CHALMERS
UNIVERSITY OF TECHNOLOGY

Future electricity demand and grid connections of electric road systems for heavy transport

A case study of a Swedish highway

Master's thesis in Sustainable Energy Systems

ROBIN FRONT
MARTIN RAISSE

Department of Space, Earth and Environment
Divison of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Master's thesis 2019

Future electricity demand and grid connections of electric road systems for heavy transport

A case study of a Swedish highway

ROBIN FRONT
MARTIN RAISSE

Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
Gothenburg, Sweden 2019

Future electricity demand and grid connections of electric road systems for heavy transport
A case study of a Swedish highway
ROBIN FRONT & MARTIN RAISSE

Supervisors: Ludwig Thorson, Department of Energy and Environment
Maria Taljegård, Department of Energy and Environment

Examiner: Mikael Odenberger, Department of Energy and Environment

Master's Thesis 2019
Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: A picture of electricity cables suspended in the air [1].

Printed by Chalmers Reproservice
Gothenburg, Sweden 2019

Abstract

This thesis investigates the potential implementation of electric road systems (ERS), a novel technology created with the purpose of electrifying future transport in order to reduce greenhouse gas emissions. Using this technology, electricity is delivered from the electricity grid to the road and further onto the vehicles travelling on the road. This thesis considers the implementation of an ERS for heavy transport such as heavy trucks and buses.

More specifically, the purpose of this thesis is to study how the connection points (electrical substations) from an ERS can be placed along the road and how the varying electricity demand from the road will affect the dimensional requirements of the equipment used. This was studied via a case study of the E6 route in Sweden assuming three different vehicle electrification scenarios derived from climate goals as well as electrification trends and statistics: 40%, 70% and 100% electrification. The average and peak electricity demand of the vehicles were calculated using a mathematical model. Three cases of substations placement were assumed; the first case was based on a previous proposition from the report *Slide-in Electric Road System* where the electrical substations are placed with a 40 km distance between each other, the second case was based on assuming there is available capacity in existing substations and connecting the ERS to these, the third case was based on the geographical load distribution of the ERS by making an investment cost optimization based on cost of cables and substation equipment. This was done assuming all substations were dimensioned by the same power and the optimization model was created to find out the optimal substation dimension, balancing the number of substations and their investment cost against the cost of the cables connected to the road between the stations.

It can be concluded that if spare capacity in existing substations is sufficient it would obviously be the least cost alternative to use these substations. However, data regarding existing capacity is classified making it difficult to draw any conclusions. But generally the grid strength is weaker in southern parts of route E6 where demand is high and production is low, possibly making current substations unsuitable. Therefore, if additional substation capacity is required a cost optimization will lead to best return of investment. The substation dimensions for the three scenarios based on the cost optimization were 45 MW for the 40% scenario and 48 MW for both the 70% and the 100% scenario, for route E6. At larger dimensions, the cable costs are increasing rapidly while the investment cost of the substations are low. As the cables make up most of the total cost, the solution is defined by the balance of cable versus substation cost at these dimensions. Another conclusion is that the expected peak electricity demand is a large factor when dimensioning the substations, as traffic during peak hours can be 3-4 times higher than the average yearly traffic. If usage of the ERS during the worst peak hours can be avoided, large dimensioning requirements can be cut and the investment costs can be reduced by a considerable amount. For the cases with low electrification, the model resulted in few substations along route E6, making the distance between stations very long which can have negative effects related to voltage drop and power losses.

Keywords: Electric road system, ERS, Electricity grid, Electrical substations, Ramp-up, Climate target, Cost optimization

Acknowledgements

We would like to express our utmost gratitude towards our dear supervisors, Maria Taljegård and Ludwig Thorson, for always standing by our side during our ups and downs and for believing in us at times where we had trouble believing in ourselves, thank you.

A big thank you goes out to Per Norberg whom tirelessly answered all our questions regarding electric power engineering and sat down with us several times without having any prior connection to our thesis. We would not have been able to finish this project without you.

We would like to thank Karin Rådegran, Oscar Skoglund, Peter Thelin and Neil Hancock at E.ON for showing a big interest in our thesis and helping us push the project forward and also for providing us with guidance regarding the electricity grid.

We would also like to thank Conny Börjesson at RISE, Henrik Forsgren at Göteborg Energi, Torbjörn Nordgren and Björn Fahlgren at Varbergsortens Elkraft, Henrik Rinnemo at Ellevio, Magnus Sjunnesson at Öresundskraft AB for their willingness to sit down with us and discuss our thesis and helping us shape our project during its early stage.

Lastly, we would like to thank Maria Varedian and Andreas Jansson at the Swedish Transport Administration for providing us with necessary data.

Robin Front & Martin Raisse, Gothenburg, June 2019

Contents

1

Introduction

Anthropogenic global warming is on a steady incline [2]. Reducing the emissions, mainly of carbon dioxide (CO_2), is an urgent matter and currently one of the greatest challenges in human history [3]. There are climate goals set by governments and organizations in order to push for changes to happen, for example the 1,5^{o}C target which aims to be fulfilled by The Paris Agreement [4]. In order to reach the climate goals, changes needs to happen all around the world and reducing the amount of fossil fuels is one of the key factors of reducing CO_2-concentrations to within acceptable limits [2]. A large share of consumption of fossil fuels takes place within the transport sector. In 2017, the emissions of carbon dioxide from Swedish road transportation reached 15,5 MtCO_2-equivalent which represented thirty percent of Sweden's total CO_2 emissions [5]. This means that there are large environmental benefits in making the transportation sector run on renewable alternatives, where one alternative is the implementation of electric vehicles (EVs).

During previous years, passenger EVs have seen an incremental increase in usage in Sweden with a growth of 434 percent at the end of 2018, compared to 2015 [6]. However, the use of electrical heavy trucks and buses used for long range transport is close to none [7]. For these vehicle categories, there are still concerns regarding the need for having to charge the battery multiple times when driving longer distances than the battery range. By adding additional fast charging stations the waiting time can be somewhat decreased, but the discomfort of having to continuously charge the battery is still evident. One of the measures that can be taken in order to solve this problem is construction of bigger batteries, this can however imply high costs, especially for heavy trucks and buses which aim to be driven long distances without interruptions. The weight and volume of the battery also increases with size, which decreases the amount of cargo that can be transported. Moreover, a larger battery also requires certain natural resources which are of limited supply and potentially negative for the environment [8]. By introducing an electric road system (ERS), which provides the vehicle with electricity while driving, issues regarding range and battery will be diminished, especially when considering longer transports.

ERS can be implemented either through conductive or inductive technologies. The conductive methods work similar to how trams and trains are powered today, through overhead lines or through a rail in the ground or alongside the road [9]. For inductive transmission, currently only ground-based technologies are used [10]. The electricity required to power the EVs through these technologies is to be supplied from the electricity grid. Because of this, an ERS entails an additional load on the grid, with a varying electricity demand depending on the number of vehicles using the system in each instance and their electricity consumption. This varying electricity demand is one of the main characterizations when it comes to the electricity demand of an ERS as the potential peak demands for certain hours can be high compared to the average demand throughout the year.

As the peak demands of electricity decides the dimensions of equipment and cables required to operate an ERS, the geographical load distribution of an ERS at peak traffic hours should be studied in order to find how substations and grid cables can be placed along the road in a cost-effective way.

1.1 Aim and objective

The purpose of this thesis is to analyze how the connections points to an ERS can be placed along a road and how the varying electricity demand from the road will affect the dimensions of the required equipment, assuming various electrification scenarios. This is achieved by performing a case study of route E6 which stretches from Trelleborg in southern Sweden to Svinesund close to the Norwegian border on the west coast. Since information, such as capacity and geographical locations, regarding the electricity grid is under secrecy by grid operators, the methods used to define eligible connection points were based on existing and future regional loads as well as the electricity demand of a potential ERS. Information about expansion plans related to industry close to route E6 was also gathered to pinpoint potential connection points over the upcoming years. Moreover, the geographical load distribution of the ERS was evaluated to be able to dimension the connection points accordingly.

As ERS is a novel technology, one of the challenges is to predict how the share of electrified vehicles on the road will develop over time. With the help of trends and climate goals, a few different electrification scenarios have been developed and analyzed in order to include an uncertainty of the ramp-up of vehicles using ERS. For each scenario, the required dimensions of the connection points at different points in time could be found, based on the ramp-up.

The specific questions that will be answered in this thesis are:

- Where can the substations be placed along route E6 based on existing and future electricity demands?
- What will the dimensions (electricity demands) be at these substations?

Given that light vehicles, such as cars and light trucks, generally drive shorter distances they are less susceptible to stopping the vehicle for charging during a single trip and can therefore charge in between trips. As heavy vehicles drive longer distances and don't wish to spend a lot of time stopping and charging their batteries this thesis is focused on introducing ERS as a solution for electrifying heavy transport on Swedish roads.

2

Background/Theory

2.1 Electric road systems

An ERS uses either conductive power transfer (CPT) or inductive power transfer (IPT), either supplying power from above, below or the side of the vehicle [11]. Overhead lines are used to supply the vehicle with power from above while a rail in the ground is used for supply from underneath. One drawback between overhead lines and rail technology is that overhead lines can only power heavy vehicles since the lines are suspended a little more than five meters above the ground, making it challenging for passenger cars to connect onto the ERS [9]. Independent of which technique is used, the layout of the system from the electricity grid to the side of the road looks the same, an illustration is shown in Figure 2.1.

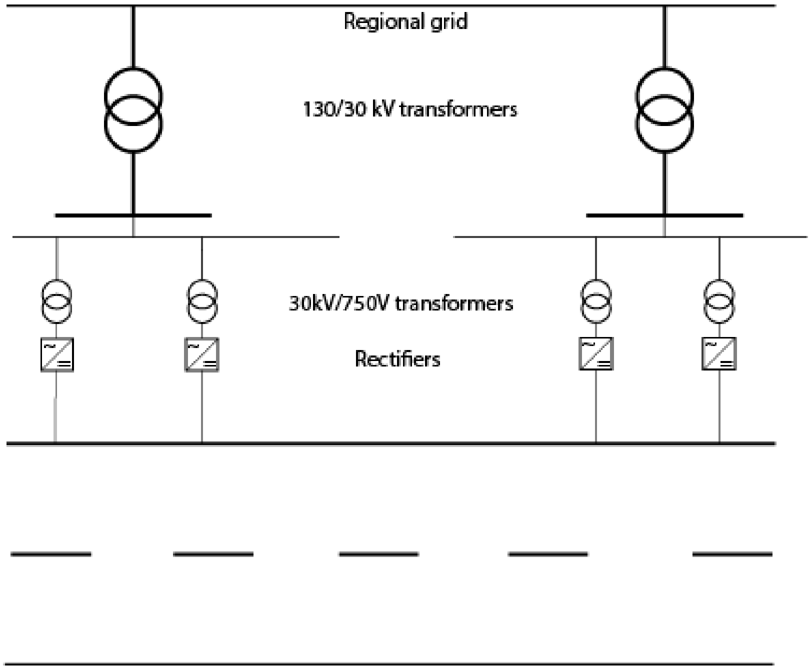

Figure 2.1: An illustration of how the electricity is converted from the regional grid and transported to the wayside grid. From there it is transformed to 750 V which is fed to the road.

The voltage level that is being fed to the vehicles is at 750 V direct current, implying that an ERS can be connected to grids which are operated above this voltage level. Depending on which voltage level the ERS is connected to, it requires different amounts of substations along the way. If the ERS is fed by a 30 kV grid that is transformed from 130 kV, one Swedish distribution system operator, Vattenfall AB, has estimated the need for a new substation every 40 kilometer [12].

2.2 Electricity grid

In Sweden there are three types of grids: the national grid, regional grids and local grids [13]. As each of these grids have a different purpose, different voltage levels are used to best serve the purpose while keeping the costs minimal. Per Norberg from Vattenfall and Oscar Skoglund from E.ON. claims that the power demand from an ERS is too high to be supplied by the local grid as the capacity of the local grid is too low [14] [15]. This means, according to Norberg and Skoglund, that the electricity has to be supplied by either the national or regional grid.

2.2.1 Regional grid

The regional grid is used to transport electricity from the national grid either to large electricity consumers, such as industries, or to the local distribution grids. The grid is operated at voltage levels between 20-130 kV [16].

The specific locations of the regional grid is generally not accessible as public information. This fact makes it harder to estimate the feasibility of connecting an ERS to the regional grid, as it is difficult to identify where the connections can be made as well as the available capacity on the cables. According to E.ON Energidistribution [14] and Vattenfall Eldistribution [15], the current regional grid infrastructure is located close enough to route E6 to be able to make feasible connections to an ERS.

As an alternative to connecting an ERS to only the existing grid, Vattenfall Eldistribution has suggested building a new grid at a voltage level of 30 kV along route E6 with the purpose of supplying electricity to an ERS. This voltage level was chosen mainly because it would be easier to get permits and thereby make the concession process faster. A 30 kV grid could also have possible synergies with nearby wind farms as it would remove the need for expensive transformer equipment [12] [17].

2.3 Development of ERS

In year 2017, about 0,9% of the Swedish car fleet consisted of electric cars and plug-in hybrids while the heavy transport fleet, as mentioned in the introduction, was close to zero [7]. To be able to create a scenario describing how the usage of an ERS will take shape, it is important to analyze the ramp-up of electrification which in turn allows for a prediction of the electricity demand for the ERS. When it comes to heavy transportation fleet, the ramp-up of vehicle electrification and ERS implementation will most likely be heavily dependent on each other, since introducing batteries in trucks and buses that travel long distances are generally not sought after (because of the previously stated battery size issue). Because of these reasons, the plans for building an ERS along a major highway likely has to be settled in order to promote a shift towards fully electric commercial freight. In past studies, a varying degree of electrification (DoE) have been used. Depending on what aspects are of interest, the DoE can be chosen differently.

In previous studies, such as slide-in phase two [12], Lund University assumed an increase from 15 to 100% electrification, regarding heavy vehicles, in four steps. While others performed calculations without considering the ramp-up aspect [12]. As there is a low amount of information available regarding likely ramp-up scenarios, estimations can be made using climate goals as a reference. Currently, there are climate goals set for Sweden which aim to be reached in 2030 and 2045. The aim for 2030 is to reduce the emissions of carbon dioxide from the transport sector by 70% compared to 2010 [18]. In 2010, the emissions from road transport equaled 18 $MtCO_2$ and 15 $MtCO_2$ in 2017, which represents a reduction of 18% over seven years and a required 52 percent point reduction over the coming 13 years [5]. Looking at the goal set for 2045 instead, which states that the Swedish transportation fleet should be free from fossil fuels, it can be determined that Sweden stands before a great challenge which puts a lot of pressure on the electrification of the transport sector and indicates that measures has to be taken at once [19].

2.3.1 Expected increase in transport of goods

One factor that is of importance in order to estimate the future demand of ERS is the expected increase in transport of goods. The Swedish Transport Administration is creating forecasts for the transports of goods in Sweden based on historic data. Transport Analysis gathered previous forecasts and presented three of them along with statistics, this can be seen in figure 2.2 [20].

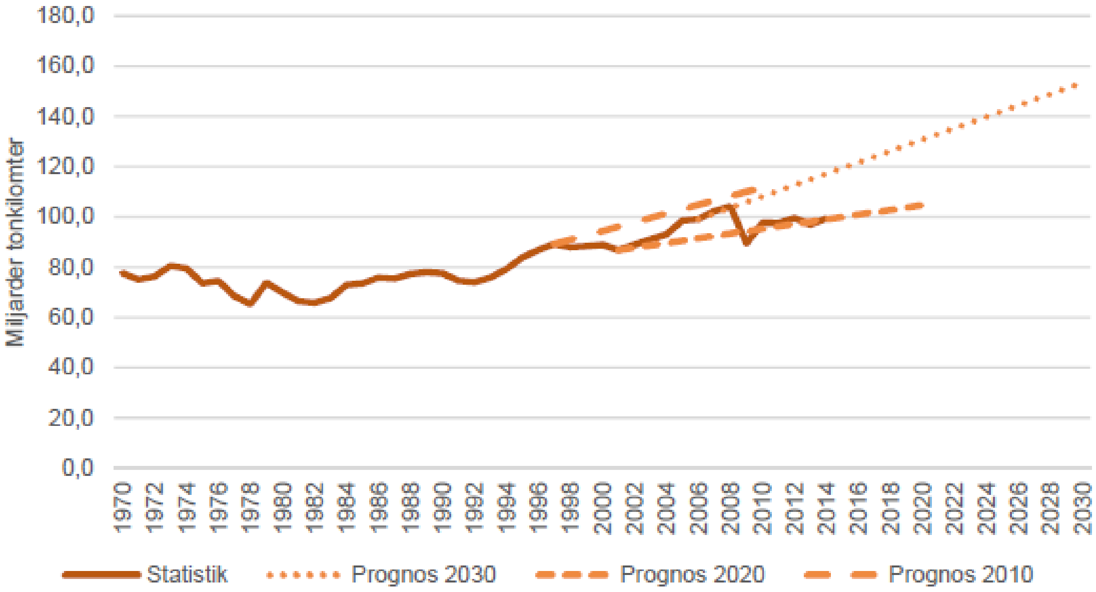

Figure 2.2: Expected increase in transport of goods in Sweden (excluding flight). The y-axis represents billions of vehicle ton kilometers. The three dotted lines represent three forecasts for 2010, 2020 and 2030 [20].

The most recent of these forecasts, made for 2030 (dotted line), predicts that the amount of ton kilometers in Sweden can increase up to 150 billion which is about a 50% increase compared to the 100 billion in the current state. However, the statistics from 2009-2016 along with older forecasts shows lower numbers compared to the 2030 forecast which indicates that predicting the future transport of goods is a hard task. Under the assumption that heavy transport will be the main user of ERS, these values are of high importance when calculating the expected electricity demand from the roads.

2.4 Electrical substations

There are several different substations that are being used in an electrical grid, the ones of interest in this thesis are the transmission substations [21]. The main function of the substation is to transform voltages to higher or lower levels and typical for transmission stations is that they serve as an intermediate between the generation and consumption of electricity [22]. The main components considered for cost calculations in this thesis with regards to the substation are the transformers with breakers and cables with circuit breakers. A list of all the components is shown in Appendix B, Table B.1.

3

Method

A mathematical model was used to calculate the electricity demand for route E6 in Sweden, this model was previously created by Taljegård et al. to perform calculations on the electricity consumption of the E39 road in Norway [23], it is described in section 3.2.1. Yearly vehicle statistics and topography data from the Swedish Transport Administration was used to apply this model to route E6 for the case study. Based on scientific papers and reports, various transportation scenarios were studied in order to predict a share of electrified vehicles compatible with the ERS as well as the ramp up over time.

A geographical mapping of potential substations was done, where the ERS could be connected to the regional electricity grid (130 kV grid). This is of importance in order to see how the electricity demand of the road is distributed and where additional capacity might be required in the future. To dimension the substations based on the highest load, the demand peaks of the year had to be identified. This was done using traffic flow data from the Swedish Traffic Administration.

3.1 Road and traffic data

To calculate the electricity demand of the road, information regarding the road's terrain and traffic is needed. The Swedish Transport Administration provided a data set containing the change in inclination along route E6, expressed in meters above sea level, with 13 911 data points northbound and 13 499 southbound. Out of these, a total of 339 points were missing data, 160 and 179 points respectively which were discarded and restored with interpolation between adjacent data points.

A second data set provided by the Swedish Transport Administration contained a total of 57 960 points which specified coordinates for each point, speed limit and average daily traffic (ADT).

The two data sets were merged in order to be compatible with the model used to calculate the energy demand. The merging was done in ArcMap and resulted in a total of 29 371 data points, 14 853 northbound and 14 518 southbound. The final set consisted of the following data:

- Length of each segment
- Meters above sea level for each segment
- ADT
- Percentage heavy traffic
- Road wear
- Speed limit
- Coordinates for each point
- Slope gradient

The length of each segment was calculated by using the Pythagorean theorem on adjacent data points. The slope gradient was also used to disregard certain segments which were short and had a high difference in height. These points were excluded and the missing data points were interpolated. This is due to the model being built in a way that it analyzes each segment independently, which caused these specific points to result in a very steep slope gradient and thereby an energy demand that is unrealistic.

3.1.1 Peak traffic hours

The substations should be dimensioned after the highest predicted load to be able to supply electricity at all hours of the year, which in this case is implied by the number of vehicles using the ERS. Figure 3.1 shows an example of the distribution of road traffic over a year for traffic point 7346 (set by The Swedish Transport Administration) north of Gothenburg. As can be seen, the peak traffic only occurs during a few hours of the year.

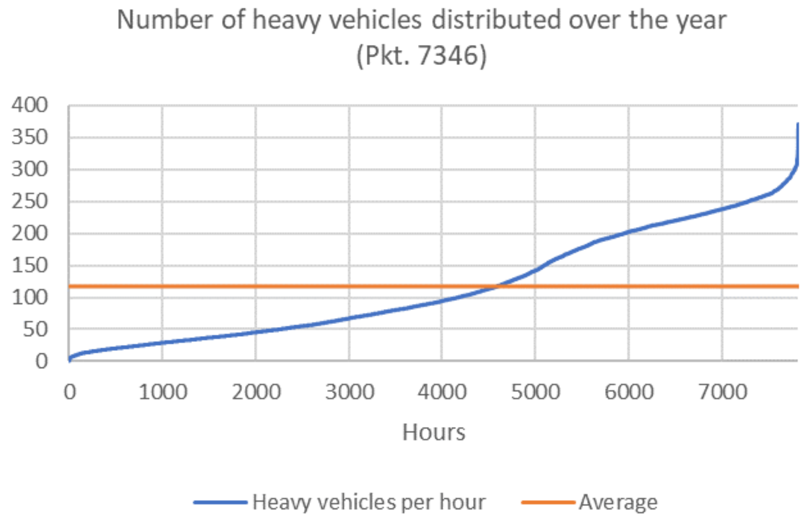

Figure 3.1: Distribution of heavy vehicles travelling through a measure point (Point 7346) north of Gothenburg over one year (2013).

As described later in section 3.3, four other data points are used to calculate peak traffic. The pattern for these data points follow similar trends and can be found in Appendix A. As the peak hours are few, the dimensioning requirements can be reduced if the peak load issue can be handled in another way, significantly reducing investment costs.

3.2 Calculations

The following section explains the methods used to calculate the electricity usage of the ERS. How the ramp-up scenarios regarding vehicle electrification was calculated is also explained. These calculations were based on electrification scenarios derived from climate goals, allocating how large a share of carbon dioxide emissions route E6 have to reduce.

3.2.1 ERS energy usage

The energy usage of an ERS was obtained using an existing mathematical model that calculates the electricity consumption of electric vehicles based on the forces acting upon the vehicle [23][24]. The road data acquired from the Swedish Transport Administration was used to calculate the electricity requirement along route E6, based mainly on road inclination, speed limits and ADT for different road segments.

Using the data from the Swedish Transport Administration. The heavy vehicles travelling on the road were divided into two different categories, as these vehicles have different characteristics: buses and heavy trucks. The assumed distributions were that 77% of the heavy vehicles were heavy trucks and that 23% were buses [25]. The chosen mass, m, frontal area, A and aerodynamic drag coefficient, C_d, for each vehicle is represented in table 3.1. Other parameters which differs slightly from each vehicle category is aerodynamic coefficient of resistance, number of tires and tire radius.

Table 3.1: Key parameters for the two vehicle classes.

	Bus	Heavy truck
m $[kg]$	20 000	40 000
A $[m^2]$	7,2	9,7
C$_d$ [-]	0,61	0,63

As explained in the paper regarding the electricity consumption of the E39 in Norway [23], the external forces that act on a vehicle when driving are air drag, rolling resistance and grading. The total force that has to come from the drive and break systems is acquired by also adding the acceleration force. The energy consumption for one type of vehicle, n, on a road segment, i, is obtained by multiplying the required force with the length of the segment, l_i. This is done in equation (3.1). The vehicles are assumed to be driving at the speed limit, with a cap of 90 km/h for heavy trucks [26].

$$E_{n,i} = P_{wheel,n} l_i \tag{3.1}$$

To get the actual consumption of the vehicles, losses had to be included in the calculation. The used efficiencies were: engine efficiency (η_{engine}) of 90%, battery efficiency ($\eta_{battery}$) of 81% and a grid to vehicle (G2V) efficiency (η_{G2V}) of 93% [23].

To calculate the actual power demand of an ERS, equation (3.2) was used.

$$P_{segment} = \sum_{i=1}^{i} ADT_i \sum_{n=1}^{n} \frac{E_{n,i}}{\eta_{Engine}\ \eta_{Battery}\ \eta_{G2V}\ t_i} \tag{3.2}$$

In this equation, ADT_i is the average daily traffic for each individual road segment, l_i is the length of the segment, i is the road segment number and n is the vehicle type, t_i is the time each vehicle spends on each segment, expressed in hours to convert the unit from MWh to MW (or MWh/h). The energy consumption for each of the road segments (the distance between two data points) individually were also available from the model, this made it possible to calculate the consumption of any given distance of the road.

3.2.2 Ramp-up scenarios

As described in section 2.3, the current climate goals set for Sweden can be used in order to create a scenario describing how the electrification of the transport sector will take shape.

As mentioned earlier, the climate goal for 2030 is to reduce emission by 70% as compared to the figures from 2010. This would imply a 70% DoE for heavy transport and as the climate target for 2045 states that the entire transport sector should be free from fossil fuels, this case results in a 100% electrification of heavy transport.

By using an S-curve, which describes the development of novel technologies [27], the growth of heavy vehicles connected to the ERS can be estimated for each year and is shown in Figure 3.2.

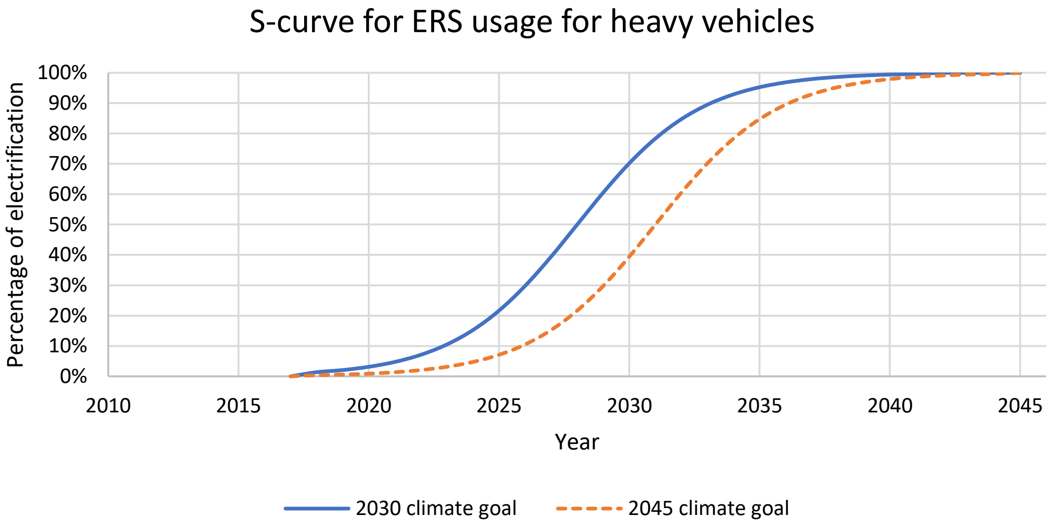

Figure 3.2: Estimated growth of ERS compatible heavy vehicles driven on route E6 which fulfills the 10% reduction of carbon dioxide emissions.

The three scenarios are:

- 40% electrified heavy vehicles by 2030 to stay on track for the 2045 target
- 70% electrified heavy vehicles by 2030 to reach the climate goal set for 2030
- 100% electrified heavy vehicles by 2045 to reach the climate goal set for 2045

3.3 Connection points to the electricity grid

To visualize the geographical load distribution, the connection points to the grid (substations) were identified and placed on a map. Based on the length of the road that each substation covers, the individual electricity demand at each substation could be calculated by adding the electricity demand of each road segment covered within the range. The placement and distribution of substations were based on one suggestion from Vattenfall as well as two additional cases. The first case, the suggestion by Vattenfall [12], proposes that a substation is placed every 40 km. The second case was based on current and future areas with high electricity demand which implies a regional grid connection is, or will be, available there, with the goal of using as much of the existing equipment as possible to reduce costs. The third case was created by dimensioning all substations along the road for the same maximum load, assuming all new equipment has to be invested in. Because of the statements made by E.ON and Vattenfall in section 2.2.1, but also because of time restrictions, all substations were assumed to be connected to the regional (130 kV) grid.

As electricity has to be delivered to the ERS at all times to not cause any stops in traffic, the substations have to be dimensioned for the expected peak demands. Five different yearly data points from the Swedish Transport Administrations traffic flow map [28] was identified along route E6 which were used to compare the peak traffic hours to the average traffic. For each yearly data point, a factor for peak traffic divided by average traffic was calculated (based on heavy vehicles) which could be applied to the power demands from equation 3.2 to find the peak electricity demands for each road segment. It is assumed that the peak factor for each data point is valid for each road segment stretching half the distance to the adjacent data points. The data points and peak factors used are presented in table 3.2.

Table 3.2: Data point, location and peak factor of the five yearly data points used. Collected from The Swedish Transport Administrations traffic flow map [28].

Data point ID	**Location**	**Peak factor**
9559	Uddevallabron	3,59
7346	Göteborg mot Kungälv	3,16
9685	N. Varberg	3,18
9454	Kvibille	3,37
9392	Ö Hofterup mot Malmö	3,86

3.3.1 Cost calculations

To calculate estimated investment costs of the required equipment for each case, the norm value list for electrical equipment was used which is published by the Swedish Energy Markets Inspectorates [29]. The used components from this list are presented in Appendix B. For cost calculations regarding distribution of electricity from the transformer substation to the road, it is assumed that a 30 kV separate grid is built next to the road, according to the proposition by Vattenfall [12]. The cable costs were divided into material and operational costs which is further explained in Appendix C. The power for each cable size can be calculated using equation 3.3, where U is the voltage, I is the current and $cos(\varphi)$ is the power factor. The current carrying capacity for each cable size was taken from Nexans [30] and a power factor of 0,9 was used as suggested by Per Norberg from Vattenfall [15].

$$P = \sqrt{3}UIcos(\varphi) \tag{3.3}$$

Depending on the required power flow to the road, different cables were used which can be found in Appendix B. For cables, the cost is a function of power flow, length and whether they are buried in a city region or on the countryside. Regarding the transformers, they were assumed to tolerate an overload of 30% [31] and the cost is only dependent on the power flow from the substation. The substation cost is made up of transformer breakers, circuit breakers and the size of the station (which is a function of how many transformers that are needed to provide the necessary power). Moreover, the system was also designed according to the n-1 criteria, meaning that one cable can brake without cutting the power supply to the road.

Note that the cost calculations only considered the components needed from the substation to the 30 kV road-side grid, which does not include the rectifiers and transformers required to go from the 30 kV grid to the 750 V grid. This decision was made as the additional components were expected to cost about the same for each of the cases and would therefore not affect the cost optimization calculations. The cost of these components would also depend on which technology is used.

3.3.2 Case 1: 40 km between substations

The first case of substation placement in this thesis is based on Vattenfall's suggestion of placing a new substation every 40 km when transforming electricity from 130 to 30 kV which is the voltage level of the new wayside grid proposed by Vattenfall [12]. As the distance between Trelleborg and Svinesund is about 480 km, by placing the first substation after 20 km, each station covers close to the suggested 40 km. This suggestion does not take any of the variations in demand along the road or electricity grid into consideration, but simply allocates the electricity demand of the assigned 40 km to each substation. This results in varying substation sizes along the road. This case was included to have a reference case based on an existing suggestion.

3.3.3 Case 2: Placement of substations based on grid-side demands

The second case is based on connecting the ERS to existing substations. Assuming there is available capacity in these substations, less transmission lines and substation equipment have to be invested in, reducing the total costs of the ERS implementation.

The method used to identify existing substations was to find areas with high electricity demand, such as cities or heavy industries. With the high amount of power needed in these areas, it can be assumed that it exists a nearby connection to the regional grid. The first selection criteria in order to find geographically distributed electricity demands of considerable size was the largest cities in each municipality along the road. Figure 3.3 shows the location of each municipality covered by route E6, a total of 23 municipalities listed from north to south. As can be noted, there are more municipalities in the south of Sweden. However, the electricity demand from the ERS is also higher there.

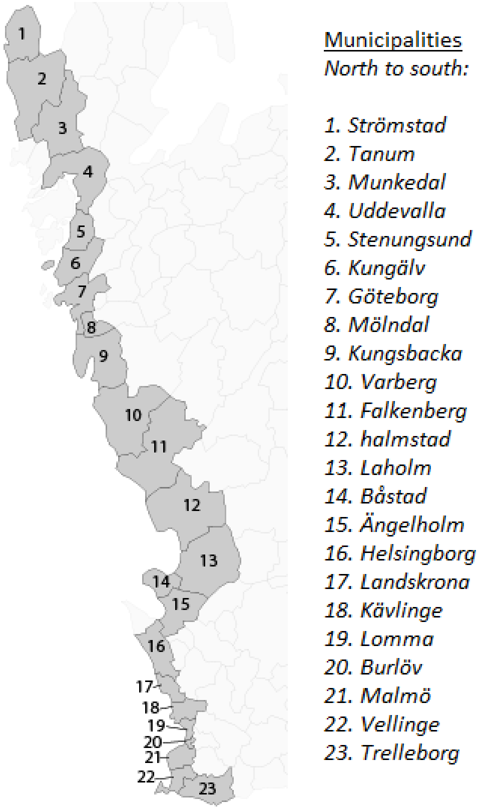

Figure 3.3: Map displaying the 23 municipalities which route E6 stretches through.

Additional locations where there is likely to exist a regional grid connection is close to large industries. Municipalities with a large share of industries could be identified using *Statistics Sweden*'s data regarding each municipality's end use of electricity expressed in MWh per year. The statistics used were from 2013 as it was the only data set without missing values regarding the end use of industries. The average power demand of the year for industries in MW was found by dividing the end use by number of hours per year. This led to a clear distinction between municipalities that had a large amount of industries and those that did not. Those without a large power demand from industries had an average demand of 1-10 MW while the others had an average demand within the range of 35-200 MW. The individual industries were identified by searching the relevant municipalities websites. All the large industries found were located either in or close to the largest cities where a substation placement already was proposed. For these cities, only one substation was placed.

The substations in this case were assumed to be placed in the center of each city and cover half the road distance to each adjacent substation, covering the demand of all calculated road segments included in this distance (from equation 3.2).

Validating locations of existing substations

In order to determine what sort of implementations that has to be made from a grid stand point in terms of new substations, additional cables and new transformers. The placement of current stations has to be mapped and how far they are located from route E6. This particular information is something that the distribution system operator (DSO) will not share, therefore a map from the Swedish National Heritage Board was used where the regional and national grid is shown as well as the placement of current substations and corresponding length from route E6. The locations were also verified using satellite images from Google Maps.

3.3.4 Case 3: Placement of substations based on way-side demands

The third case of substation placement was created by neglecting the existing substations and instead proposing new substations along the road based on the geographical load distribution of the ERS.

The substations were distributed geographically with the notion of keeping the dimensions for every substation the same, in order to keep costs to a minimum. The reason why this minimizes the costs is that smaller substations (as well as cables) have a higher investment cost per MW of capacity and dimensioning all substations as large as possible (i.e. the same size) thereby provides the lowest investment cost. The costs per MW for each transformer capacity can be found in figure 3.4, which is based on the numbers provided in Appendix II.

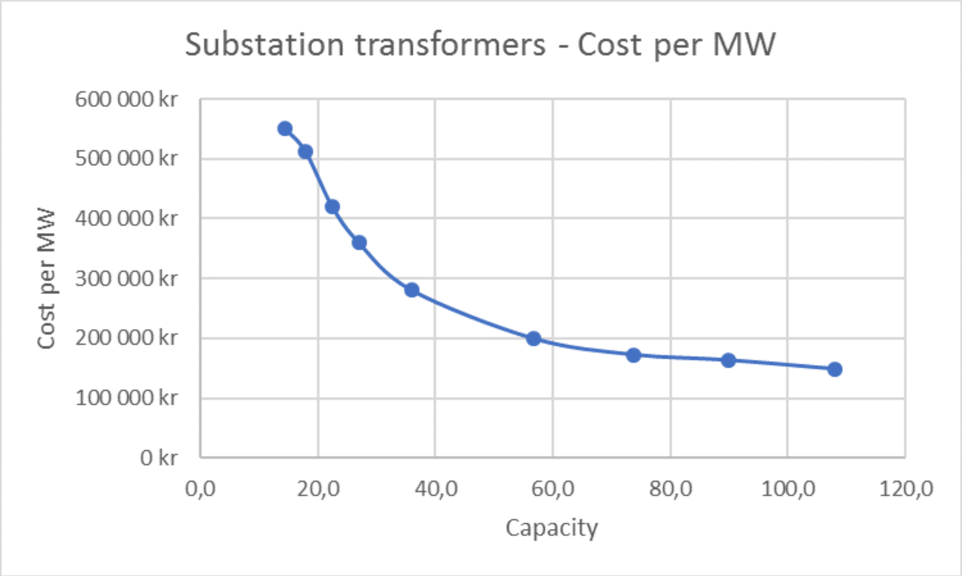

Figure 3.4: Cost (in *SEK*) per MW for different transformer capacities (in *MW*).

By choosing a dimension which applies to all substations (In MW, with regards to peak demand), the number of substations could be calculated by dividing the dimensioning power with the total peak demand of the whole E6 route. The substations were then placed so that they cover the peak load of a certain distance based on the geographical load distribution of the ERS.

For the model to add up mathematically, the residual electricity demand from the division was assigned to one final, smaller, substation. The positions of the substations were distributed based on the demand of the ERS, meaning that the substations were placed closer to each other at the distances where the road had a higher electricity demand. In this case the substations covered half of the electricity demand towards each adjacent substation.

The number of total substations were based on an investment cost optimization. The components included in the cost calculations were substations and substation components as well as ground cables from the substations towards and including the road-side 30 (36) kV grid. The distance to the closest regional grid was assumed to be 1,5 km for all substations in this case, which were the average length from the road to the identified substations located in the map from the Swedish National Heritage Board. By calculating the total system cost for different substation (and transformer) sizes the cheapest alternative could be found by plotting the costs to the substation size.

4

Results

4.1 Electricity demand of ERS

The following sections contains the results of each of the three cases presented in section 3.3. For each case the substation placement is presented along with the average and peak electricity demands for the three scenarios. A cost calculation for the system from the regional grid to the way side grid was done for each case in order to compare the different cases based on investment costs. Additionally, for case 3, a cost-optimization was done for each scenario as the required equipment varied depending on which substation dimensions were chosen. Finally, the electricity demand of the ramp-up is presented.

4.1.1 Case 1: 40 km between substation

The suggested substation placement based on Vattenfall's proposition of a substation every 40 km is presented in Figure 4.1. As route E6 is 480 km and each substation covers 40 km the total number of substations needed are 12.

Figure 4.1: A map representing the substations along the road with 40 km between each substation.

Table 4.1 shows the average and peak electricity demands of each substation for case 1, based on the calculated electricity demand of the road segments from the mathematical model used. The demand is highest at substation 11 and the demand generally increases in southern areas of the road.

Table 4.1: Average and peak demands of each substation for each transportation scenario based on Vattenfall's proposition of placing a substation every 40 km. As the peak demands for each substation occurs at different hours of the year, the total peak demand of the year is unlikely to be the one presented.

	Electricity demand [MWh/h] per scenario					
	40% (2030)		70% (2030)		100% (2045)	
Substation	Avg.	Peak	Avg.	Peak	Avg.	Peak
1	1,7	6,0	3,0	10,6	4,3	15,2
2	2,7	9,3	4,7	16,3	6,7	23,3
3	2,9	10,3	5,1	18,0	7,3	25,7
4	3,5	12,3	6,2	21,6	8,8	30,8
5	5,8	20,2	10,1	35,4	14,4	50,5
6	4,2	14,8	7,4	25,9	10,6	37,0
7	3,7	13,0	6,5	22,7	9,3	32,5
8	4,1	14,4	7,2	25,3	10,3	36,1
9	4,0	13,9	7,0	24,3	9,9	34,8
10	4,8	16,9	8,4	29,6	12,1	42,2
11	5,9	20,7	10,4	36,3	14,8	51,8
12	3,7	12,8	6,4	22,5	9,2	32,1
Total	47,1	164,8	82,4	288,4	117,7	412,0

The total costs of the first case for the three scenarios are presented in table 4.2. The largest costs for each case are the cable costs, which make up about 60% of the total cost. The *substation* category includes costs for bays and circuit breakers.

Table 4.2: Component and total cost for case 1 for the three different scenarios.

	Cost [MSEK]			
DoE	Substation	Transformer	Cable	Total
40%	273	204	537	1 014
70%	273	231	545	1 049
100%	273	251	588	1 111

4.1.2 Case 2: Placement of substations based on grid-side demands

The substation placement based on the largest cities in each municipality along route E6 can be seen in figure 4.2. In this case the substations are not as evenly distributed as the other cases and a few substations are placed very close to each other, the shortest distance of 2,6 km being found between substations 19 and 20 and the longest distance of 47 km between substations 9 and 10.

Figure 4.2: A map representing the substations along the road based on current demands in the electricity grid.

Table 4.3 shows the average and peak electricity demands of each substation for case 2, calculated by the mathematical model. In this case, there is a large difference in peak load (dimensioning needs) when comparing the smallest and largest substations (at 100% DoE) of 3,8 and 32,6 MW respectively.

Table 4.3: Average and peak demands of each substation for each transportation scenario based on existing loads on the grid-side. As the peak demands for each substation occurs at different hours of the year, the total peak demand of the year is unlikely to be the one presented.

	Electricity demand [MWh/h] per scenario					
	40% (2030)		70% (2030)		100% (2045)	
Substation	Avg.	Peak	Avg.	Peak	Avg.	Peak
1	1,3	4,6	2,3	8,0	3,3	11,4
2	2,2	7,8	3,9	13,6	5,6	19,5
3	1,9	6,6	3,3	11,6	4,7	16,5
4	1,7	6,0	3,0	10,5	4,3	15,0
5	2,4	8,3	4,1	14,5	5,9	20,6
6	2,6	9,0	4,5	15,8	6,4	22,6
7	2,1	7,4	3,7	12,9	5,3	18,4
8	1,8	6,3	3,2	11,1	4,5	15,8
9	3,7	13,0	6,5	22,8	9,3	32,6
10	3,5	12,2	6,1	21,3	8,7	30,5
11	3,2	11,0	5,5	19,3	7,9	27,6
12	2,9	10,1	5,0	17,6	7,2	25,2
13	1,3	4,4	2,2	7,8	3,2	11,1
14	1,6	5,7	2,8	10,0	4,1	14,2
15	2,2	7,6	3,8	13,3	5,4	19,0
16	3,0	10,5	5,3	18,4	7,5	26,3
17	2,7	9,4	4,7	16,5	6,7	23,5
18	2,0	7,1	3,6	12,4	5,1	17,8
19	1,3	4,5	2,3	7,9	3,2	11,3
20	0,6	2,3	1,1	4,0	1,6	5,6
21	1,5	5,4	2,7	9,4	3,8	13,4
22	1,2	4,1	2,0	7,2	2,9	10,2
23	0,4	1,5	0,8	2,7	1,1	3,8
Total	47,1	164,8	82,4	288,4	117,7	412,0

The total costs of the second case for the three scenarios are presented in table 4.4. If existing substations and transformers are assumed to be used, only the cost of the cables would be applicable to this case, making it considerably cheaper than the other cases. However, if new substations and transformers are being built the total cost far exceeds the costs of the other cases.

Table 4.4: Component and total cost for case 2 for the three different scenarios.

	Cost [MSEK]			
DoE	Substation	Transformer	Cable	Total
40%	522	365	584	1 472
70%	522	388	584	1 495
100%	522	415	589	1 526

4.1.3 Case 3: Placement of substations based on way-side demands

The results presented in this section are based on the most cost-efficient dimensions of substations for the three electrification scenarios studied. The cost-optimization results are presented along with the mapping of substations as well as average and peak electricity demands.

4.1.3.1 Scenario 1: 40% DoE

Figure 4.3 shows the cost curve of substations, cables and transformers based on the dimensions of each substation for 40% electrification of heavy vehicles. The lowest total investment cost of 732 million SEK was found when dimensioning the substations at 45,1 MW.

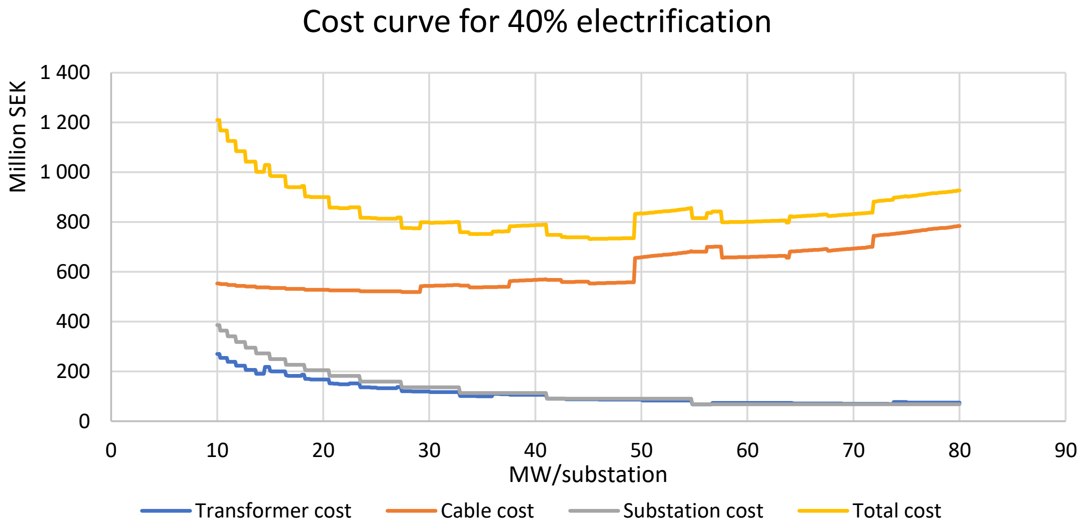

Figure 4.3: Cost curve of substations, cables and transformers based on substation size for 40% electrification of heavy vehicles.

Figure 4.4 shows the placement of substations with the dimension 45,1 MW. This resulted in 4 substations needed to meet the peak demands. There is a notably long distance between the substations in this figure.

Figure 4.4: A map showing the distribution of substations for the case of 40% electrification.

4.1.3.2 Scenario 2: 70% DoE

Figure 4.5 shows the cost curve for 70% electrification of heavy vehicles. In this figure the lowest total investment cost was 847 million SEK with 48,0 MW being the least cost dimensioning size.

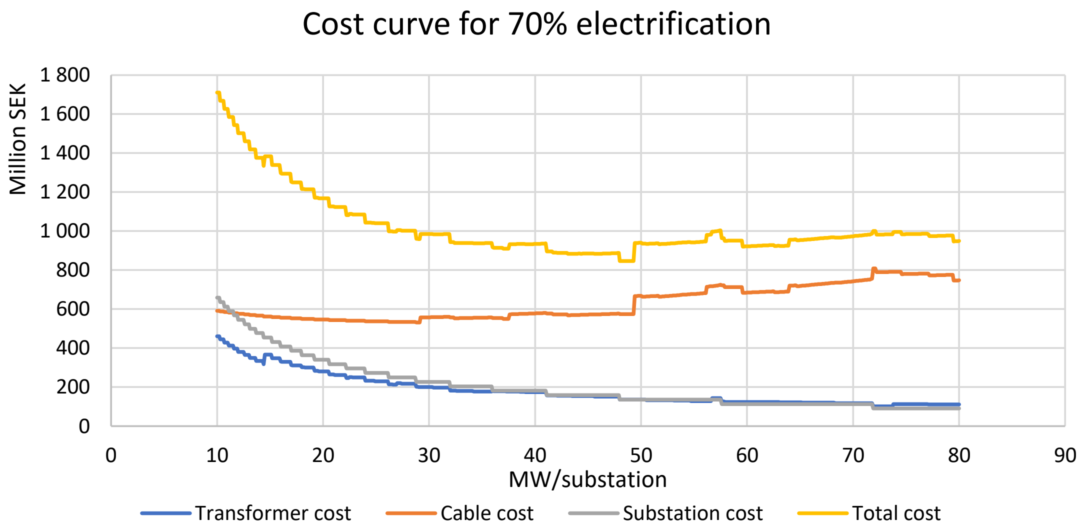

Figure 4.5: Cost curve of substations, cables and transformers based on substation size for 70% electrification of heavy vehicles.

Figure 4.6 shows the placement of substations with the dimension 48,0 MW. This resulted in 7 substations needed to meet the peak demands.

Figure 4.6: A map showing the distribution of substations for the case of 70% electrification.

4.1.3.3 Scenario 3: 100% DoE

Figure 4.7 shows the cost curve for 100% electrification of heavy vehicles. The cheapest total investment cost of this case was 983 million SEK with 48,1 MW being the optimal dimensioning size which is almost the same as the 70%-scenario.

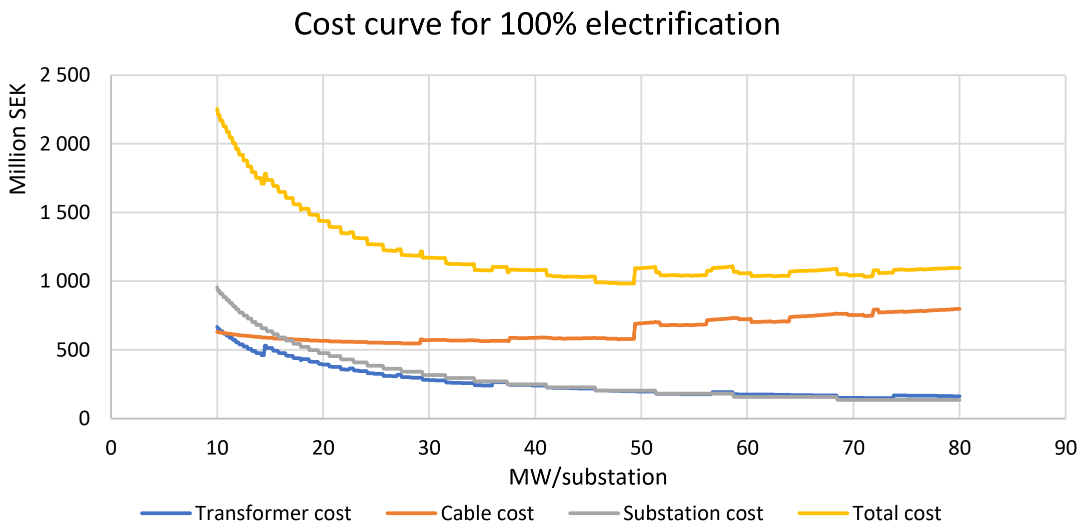

Figure 4.7: Cost curve of substations, cables and transformers based on substation size for 100% electrification of heavy vehicles.

Figure 4.8 shows the placement of substations with the dimension 48,1 MW. This resulted in 9 substations needed to meet the peak demands.

Figure 4.8: A map showing the distribution of substations for the case of 100% electrification.

Table 4.5 shows the average and peak demands of each substation for case 3. With the peak demands being the same for all except the first substation, only the average demands are different between stations depending on which peak factor is applied.

Table 4.5: Average and peak demands of each substation for each transportation scenario based on the way-side demands of the ERS. As the peak demands for each substation occurs at different hours of the year, the total peak demand of the year is unlikely to be the one presented.

	Electricity demand [MWh/h] per scenario					
	40% (2030)		70% (2030)		100% (2045)	
Substation	Avg.	Peak	Avg.	Peak	Avg.	Peak
1	8,1	29,1	13,3	47,6	7,3	26,1
2	14,1	45,1	15,1	48,0	13,5	48,1
3	13,2	45,1	14,8	48,0	15,4	48,1
4	11,6	45,1	14,4	48,0	14,9	48,1
5	-	-	12,5	48,0	15,0	48,1
6	-	-	12,3	48,0	14,2	48,1
7	-	-	-	-	12,8	48,1
8	-	-	-	-	12,6	48,1
9	-	-	-	-	12,2	48,1
Total	47,1	164,8	82,4	288,4	117,7	412,0

4.1.4 Electricity demand ramp-up

Figure 4.9 shows the average yearly electricity demand increase over time based on fulfilling only the 2045 goal (orange dotted line) or both the 2030 and 2045 climate goals (blue line). If both climate goals are to be fulfilled a quicker adoption of the ERS technology is needed with a 70% electrification already by 2030.

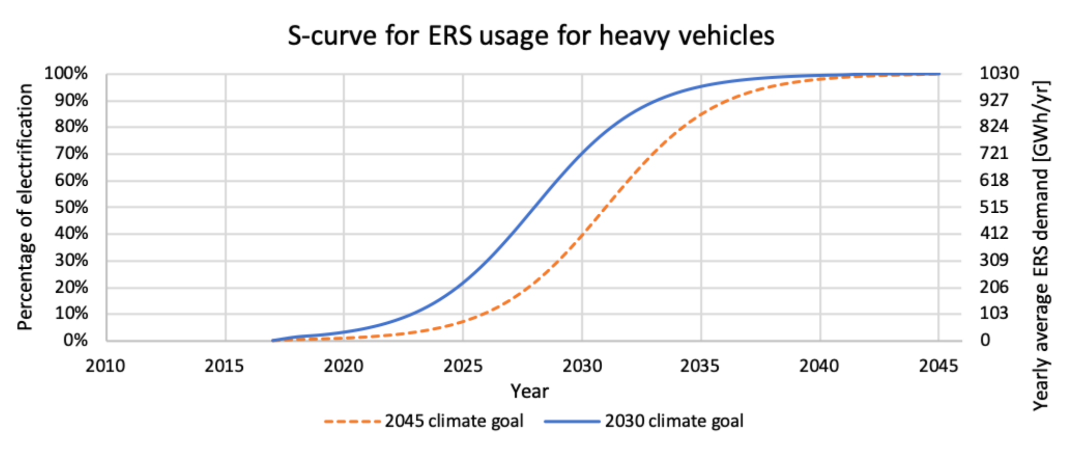

Figure 4.9: A graph showing the average yearly electricity demand for route E6 to corresponding DoE based on the climate goals set for Sweden.

4.2 Comparison

In Figure 4.10 all the total costs for the different scenarios have been gathered and presented for comparisons. For each of the electrification scenarios it can be noted that case 3 is the cheapest if new substations and equipment is needed for each case. This is because of the optimized substation size as well as cable length and size. The striped stacks represent the potential costs that can be saved in case 2 if existing substations and transformers can be utilized.

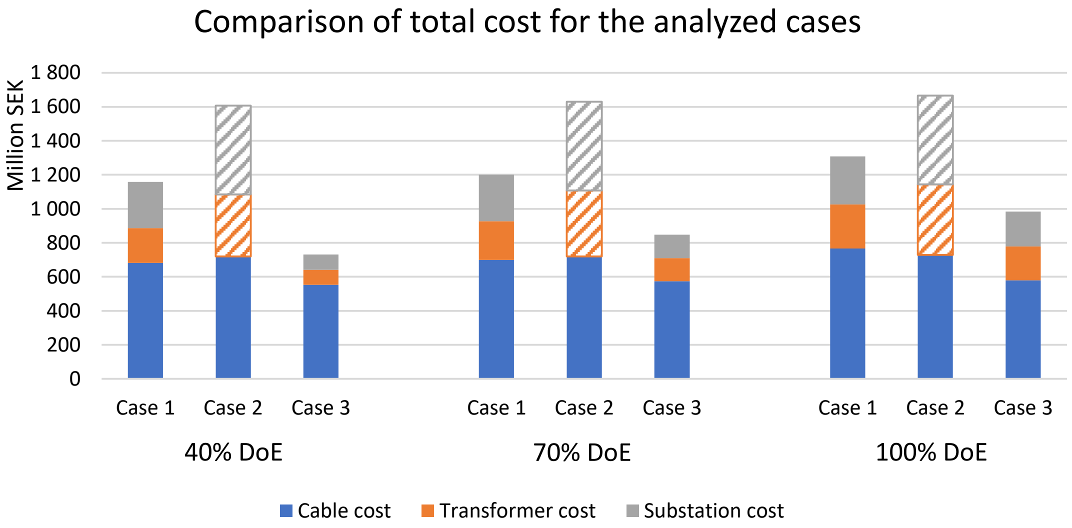

Figure 4.10: A cost comparison between the three different cases based on electrification. The striped stacks represent the potential savings that can be made from using existing infrastructure.

4.3 Increase in electricity demand

Figure 4.11 shows percentage of electricity demand the ERS (with 100% electrification) would compose in each municipality compared to the electricity demand in 2013. A few municipalities, most notably Tanum, Ängelholm and Lomma, would see a significant increase in electricity usage in the range of 15-30%.

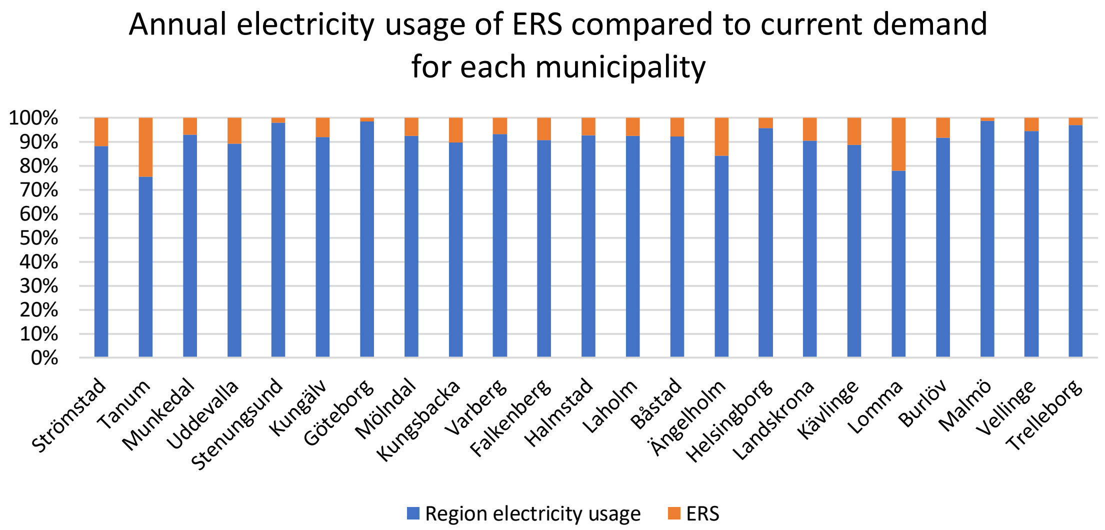

Figure 4.11: Assuming 100% electrification, the graph shows how large a share of each municipality's electricity demand the ERS would stand for. Given the current demand remains unchanged.

The actual consumption values of each municipality in 2013 as well as the power demand an ERS at 100% electrification would imply is presented in table 4.6.

Table 4.6: The electricity use in 2013 for each of the municipalities covered and the power demand of an ERS at 100% electrification.

Municipality	**Electricity use 2013 [GWh/yr]**	**ERS use [GWh/yr]**
Strömstad	199,0	26,9
Tanum	172,5	56,0
Munkedal	411,9	31,7
Uddevalla	432,9	52,0
Stenungsund	1 926,4	41,2
Kungälv	361,7	31,4
Göteborg	4 567,7	73,0
Mölndal	564,4	45,4
Kungsbacka	628,8	72,2
Varberg	1 081,2	79,3
Falkenberg	552,0	56,9
Halmstad	1 069,2	84,7
Laholm	278,2	22,9
Båstad	248,8	20,9
Ängelholm	331,9	62,0
Helsingborg	1 303,9	60,0
Landskrona	561,7	59,1
Kävlinge	238,4	30,3
Lomma	159,1	45,2
Burlöv	144,7	13,0
Malmö	2 557,7	35,8
Vellinge	311,5	18,5
Trelleborg	409,7	12,9

5

Discussion

5.1 Electricity demands

In 2017 the Swedish electricity demand reached 130,5 TWh [32]. The average annual load from the ERS on route E6 with 100% electrification of heavy vehicles, based on present traffic, is 1,03 TWh/yr. Comparing these numbers we can see that the ERS on route E6 represents 0,8% of Sweden's current electricity demand. Considering this is only one highway, which constitutes about 10% of Sweden's heavy traffic, the total electricity demand if more roads are to be electrified can become considerably higher.

As the electricity demand calculations for the ERS are based on climate goals related to traffic, the two main scenarios to consider when implementing an ERS are 70% electrification in 2030 and 100% electrification in 2045 if both climate goals aim to be reached. However, these are ambitious goals and the scenarios imply electricity demands on the grid which realistically may prove hard to implement within the desired time frame. Looking at the increase in electricity demand for each region, presented in figure 4.11, it is hard to predict whether the current capacity is enough to support the ERS as some municipalities may see a significant increase in demand (without considering electricity demand increase from other sources). E.ON states that southern Sweden is currently heavily constrained and might not be able to implement new spot demands over 5 MW, but that new capacity is planned to be built and ready by 2030 [14]. Until then it will likely be hard to implement any considerable share of electrification in an ERS.

An increase in transport of goods can have a large impact on the future electricity demand of ERS. As can be seen in figure 2.2, previous forecasts have not been very accurate but the one made for 2030 seems to be promising based on the last few years. This points to a small increase in goods transport compared to today, possibly increasing the electricity demand beyond the calculations performed in this thesis. However, there is still a big uncertainty in how the transport of goods will change the coming years.

If the way of travelling will change in the future that might lead to a change in traffic patterns. For example, autonomous vehicles can enable shifting more of the daytime traffic to the night. Since no driver is required, such vehicles can drive at more flexible hours, like in the middle of the night. This will smoothen the peaks and in such a manner lead to smaller cables and substations having to be installed to supply the ERS with power. As more of the power peaks are removed, the hourly electricity demands shifts more towards the average. Since the demand peaks can be up to 3-4 times higher than the average, dimensioning requirements can become significantly lower, resulting in a lower investment costs. Worth noting is that the identified demand peaks (highest at 3,86 times the average value) are hourly values which means that within the certain hours even larger shorter peaks may occur, yet this is not represented in the data acquired.

According to Siemens, the power demand of a 60 ton truck driving at 80 km/h is about 120 kW [33]. This demand was measured at their eHighway in Sandviken, Sweden, which is part of a two kilometer demonstration project [34]. The calculated average electricity demand for one truck in the model used in this thesis was 130 kW at 40 tons and 90 km/h, this is relatively close to the actual measured consumption but is something that can be studied further if more accurate results are needed.

5.2 Substation placement and cost

As can be noted in figure 4.10, the least cost case is number 2: the suggestion based on existing substations. This is rather obvious as if existing substations and transformers can be used a lot of investment costs can be saved. If new substations are to be built, case 3 would be the cheapest of the cases presented. In a realistic implementation there can be some capacity available in current substations, but not enough for the whole ERS, which means the total investment cost would end up somewhere between that of case 2 (without investing in transformers and substation) and case 3. With a varying electricity demand along the road there is little reason to why the substations would be built with a fixed 40 km distance between them, rendering case 1 the most expensive one because of the varying size of the equipment. There are no identified arguments to why the substations would be built this way.

As there are many variables when it comes to cost calculations it is always an uncertainty as to how applicable the cost calculations are to a real project. This means that the real costs can look different compared to the costs presented in this project. As there are multiple substation dimensions which are close to each other in investment costs in the results presented, it's not with certain that the results presented in this report would entail the least cost in a real project.

For the three scenarios presented in case 3, the optimal substation dimensions proved to be similar with 45,1 MW at 40% DoE, 48,0 MW at 70% DoE and 48,1 MW at 100% DoE. These proved to be the optimal substation dimensions as the cable costs are increasing for larger substations and the costs of the substations are low at this point. As can be seen in figures 4.3, 4.5 and 4.7, the cable costs make up the most of the total cost and will result in high expenses for substations at around 49 MW and above. For an increasing DoE over time it could be possible to only build substations of this size but increasing the quantity of them as the electricity demand increases.

5.3 Limitations of the study

The largest limitation of this study is the lack of information regarding the electricity grid. There is no official information available regarding regional grid location and capacity. The best available source for the geographical location of the regional grid was found to be *Fornsök*, an interactive map by the Swedish National Heritage Board. However, no grid operators will confirm the locations nor provide any data regarding the identified substations or transmission lines found on this source. Either way, this source was considered good enough to validate the substations from case 2 as well as calculating the average distance to the closest regional grid of 1,5 km in case 3.

An additional limitation of the work is the lack of more specific vehicle categories from the original data set regarding ADT. This meant that the categorization of heavy vehicles into heavy trucks and buses had to be done using statistics for all of Sweden which might not be as accurate for route E6.

5.4 Further studies/Continued work

As this study is performed on a energy system basis and the optimizations are performed mainly with aspect to component investment costs, further studies can proceed to optimize substation placement based on power flow aspects. As there is a long distance between substations (especially in the cases generated by the cost optimization model) this would likely be the most relevant area to study further.

All cost calculations in this study is performed based on the assumption that a new 30 kV grid is built next to the road. Further studies can conclude whether a 30 kV grid is the best solution or if another voltage level would suit the ERS better. All substations are also assumed to be connected to the 130 kV grid. Other grid connections can also be of interest to study.

Further studies can also conclude which investment costs can be saved if the substations are dimensioned for lower than the peak traffic hours.

6

Conclusions

The first conclusion in this thesis is that using existing capacity, if possible, is the least cost option. If new equipment has to be invested in, it is financially better to construct the system based on the geographical load distribution of the road (which was done in case 3) as the substation dimensions as well as cable length and size can be optimized. Any conclusions regarding how a real solution would be implemented cannot be drawn without additional knowledge of existing capacity in substations as well as other loads in the vicinity, which is one of the major limitations of this study.

Another conclusion from the work within this thesis is that the peak demands of the ERS are very high compared to the average. The largest hourly peak factor identified in this thesis was an hourly peak of 3,86 times the average consumption. As the dimensions of the required equipment needs to be dimensioned for the peak demands in order to supply electricity at all times, the peaks in traffic demand is an important factor when calculating the investment costs of the system.

The concluded optimal substation dimensions based on the cost optimization performed for case 3 proved to be very similar with 45,1; 48,0 and 48,1 MW for the 40%; 70% and 100% cases respectively based on the peak traffic hours identified.

It is concluded that a few municipalities will see a significant increase in electricity demand. It is however hard to conclude how problematic the implementation of new capacity will be, or if it is required everywhere along the road.

There are no conclusions in this thesis regarding solutions to remove the peak demands and thereby lower the required dimensions of the substations.

Bibliography

[1] E. Kehinde. Electrical Grid. `https://www.studentenergy.org/topics/electrical-grid`. [Accessed: 2019-08-20].

[2] V. Masson-Delmotte, H. O. Pörtner, J. Skea, A. Pirani, R. Pidcokc, Y. Chen, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield, W. Moufouma-Okia, S. Connors, X. Zhou, C. Péan, J. B. R. Matthews, M. I. Gomis, P. Zhai, D. Roberts, and P. R. Shukla. Global Warming of $1.5^{o}C$. Report, IPCC, Switzerland, October 2018.

[3] C. Azar. *Solving the climate challenge*. Albert Bonniers, 2012.

[4] UNFCCC (United Nations Framework Convention on Climate Change). The Paris Agreement. `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement`, 2015. [Accessed: 2019-01-25].

[5] J. Morfeldt. Territoriella utsläpp och upptag av växthusgaser. `http://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-territoriella-utslapp-och-upptag/?visuallyDisabledSeries=5ea9dd97fdc16b48`, 2018. [Accessed: 2019-01-24].

[6] Power Circle. Elbilsstatistik. `https://www.elbilsstatistik.se/elbilsstatistik`, December 2018. [Accessed: 2019-02-01].

[7] Trafikanalys. Fordon 2017. Technical report, Trafikanalys, March 2018.

[8] F. Chen, N. Taylor, and N. Kringos. Electrification of roads: Opportunities and challenges. *Applied Energy*, 150:109–119, July 2015.

[9] Viktoria Swedish ICT. Slide-in Electric Road System - Conductive project report. Technical report, IPCC, April 2014.

[10] Scania CV. Slide-in Electric Road System - Inductive project report. Technical report, Viktoria Swedish ICT, April 2014.

[11] F. Connolly. Economic viability of electric roads compared to oil and batteries

for all forms of road transport. *Energy Strategy Review*, 18:235–249, December 2017.

[12] O. Hjortsberg. Slide In-teknik för kontinuerlig överföring av energi till elektriska fordon, Fas2. Report, Energimyndigheten, Sweden, October 2018.

[13] A. Nordling. Sveriges framtid elnät - En delrapport. Technical report, IVA, Sweden, 2016.

[14] Meeting with E.ON, 2019.

[15] Meeting with Per Norberg, Vattenfall, 2019.

[16] Södra Hallands Kraft. Sveriges Elnät - Lite fakta. `https://www.sodrahallandskraft.se/produkter-och-priser/elnaet/sveriges-elnaet-lite-fakta/`. [Accessed: 2019-03-04].

[17] Z. Chen. Issues of Connecting Wind Farms into Power Systems. Technical report, IEEE, 2005.

[18] B. Risinger. Med de nya svenska klimatmålen i sikte. Technical Report 6795, Naturvårdsverket, November 2017.

[19] Regeringskansliet. Sverige ska bli ett fossilfritt välfärdsland. `https://www.regeringen.se/artiklar/2018/04/sverige-ska-bli-ett-fossilfritt-valfardsland/`, April 2018. [Accessed: 2019-03-22].

[20] B. Saxton. Godstransporter i Sverige - en nulägesanalys. Report 2016:7, Trafikanalys, April 2016.

[21] B. D. Stockton. Design Guide for Rural Substations, June 2001.

[22] T. Krieg and J. Finn. *Substations.* Springer International Publishing AG, 2019.

[23] M. Taljegard, L. Göransson, M. Odenberger, and F. Johnsson. Spacial and dynamic energy demand of the E39 highway – Implications on electrification options. *Applied Energy*, 195:681–692, June 2017.

[24] D. Jelica. The effect of electric roads on future energy demand for transportation - A case study of a Swedish highway. Master's thesis, Chalmers University of Technology, 2017.

[25] M. Taljegård, L. Thorson, M. Odenberger, and F. Johnsson. Large-scale implementation of electric road systems: Associated costs and the impact on CO_2 emissions. *International Journal of Sustainable Transportation*, April 2019.

[26] Transportstyrelsen. Lastbil. `https://www.transportstyrelsen.se/sv/vagtrafik/Fordon/Fordonsregler/Lastbil/`. [Accessed: 2019-05-29].

[27] L. Robinson. A Summary of Diffusion of Innovations. *Enabling Change*, January 2009.

[28] Trafikverket. Vägtrafikflödeskartan. `http://vtf.trafikverket.se/SeTrafikinformation#`. [Accessed: 2019-05-29].

[29] Energimarknadsinspektionen. Normvärdeslista elnät 2016-2019. `https://www.ei.se/sv/for-energiforetag/el/Elnat-och-natprisreglering/forhandsreglering-av-elnatstariffer-ar-2016-20191/dokument-elnatsreglering/normvardeslista-elnat-2016-2019/`. [Accessed: 2019-05-23].

[30] Nexans. Medium Voltage Cables. `https://www.nexans.com/Lebanon/2011/mediumvoltage_2.pdf`, 2011. [Accessed: 2019-06-12].

[31] M. Jarl and F. Bengtsson. Reservmatningsmöjligheter vid transformatorhaveri. Bachelor's thesis, University West, 2015.

[32] C. Dellby and S. Enmalm. Electricity supply, district heating and supply of natural gas 2017. Final statistics. Report, Energimyndigheten & SCB, November 2018.

[33] A. Bylund. Siemens, May 2018. Mail conversation.

[34] M. Ernström. The World's first electric road on the E16. `http://www.regiongavleborg.se/regional-utveckling/samhallsplanering-och-infrastruktur/elvag/the-electric-highway-in-english/`, December 2015. [Accessed: 2019-05-31].

A

Appendix I: Yearly traffic hours distribution

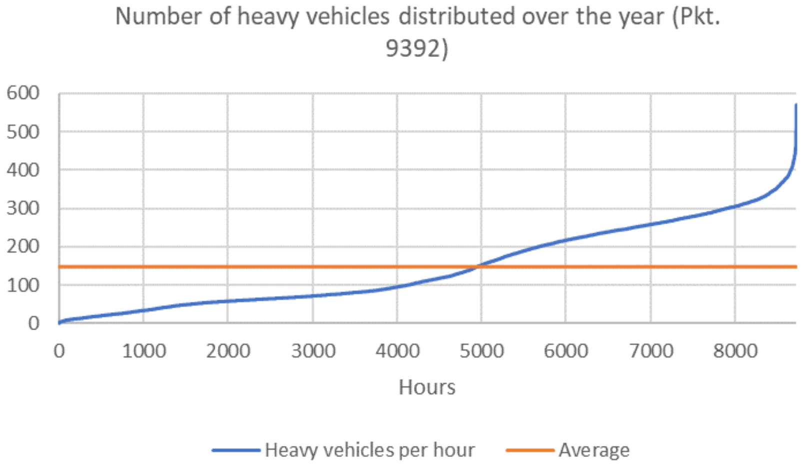

Figure A.1: Distribution of heavy vehicles travelling through a measure point in Hofterup, between Malmö and Helsingborg, over one year (2018).

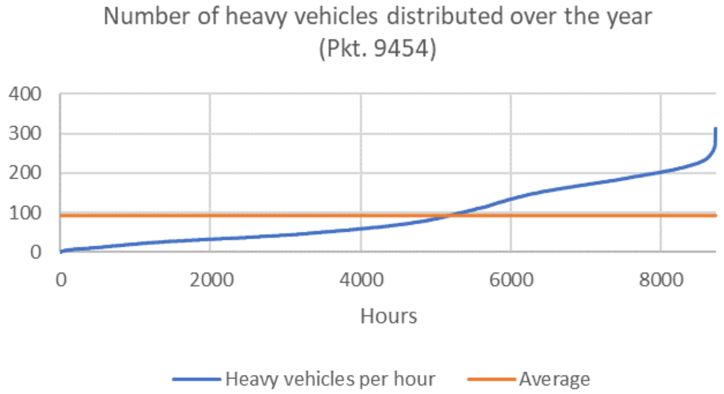

Figure A.2: Distribution of heavy vehicles travelling through a measure point in Kvibille, close to Halmstad, over one year (2017).

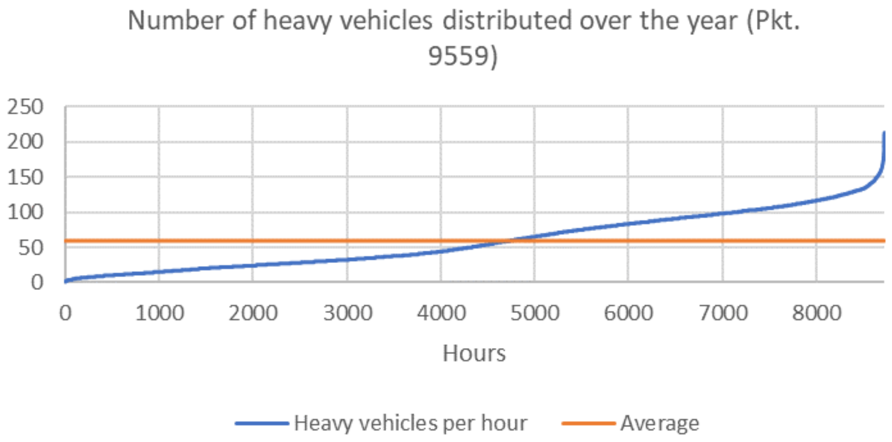

Figure A.3: Distribution of heavy vehicles travelling through a measure point south of Uddevalla over one year (2018).

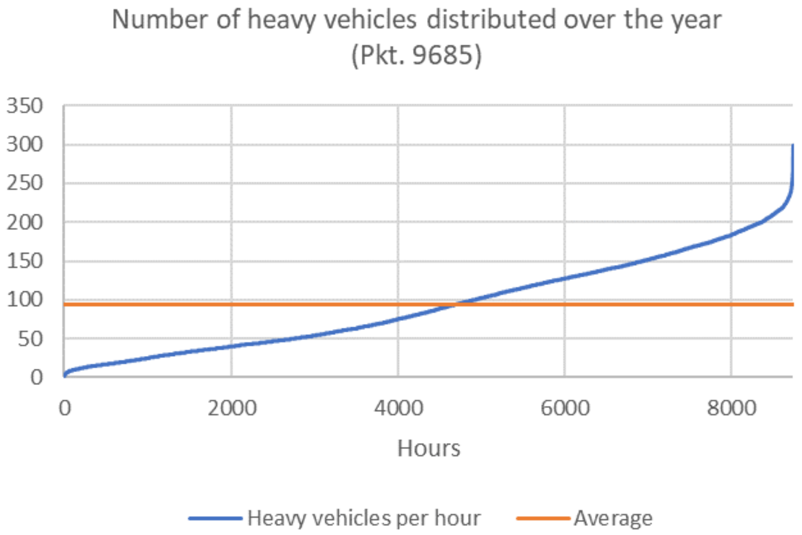

Figure A.4: Distribution of heavy vehicles travelling through a measure point north of Varberg over one year (2018).

B

Appendix II: Cost components

Table B.1: Cost of all components used for cost calculations and optimizations.

Component	**Voltage [kV]**	**Cost [kr]**	**Unit**
Small station Total <6 bays HV area < 7500 m^2	123-145	2 425 114	ea
Large station Total >6 bays HV area < 15000 m^2	123-145	3 700 343	ea
Transformer 16 MVA	123-145/36-52	7 945 409	ea
Transformer 20 MVA	123-145/36-52	9 215 615	ea
Transformer 25 MVA	123-145/36-52	9 468 258	ea
Transformer 30 MVA	123-145/36-52	9 728 281	ea
Transformer 40 MVA	123-145/36-52	10 089 614	ea
Transformer 63 MVA	123-145/36-52	11 306 664	ea
Transformer 82 MVA	123-145/36-52	12 702 205	ea
Transformer 100 MVA	123-145/36-52	14 671 561	ea
Transformer 120 MVA	123-145/36-52	16 025 227	ea
Circuit breaker AB(AC)	145	3 014 637	ea
Disconnector transformer AB(AC)	145	2 440 689	ea
Circuit breaker AB(AC)	36-52	2 545 570	ea
Disconnector transformer AB(AC)	36-52	2 144 834	ea
Undergrnd cable rural Al 3x1x95 mm^2 PEX	36	991 095	km
Undergrnd cable rural Al 3x1x150 mm^2 PEX	36	1 020 299	km
Undergrnd cable rural Al 3x1x240 mm^2 PEX	36	1 047 069	km
Undergrnd cable rural Al 3x1x300 mm^2 PEX	36	1 166 123	km
Undergrnd cable rural Al 3x1x400 mm^2 PEX	36	1 200 194	km
Undergrnd cable rural Al 3x1x500 mm^2 PEX	36	1 236 698	km
Undergrnd cable rural Al 3x1x630 mm^2 PEX	36	1 292 671	km

C

Appendix III: Cost calculations

C.1 Transformers, cables and substations

The costs of underground cables were divided into material and operational costs. When using more than one cable for the same distance the operational costs were assumed to be constant while only the material costs were increased. The operational costs used were found using linear regression on seven different cable sizes and finding the intersection with the Y-axis where the material costs is assumed to be 0. The linear regressions can be seen in figure C.1.

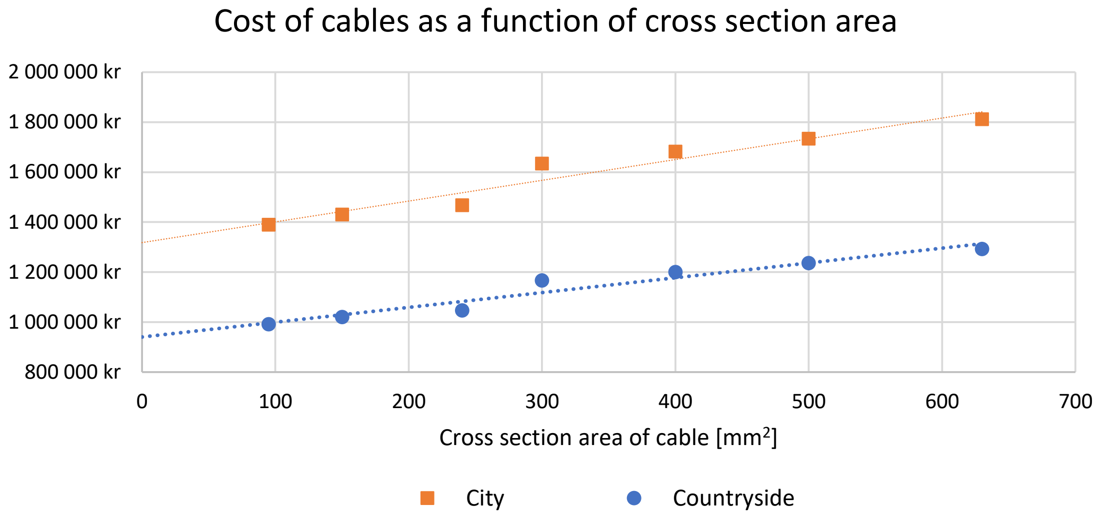

Figure C.1: Linear regression used to calculate the operational costs of underground cables.