare different options for electrifying city buses, but since the bus fleet in Linköping operate on biogas today, an additional cost comparison between electric and biogas buses is in place. It is important to understand that there are large uncertainties and such comparisons need to be interpreted with care.

If it is assumed that the biogas consumption is 0.5 kg/km and the cost of biogas including distribution but excluding VAT is 14 SEK/kg (14 SEK/kg excluding VAT is a typical consumer price of biogas in Sweden for February 2017), the fuel cost becomes 7 SEK/km. The different electrification options that this report considers roughly fall in the range of 5 to 11 SEK/km. This includes an assumed additional cost per bus of 200 kSEK. The cost model used in this report is shown in Figure 2.

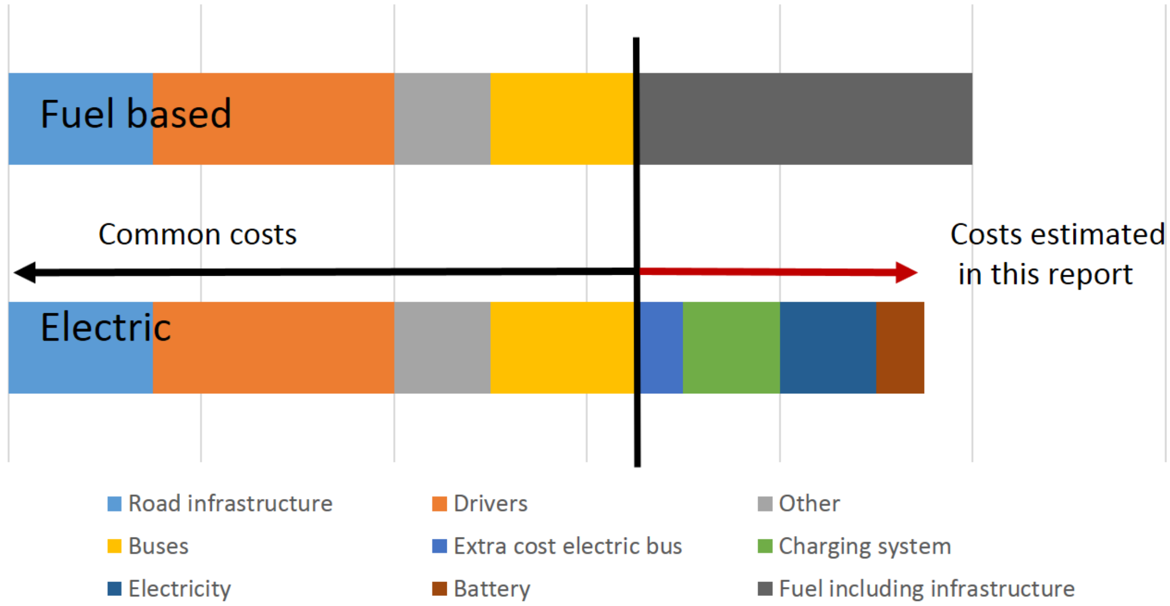

Figure 2 Illustration of included and excluded costs in this report. Road infrastructure does not include electric road related costs, they are included in charging system. The figure does not describe any calculated cost distribution. The capital costs are annualized. The yearly cost of the charging system includes maintenance cost of 4% of the investment.

7.3 Economics

Downwards follows the economic assumptions that this report considers

- The interest rate for the investments is assumed to be 4 %, which is a commonly used level for infrastructure investments.
- The used depreciation time is 10 years for all investments. All costs are excluding VAT-tax.
- The maintenance cost of the infrastructure is assumed to be 4 % of the investment per year.
- The cost of the electric buses without the battery is assumed to be 200 kSEK higher than the corresponding gas buses. According to Edward Jobson at Volvo Buses (Personal communication 2015-03-20) the price difference between 12-meter gas buses and electric buses is 150 kSEK. Therefore, it is assumed that 200 kSEK is a reasonable figure for 18-meter buses. However, in high volume production, electric buses (excluding the battery) are likely to be cheaper than buses with a combustion engine.
- Tekniska verken - the distribution grid operator in Linköping - gave these estimates of the grid connection costs:
  - 200 kW, low voltage at a typical bus stop: 100 kSEK.
  - 400 kW, low voltage at a typical bus stop: 250 kSEK.
  - 1000 kW, medium voltage next to an existing transformer station along the main bus street in Linköping: 350 kSEK.
  - 2000 kW, medium voltage next to an existing transformer station along the main bus street in Linköping: 750 kSEK.

  The optimizations and simulations of this study assume a grid connection cost of 100 kSEK per charging station and segment of electric road except for the case of 600 kW charging power where a grid connection cost of 300 kSEK is assumed. The grid connection cost of the final solution in the different cases has been manually calculated from the figures above.

- The yearly low voltage grid connection fee per connection point excluding energy based grid connection fee in Linköping assuming the maximum hourly average power, P_{max} kW, is the same in each month and occurs at daytime on weekdays. This fee is calculated as:
    - Yearly grid connection fee: $11\,000 + 335 \cdot P_{max}$

  For medium voltage connections the corresponding formula is:
    - Yearly grid connection fee: $60\,000 + 350 \cdot P_{max}$

  The optimizations and simulations assume a yearly grid connection fee of 50 kSEK per charging station and segment of electric road. The yearly grid connection fee of the final solutions in the different cases has been manually calculated from the figures above.
- The cost of electric energy including energy based grid connection fee is assumed to be 700 SEK/MWh. This is composed of:
    - Lowest price without promotional offer for "green electricity" at price comparison service Compricer for 5-year contract for Linköping, supplier Nordic Green Energy: 329 SEK/MWh.
    - Electricity tax: 292 SEK/MWh.
    - Average Energy based grid connection fee over the year, assuming half the energy is supplied at low voltage and half at medium voltage: 88 SEK/MWh.

    The costs above sum up to 709 SEK/MWh, which is rounded down to 700 SEK/MWh.

7.4 Energy consumption

Prior studies show that a 12-meter electric bus consumes around 0.96 kWh/km (6). Furthermore, the Landskrona trolley bus consumes about 1,2 kWh/km, and the study on electrification of Lund buses assumes 1,2 kWh/km based on a scenario with mostly 12-meter buses. In Linköping, most buses are 18 meters instead of 12, and the estimate must be adjusted accordingly. 18-meter buses are estimated to consume slightly less than 150 % of a 12-meter bus. Given this data, an estimation of 2 kWh/km gives some margins in the energy budget (this assumption is of course dependent on the specific buses used). The 2 kWh/km is the energy delivered to the vehicle including losses in the battery, but excluding losses due to the charger or electric road system. The 2 kWh/km figure is assumed to include drive system, air-conditioning, other auxiliary loads and on-board losses.

Other considerations regarding energy consumption are:

- The heating energy in the winter is assumed to be supplied by a fuel based system and is therefore not included. This assumption is made based on the study on electrification of city buses in Lund, which shows that it is uneconomic to dimension the batteries and charging system for electric heating of the buses (1). During cold days the heating system can consume as much power as the rest of the vehicle. The next section discusses this topic further.

- The simulated charging power is limited to 75 % of the rated power of the charger in all cases to create a margin that allows for shorter stops than scheduled, missed charging opportunities and some limitation on the charging rate of the batteries.

7.5 Heating

As seen in the report on Lund City buses, on board electric heating can increase the cost of the electric buses operation a lot (1). From both an economic and an environmental point of view it is probably better to use a fuel based on board heater, e.g. a diesel or gas heater. The main argument for this is that on cold days when heating the buses is needed the most, the total societal demand for electrical power is high. This leads to a high electricity price since power plants with high marginal cost, e.g. fossil fuel based thermal power plants, are operating. Furthermore, since these plants are fossil fuel dependent, it also makes sense out of an environmental point of view to try to reduce the electrical power consumption as much as possible during the cold days.

Fuel based heating systems are already installed in many city buses. The cost of fuel for heating the bus in the winter on average over a year can very roughly be estimated to 0.5 SEK/km total driving distance for an 18-meter bus. This estimate is based on 0.67 kWh heat /km during the winter for a 12-meter bus and a HVO (biodiesel) price of 1.1 SEK/kWh (6). Depending on prices and other factors a mix of fuel-based end electric heat can also be used.

An interesting alternative to a pure fuel heater would be to have a small (e.g. 20 kW electric power) combustion engine with a generator. This assembly should be optimized for heat generation by being well insulated to minimize heat losses and using heat exchangers to extract heat from the exhaust. This would decrease the power consumption on cold days even more. It would also act as an emergency range extender that makes it possible to continue operation when changes in scheduling or failure in charging system or battery would otherwise make it impossible. Another possibility is to use cheaper more environmentally friendly fuel such as wood pellets, but this would probably require some development of burners and so on. Better insulation of the vehicles, heat-containment measurements during door opening – closing (e.g. air curtains or double doors) and thermal compartmenting of the bus space would be other improvements worth of consideration. Waste heat recovery from the drivetrain can also give a contribution, but due to the drivetrain's high efficiency this would probably give a minor improvement.

7.6 Routes, operation etc.

The city bus lines in Linköping are shown in Figure 3 and Table 1. Five different combinations of electrified bus lines are simulated. The selected city bus routes are modelled as fully electric with unmodified timetables as they were on Tuesday 2016-04-12. A full year is calculated as equivalent to 300 times the traffic on this day. This is reasonable given the lower traffic on weekends and during the summer.

The bus schedule data and position of the bus stops are extracted from a data file provided by Samtrafiken (7). In total the buses run about 1250 trips per day and the total distance of the bus trips sums up to about 15000 km. The bus network contains around 240 bus stops, and the maximum number of simultaneous bus trips is 60 (in reality 62 buses operates this traffic). In addition to the data from Samtrafiken, data from Östgötatrafiken - who has a system for recording all bus movements in real time (used for traffic information to passengers and for statistics) – is used in this project. Downwards follows a few considerations of the project data.

- The data from Samtrafiken only contains the public schedule. The movements of empty buses from the bus depot to the start of the route and other movements of the empty buses have therefore been scheduled by an automatic algorithm. This scheduling is independent of the charging system and is not optimized for electric buses.
- The times in the time tables are rounded to full minutes meaning that many bus stops are given as 0 minutes. In the model it is assumed that all bus stops take at least 15 seconds and that all buses stop at every stop. The average stop time for a combination of bus line and bus

stops is calculated from the real time data and the charging power is adjusted to compensate for the differences in stop time, within some limits.

- The driving distances between the bus stops are taken from the Östgötatrafiken real time data. Routes that pass bus stops but do not stop there are corrected manually.
- The altitude levels of all bus stops are imported from a digital elevation map from Lantmäteriet (the Swedish National Land Survey).
- Different bus stop positions are added automatically from the real time data (Named A, B and so on) and the bus routes are assigned to them.
- The different combinations of simulated bus lines are shown in Table 1. Östgötatrafiken suggested the first four cases and a case with all the bus lines.

The case with all the bus lines gave problems with the bus allocation algorithm. The algorithm had problems in planning how to move buses between bus trips and required more buses than those operating in practice. This gave unrealistic extra charging opportunities. An attempt to solve this by importing the bus allocation along with the timing of the actual bus movement from the real time data was made, but the required software development turned out to be too time consuming to fit in the scope of this project. This problem was solved by excluding bus lines with less than 40 trips per day from the simulation as shown in case 1-17+24 in Table 1.

As can be seen in Table 1, the daily driving distance per bus are in almost all cases lower than in reality. This may somewhat skew the results. The extra charging time due to the inefficient bus utilisation is not evenly distributed over the buses, which means that it should not influence the needed battery size or charging infrastructure too much.

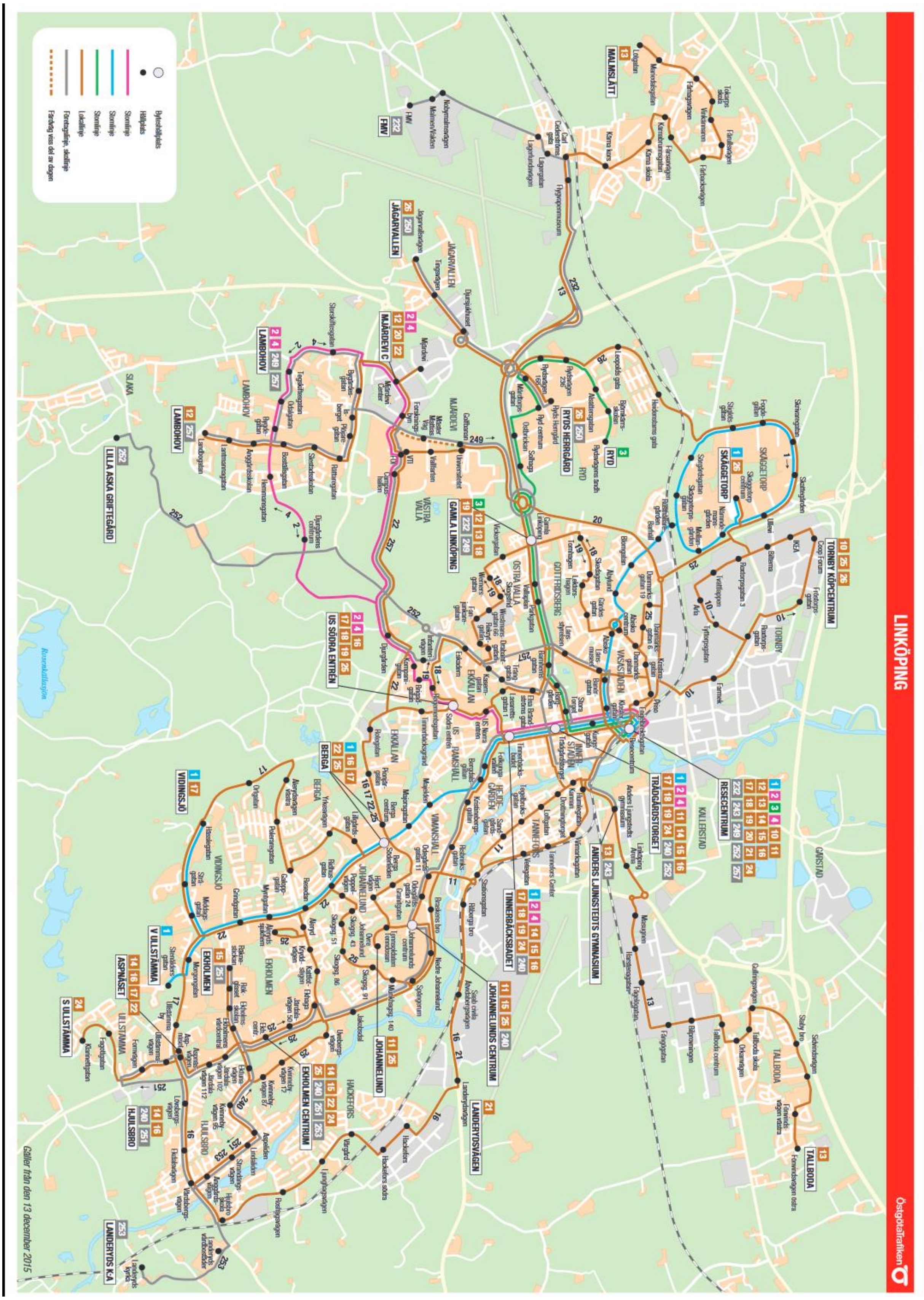

Figure 3 The bus line map of Linköping from Östgötatrafiken

Table 1 Bus lines in Linköping. The first column is the official short name for the bus line. The cases 1-4 and 9 are different selections of bus lines to electrify. Each bus line can be operated by more than one bus. The driving distances does not include empty driving to and from end stops. The driving distance is approximate since some bus lines take a shorter route e.g. early mornings.

Bus Line	Length (km)	Number of trips per day	Total driving distance	Simulation case (Bus lines), Driving distance (km)				
			(km/day)	1	2+4	3	1-4	1-17+24
1	25	100	2500	2500			2500	2500
2	16	40	640		640		640	640
3	7	178	1246			1246	1246	1246
4	16	50	800		800		800	800
10	8	56	448					448
11	5	79	395					395
12	9	118	1062					1062
13	20	118	2360					2360
14	11	56	616					616
15	8	114	912					912
16	16	71	1136					1136
17	12	70	840					840
18	10	35	350					
19	10	35	350					
20	7	23	161					
21	5	10	50					
22	14	8	112					
24	10	58	580					580
25	21	16	336					
26	11	16	176					
Driving distance (km/day)			15070	2500	1440	1246	5186	13535
Percentage			100%	17%	10%	8%	34%	90%
Number of buses			62	11	5	8	24	59
Driving distance per bus (km)			243	227	288	156	216	229

7.7 Cost models

In the Lund City bus project (1) three different systems with different cost models and performance were tested: a conductive stationary charging system, an inductive ERS-system and a conductive ERS-system. This project considers cost models based on a conductive ERS-system, and the prices have been updated with a more conservative estimate compared to the Lund study; the used cost models are shown in Table 2. Some assumptions and considerations regarding the models are listed below.

- The estimated costs are based on an assumption of series production and a competitive market.
- Most of the simulations are made with both electric road system (ERS) and charging stations.
- In the case of charging stations next to an ERS installation they can be made much cheaper as part of the ERS-system, this is not accounted for in this study.
- As a comparison pantograph style charging stations of about 300 kW have been quoted for 2 to 5 MSEK in early projects and prices should go down as they go into series production.
- In the base case it is assumed that the vehicles have a pickup and a DC/DC converter for ERS operation on-board costing 300 kSEK. This is not the case for the high power case so the on-board system cost is reduced to 100 kSEK.
- The additional cost of charging stations in the high power case is very uncertain.

Table 2 Charging system assumptions and costs, night charging is included in all cases.

	Base case	*High power charging stations*
Charging station	*1 MSEK*	*2.5 MSEK*
Max Power	*200 kW*	*600 kW*
Simulated Power	*150 kW*	*450 kW*
ERS	*10 MSEK/km*	*Infinite*
Battery price	*3 SEK/Wh*	*3 SEK/Wh*
Pick-up and on board system	*300 kSEK*	*100 kSEK*
Grid connection of ERS segment or charger station	*100 kSEK*	*300 kSEK*

8 Software

8.1 Simulator

The code for the simulations is written in the programming language Python. The program simulates all bus movements according to the published bus schedule with a time resolution of 15 seconds. Simulation of the charging discharging cycles for 24 hours' city bus traffic in Linköping requires about 100 milliseconds of CPU-time.

8.2 Algorithm for charging system optimization

The algorithm for the charging system optimization works by starting from an initial charging infrastructure. Afterwards, the algorithm systematically inserts and removes charging systems at all possible locations. The order of insertion and removal of charging stations is based on an estimate of demand divided by estimated cost. After each change in the charging station setup a simulation of the bus traffic during a day is performed, and the battery life and yearly total cost is calculated. If the cost is reduced, then the change is accepted. Otherwise it is rejected and the next setup of charging stations is tested. Downwards follow some considerations of the algorithm.

- Each bus stop position can have zero or one charging station and only one bus at a time can charge at a charging station.
- Each driving direction along a bus route between bus stops or other modelled junctions are considered a possible location of ERS. The algorithm assumes that ERS is either installed on 0% or 100 % of such a distance, ERS installation on parts of such a distance is not considered.
- The computation time for one charging system optimization is less than 10 minutes. During the iterations, changes of the battery size are also tested and evaluated.
- Since the selection of charging infrastructure is a combinatorial search problem with a very large search space and is likely to be NP-hard, the algorithm makes a heuristic attempt to minimize the cost but cannot guarantee that the generated solutions are global minimums.

9 Results

Two different simulation studies were made in this project.

The first study compare the electrification of different sets of bus lines according to Table 1. In this case both ERS and Bus stop charging at 200 kW are considered.

The second study compare different options for electrification for the same set of bus lines.

9.1 Bus line combinations

The goal of the simulation of different bus line combinations is to see how the costs and charging solutions depends on which bus lines are electrified. It is also shown that almost all the charging infrastructure used in the cases with few electrified bus lines remains useful in later stages with more electrified bus lines. These simulations are based on the base case from Table 2 with both electric road (ERS) and charging stations. The assumed charging system power is 200 kW but only 150 kW is utilized in the simulation to get some margin in the charging time.

General data for the simulated cases are shown in Table 3. The different charging solutions and the mean power levels over 24 hours a weekday are shown in Table 4. Figure 4 and Figure 5 shows the investments and cost per driven distance for the simulated cases.

Table 3 Data for the simulated cases of different combinations of bus lines.

	Bus lines				
	1	2+4	3	1+2+3+4	1-17+24
Number of buses	11	5	8	24	59
Simulated driving distance (km)	2654	1415	1340	5409	13757
Battery (kWh/bus)	120	160	100	118	152
Electricity usage (MWh/year)	1725	915	849	3945	8945

Table 4 Charging system and mean charging power for the simulated cases of different combinations of bus lines. The mean charging power is calculated as the energy consumption for the simulated weekday divided by 24 hours.

Charging station mean power kW	Bus lines				
Bus stops	1	2+4	3	1+2+3+4	1-17+24
	(kW)	(kW)	(kW)	(kW)	(kW)
Aspnäset: A					84
Berga centrum: B					12
Fönvindsvägen östra: A					62
Hässlegatan: A	26			27	27
Landbogatan: A					71
Linköping Centralstation: A1					32
Linköping Centralstation: A3	19				
Linköping Centralstation: A4	20			19	19
Linköping Centralstation: A5			43		
Linköping Centralstation: A6		46		60	44
Linköping Centralstation: B6					21
Lötgatan: A					67
Räknestickan: A					38
Rydsvägens ändhållpl.: A			62	44	49
Stenåldersgatan: A	42			44	45
Total mean Charging station power (kW)	*107*	*46*	*105*	*194*	*571*
Number of charging stations	4	1	2	5	13
	Bus lines				
ERS sections	1	2+4	3	1+2+3+4	1-17+24
	(kW/km)	(kW/km)	(kW/km)	(kW/km)	(kW/km)
Kungsgatan -> Linköping Centralstation, 481 meter	75	33		141	260
Linköping Centralstation -> Kungsgatan, 703 meter	92	41		141	341
Linköping Trädgårdstorget -> Kungsgatan, 460 meter		46		141	274
Total ERS length, (meter)	1184	1644	0	1644	1644
Total ERS mean power density (kW/km)	85	40	0	141	299
Total mean ERS power (kW)	*101*	*66*	*0*	*232*	*491*
Depot charging, total mean power (kW)	*14*	*5*	*7*	*25*	*91*
Total mean power (kW)	222	117	112	451	1153

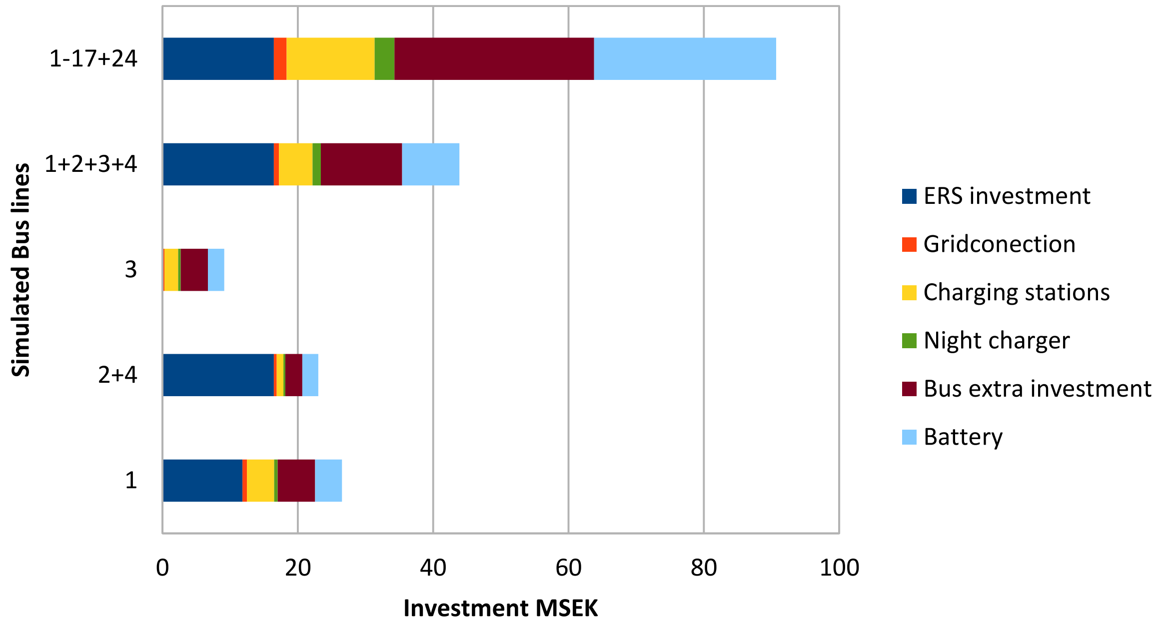

Figure 4 Investment cost for the simulated cases of different combinations of bus lines.

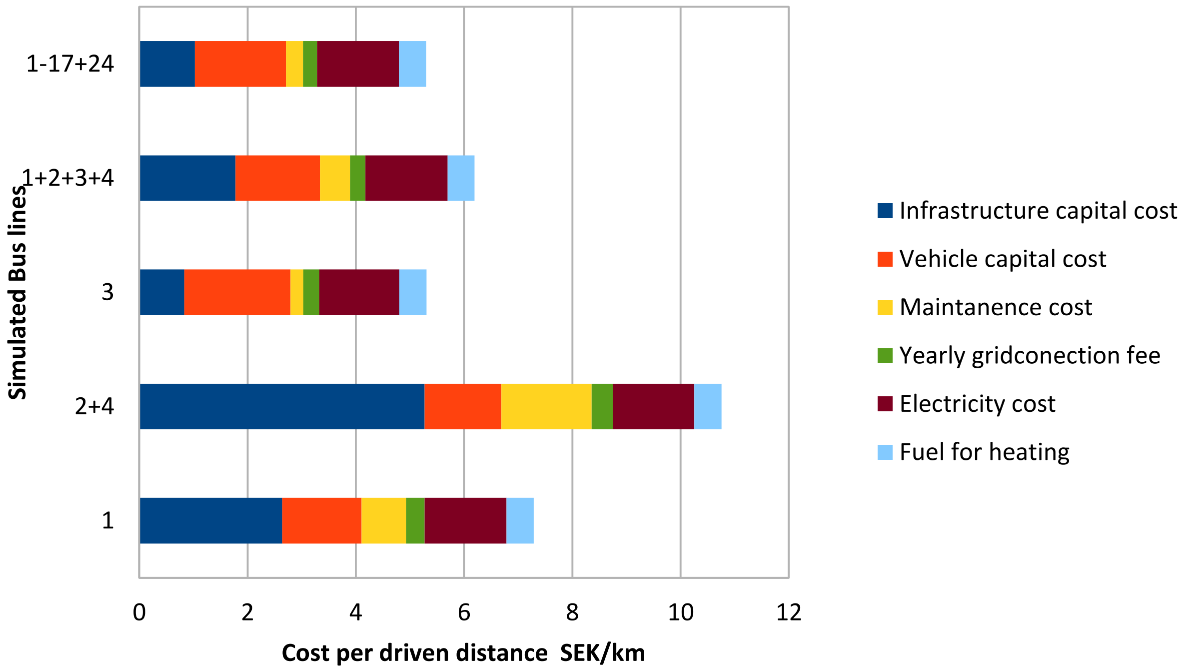

Figure 5 Cost per kilometer driven for the simulated cases of different combinations of bus lines.

9.1.1 Bus line 1

Figure 6 A map of bus line 1. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 6 shows bus line 1 with the suggested charging system. This bus line needs 11 buses to operate, each of these are equipped with a 120 kWh battery. The battery size is mainly set to get a predicted operational lifetime of ten years.

9.1.2 Bus line 2 and 4

Figure 7 A map of bus line 2 and 4. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 7 shows bus lines 2 and 4 with the suggested charging system. The difference between these bus lines are the direction they travel in the loop in the south west part of the route. These bus lines need 5 buses in total to operate, each of these are equipped with a 160 kWh battery. The battery size is mainly set to get a predicted operational lifetime of ten years. The low number of trips per day in combination with the need for electric road gives a rather high cost for electrifying these bus lines. The cost per driven distance of 10.8 SEK/km is dominated by infrastructure costs.

9.1.3 Bus line 3

Figure 8 A map of bus line 3. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 8 shows bus line 3 with the suggested charging system. This bus line needs 8 buses to operate, each of these are equipped with a 100 kWh battery. The battery size is mainly set to get a predicted operational lifetime of ten years. This bus line has rather low utilization of the buses at 156 km per bus and day when operated separately form the rest of the bus network. This leaves enough time at the end stops to only charge the batteries at the end stops. This gives a very low electrification cost per driven distance of 5.3 SEK/km. The fact that the buses are rather poorly utilized when operating this bus line with a separate bus fleet according to current time table indicates that the overall economy of such operation probably will be less favorable.

9.1.4 Bus lines 1 to 4

Figure 9 A map of bus line 1, 2, 3 and 4. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 9 shows the combination of bus line 1, 2, 3 and 4 with the suggested charging system. This bus line needs 24 buses to operate, each of these are equipped with a 118 kWh battery. The battery size is mainly set to get a predicted operational lifetime of ten years. The cost per driven distance is 6.2 SEK/km, this rather low value is partly due to the fact that the electric road sections can be shared between the bus lines. This combination of bus lines is the combination used to compare different charging solutions in subchapter 9.2 later in this report.

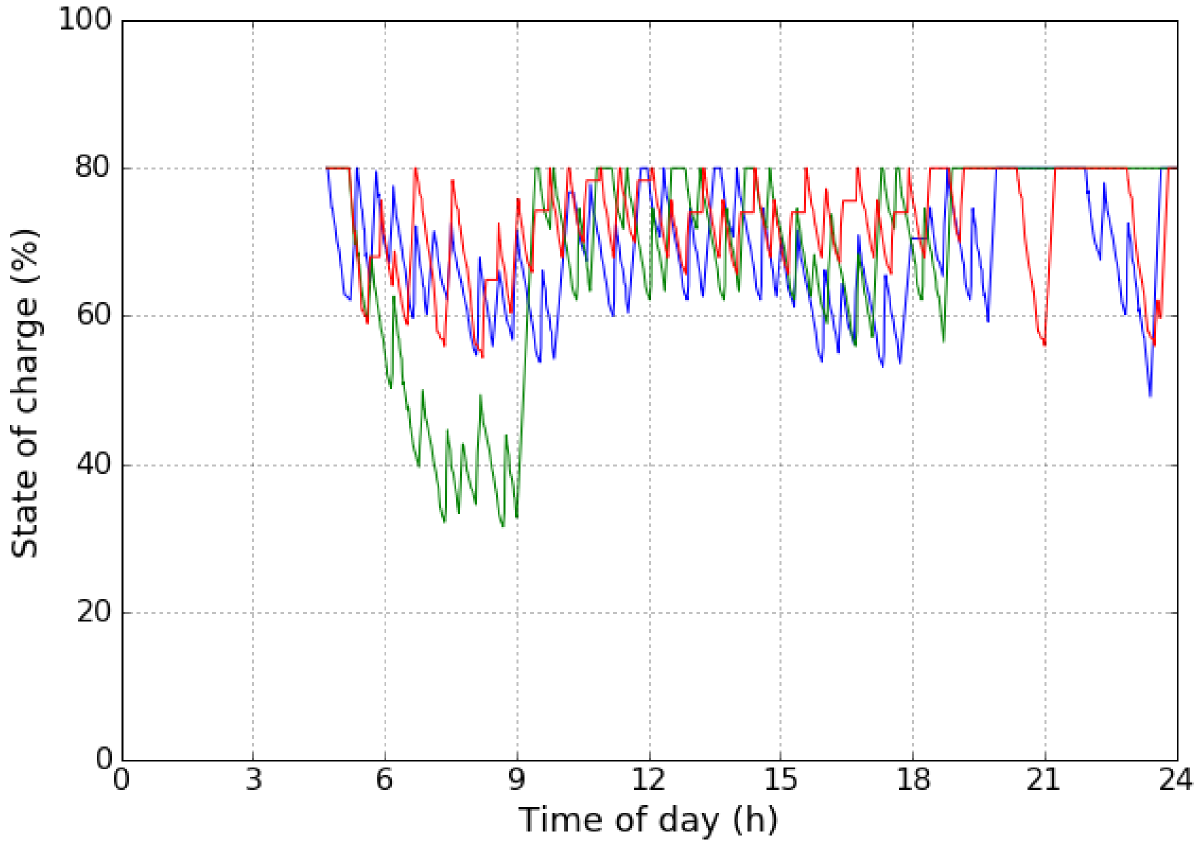

Figure 10 State of charge of the batteries in three typical buses in the simulated case of bus lines 1 to 5 with both electric road and charging stations.

The state of charge (SOC) over the day on a few typical buses is shown in Figure 10. As can be seen the buses do not have time to fully charge between 6 and 9 in the morning but otherwise the state of charge mainly varies between 60 % and 80 %. The charging infrastructure for bus line 2 and 4 are the same as when these are operated separately in section 9.1.2, despite this the needed battery is reduced from 160 kWh to 118 kWh when operated together with the other bus lines. The reason for this is that it is not the same buses that runs on these demanding bus lines all the time.

Figure 11 and Figure 12 show the distribution of stop times recorded from the Östgötatrafiken real time data[1] for bus lines 1 to 4 in order to illustrate the amount of time available for charging. The buses do not stop at 33 % of the stops on average, at the stops selected for charging they do not stop in only 3 % of the cases.

This data shows that while most stops are shorter than 30 seconds 48% of the total stop time is spent on stops longer than 100 seconds but typical stops at the sites selected for charging stations are around 500 seconds.

[1] Timing data is missing for about 6 % of the times a bus should pass a bus stop.

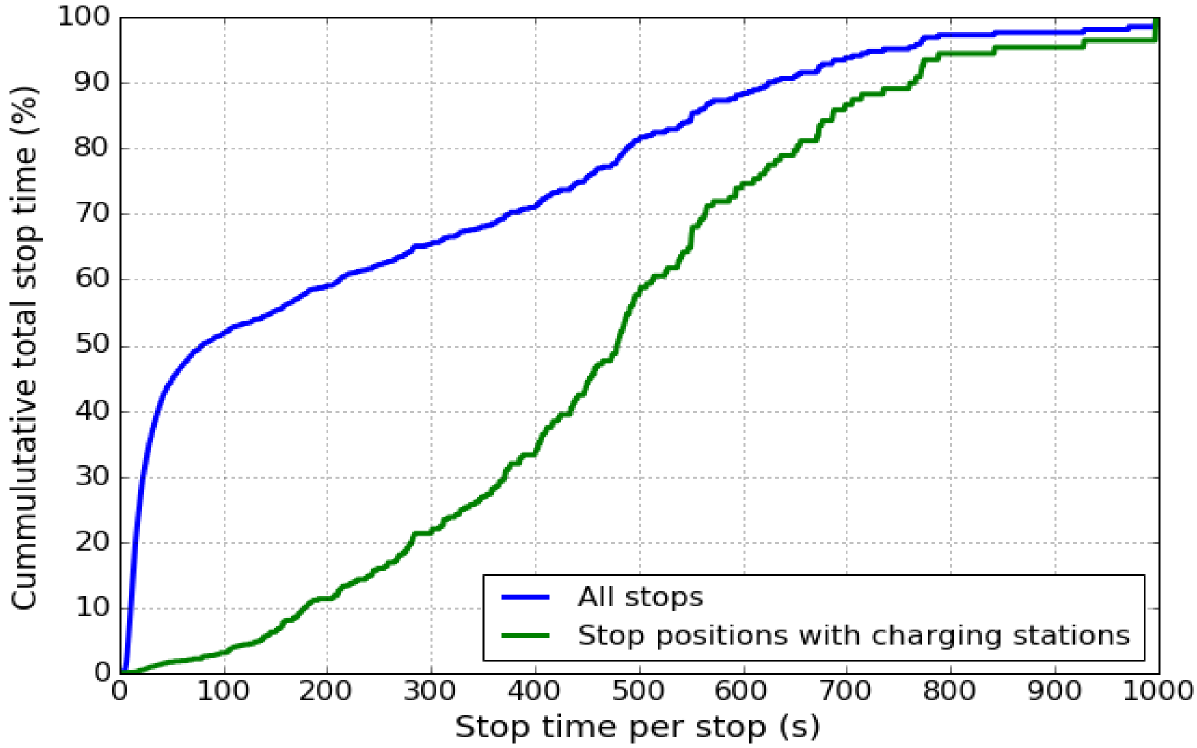

Figure 11 Cumulative distribution of time at bus stop vs stop time for bus line 1 to 4. The time at bus stops are from real recorded data while the placement of charging stations is according to simulations. In total 2.5 hours/bus/day was spent at bus stops, of these 1 hour/bus/day was spent at stop positions with charging stations. As an example the blue line shows that approximately 60% of the total stop time for all busses and for all bus stops is spent on stops shorter than 200 seconds.

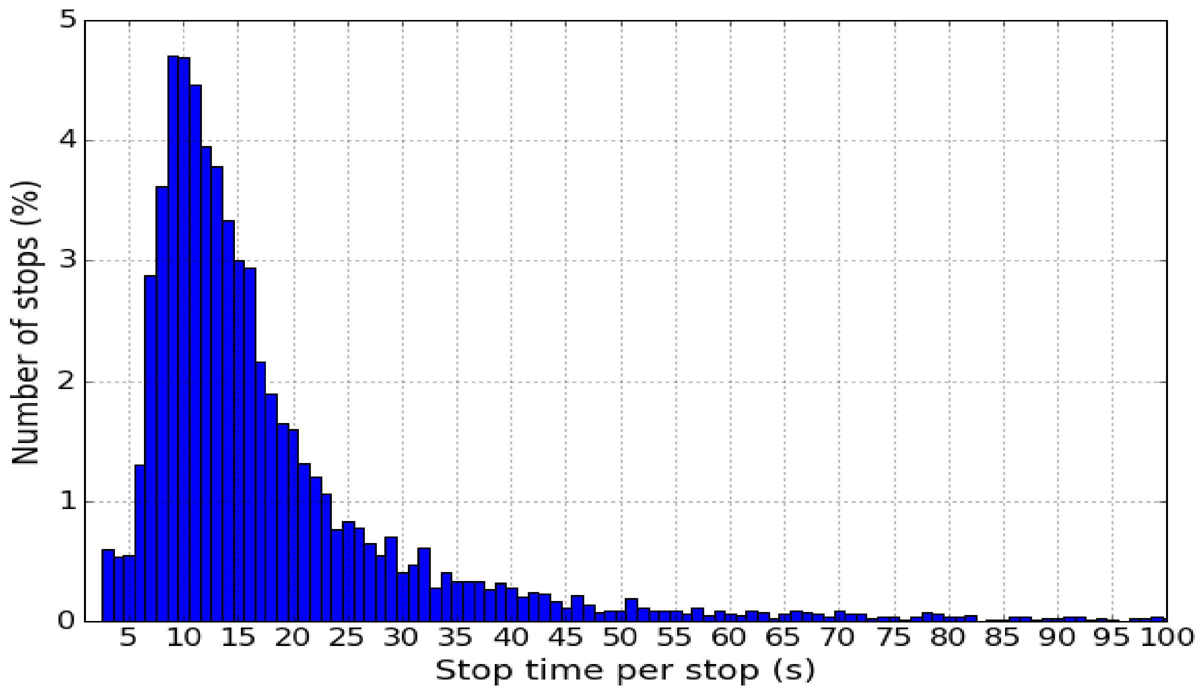

Figure 12 Distribution of stop times for stops shorter than 100 s, 95% of all stops are shorter than 100 seconds but they only represent 52 % of the total time spent at bus stops.

9.1.5 Bus line 1 to 17 and 24

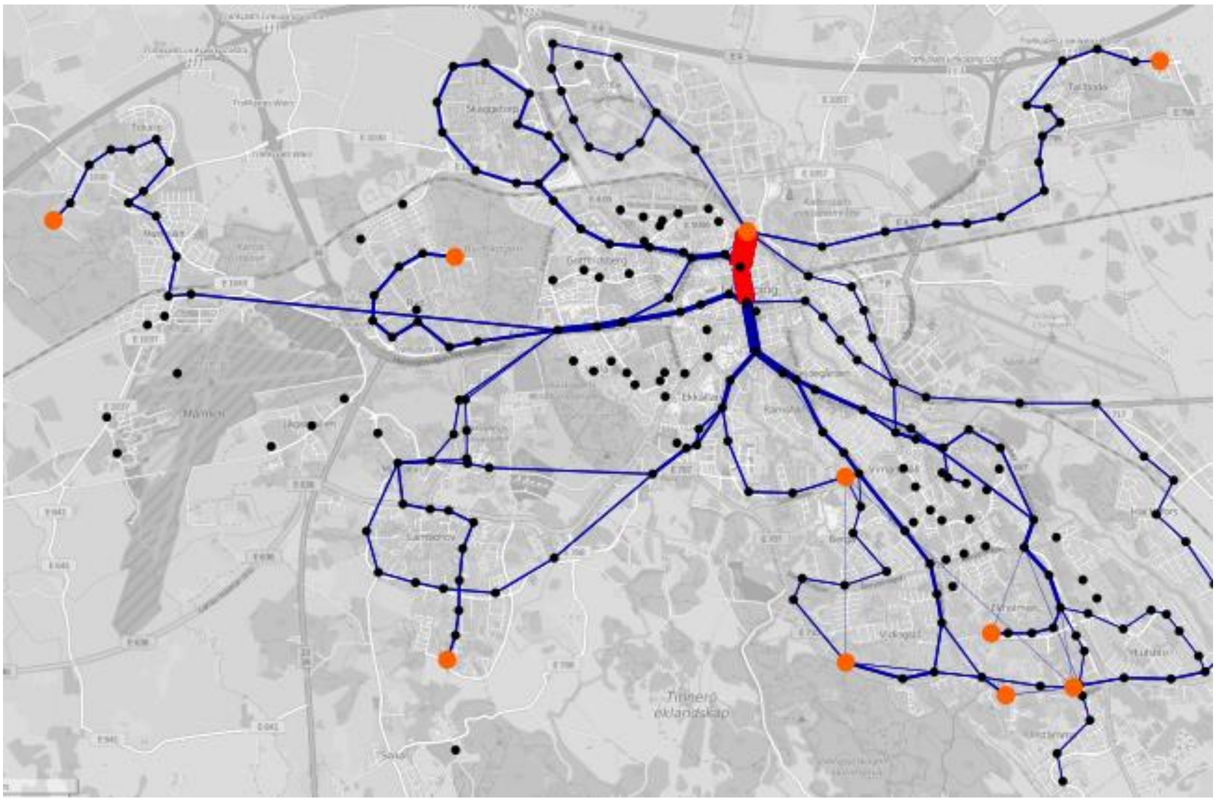

Figure 13 A map of bus line 1 to 17 and 24. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 13 shows the combination of bus line 1 to 17 and 24 with the suggested charging system. This bus lines needs 59 buses to operate, each of these are equipped with a 152 kWh battery. The battery size is mainly set to get the required driving range in this case unlike the earlier cases were the operating life of the battery was the limiting factor. The cost per driven distance is 5.3 SEK/km, this low value is partly due to the fact that the electric road sections can be shared between the bus lines. This is the most extensive example in this report and cover about 90% of the daily driven distance in the city bus traffic in Linköping.

9.2 Charging systems

In this subchapter the case with bus lines 1, 2, 3 and 4 are used to compare different charging systems.

The charging systems compared are:

- A combination of electric road and charging stations, this is the system used in sub chapter 9.1. (ERS + CS) The combination of electric road and charging stations is decided by the optimization algorithm.
- Only electric road (ERS)
- Only charging stations
- Only high power charging stations of 600 kW as opposed to the 200 kW used in the other simulated cases. The cost assumptions are given in Table 2. (CS 600 kW)

All the systems assume night time charging at the bus depot.

General data for the simulated cases are shown in Table 5. The different charging solutions and the mean power levels over 24 hours a weekday are shown in Table 6. Figure 14 and Figure 15 shows the investments and cost per driven distance for the different charging solutions. As seen, the differences in cost are rather small so the comparisons are rather sensitive to cost assumptions.

Table 5 Data for the simulated cases of different charging systems. The abbreviations are: ERS, Electric road system, 200 kW; CS, charging stations, 200 kW; CS 600 kW, charging stations, 600 kW

	Charging solution			
	ERS+CS	ERS	CS	CS 600 kW
Number of buses	24	24	24	24
Simulated driving distance (km)	5409	5409	5409	5409
Charging power, (kW)	200	200	200	600
Battery (kWh/bus)	118	143	289	300
Electricity usage (MWh/year)	3516	3603	3433	3418

Table 6 Charging system and mean charging power for the simulated cases of different combinations of charging systems. The mean charging power is calculated as the energy consumption for the simulated weekday divided by 24 hours. The abbreviations are: ERS, Electric road system, 200 kW; CS, charging stations, 200 kW; CS 600 kW, charging stations, 600 kW

Charging station mean power	Charging solution			
Bus stops	ERS+CS	ERS	CS	CS 600 kW
	(kW)	(kW)	(kW)	(kW)
Berga Söderleden: B			6	
Hässlegatan: A	27		29	
Klostergatan: A			3	
Linköping Centralstation: A3			19	54
Linköping Centralstation: A4	19		20	58
Linköping Centralstation: A5			72	106
Linköping Centralstation: A6	60		68	106
Linköping Skäggetorp centrum: A			9	
Linköping Trädgårdstorget: A			9	
Linköping Trädgårdstorget: C			10	
Rydsvägens ändhållpl.: A	44		50	
Stenåldersgatan: A	44		75	93
Stora Torget Linköping: A			6	
Tinnerbäcksbadet: A			4	
Tinnerbäcksbadet: B			4	
US Norra entrén: B			3	
US Södra entrén: B			3	
Total mean Charging station power (kW)	194	0	390	417
Number of Charging stations	5	0	17	5

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ERS sections mean power density	Charging solution			
ERS sections	ERS+CS	ERS	CS	CS 600 kW
	(kW/km)	(kW/km)	(kW/km)	(kW/km)
Abisko -> Banérgatan, 403 meter		27		
Banérgatan -> Abisko, 387 meter		23		
Klostergatan -> Kungsgatan, 325 meter		58		
Kungsgatan -> Linköping Centralstation, 481 meter	141	141		
Kungsgatan -> Linköping Trädgårdstorget, 360 meter		103		
Linköping Centralstation -> Kungsgatan, 703 meter	141	203		
Linköping Trädgårdstorget -> Kungsgatan, 460 meter	141	141		
Tinnerbäcksbadet -> Linköping Trädgårdstorget, 513 meter		62		
Total ERS length, (meter)	1644	3632	0	0
Total ERS mean power density (kW/km)	141	106		
Total mean ERS power (kW)	232	384	0	0
Depot charging, total mean power (kW)	25	70	63	34
Total mean power (kW)	451	454	453	451

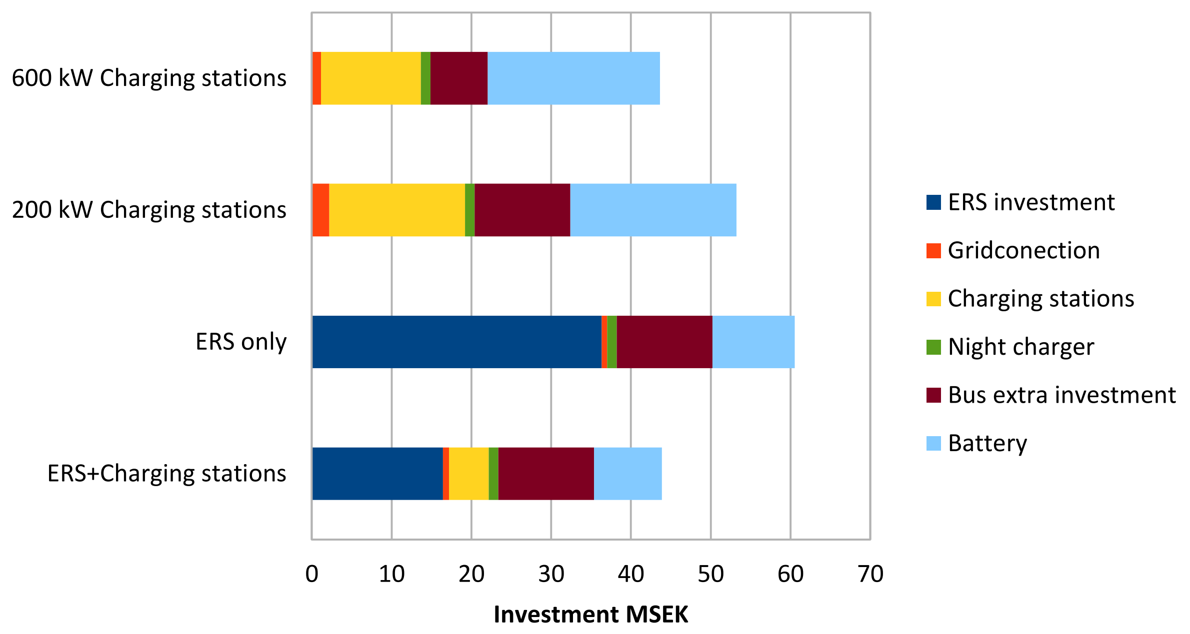

Figure 14 Investment cost for the simulated cases of different combinations of charging systems.

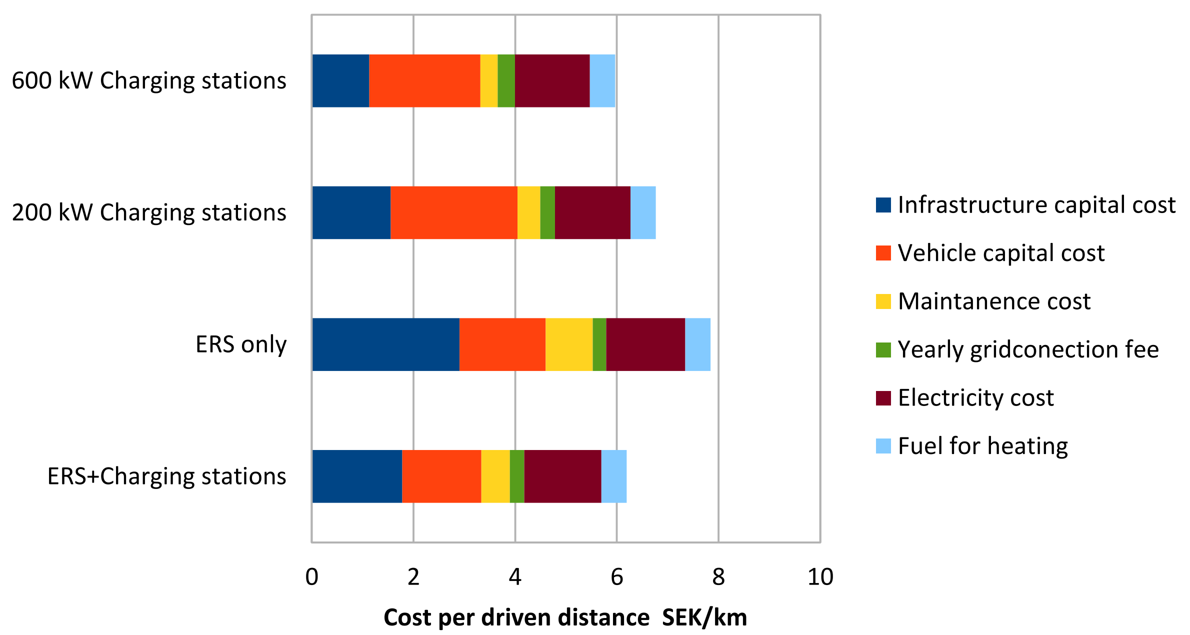

Figure 15 Cost per kilometer driven for the simulated cases of combinations of charging systems.

9.2.1 Electric road only

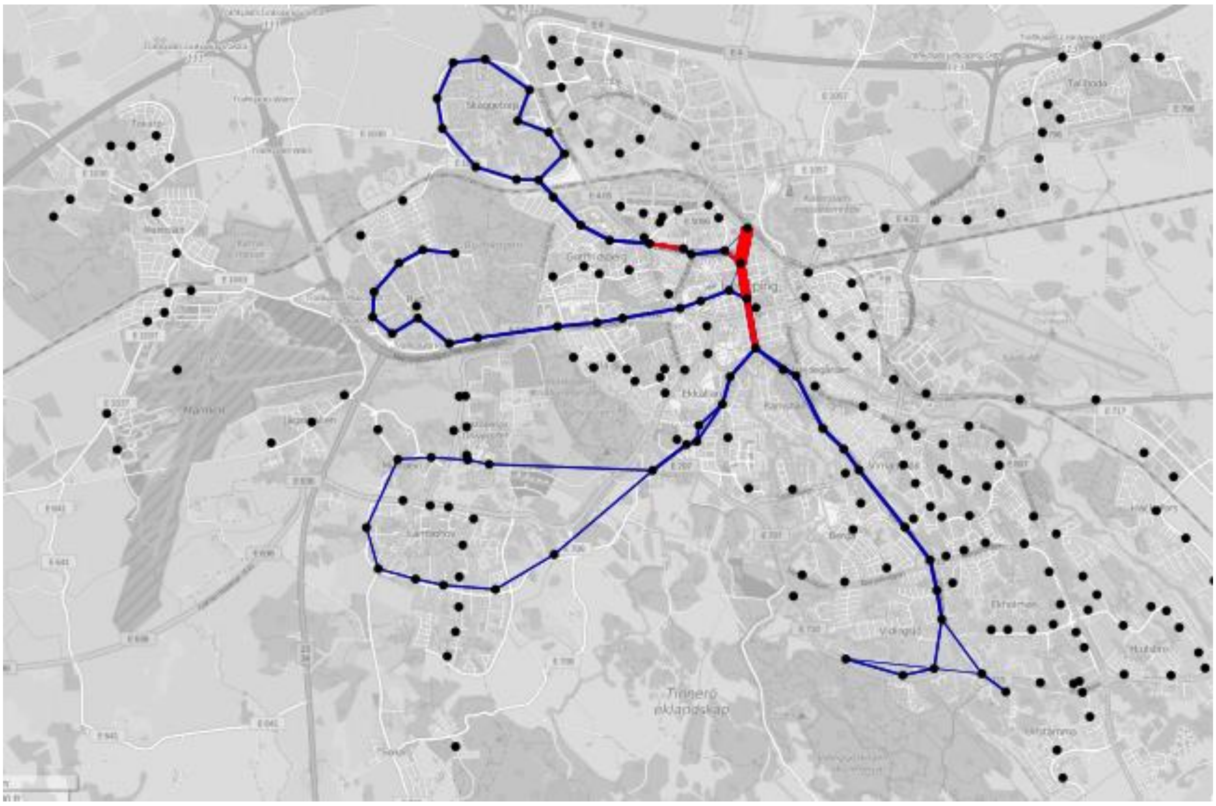

Figure 16 A map of bus line 1, 2, 3 and 4 electrified with only electric road. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 16 shows the combination of bus line 1, 2, 3 and 4 with only electric roads as a charging system. The buses are equipped with a 143 kWh battery. The battery size is mainly set to get a predicted operational lifetime of ten years. The cost per driven distance is 7.8 SEK/km. Since all charging during daytime needs to come from the electric road system some of the electric road needs to be installed on sites with low utilization. Part of the electric road only have an average load of 23 kW/km, see Table 6.

One advantage of a charging system with no charging stations is that the system is insensitive to delays in the bus schedule. When the bus is late the time at end stops will be shorter but the driving time between bus stops will not change that much.

9.2.2 Charging stations only

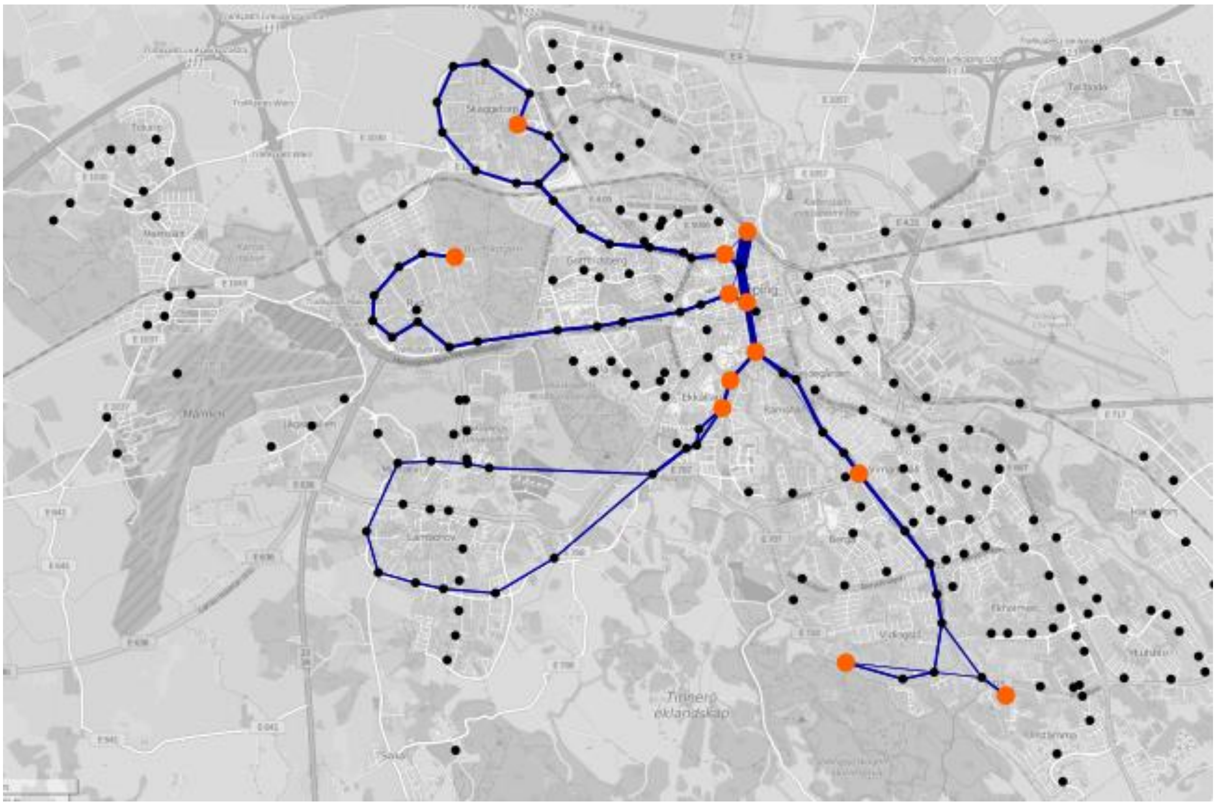

Figure 17 A map of bus line 1, 2, 3 and 4, electrified with only 200 kW charging stations. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 17 shows the combination of bus line 1, 2, 3 and 4 with no electric road. The buses are equipped with a 289 kWh battery. In contrast with the previous cases, the battery size is mainly set to get the required driving range in this case. The weight of the large battery is not considered in this study but it could be an important factor. The cost per driven distance is 6.8 SEK/km. The largest cost in this system are the batteries. Since all charging during daytime needs to come from the charging stations some of these needs to be installed also on sites with low utilization, some of them present as low average power over the day (24 hour) as 3 kW, see Table 6. The fact that it is hard to find enough good bus stops for charging stations without changing the time table is reflected in the large battery, some of the buses run with less charging time than needed to maintain a stable state of charge for parts of the day.

9.2.3 High power charging stations only

Figure 18 A map of bus line 1, 2, 3 and 4, electrified with only 600 kW charging stations. Red lines show electric roads. Orange dots show charging stations. Black dots show bus stops.

Figure 18 shows the combination of bus line 1, 2, 3 and 4 with no electric road and high power charging stations. The buses are equipped with a 300 kWh battery. The largest cost in this system are the batteries. The battery size is set to get the required maximum charging power of 600 kW at 2 kW/kWh. It could very well be that it would be more economical to use batteries more optimized for power with this kind of charging stations but that has not been investigated. The weight of the large battery is not considered in this study but it could be an important factor. The cost per driven distance is 6.0 SEK/km, this is the lowest cost of the compared cases with this combination of bus lines. The cost is very close to the system with both electric road and charging stations and sensitive to uncertain assumptions. In this solution only five charging stations are needed and four of them are at the railway station.

10 Conclusions and discussion

The list below presents conclusions and reflections derived from the work presented in this report.

- The development of bus stop charging systems is in an early phase of commercialization. Accounting for expected future cost reduction on batteries and full electric vehicles and charging systems, a full electric bus fleet is likely to be competitive based on cost only. In addition, electric buses also give other benefits such as potentially lower environmental impact, cleaner air and less acoustic noise.
- Minor adjustments in the scheduling of the buses, e.g. a few more minutes at the end stops, could potentially reduce the needed investments significantly. This would however generate other costs since more buses and drivers are needed to operate the system. This is not calculated in this report.
- In a full bus line network such as in Linköping, a small installation of electrical road systems (ERS) on the most heavily used streets seems to be economically favorable in most cases that are considered in this study. Furthermore, the electric road system installations could also potentially be used by several vehicles other than buses, e.g. city distribution trucks, taxis or refuse trucks.
- The use of high power (600 kW) charging stations only seems to give about the same costs as the combination of charging stations and electric roads at the 200 kW power level. This is very dependent on the cost assumptions. It is probably easier to install and maintain a few high power charging stations than a combination of electric road and charging stations but high power charging stations are probably more sensitive to delays in the bus schedule.
- Conductive systems are generally cheaper than inductive systems but can potentially be more sensitive to weather. The safety against electric shocks also needs to be considered, but it is proven very safe with trams with similar technology. More flexible conductive systems suitable both for bus stop charging and use on electrical road systems are being developed but have not been proven in public operation yet.
- The different charging systems can be mounted on different vehicles from different manufacturers, but no standard interfaces exist yet so this is a rather complicated process. In many cases it is possible to mount pickups for more than one system on the same vehicle, or to install charging stations for more than one system on the same bus stop to handle incompatible systems, but that will introduce extra costs. Even if it turns out that the system initially chosen is not the most economical to continue with, the investments in grid connection, electric buses and batteries can still be utilized.
- Standardized systems would be preferred and are necessary in order for automatic charging and ERS to be useful for vehicles in general traffic. Since several incompatible systems are under development and need operational experience in order to asses them, standardization will probably not happen soon.
- Another large uncertainty is the battery price development. Currently battery packs for electric buses are rather expensive due to low volume production and high requirements on expected lifetime. On the other hand, the prices of battery cells and battery packs to electric cars are falling rapidly.

- All together it seems that with a few adjustments in the time table and fuel-based heaters, electric bus systems can be an economical alternative for Linköping's city bus traffic in the near future. This is probably only relevant if the biogas currently used is needed for other applications.

11 Further work

Areas that can be improved in future studies on electrification of city buses include:

- Improving battery modeling and including the degradation generated by fast charging and the limited charging rate on batteries.
- Utilizing the data from the real time information system better so the actual bus allocation and timing in real traffic can be simulated as if it was operated with electric buses. In this study only the mean stop times and driving distances are utilized from the real time information system.
- Using GPS tracking data in order to get better data on where the buses spend time and hence where the best charging opportunities are.
- Studying how the bus routes and scheduling can be optimized for electric operation.
- Verifying and updating cost estimates and other assumptions.
- Improving the modeling of grid connection costs.
- Studying bus networks in other cities.

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