CODEN:LUTEDX/(TEIE-5488/1-68/(2023)

Industrial Electrical Engineering and Automation

Designing an Electric Road System

A study on power demand, peak shaving and emergency backup

David Pålsson
Samuel Henley

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

EXAMENSARBETE

Ekosystemteknik

CODEN:/LUTEDX/(TEIE-5488/1-68(2023)

Designing an Electric Road System

David Pålsson, Samuel Henley

Designing an Electric Road System

A study on power demand, peak shaving and emergency backup

David Pålsson
dpalsson96@gmail.com

Samuel Henley
samuel.henley@outlook.com

February 21, 2023

Master's thesis work carried out at Division of Industrial Electrical Engineering and Automation, LTH and Elonroad AB.

University supervisors:
Mats Alaküla, mats.alakula@iea.lth.se
Olof Samuelsson, olof.samuelsson@iea.lth.se
Jonas Johansson, jonas.johansson@risk.lth.se

Industry supervisor:
Anton Torstensson, anton@elonroad.com

Examiner:
Johan Björnstedt, johan.bjornstedt@iea.lth.se

Abstract

Electric road systems (ERS) provide electric power to vehicles en route (dynamic charging) and can reduce the need for onboard battery capacity. This thesis sets out to examine the power demand of an ERS and the integration of energy storage in its power supply for grid load alleviation and backup power. Specifically, the analysis is based on the ongoing project to build a permanent ERS on a 21 km section of highway E20 between Hallsberg and Örebro, Sweden. Power demand is calculated as a function of hourly traffic flow during a heavily trafficked day, vehicle energy consumption over the distance and the placement of ERS segments. An energy storage system (ESS) for leveling peak power demand (peak shaving) is dimensioned as a function of power demand and some set grid power limits. It is assumed that the vehicles in need of emergency backup can be represented as a share of the traffic flow.

Conclusively, the power demand varies significantly in both time and space. The peak power demand from the ERS is 15 MWh/h when all trucks are assumed to use the system and 36 MWh/h when all cars are included too. The power demand from cars has a very distinct peak during the afternoon, whereas that from trucks has a more even demand throughout the day. ESS can make the most difference when intense but short peaks are present, making it appear most suitable when cars are included as ERS users. The suggested ESS capacities for peak shaving (6-45 MWh) can also be used to sustain critical transport 1-12 days, where the number of days depends on what share of the traffic is considered critical. Finally, only vehicles driving further than the range of the onboard battery are likely to need the ERS. A sensitivity analysis is done to estimate what power demand can be expected in both the short and long term.

Keywords: ERS, Electric Road System, Power Demand, Energy Storage, Peak Shaving, Emergency Backup, Elväg E20, Hallsberg, Örebro

Sammanfattning

Elvägar förser fordon med ström under färd (dynamisk laddning) och kan minska behovet av batterikapacitet ombord. Detta examensarbete syftar till att undersöka en elvägs effektbehov och integrering av energilagring i dess strömförsörjning för att minska belastningen på elnätet och möjliggöra reservkraft för kritiska transporter. Analyserna baserar sig på ett pågående projekt där en permanent elväg ska byggas på en 21 km lång sträcka av motorväg E20 mellan Hallsberg och Örebro. Effektbehovet beräknas som en funktion av trafikflödet per timme under en tungt trafikerad dag, fordonens energiförbrukning över sträckan samt placering av elvägssegmenten. Ett energilagringssystem för att utjämna toppar i effektbehovet (peak shaving) dimensioneras för att begränsa elvägens last på elnätet till en satt nivå. Det antas att de fordon som är i behov av reservkraft i nödsituationer kan representeras som en andel av trafikflödet.

Sammanfattningsvis kan det sägas att effektbehovet varierar betydande i både tid och rum. Toppeffekten från elvägen är 15 MWh/h då alla lastbilar antas använda systemet och 36 MWh/h då alla personbilar också inkluderas. Personbilar bidrar med en mycket tydlig effekttopp under eftermiddagar, medan lastbilar har en mer jämn efterfrågan över dagen. Intensiva men korta toppar är också där energilagringssytem i form av batterier kan göra störst skillnad. Detta gör att integreringen av energilager i elvägens effektförsörjning tycks vara mer effektivt då bilar inkluderas bland användarna. Den föreslagna energilagerkapaciteten för att minska toppar (6-45 MWh) kan också användas för att upprätthålla kritiska transporter i 1-12 dagar, där antalet dagar i största grad på beror på hur stor andel av trafiken som anses vara kritisk. Slutligen kan det väntas att endast fordon som kör längre än räckvidden för det inbyggda batteriet behöver använda elvägen. En känslighetsanalys görs för att uppskatta vilket effektbehov som kan förväntas, både på kort och lång sikt.

Acknowledgments

The work carried out to form this master thesis is the result of collaboration in all its forms. First and foremost, it would not have been possible without the help of our supervisors at Industrial Electrical Engineering and Automation (IEA) at the Faculty of Engineering, Lund University and Elonroad AB in Lund.

Thank you Mats Alaküla for all ideas and your bottomless optimism in our work. Olof Samuelsson and Jonas Johansson for providing your expertise and sharing much-needed external connections. Alice Jansson, David Wennander and Mattias Ingelström for all the discussions and support you might not have expected to provide when passing by our desk. Thanks also to Ebba Helfer for providing insights from your thesis.

We would also like to thank Anton Torstensson for helping us remember purpose and for making us the best presenters we can be. Our work has also in no small part been enabled by Karin Ebbinghaus, Dan Zethraeus and all dedicated employees at Elonroad.

Finally, we would also like to thank the following people for providing valued technical support and feedback: Ylva Lindström (Trafikverket), Maria Sundström (MSB), Carl-Fredrik Gyllenhammar (Holtab), Jonas Backéus and Anneli Bernebrand (E.ON), Wilhelm Leissner (Polarium), Alexandra Goodson and Regina Leandersson (ABB).

On to new challenges!

Lund
February 21, 2023

David Pålsson & Samuel Henley

Preface

This master thesis has been carried out in collaboration between Samuel Henley and David Pålsson. Both partners have contributed to all parts of the thesis, however for certain parts, one has had the main responsibility.

Samuel has taken main responsibility for:

- Project area and topography (described in 2.1)
- Obtaining drive cycles and using the Simulink model (described in 3.1.2)
- Power demand calculations (described in 3.1.4)

David has taken responsibility for:

- Obtaining the traffic flow (described in 3.1.1)
- The power supply model (described in 3.2)
- The lifetime model (described in 3.3.1)

Contents

Abbreviations

AC	Alternating current
BESS	Battery energy storage systems
DC	Direct current
DoD	Depth of Discharge
ERS	Electric road systems
ESS	Energy storage systems
EV	Electric vehicle
MSB	Swedish Civil Contingencies Agency
SoC	State of Charge

1. Introduction

Electric road systems (ERS) both provide a solution to charging infrastructure as well as reduce the need for batteries in each electric vehicle (EV) (Márquez-Fernández et al., 2022). By enabling charging while driving, an ERS can reduce range anxiety while freeing up vast land areas otherwise dedicated to stationary fast chargers. By implementing an ERS, some estimates say the needed range could be as low as 50 km for cars as well as long-haul vehicles (Fyhr et al., 2017). Additionally, reducing battery sizes can cut down on EV prices and increase adoption (Shi and H. O. Gao, 2022).

However, the charging of electric road vehicles makes for a significant additional load on the grid. To mitigate the risk of EV:s exceeding available capacity, grid-scale energy storage systems (ESS) can be used (Preusser, Wei, and Schmeink, 2022). Additionally, the need for ESS could be further amplified by an increasing share of renewable variable energy sources. A recent study by Shi and H. O. Gao (2022) shows that a well-controlled ESS, coupled with an ERS, can lower the strain on the existing grid infrastructure while cutting down the cost of energy by reducing peak loads.

Critical transport, i.e transport vital for societal functions, needs to be able to keep on rolling during times of societal disruptions (Trafikverket, 2021). Kelly et al. (2015) show the impact of vehicle range on the transport sector's resilience. The reduced in-vehicle battery need when installing an ERS may adversely affect resilience to disruptions. Simultaneously, there is a stated need for increased resiliency and redundancy in the transport sector (Regeringen, 2022). One way of solving this issue could be to install an ESS for emergency backup, thereby increasing the availability of power to the vehicles that need it.

1.1 Goal and Scope

The goal of this thesis is to examine the power demand of an ERS and the integration of energy storage in its power supply for grid load alleviation and backup power. The study should be done for a given specific traffic flow, with specific speed limitations and a specific road topography. In addition, the distribution of the power demand on specific feed-in points to the ERS will be investigated.

1.2 Problem Formulation

In order to achieve the goals set up for this thesis, the following questions will be answered:

- How much power is needed to supply the vehicles using the ERS?
- How does the distribution between vehicle classes affect the power demand?
- How can energy storage be used to reduce the electric road's load on the grid?
- How large does the capacity of the energy storage need to be to ensure that the electric road's power demand does not exceed the supply?
- How large does the ESS need to be to sustain critical transport during times of energy scarcity?

1.3 Limitations

For the purpose of being able to answer the questions, some limitations are put in place. Most importantly, the ERS is represented by the Swedish project "Elväg E20" (WSP Sverige AB, 2021) and the technology used is assumed to be the one developed by the thesis partner Elonroad (Elonroad, 2022). Finally, the power demand is calculated as an hourly average, MWh/h, as the obtained traffic flow is given per hour.

1.4 Outline

The report is divided into several parts which reflect the complex nature of the work. Generally, three areas are covered: power demand, power supply and energy storage. These three areas are analyzed throughout the report.

Following the Introduction comes the System Description, where an overview of the project area as well as technical prerequisites are given. In Modeling, the fundamental equations, models and partial results are shown. Simulation Results contains the final results for each area and provides a sensitivity analysis. The Discussion answers the problem formulations and provides some recommendations and suggestions for future work. Finally, the report is ended with the Conclusion.

2. System Description

In 2018, the Swedish Transport Administration (Trafikverket) published a national plan for the transport system 2018-2029 by request from the Swedish government (Trafikverket, 2018). The plan from Trafikverket (2018) contains the improvement and modernization of the roads, railways and routes at sea. One part of the plan is to build a permanent electric road system on an existing highway, hereinafter referred to as the Project.

The Project is currently in the tendering phase where four companies with different technologies are competing for the contract (WSP Sverige AB, 2021). The ERS will be placed on a 21 km road section of the E20 highway between Örebro and Hallsberg (WSP Sverige AB, 2021). However, not all of the 21 km needs to be covered with electric road. Each participant in the tender can decide, based on their technology, where it is most appropriate to place the electric road. According to WSP Sverige AB (2021), E20 between Hallsberg and Örebro was chosen because it is a divided highway and one of Sweden's most busy road sections in terms of heavy traffic. Furthermore, Örebro is a central hub for logistics (WSP Sverige AB, 2021).

2.1 Description of the Area

The map in figure 2.1 below gives an overview of the Project's location and its surroundings. The electric road will be placed between the interchanges Brändsåsen and Adolfsberg. The highway has two lanes in each direction and the electric road will be placed in the rightmost one in both directions. 15 feeding stations will be built to provide power to the electric road, the placement of which has already been decided by Trafikverket. Feeding station number 1, 4, 9, 13 and 15 are located at interchanges.

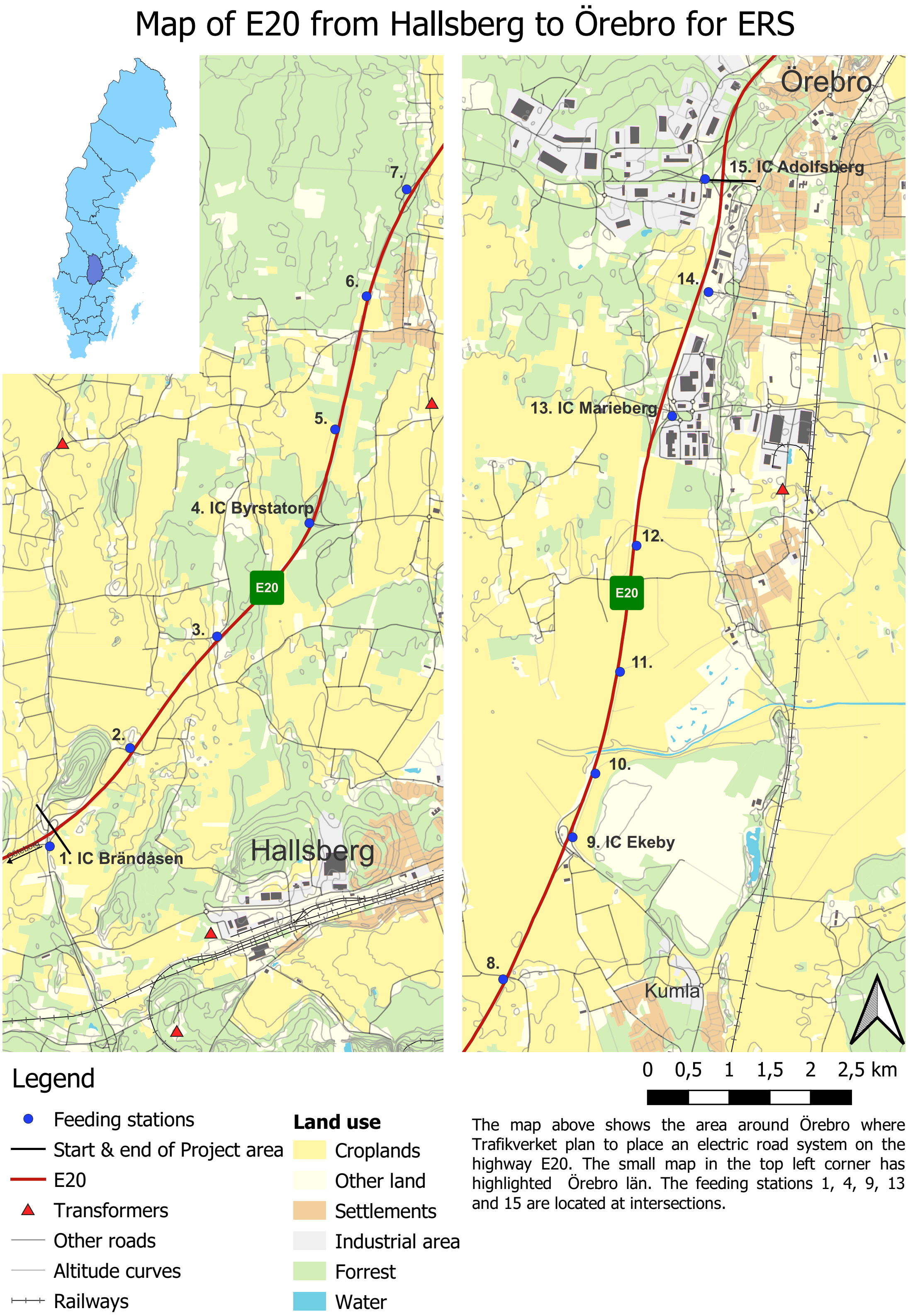


Figure 2.1: Map of the Project area with the ERS and its feeding stations marked. Created using QGIS with maps from Swedish University of Agricultural Sciences (2022).

Figure 2.2 below shows the topography of E20 between Brändåsen and Adolfsberg. It also shows the placement of the feeding stations as white vertical lines, which are separated by a distance of 1-2 km. The maximum slope is located between feeding stations 2 and 3 and measures 1.54°.

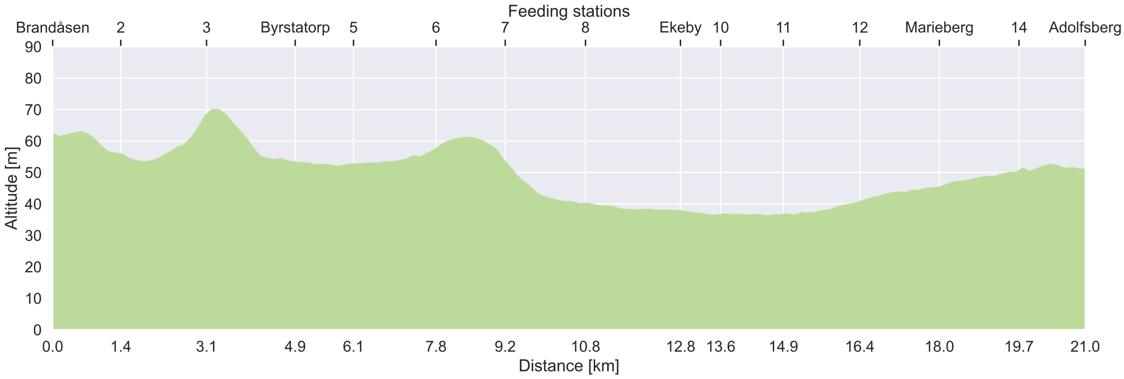


Figure 2.2: Topography of the Project area

2.2 Electric Road Systems

There are several different types of ERS technologies. In Sweden, four technologies have been tested in pilot projects and these are now the ones competing in the tender to build the electric road between Hallsberg and Örebro (WSP Sverige AB, 2021). Figure 2.3 below shows the major differences between the technologies, where (b) represents two of the four technologies as they share the main principles.

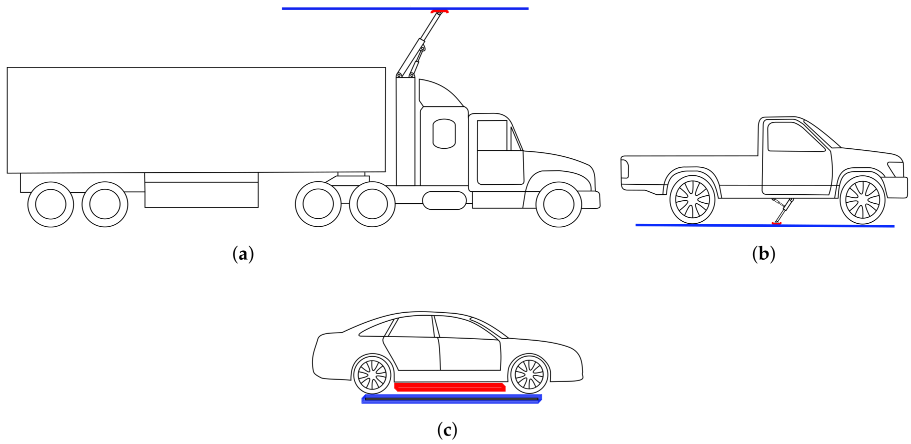


Figure 2.3: Three types of ERS technologies. Modified from Domingues-Olavarría et al. (2018) with permission.

ERS technology (a) in figure 2.3 represents a conductive system where overhead lines (catenary wires) are used to supply electricity to the vehicle (Domingues-Olavarría et al., 2018). A pantograph is mounted on the top of the vehicle and connects it to the lines above. The height of the wires increases safety as it reduces the risk of accidental human contact (Domingues-Olavarría et al., 2018). On the other hand, the height limits the system to only work with larger vehicles such as trucks and buses (Domingues-Olavarría et al., 2018).

Technology (b) represents all conductive electric road systems where the contact is below the vehicle. Two of the participants use this system. One has two grooves in the road with a conductor in each (positive and negative pole) which are connected to the vehicle with a moveable arm (Elways, 2022). The other has a longitudinally segmented rail, with alternating negative and positive segments, using three or more pick-ups mounted underneath the vehicle for continuous power supply (Elonroad, 2022). The first system uses its grooves to countersink the conductors in the road surface, reducing the risk for human contact (Elways, 2022). The second system only electrifies the segments which are under the vehicle to ensure no accidental contact (Domingues-Olavarría et al., 2018).

Technology (c) represents an inductive system that uses coils to charge the vehicle, one or more in the vehicle and several integrated into the road. The system is similar to a transformer and supplies energy through magnetic induction (Domingues-Olavarría et al., 2018). As the coils are installed inside the road, the system has a minimal impact on the surrounding environment (Electreon, 2022). However, according to Domingues-Olavarría et al. (2018), the system is sensitive to misalignment of the coils which can reduce the maximum power output.

For this study, the ERS system with a longitudinally segmented conductive rail is used. With this system, the maximum charging power is currently 300 kW (Elonroad, 2022). For the other ERS technologies, the maximum charging power ranges from 180 to 540 kW (Natanaelsson et al., 2021).

2.3 The Power Grid

The Project site is located in the power zone (bidding area) SE3, which is one of two zones in the southern parts of Sweden (Svenska Kraftnät, 2022a). Generally, the northern parts of Sweden are net producers of cheap electricity, whereas the majority of the consumption takes place in the southern parts (Svenska Kraftnät, 2022a). Apart from zones, the power grid is divided into several voltage levels with different purposes. A breakdown of the power grid can be seen in further detail in the figure below:

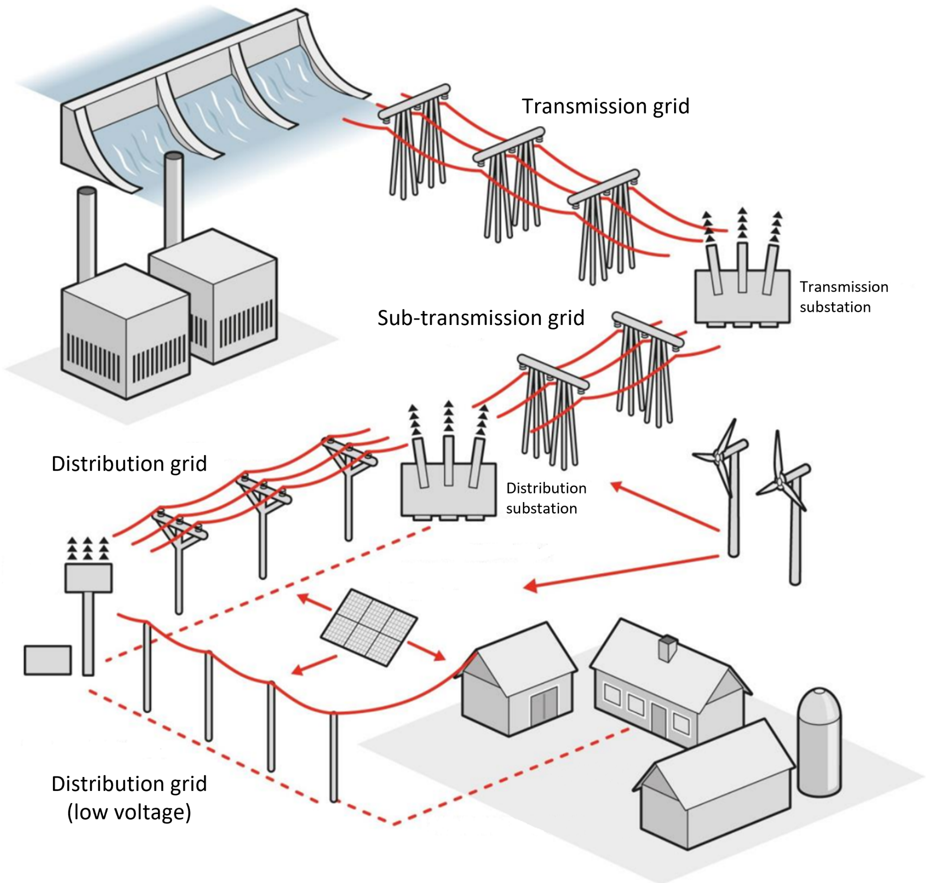


Figure 2.4: The Swedish power transmission system. Modified with permission from Energiföretagen (2021)

.

The Swedish power grid is built up from transmission- and distribution grids. The transmission grid operates at high voltages (220-400 kV), over long distances and transfers large amounts of power, generally from north to south (Svenska Kraftnät, 2022b). The sub-transmission grid normally operates at 130 kV and transfers power from the transmission grid to the local distribution grids (Svenska Kraftnät, 2022b). The distribution grid operates at or below 40 kV and serves most consumers (Svenska Kraftnät, 2022b).

2.4 Energy Storage

According to Rouholamini et al. (2022), there are three main types of ESS, pumped hydro, compressed air and batteries. Rouholamini et al. (2022) explain that battery energy storage systems (BESS) are the most flexible of the three as those can be used almost anywhere. The authors also state that Li-ion BESS has the greatest commercial interest because of its high energy density, fast charging, compact size and long lifetime. In this study, Li-ion BESS is assumed to be the technology of choice.

2.4.1 ESS for Peak Shaving

According to Uddin et al. (2018), a major challenge for the electric utility industry is to meet the varying electricity demand during a day, especially the peak hours. Energy storage systems can be used for peak shaving, where load from power peaks are moved to times of lower power demand. The authors also state that peak shaving can reduce the risk of power failure and decrease the cost of electricity. Figure 2.5 below shows how the peak power is reduced with peak shaving. N-1 secure capacity represents a set power limit and the battery is assumed to be charged during the night when the demand is lower.

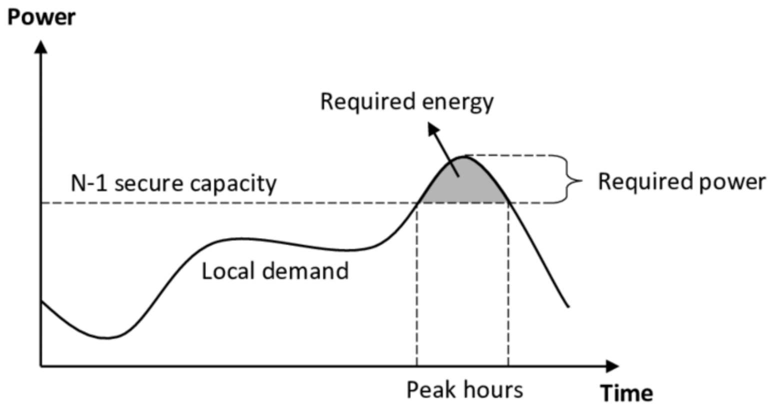


Figure 2.5: Example of peak shaving with ESS over a day (Strbac, Konstantelos, and Djapic, 2016)

2.4.2 ESS for Emergency Backup

There are several vital societal functions that are dependent on a continuous energy supply and require backup in case of supply disturbances (MSB, 2022b). One way to ensure uninterrupted supply of electric energy during times of energy scarcity is to use ESS as a backup (Szott et al., 2021). A case study in Croatia by Barać et al. (2022) shows that a BESS has the potential to provide ancillary services to healthcare facilities in extreme events, such as earthquakes. According to Jansen, Dehouche, and Corrigan (2021) ESS can also be used to en ensure electricity to mobile network operators.

Reasons for loosing the ability to supply energy could be natural disasters, conflicts or other types of emergency situations. In the case of an emergency situation in general, the Swedish Civil Contingencies Agency (MSB) recommends that households should have supplies to cope with one week without external help (MSB, 2022a). This means keeping extra batteries, an alternative heating source, fuel and drinking water etc. The duration has recently been increased from 72 hours which was the previous recommendation (MSB, 2022a). The Swedish Armed Forces are working to make sure the country is able to handle an emergency lasting 3 months (Regeringen, 2020). Furthermore, the Armed Forces communicate that a major goal for emergency situations is to ensure that important societal functions are sustained.

One type of vital societal function is critical transport, such as the delivery of groceries, chemicals for drinking water purification as well as emergency vehicles[1]. All of which need to be sustained in an emergency situation. A discussion with MSB shows that the amount of traffic flow which can be regarded as critical currently is unknown[1].

2.4.3 Dimensioning an ESS

When dimensioning an ESS there are several factors that affect the storage system's functionality and profitability. Specifically for BESS installations, the system can either be designed as one large installation or multiple smaller units distributed over a larger area. According to Alsaidan, Khodaei, and W. Gao (2018), a distributed BESS provides increased redundancy and will also increase the lifetime of the system. The authors also state that the profitability is heavily dependent on the size of the BESS, where an over-dimensioned system can be too expensive and an under-dimensioned one may fail to deliver the desired benefits.

According to Alsaidan, Khodaei, and W. Gao (2018), an important factor when designing a BESS is the batteries' rate of degradation. The authors state that the degradation of a battery is dependent on two factors, calendar aging and cyclic aging. As described by the authors, calendar aging occurs even if the battery is unused and depends on the system's voltage and temperature. The cyclic aging varies with the Depth of Discharge (DoD) (Alsaidan, Khodaei, and W. Gao, 2018), i.e the percentage of the battery's capacity that is utilized each cycle (Khizbullin, Chuvykin, and Kipngeno, 2022). Deep DoD degrades the batteries faster than shallow DoD levels (Alsaidan, Khodaei, and W. Gao, 2018).

[1]Personal communication, Sundström, Maria, MSB, Interview, 2022-08-12

3. Modeling

The need for energy storage is determined by the power demand as well as the available supply. Therefore, two models are constructed, one for the power demand at each feeding station and one for the supply. Subsequently, the ESS need for peak shaving and backup can be determined using these models.

3.1 Power Demand

The model for average hourly power demand per hour, P [MWh/h], is constructed as follows.

$$P = q \cdot E_{veh} \tag{3.1}$$

Where q is the traffic flow [vehicles/h], E_{veh} is the energy needed for each vehicle [kWh/vehicle]. The energy, E_{veh}, can be calculated using the following equation.

$$E_{veh} = \int_{t_0}^{t_1} P_{veh}(t)\, dt \tag{3.2}$$

Where $P_{veh}(t)$ is the power needed for each vehicle using the ERS [kW/vehicle]. P_{veh} varies over time as it travels over some distance with changing conditions, such as topography. t_0 to t_1 is the time when the vehicle enters and leaves the ERS.

Calculation of the power demand is done in four steps. First, the traffic flow is collected from real-world data (section 3.1.1). Second, the power for each vehicle is determined with the help of a Simulink model which gives the power over time and distance (section 3.1.2). The third step is to decide on which parts of the highway to place the electric road (section 3.1.3). Finally, equation 3.1 is used to get the total power demand at each feeding station (section 3.1.4). The results are shown for each feeding station in section 4.1.2 and aggregated in 4.1.3.

3.1.1 Traffic Flow

The traffic flow data are taken from Trafikverket's service called TIKK (Trafikverket, 2022), a clickable map of Sweden with data points containing measured traffic flow. Measurements were done some years apart, where each one contains hourly data for one or several consecutive days. Data for the Project's road sections are available from 1994-2022. In this analysis, data from 2010-2022 is taken to represent present day while keeping enough information to perform the analyses.

For the entire Project area, Brändåsen-Adolfsberg, there are sample measurements for the four road sections between each of the five interchanges. There are data for traffic flow around the interchanges as well, but for the purposes of this report, interchanges are represented and considered as points. This is done by assuming that each road section starts and ends where feeding stations 1, 4, 8, 13 and 15 are located respectively (see section 2.1).

Each sample of traffic flow can be separated into cars (including motorcycles) and trucks. Within these two categories, vehicles with and without trailers can be distinguished. The trucks can also be separated into two-or three-axle tractors. For the purposes of this report, data are separated into cars without trailers, trucks without trailers as well as trucks with a trailer. The flow of cars with trailers is excluded.

Motorcycles are included in the cars' traffic flow data. However, the average daily flow of motorcycles during the summer months is 101-250 for all road sections. Compared to the total daily average of 7000-19000 for cars and motorcycles combined, this amount is deemed negligible.

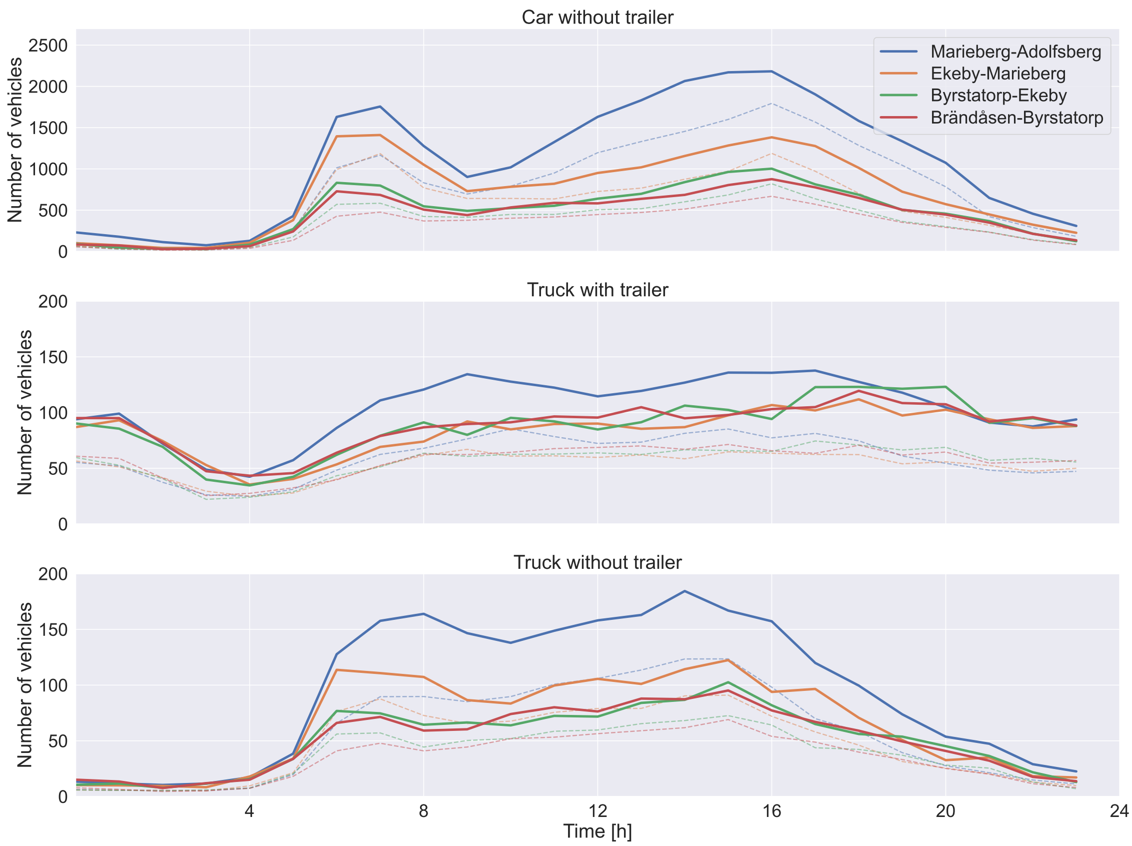
The sampling of measurements have been done for both directions and for all days of the week. However, the measurements do not always provide complete 24 hour days. Therefore, data points for hourly traffic flow from different days are aggregated to create a representative day. To avoid underestimating the power demand, sample measurements from weekends are excluded. This leaves 552-696 data points for each road section, divided into 240-456 data points for each direction.

With Python, an average weekday is calculated using the hourly traffic flow data for each vehicle class. To cover most of the probable traffic flow scenarios, the 95th percentile for the samples is chosen. This means 95% of days will have a traffic flow at or below the chosen level. The equation used to get the 95th percentile is shown below.

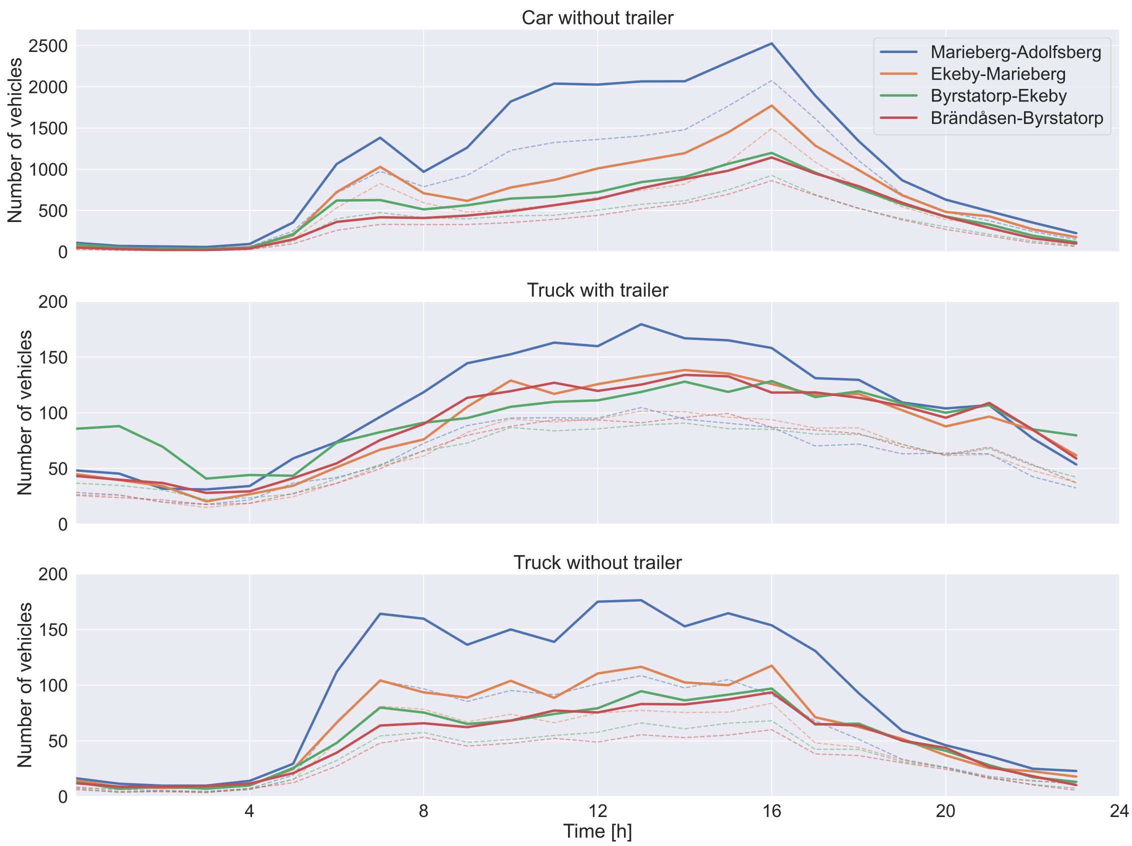
$$q(t) = \mu(t) + 1.64 \cdot \sigma(t) \tag{3.3}$$

Where q is the calculated traffic flow during a specific hour t, μ is the mean of the traffic flow and σ is the standard deviation.

The result of the data analysis is shown in figure 3.1. In the figure, the 95th percentile is shown with a solid line and the mean with a dashed line. Direction 1 represents northward from Hallsberg to Örebro, whereas direction 2 represents the opposite.



(a) Direction 1



(b) Direction 2

Figure 3.1: Traffic flow over 24 hours separated by road section, vehicle class and direction.

3.1.2 Vehicle Energy Consumption Model

An overview of the Simulink model used to simulate the energy consumption of electric vehicles is shown in figure 3.2 below.

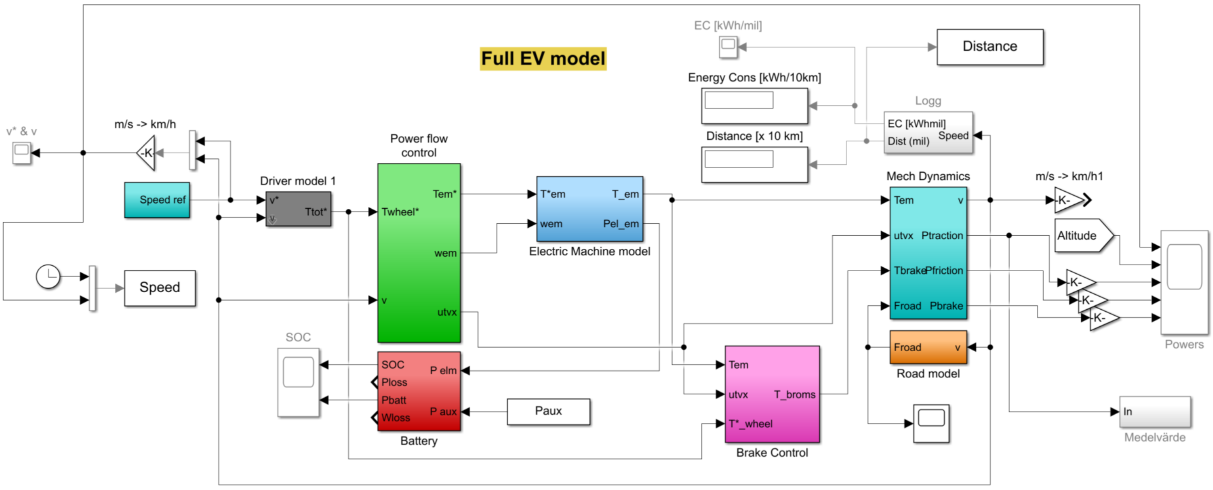


Figure 3.2: Overview of the electric vehicle Simulink model

Two sets of input are required to run the model. Firstly, a drive cycle is used in the speed ref module (on the left side). The drive cycle describes the road and desired vehicle behavior. The Driver model controls the wheel torque needed to maintain the desired speed. Secondly, vehicle attributes are needed to calculate the vehicle dynamics. These attributes are used in the modules called Power flow control, Battery, Electric Machine model as well as Brake Control. Finally, the power consumption over time and distance is calculated in Mech Dynamics.

The drive cycle used, the vehicle attributes chosen as well as the results from the Simulink model are shown in the following subsections.

Drive Cycle

To construct the drive cycles, data on time, speed, distance, altitude and slope data at each point of the road are needed.

The Swedish land survey authority's database "Geotorget" provides data on altitudes in Örebro län (Lantmäteriet, 2022). Their product "Markhöjdmodell Nedladdning, grid 50+" contains altitudes in a grid with points 50 meters apart. Using this grid and the terrain profile tool in QGIS, an interpolated profile of the road from Hallsberg-Örebro is acquired. The profile is then exported as points containing horizontal distance (x) and altitude (y).

In Python, the road data are used to generate the drive cycles. Measures are taken to make sure the vehicles have a running start and finish. To simplify the model, the desired speed of the vehicles is assumed to be constant. Trafikverket's traffic flow data provide the speed of different vehicles, from which the speed is chosen. As the speed for cars and trucks differ, separate drive cycles are created for the vehicle groups. Table 3.1 below illustrates the drive cycle and describes how the values in the columns are obtained. The two drive cycles are also inverted to represent the opposite direction (Örebro-Hallsberg).

Table 3.1: Illustration of the drive cycle used in the Simulink model

Time	Speed	Distance	Altitude	Slope
$t = \frac{d}{v}$	Cars: 110 km/h Trucks: 85km/h	$d = \sqrt{\Delta x^2 + \Delta y^2}$	The y values from QGIS are used directly	$tan\theta = \frac{\Delta y}{\Delta x}$

Vehicle Attributes

The following table (3.2) displays the chosen vehicle attributes. The car represents a Tesla model 3 specified by Bramerdorfer and Marth (2021), a modern mid-sized electric vehicle. The trucks are divided into trucks without trailers as well as trucks with trailers. This separation is done as it provides some granularity regarding the weight of the vehicles, which can be matched with available traffic data from Trafikverket (2022). In this report, the truck without trailer represents a fully loaded rigid body. In the traffic data, the truck with trailer includes all trailer constellations, such as semi-trailer trucks and rigid body trucks with trailer[1]. In this report, it is assumed that a truck with trailer is a fully loaded rigid body with trailer.

Table 3.2: Vehicle attributes for the three vehicle classes

Vehicle class	E_{batt} [kWh]	m_v [kg]	r_w [m]	C_d	C_r	A_v [m^2]	$P_{em,max}$ [kW]	P_{aux} [kW]
Car	54[a]	1645[a]	0.34[a]	0.23[a]	0.013[a]	2.28[a]	208[b]	2.2[c]
Truck w/o trailer	200[d]	27000[e]	0.548[e]	0.36[f]	0.0038[e]	8[e g]	225[d]	7[h]
Truck with trailer	360[i]	60000[e]	0.548[e]	0.5	0.0038[e]	9[e g]	490[i]	7[h]

[a] Bramerdorfer and Marth, 2021
[b] Electric Vehicle Database, 2022
[c] Fiori, Ahn, and Rakha, 2016
[d] Volvo AB, 2022a
[e] Hammarström et al., 2012
[f] Zhang, Qu, and Tong, 2022
[g] Holmberg et al., 2014
[h] Singh et al., 2022
[i] Volvo AB, 2022b

Where E_{batt} is the battery capacity, m_v is the vehicle mass, r_w is the wheel diameter, C_d is the drag coefficient, C_r is the rolling resistance coefficient, A_v is the vehicle front area, $P_{em,max}$ is the traction motor's max power and P_{aux} is the auxiliary power draw.

[1] Personal communication, Lindström, Ylva, Trafikverket, e-mail, 2022-10-26

Power Consumption

The result from the power consumption simulations is shown for each vehicle class in figure 3.3 - 3.5 below. The figures show power as a function of distance, where $distance = 0km$ represents junction Brändåsen and $distance = 21km$ represents junction Adolfsberg. All figures have two subplots, where the upper one represents traveling Hallsberg to Örebro (1) and the lower represents the opposite direction (2).

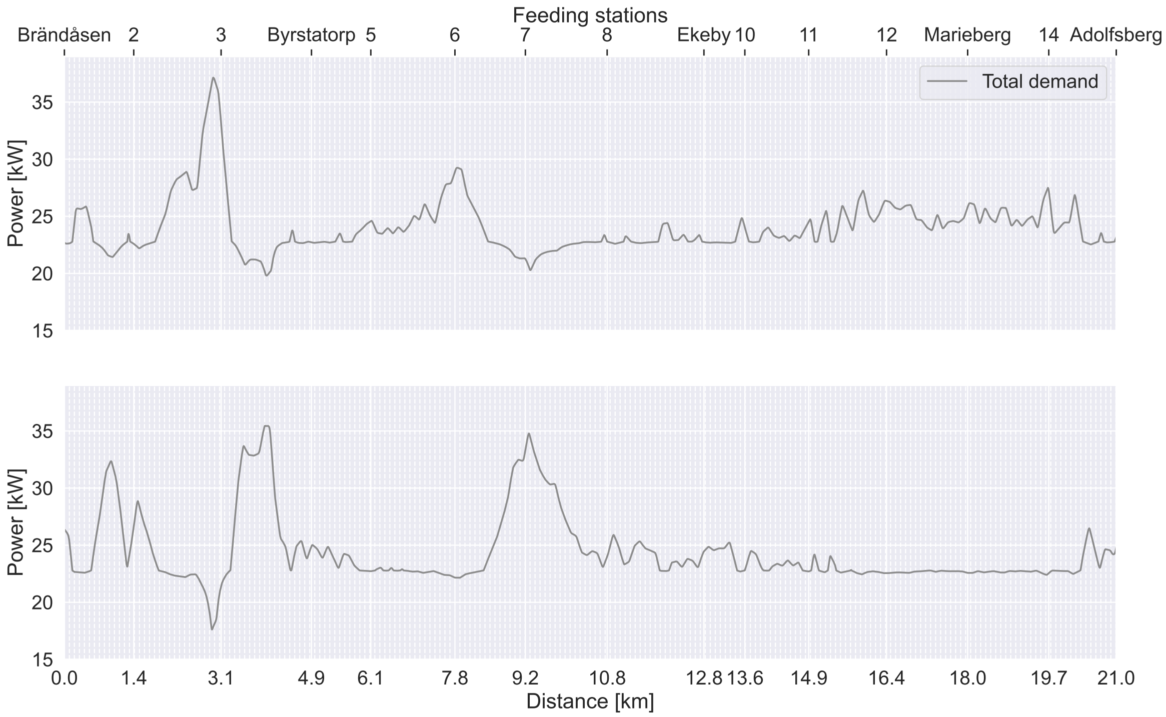


Figure 3.3: The car's power demand over the distance, one plot for each direction

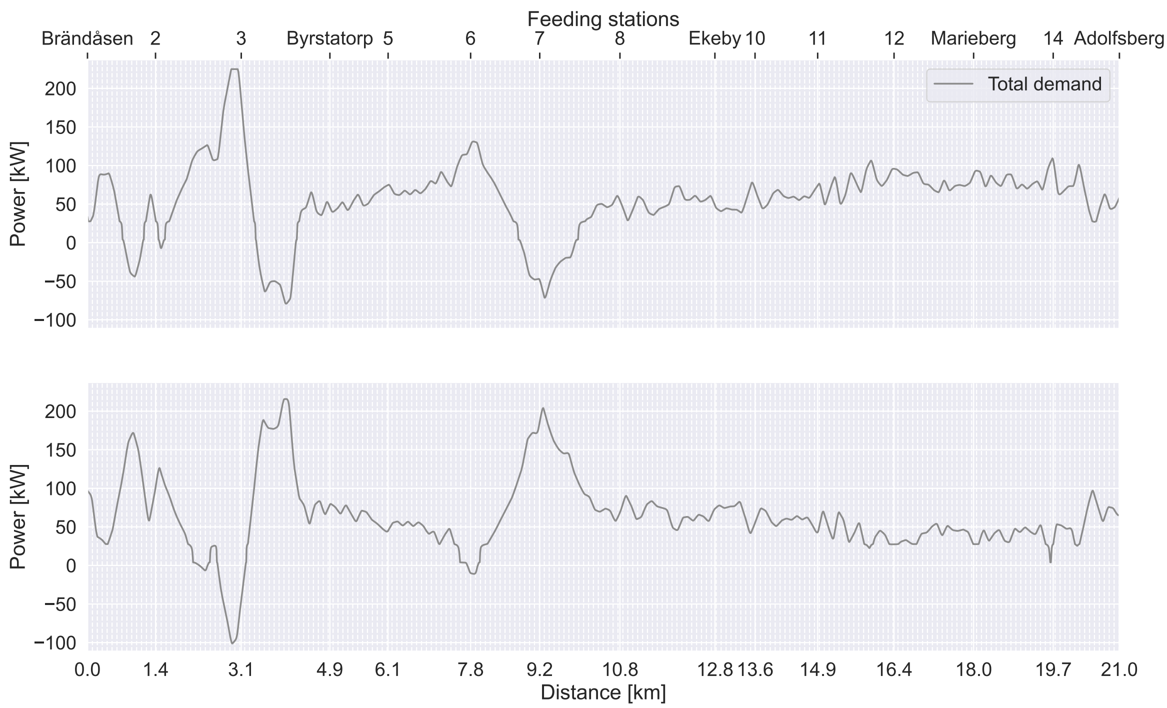


Figure 3.4: The trucks without trailer's power demand over the distance, one plot for each direction

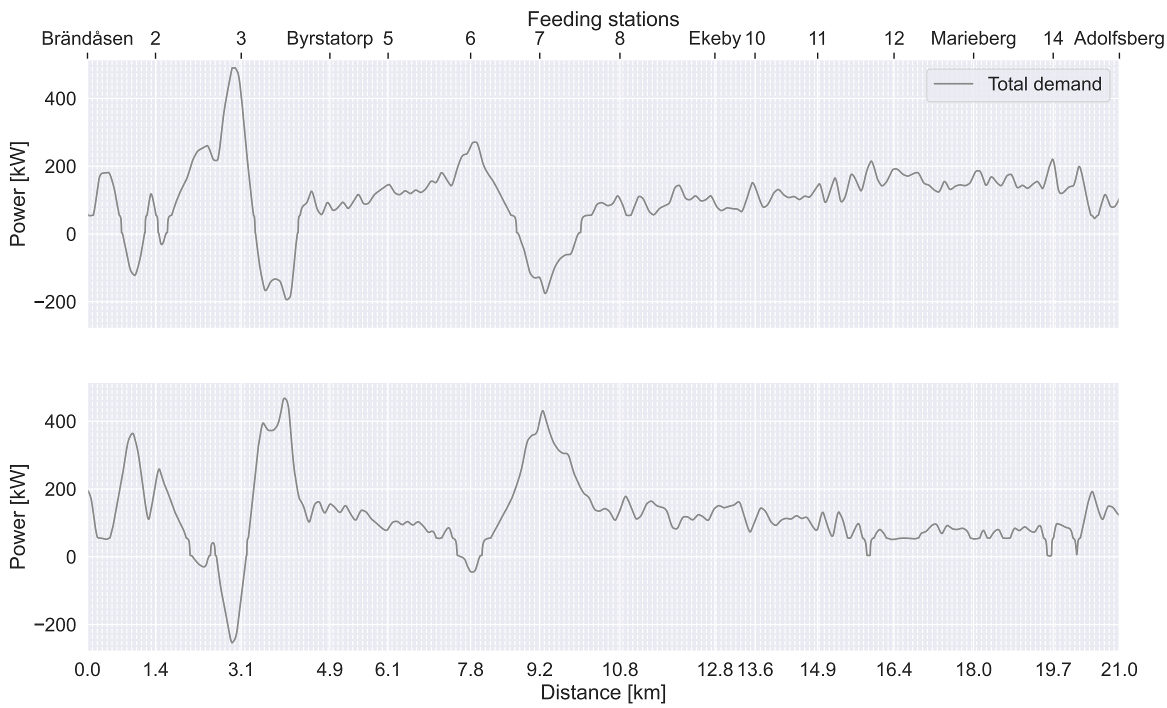


Figure 3.5: The truck with trailer's power demand over the distance, one plot for each direction

3.1.3 Electric Road Model

The electric road is placed in segments, the placement of which will hereinafter be called the *electric road model*. The electric road model is designed from a number of principles. First and foremost, the model is designed to provide power where the vehicles need it the most. The parameters and the method used to accommodate them are shown in table 3.3. Additionally, each ERS segment is connected to a suitable feeding station. It is also assumed that the onboard battery has an efficiency of 90%, meaning the energy needed to propel the vehicle is slightly higher when it is passed through the battery.

Table 3.3: Design parameters used when modeling the ERS.

Design Parameter	Method used	Cause
Targets		
ERS prioritized where the power demand is largest	Primarily, the electric road is placed where the power demand is in the top three-quarter range. This is done by drawing a line in the power-distance graph through the 25th percentile.[a] Locations, where power is larger than this line, are covered with electric road.	Done to maximize direct usage of electricity, minimizing detours via the battery which puts strain on the cells and reduces efficiency.
75% ERS coverage	The coverage is accomplished by using the 25th percentile as a baseline for where to put the ERS and by ensuring removed electric road caused by some criteria is placed somewhere else suitable.	A trade-off between cost, efficiency and performance. Allowing uphill slopes to be covered, while downhill slopes can be left without ERS.
Requirements		
Maximum 750 m between feeding station and end of electric road	Electric road is terminated where the distance from the electric road to the connected feeding station is larger than allowed.	Too far of a distance can cause voltage spikes, reduced efficiency and heat issues. Simulations so far have been used to approve a spacing of up to 750 m.
Minimum 500 m per ERS segment	Segments shorter than 500 m are aggregated with other segments where power need is high and the other parameters fulfilled.	To avoid unnecessary lifting of pick-up and streamlining construction.
Providing 150 % of energy needed	Adjusting the battery charging power.	A public procurement requirement for the Project.

[a] The 25th percentile represents the level which 25% of values are below, meaning 75% of values are higher than this level. This is used to make sure a certain percentage of the road is electrified, see 75% coverage.

3.1.4 Power Demand for each Feeding Station

With the electric road placed and each segment connected to a feeding station, the energy needed for each vehicle and feeding station is calculated using equation 3.2. The calculations are separated for each vehicle class and done in each direction. Furthermore, three feeding stations are located at an interchange where the traffic flow changes from one road section to another. Therefore, the energy needed at each station is also divided into which road section (A-D) it is used in.

To calculate the power demand using equation 3.1, matrix multiplication is performed as shown below in equation 3.4. In the matrix with traffic flow (q), the rows represent hours over one day and the columns denote the four road sections. For the energy (E), the rows represent the road sections and the columns denote the feeding stations. The matrix multiplication is done for each vehicle class and in each direction. Finally, the power for each direction at each feeding station is summed up, giving the total power for each feeding station at every hour of the day for the selected vehicle classes.

$$\begin{pmatrix} P_{00,1} & P_{00,2} & . & . & P_{00,15} \\ P_{01,1} & P_{01,2} & . & . & P_{01,15} \\ . & . & . & . & . \\ . & . & . & . & . \\ P_{23,1} & P_{23,2} & . & . & P_{23,15} \end{pmatrix} = \begin{pmatrix} q_{00,A} & q_{00,B} & q_{00,C} & q_{00,D} \\ q_{01,A} & q_{01,B} & q_{01,C} & q_{01,D} \\ . & . & . & . \\ . & . & . & . \\ q_{23,A} & q_{23,B} & q_{23,C} & q_{23,D} \end{pmatrix} \begin{pmatrix} E_{A,1} & E_{A,2} & . & . & E_{A,15} \\ E_{B,1} & E_{B,2} & . & . & E_{B,15} \\ E_{C,1} & E_{C,2} & . & . & E_{C,15} \\ E_{D,1} & E_{D,2} & . & . & E_{D,15} \end{pmatrix} \tag{3.4}$$

3.2 Power Supply

The power system supplying the ERS is assumed to be connected to the 130 kV sub-transmission grid. The voltage will then be brought down by a distribution substation to distribution levels, here assumed to be 10 kV. This will form a private distribution grid and supply the individual feeding stations with power. The 15 feeding stations will convert the 10 kV AC to around 750 V DC which will be used to power the road. The system can be seen in figure 3.6 below where the boxes numbered 1,2 and 3 represent a few of the feeding stations, all of which are assumed to be powered by the same pair of 130/10 kV transformers.

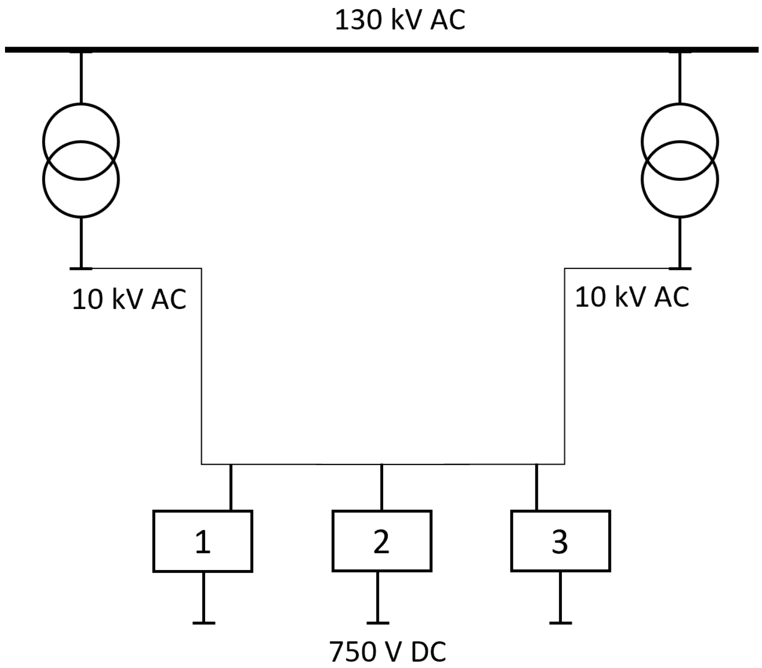


Figure 3.6: Model of the power system

When talking to Holtab and E.ON who are responsible for constructing the feeding stations and distribution substation respectively, they both stated that the power system will be dimensioned and constructed as needed to cover the peak power from the ERS[2,3]. Furthermore, the sub-transmission grid in the Project area currently has enough capacity to supply the ERS Project[3]. However, this could change quickly in the ongoing electrification of transport and industry[3].

[2]Personal communication, Gyllenhammar, Carl-Fredrik, Holtab, Interview, 2022-11-07
[3]Personal communication, Backéus, Jonas and Bernebrand, Anneli, E.ON, Interview, 2022-11-09

3.3 ESS Model for Peak Shaving

The power demand and a set power limit are the two main parameters used to estimate the ESS need for peak shaving, as shown in figure 2.5. This is primarily done for the total power demand, i.e the entire Project area. However, it is important to ensure that the lifetime of the ESS is adequate. This is done with the model described in section 3.3.1. Thereafter, the total ESS capacity is distributed between the feeding stations into 15 smaller units as described in 3.3.2.

3.3.1 Lifetime Model

The flowchart in figure 3.7, gives an overview of how the lifetime is calculated for a certain grid power limit and a number of ESS capacities.

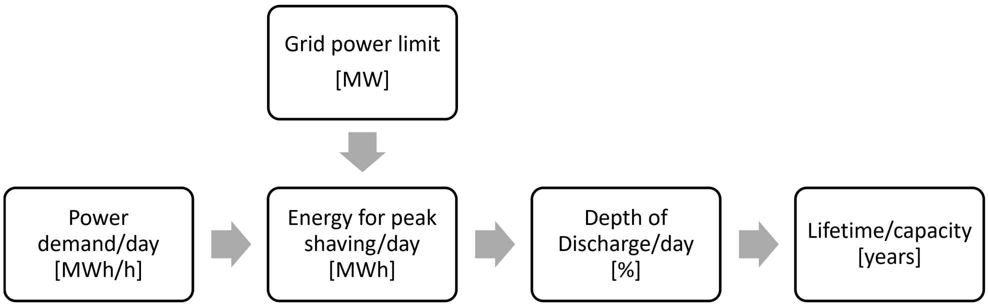


Figure 3.7: Flowchart of the lifetime model for peak shaving

Power demand is calculated hour by hour for each day. A dataset of 24 h days is created using the normal (Gaussian) distribution for power demand for each hour, t, of the day according to:

$$P(t) = \mu(t) + z \cdot \sigma(t) \qquad (3.5)$$
$$z \in N(0,1)$$

Where $\mu(t)$ is the mean, $\sigma(t)$ is the standard deviation and z is the normally distributed factor which lets $P(t)$ vary within its normal distribution. It is assumed that z is constant during one day, meaning a busy day will present as a power demand significantly larger than μ constantly throughout the day.

Energy for peak shaving is the energy needed from the battery to cap the power drawn from the distribution substation at some set *grid power limit*.

Depth of discharge is determined here by the percentage of battery capacity used per day to perform peak shaving. This is calculated for a wide range of battery sizes. It is assumed that the batteries only perform one cycle per day.

The lifetime in this study is limited to cyclic lifetime. This is determined by the cycling depth, meaning a battery that is discharged deeper can perform less cycles. As stated by Mallon, Assadian, and Fu (2017), the loss of battery life can be assumed to follow:

$$D_k = \frac{1}{N_k} \tag{3.6}$$

Where D_k is the battery damage per cycle k. N_k is the number of cycles a battery would survive if every cycle would be of a certain Depth of Discharge, DOD_k. This is called the Palmgren–Miner (PM) rule (Mallon, Assadian, and Fu, 2017; Serrao et al., 2009). The number of cycles is also called the cycle life. Mallon, Assaidan and Fu state that the cycle life can be calculated using:

$$N = \beta_0 \cdot DOD^{(-\beta_1)} \cdot e^{\beta_2(1-DOD)} \tag{3.7}$$

In this report, a LiFePO4 is assumed to be the chemistry used. Its characteristics are shown in GWL (2015). To find the coefficients ($\beta_1 - \beta_3$) applicable to this battery, a curve fit is done. However, it was found that fitting the equation to a logarithmized version of the curve resulted in a better fit. Therefore, the following equation is used:

$$ln(N) = ln\left(\beta_0 \cdot DOD^{(-\beta_1)} \cdot e^{\beta_2(1-DOD)}\right) \tag{3.8}$$

The resulting curve fit gives $\beta_0 = 6.90490, \beta_1 = 0.15372$ and $\beta_2 = 0.15735$. The curve and its input data are shown in figure 3.8.

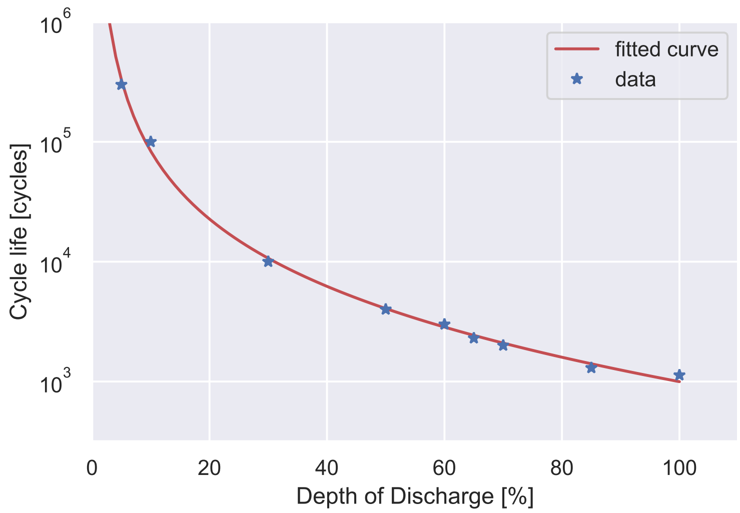


Figure 3.8: Cycle life as a function of depth of discharge shown as a fitted curve and real data, the data is taken from (GWL, 2015)

Finally, the cycle life is calculated using the data set of power demand/day created with equation 3.5 which, through integrating to get the energy used/day, can be used in equation 3.6 to get the daily cycle life loss. Summing the total cycle life loss for an average year, the percentage of the battery life lost is calculated. Equation 3.9 - 3.10 gives the lifetime of the battery.

$$D_{tot} = \sum_{i=1}^{365} D_i \tag{3.9}$$

$$L_{tot} = \frac{1}{D_{tot}} \tag{3.10}$$

Where D_{tot} is the yearly damage and L_{tot} is the total lifetime.

3.3.2 Dividing ESS Capacity Between the Feeding Stations

The ESS is assumed to be distributed between the feeding stations rather than being one aggregated system, as the construction of the feeding stations is within the scope of the Project. Co-locating the two also means utilizing ground already set aside for power electronics, transformers etc. However, this calls for a method to partition the ESS into several smaller units.

The ESS units are categorized by their individual energy need to perform peak shaving during a heavily trafficked day. Some rules are set up to make sure the ESS units are dimensioned properly. Each unit needs to cover at least 90 % of the energy demand required to peak shave its feeding station's power demand. The units are divided into as few variants of capacities as possible while ensuring as good a match as possible. Practically, this means dividing them into two or three variants.

3.4 ESS Model for Emergency Backup

The ESS model for emergency backup is mainly based on one parameter, the flow of critical traffic. Critical transport is assumed to be a percentage of the total traffic flow. 1%, 5% and 10% of the flow were determined to be appropriate levels for this context in discussion with a representative from MSB[4]. The capacity needed to provide backup power is calculated using the daily energy demand (95th percentile) and the assumed percentages. Subsequently, this is used to determine how long the critical transport can be sustained for a number of capacities.

3.5 Sensitivity Analysis - Utilization

It is unlikely that all of the traffic will use the ERS, both in the short and long term. Only vehicles traveling further than the range of their onboard battery are likely need to charge en route. Additionally, in the early stages of ERS implementation, only some fraction of the traffic is likely to be equipped for and use the technology.

Two scenarios are set up for a sensitivity analysis to exemplify this reasoning, using fractions of the traffic flow. It is estimated that 50% of cars, 75% of trucks without trailer and 100% of trucks with trailer drive such long distances that they need to use the ERS. As a low scenario, representing early adoption, it is estimated that 10% of cars, 20% of trucks without trailers and 30% of trucks with trailers will use the ERS.

[4] Personal communication, Sundström, Maria, MSB, Microsoft Teams, 2022-12-08

4. Simulation Results

In this report, the traffic flow is divided into three vehicle classes: cars, trucks without trailers and trucks with trailers, see chapter 3.1.1. When designing the electric road and calculating the power demand, these categories are used. The calculations are done using the 95th percentile of traffic flow. This high level of traffic flow is chosen as it is assumed to provide the 95th percentile of power demand and represent a heavily trafficked day. The power demand for each feeding station can be seen in section 4.1.2 and the total power demand for the Project is shown in 4.1.3.

When estimating the ESS need for peak shaving and emergency backup, the traffic flow is divided into two cases. The first case, "Trucks", includes the two types of trucks. The second case, "All traffic", includes all three vehicle classes. Since the power supply will be built purposely for the Project, no firm power limits have been established. Therefore, the ESS need for peak shaving is estimated using some assumed power limits.

Throughout the report, all vehicles have been assumed to use the ERS in the interest of finding the upper limits of the power demand using as much known data as possible. Since the adoption of the ERS technology is highly uncertain, this chapter ends with a sensitivity analysis covering other possible scenarios.

4.1 ERS Power Demand

In this section, the power demand for the ERS is calculated. The targets and requirements from table 3.3 are used to decide on the ERS design. Thereafter, the power demand for each feeding station is calculated.

4.1.1 ERS Design

Using the design parameters from table 3.3, a suggested ERS design is shown in figures 4.1 - 4.3 together with the power draw from the ERS for each vehicle class. All colored parts represent road segments covered with ERS. The blue field represents power directly used for powering the vehicle, orange represents power used to charge the battery whereas the lines represent the vehicle's power usage, just as seen in section 3.1.2.

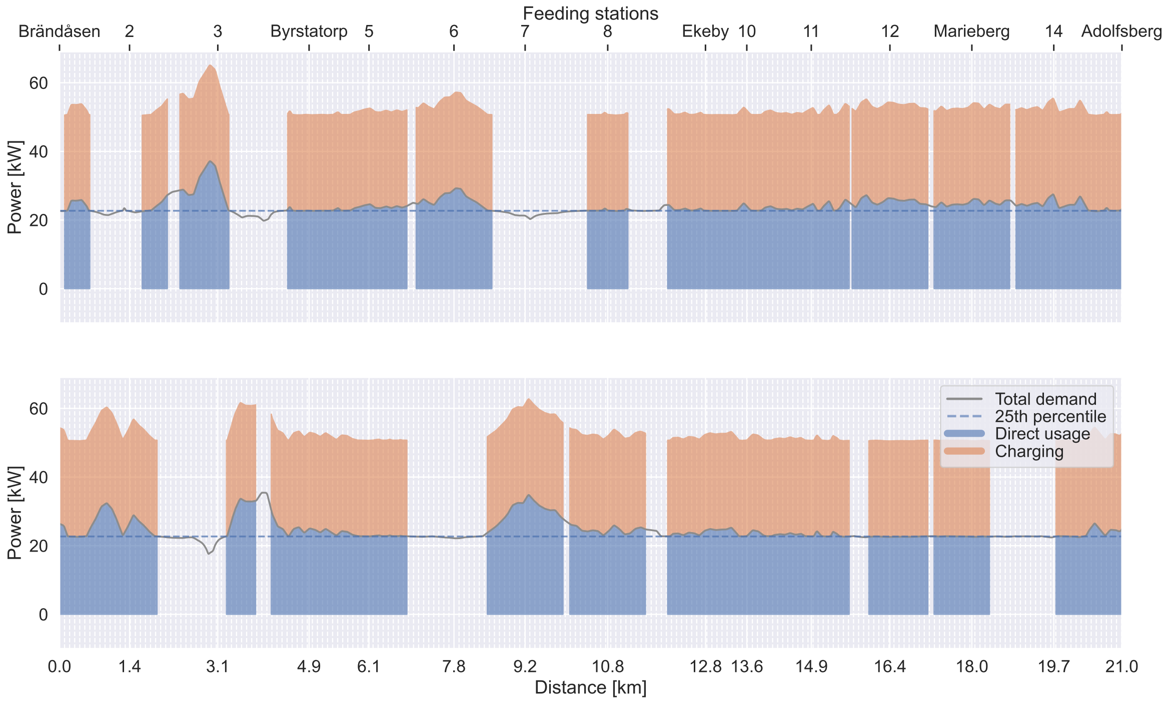


Figure 4.1: The car's power demand over the distance, one plot for each direction

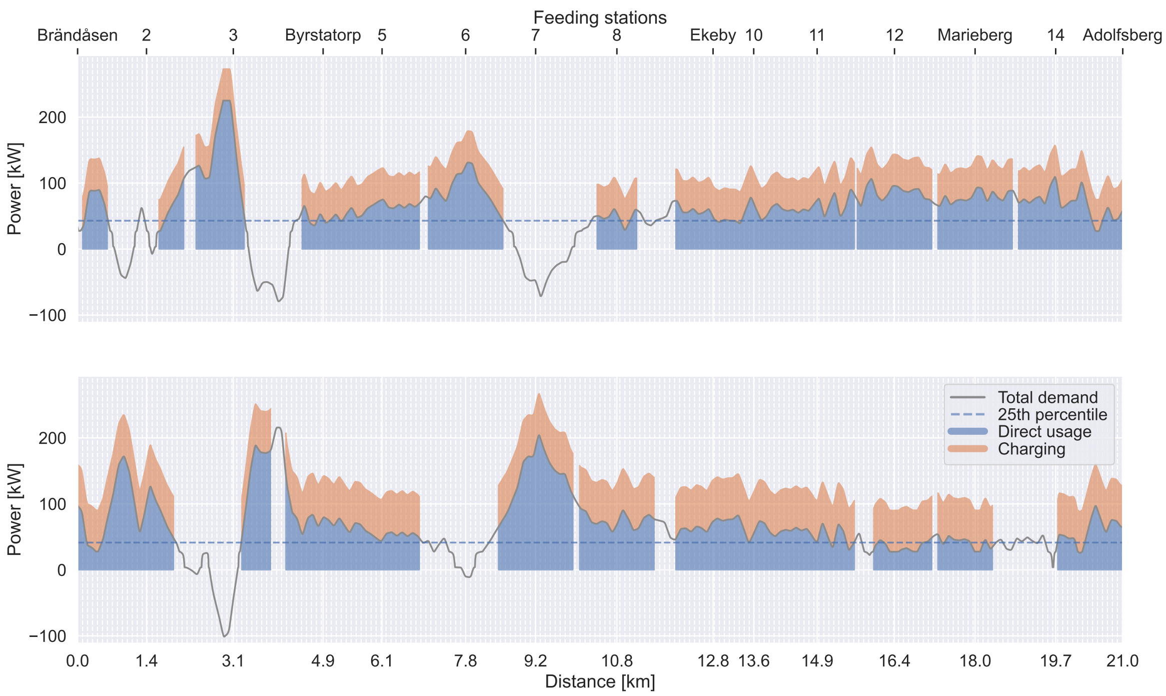


Figure 4.2: The truck without trailer's power demand over the distance, one plot for each direction

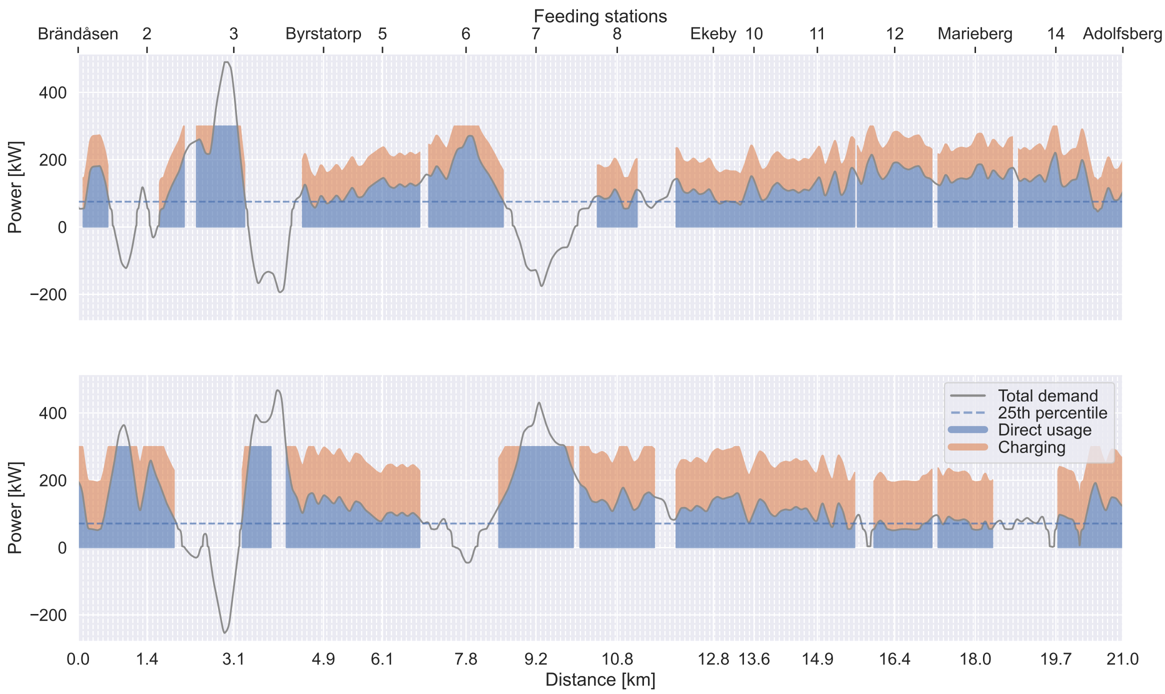


Figure 4.3: The truck with trailer's power demand over the distance, one plot for each direction

The table below shows the vehicle energy consumption, E_{veh}, and total energy provided from the ERS (direct usage and charging), E_{ERS}, for both directions.

Table 4.1: Vehicle consumption and energy provided from the ERS

Vehicle class	Direction	E_{veh} [kWh]	E_{ERS} [kWh]
Car	1	4.6	7.3
	2	4.7	7.4
Truck w/o trailer	1	14.1	22.0
	2	15.8	24.8
Truck with trailer	1	26.1	40.8
	2	30.0	47.2

4.1.2 Power Demand for Each Feeding Station

The power demand over a heavily trafficked day (95th percentile) for each feeding station is shown in figure 4.4 below. The demand from both directions are summed to give the total demand per feeding station. In the tender for the Project, Trafikverket has written that the ERS should be able to sustain one truck every 22 seconds. This is included as a base case, where every truck is assumed to be a truck with trailer.

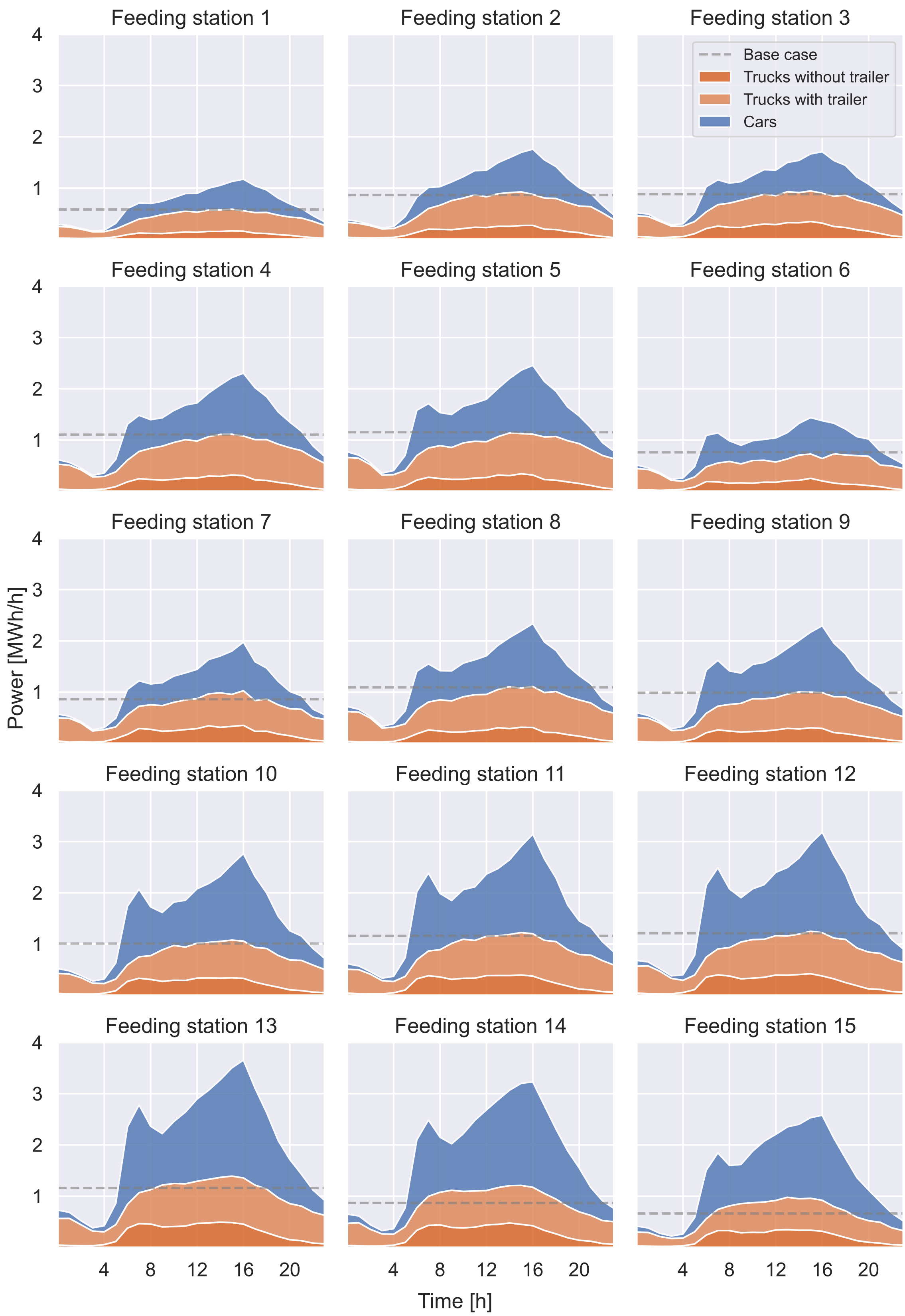


Figure 4.4: Power demand (95th percentile) for each feeding station

4.1.3 Total Power Demand

Figure 4.5 below shows the total power demand for all stations combined.

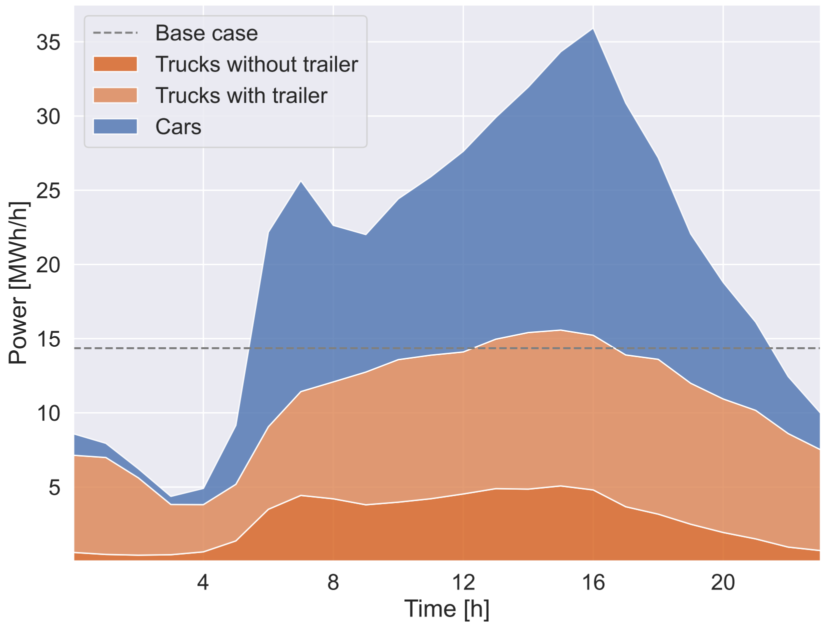


Figure 4.5: Power demand for all the feeding stations aggregated

The results show that when all vehicles types are included, the power demand varies between 5 and 36 MWh/h. For all trucks combined, the power demand varies between 4 and 15.6 MWh/h. The base case has a power demand of 14 MWh/h

4.2 Energy Storage Demand for Peak Shaving

This section explores the ESS capacity needed to limit the peak power demand from the ERS. The general analysis is done in an aggregated manner for the whole system. The resulting ESS capacity is divided between the feeding stations in section 4.2.2.

4.2.1 Dimensioning ESS for Peak Shaving

To get a starting point in setting the power limit and dimensioning the battery capacity, a graph showing how the peak power demand from the ERS can be reduced with different battery capacities is shown in figure 4.6 below. The maximum peak power in the graph below (x=0) shows the peak power from figure 4.5 for the two cases.

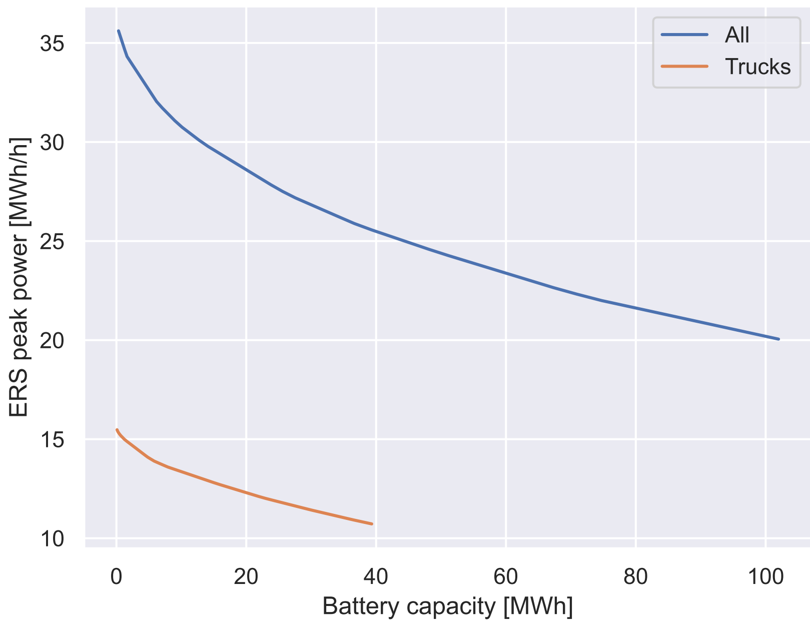


Figure 4.6: Change in ERS peak power as a function of ESS capacity used for peak shaving

From the figure, two power limits are chosen for each case. One to represent where the curves go from appearing exponential and start approaching a linear behavior. The second choice represents the point when the curves show a linear dependency between change in peak power and battery capacity. Using this reasoning, 30 MWh/h and 25 MWh/h is chosen for All traffic. The chosen limits for Trucks are 14MWh/h and 12.5 MWh/h Trucks.

These limits are subsequently used in the lifetime model. The battery lifetime versus battery capacity for the chosen power limits are shown in figure 4.7 - 4.8. The percentage of days which can be handled with each battery capacity is shown with the color bar.

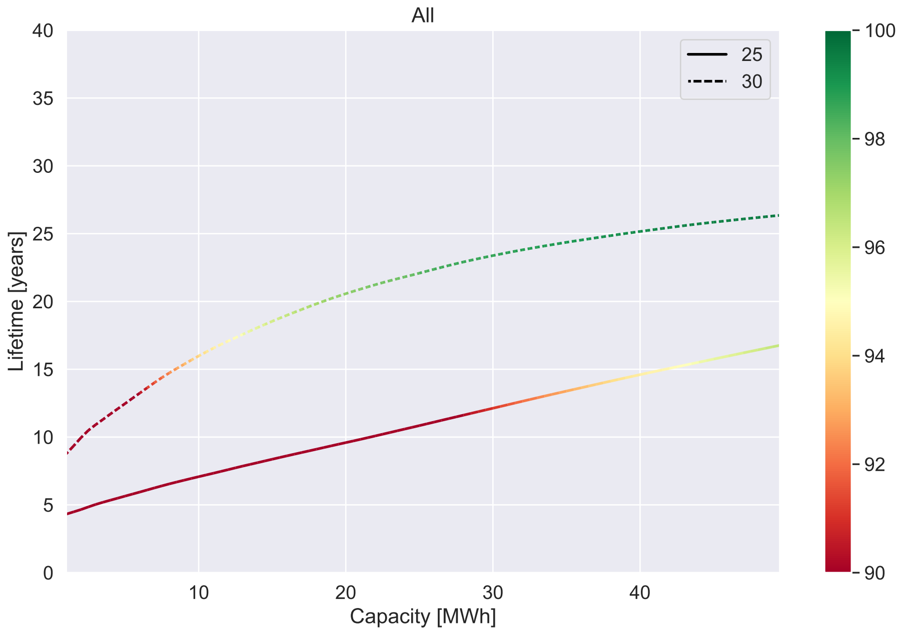


Figure 4.7: ESS lifetime vs. battery capacity for All traffic for two power limits. The color bar shows percentage of days during which the capacity is sufficient for peaks shaving.

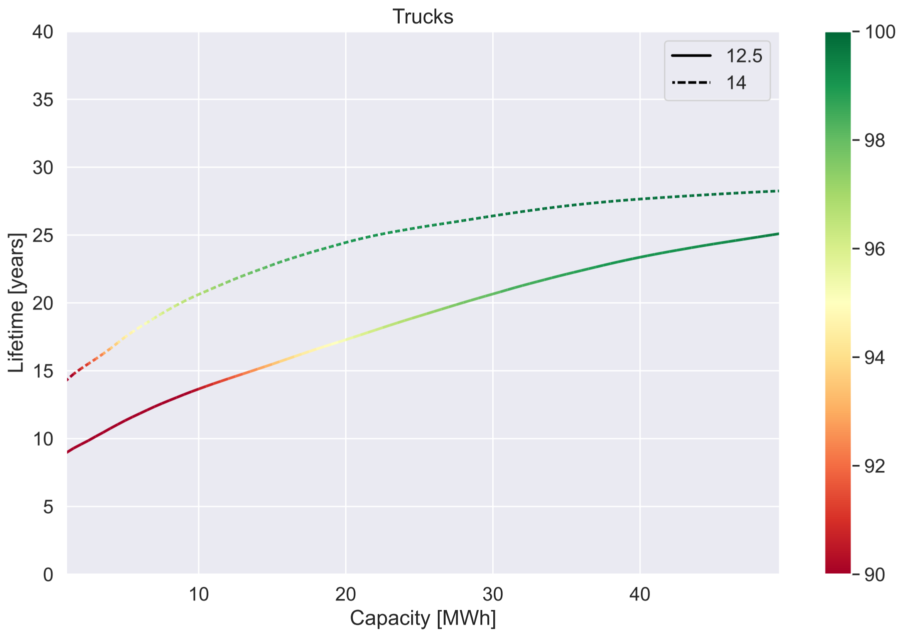


Figure 4.8: ESS lifetime vs. battery capacity for Trucks for two power limits. The color bar shows percentage of days during which the capacity is sufficient for peaks shaving.

When dimensioning for a coverage of 95% of the days in an average year, around 6MWh and 20MWh are needed to limit the peak power need from the grid to 14MWh/h and 12.5MWh/h respecitvely, assuming the case Trucks. For All traffic, the needed capacity is around 15MWh and 45MWh to limit the peak power to 30MWh/h and 25MW/h respectively.

During the analysis, it was noticed that the vast majority of days resulted in a DoD of 0-10%. This made the modeled cycle life exceed the calendar life, assuming the latter is roughly 20 years. Therefore, to make sure the battery is utilized, the ESS is forced to discharge with at least 30% of its capacity each day, e.g to avoid buying electricity during the most expensive hours. Even with this forced utilization, which is included in figures 4.7-4.8, it can be seen that the lifetime for the chosen capacities is between 15 and 20 years. This is assumed to be an adequate lifetime.

Table 4.2 below compiles the suggested capacities and relates them to the resulting reduction in peak power. The capacity ratio represents the needed ESS capacity [Wh] per unit of reduced peak power [MWh/h].

Table 4.2: Characteristics of the suggested total ESS capacities for peak shaving

Case	Power limit [MWh/h]	ΔP_{peak} [MWh/h]	ESS capacity [MWh]	Capacity ratio [$\frac{MWh}{MWh/h}$]
Trucks	14	1.6	6	3.8
	12.5	3.1	20	6.5
All traffic	30	6	15	2.5
	25	11	45	4.1

Figure 4.9 shows an example when using 45MWh for peak shaving with a power limit of 25MWh/h. The day in the example corresponds to the total power demand for All traffic during a heavily trafficked day (95th percentile). This results in a full charge (to 100%) and discharge of the battery (to 0%). Such a cycle might not be well advised, but shows the maximum capabilities of the system. The upper part shows the power demand from the ERS (ERS demand), the load on the grid (Grid Load) and the load on the ESS (ESS Load). The lower part shows how the State of Charge (SoC) changes over the day.

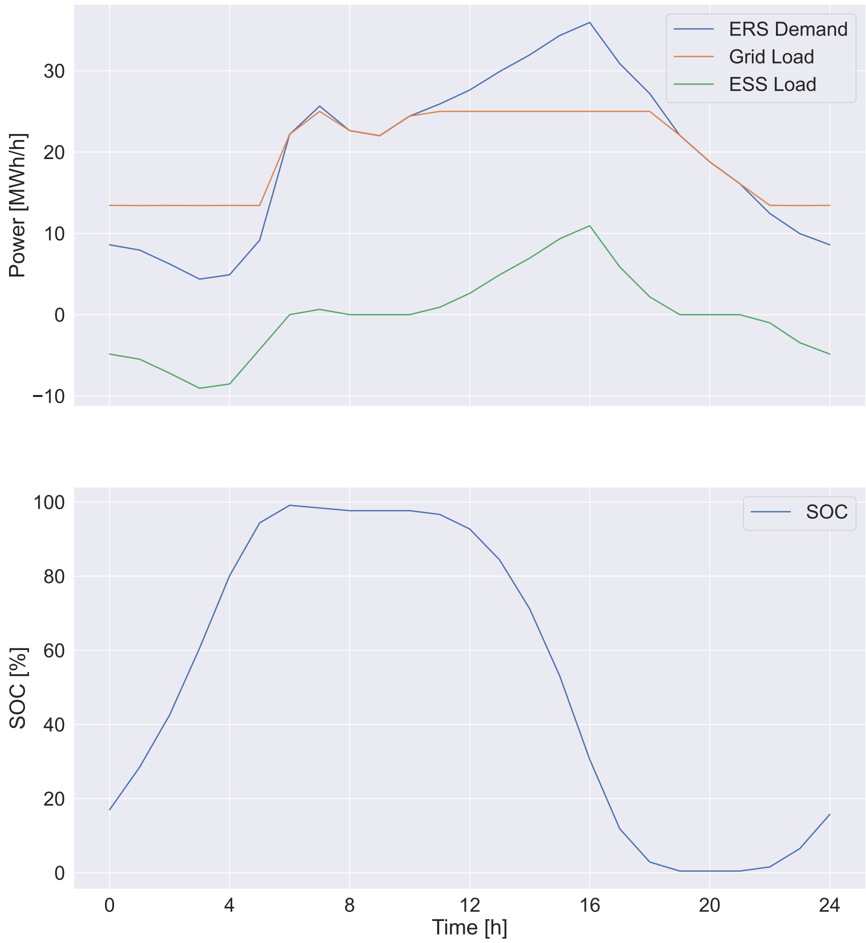


Figure 4.9: Peak shaving example using All traffic, a power limit of 25MWh/h and a ESS capacity of 45MWh. Upper graph shows power demand, lower shows corresponding SoC.

4.2.2 Dividing ESS Capacity Between the Feeding Stations

The ESS capacity needed for peak shaving at each feeding station is shown in figures 4.10 - 4.11. The result is shown for both Trucks and All traffic, where each of these has two different power limits, forming four cases.

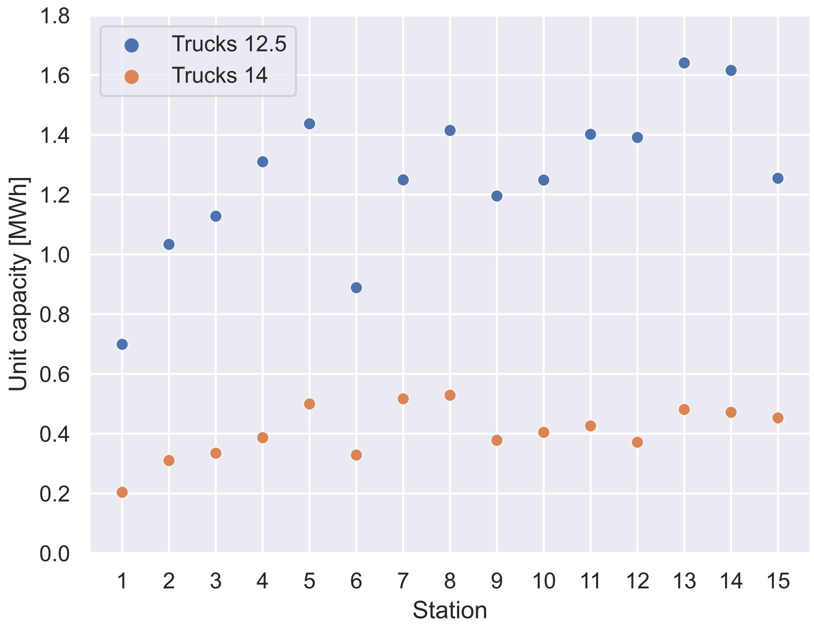


Figure 4.10: ESS capacity need for the different feeding stations when Trucks use the ERS.

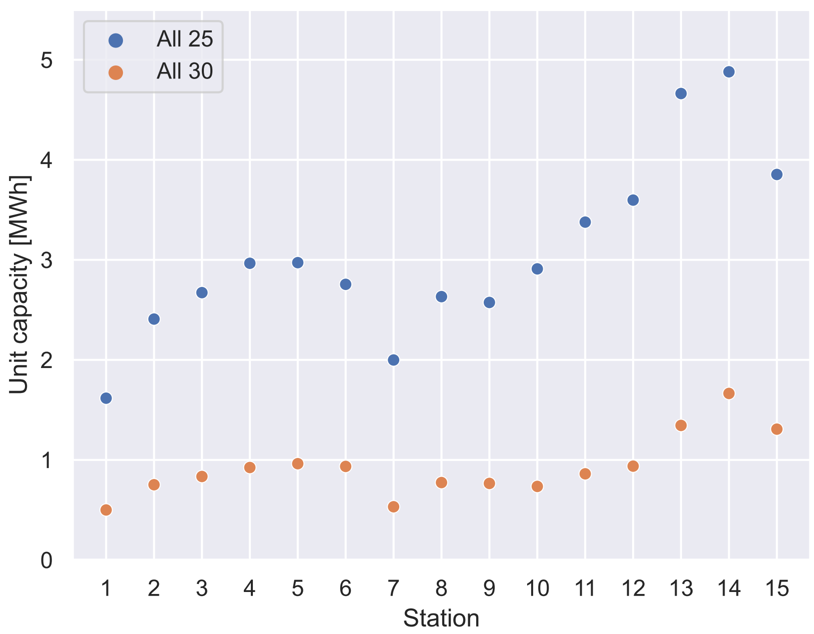


Figure 4.11: ESS capacity need for the different feeding stations when All traffic uses the ERS.

Using the graphs above, the ESS units are generally divided into two variants for each case, except for the lower power limit for All traffic. This case, "All 25", has a larger spread of ESS capacity need, causing it to call for three ESS unit variants. In determining the unit size, each unit's capacity is set to cover at least 90% of the energy demand at each station. The total capacity of the units is made to cover the total capacity needed. The resulting configurations are shown in table 4.3 below.

Table 4.3: Number of ESS units for each case, each unit capacity is expressed in MWh

Case	Power limit [MWh/h]	Unit capacity [MWh] 0.35	0.5	0.9	1.2	1.5	2.7	3.5	4.5	Total capacity [MWh]
Trucks	14	7	8							6.5
	12.5				9	6				19.8
All traffic	30			12		3				15.3
	25						10	3	2	46.5

4.3 Energy Storage Demand for Emergency Backup

The battery capacity needed to sustain critical traffic is determined by the share of traffic which is seen as critical and by how many days this traffic is to be sustained. An explorative approach to this problem is shown in figures 4.12 - 4.13. The power demand used corresponds to a heavily trafficked day (95th percentile) for each case.

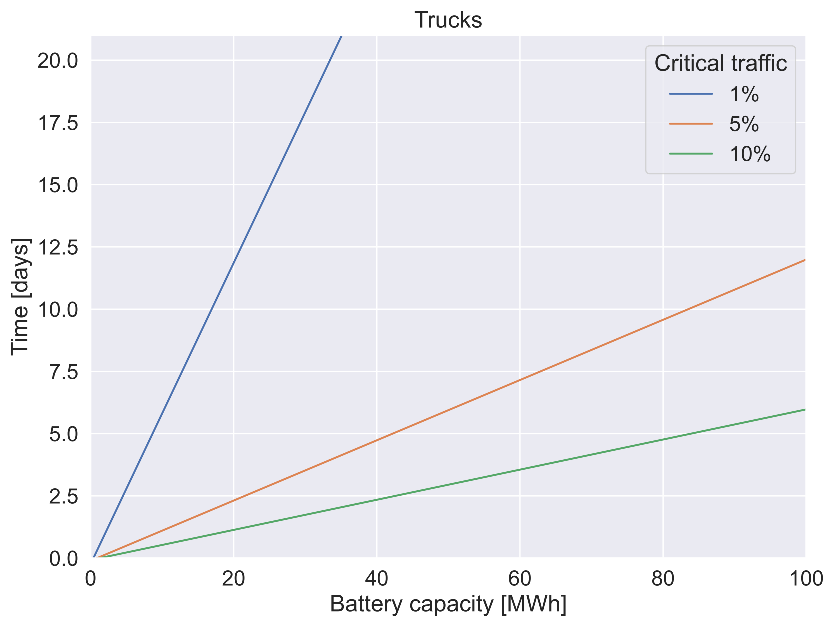


Figure 4.12: Number of days during which some fractions of the truck traffic flow can be sustained with a given ESS capacity.

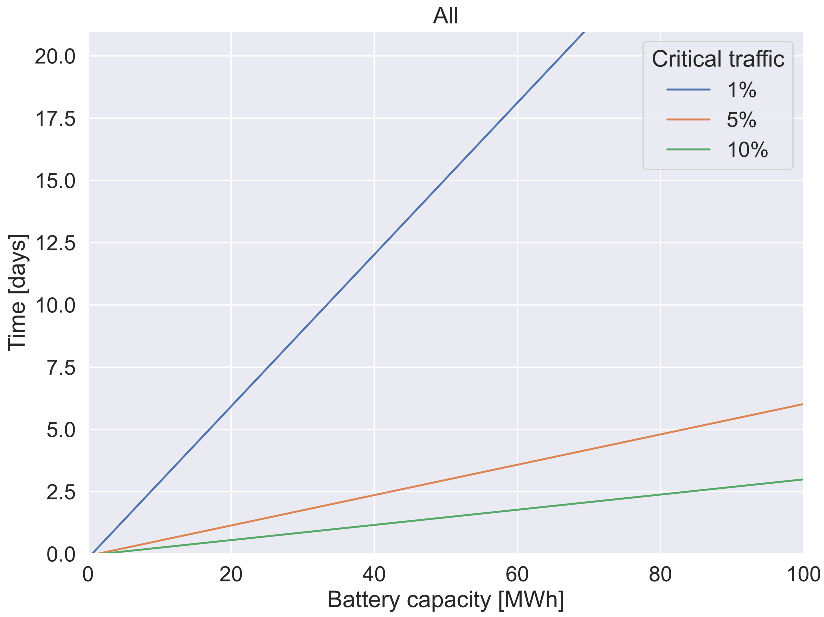


Figure 4.13: Number of days during which some fractions of the flow of All traffic can be sustained with a given ESS capacity.

The graphs show that the battery capacity increases linearly with the time needed to sustain the traffic. In the case Trucks, 12 MWh would sustain 1% of the traffic flow for a week. When critical transport is 10%, over a 100 MWh is needed to sustain a week and about 50 MWh for 72 h. For All traffic, 25 MWh can supply 1% of the traffic one week. If 10% of All traffic needs to be sustained, 100 MWh is just enough for 72h.

4.4 Sensitivity Analysis - Utilization

The graph below shows the aggregated power demand for all feeding stations over a heavily trafficked day (95th percentile) for the different scenarios set up in section 3.5. Each scenario is represented by a different line style and each group of vehicle classes (case) has its own color.

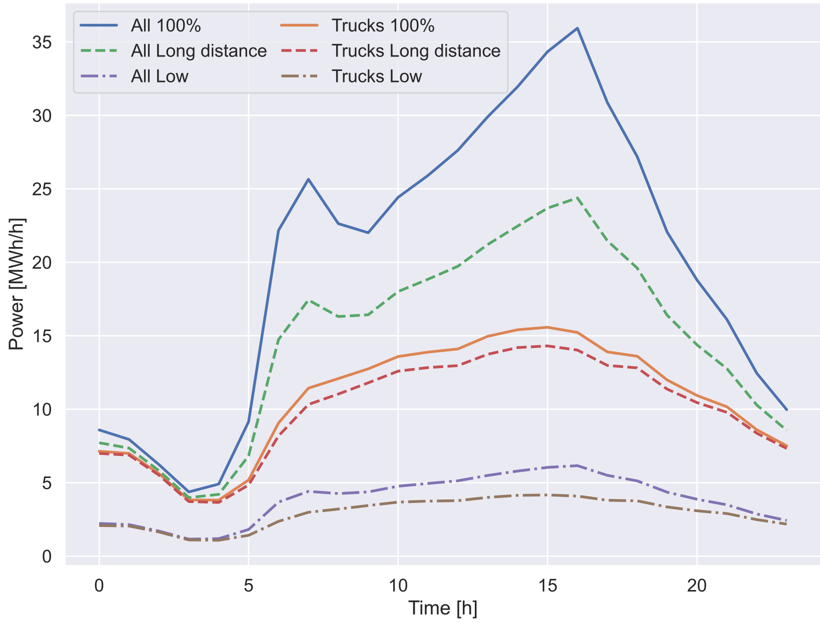


Figure 4.14: Power demand (95th percentile) over the day for All traffic and Trucks for three different scenarios

The need for ESS capacity, as a function of peak power demand, for the different scenarios is shown in figure 4.15 below. Again, each scenario is represented by a different line style and each group of vehicle classes (case) has its own color.

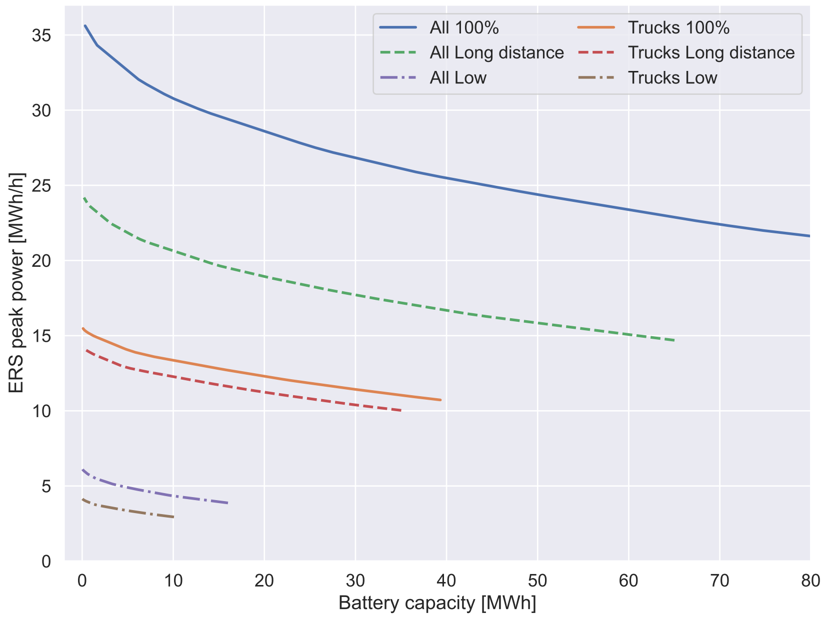


Figure 4.15: ERS peak power vs. battery capacity for All traffic and Trucks for three different scenarios

From both figures, it can be seen that the peak power demand is the largest for 100 % of All traffic by far. Additionally, there is little difference between long-distance trucks and 100 % of Trucks. The Low scenarios in general have a significantly lower power demand than the other scenarios.

5. Discussion

In this chapter, the problem formulations are answered and discussed based on the results shown in chapter 4. The discussion is divided into the main parts of the report, i.e. power demand, ESS for peak shaving and ESS for emergency backup. Finally the importance of determining the utilization of the ERS is discussed and some recommendations for the Project as well as future work is given.

5.1 Power Demand

The total peak power demand of an ERS determines the dimensions of its power supply system. In this report, the power demand is obtained using real-world traffic data and simulated vehicle power consumption. The power demand is calculated with the assumption that all vehicles driving on the road use the ERS (see 5.4 for another perspective). For the Project area, the peak power is 36 MWh/h when both truck types and cars use the ERS and 15.6 MWh/h when only the power demand for the two truck types is considered. For both cases, the peak power demand is in the afternoon, between three and five p.m.

The most evident result from the power demand analysis is that it varies in both time and space. First of all, every day has a different power demand. This can be seen from the traffic flow (section 3.1.1), where the difference between days can be identified by comparing the mean traffic flow with the 95th percentile. The power demand also shows a distinct variation within each day due to the hourly traffic flow fluctuation. At night, the demand is no more than 5 MWh/h, whereas the afternoon peak demand can be three to seven times higher.

Furthermore, the power demand varies greatly as a result of the topography. The highway is fairly flat between Hallsberg and Örebro, with a max slope of 1.54°. However, the vehicle power consumption is still significantly higher when the vehicles drive uphill. The increase is further amplified for heavier vehicles, where the max power consumption is 13 times higher for a truck with trailer compared to a car. The variation of power demand in space mainly affects the distribution between the feeding stations.

Another factor that affects the power demand distribution is the ERS design, i.e where the electric road is placed. The chosen design is one where no ERS is placed on downhill slopes. One instance where this influence can be seen is at feeding station 6, which has significantly lower power demand than its neighboring stations. This is caused by the presence of a gentle slope where the ERS segment, supplied by the station in question, is placed only in one direction. Furthermore, a certain ERS coverage has been assumed, which also affects the power demand distribution between the feeding stations. With more coverage, the power demand becomes more evenly distributed. However, changing the ERS design has little effect on the total power demand.

Finally, power demand also varies with the choice of ERS technology. The maximum distance to the feeding stations and the maximum power/vehicle is different from technology to technology. The higher the maximum distance, the more coverage is possible given fixed feeding station locations. With higher maximum power, less coverage is needed to supply the vehicle.

The distribution between vehicle classes has a significant effect on the power demand. When studying the total power demand for the Project area, the demand is doubled when cars are included. However, the number of cars is substantially more than double the number of trucks. The explanation for this is that the total vehicle power consumption from cars is between 3 and 6 times lower than for trucks. Still, the sheer volume of cars is the reason why this class of vehicles has the highest power demand.

Another difference between the vehicle classes is the character of their power demand. Cars vary more over the day and have a peak that is short and intense. On the other hand, both of the truck types have a more constant traffic flow with a more moderate peak over a longer period. This phenomenon could be seen already in chapter 3.1.1, since the power demand curves have the same character as the traffic flow for each vehicle class.

The share of each vehicle class differs between the road sections. For cars, the traffic increases significantly closer to Örebro. Both truck types have a more even flow over the entire Project area. This could be an indication that most of the trucks drive the whole distance between Örebro and Hallsberg. Cars on the other hand, predominantly use the parts of the highway which are closer to the larger city (Örebro), indicating shorter driving distances.

5.2 Energy Storage for Peak Shaving

In this report, energy storage for grid load alleviation is investigated. There are many ways of implementing an ESS, meaning some assumptions had to be made. Here, it is assumed that the ESS is distributed between the feeding stations and is designed to make sure the power drawn from the grid does not exceed a set power limit. It is also assumed that the ESS does one charge-discharge cycle every 24hrs, where charging occurs during the night. Generally, it is found that ESS can be used when the traffic flow, and subsequently the power demand, varies significantly over the day. This makes the base case from the Project, one truck every 22 seconds, unable to benefit from ESS. However, the real-world-based flow of Trucks may be able to use it. For the case All traffic, where cars are included as ERS users, ESS appears to make the most difference as light-duty vehicles in the Project area have a far more pronounced afternoon peak in traffic flow.

The needed ESS capacity is very different from case to case. For Trucks, 6MWh is needed to reduce peak power by 1.6MWh/h. To reduce it by 3MWh/h, the needed capacity is 20MWh. When cars are included to make the case All traffic, 15MWh and 45MWh are needed to reduce the peak power by 6MW/h and 11MW/h respectively.

The capacity need depends on a number of factors. The main aspects covered in this report are the power demand, power limit, battery lifetime and the percentage of days during which the ERS is required to deliver 100% of its power demand. For the Project, it turned out that the power system will be built purposely for the ERS, meaning there is no firm power limit. However, one may be able to reduce the investment in substations and feeding stations cost by installing an ESS anyway. Additionally, the cost of energy can be reduced by drawing less power from the grid during peak hours.

The character of the power demand also heavily influences the ESS potential, i.e. short and intense peaks gets a higher reduction in peak power for each installed unit of ESS capacity than longer-duration peaks. A capacity ratio is introduced in table 4.2, showing the needed capacity per reduced unit of peak power. Indeed, each unit of capacity results in the most effect when the most intense peaks are targeted. When dimensioning the system to peak shave only the most demanding hours for All traffic (power limit = 30MWh/h), the most benefit can be gained from each unit of ESS capacity. When trying to set the power limit low for Trucks (power limit = 12.5MWh/h), the capacity ratio is more than double that of the previous example. Conclusively, the dimensions of the ESS determine its efficacy.

One way of approaching energy storage for an electric road system is to see ESS as a way to increase available power down the road when usage increases. In the Project description, trucks are the main targeted customer for the ERS. One scenario is that only a fraction of the trucks will use the ERS in the early days of the technology. As more trucks start using the system, ESS could help reduce or remove the need for raising the peak power capacities of the power supply system. Another scenario, maybe even more compelling for ESS implementation, is that cars might start using the ERS after some number of years in operation. As they bring more traffic with a very clear peak during the afternoon, a large part of this peak could be handled with an ESS installation.

5.3 Energy Storage for Emergency Backup

To be able to dimension an ESS for emergency backup, it is of vital importance to know the volume of traffic that can be considered critical. During this study, it has been discovered that this volume is not well known. However, there is an ongoing effort to fill this knowledge gap ever since it recently emerged on the agenda. As a result of this gap, the approach in this study is of an explorative character.

Another important factor when dimensioning a backup system is the amount of time the ESS needs to sustain the critical traffic. This too is an uncertain topic since the duration of energy scarcity can vary greatly depending on the cause. The recommendation from MSB, which states that households to be able to endure one week without external help, is therefore used as a baseline in the further analyses.

The results show that if the critical transport corresponds to 1% of Trucks, a battery of around 12 MWh would sustain the traffic for a week. 25 MWh would suffice to assist 1% of All traffic. These results show that battery sizes for peak shaving could be used to sustain the baseline in this case.

When the critical transport is increased to 5% of the flow, the battery sizes increase drastically. For Trucks, it is possible to power the traffic for a week with a capacity of around 60 MWh. This is three times the size of the largest ESS installation suggested in this report for peak shaving Trucks' power demand. However, it is just about possible to sustain the traffic for 72 hours with the same capacity used for peak shaving. When including 5% in the All traffic case, over a 100 MWh would be required to reach the baseline. 72 hours could be sustained with a capacity of around 50 MWh, close to the capacity needed for peak shaving.

If the critical transport is 10% of the traffic, both cases would require well beyond 100 MWh to reach the baseline. In this case, 50 MWh would be enough to sustain 72 hours for Trucks whereas it would require 100 MWh for All traffic.

The results discussed above are based on an important assumption, that the batteries are fully charged when the power outage occurs. If the ESS has been used for peak shaving, the capacity left for backup in case of an emergency that day is decreased and the critical transport can be sustained for a shorter period of time. As a consequence, the reliability of the emergency backup may be jeopardized. However, as the power demand most days stays below, or only slightly above the power limit, the ESS' State of Charge will stay high and available for emergency backup most of the time. Additionally, the power demand considered for backup corresponds to a heavily trafficked day and exceeds the average conditions by far. Consequently, a combined peak shaving and emergency backup system will require an in-depth risk assessment and decision on the required availability of the backup.

The battery capacity needed for emergency backup varies greatly with the different cases. When the sizes are similar to the need for peak shaving, the incentives might be more evident. However, when the required capacities approach 80-100 MWh, further incentives might be needed to motivate the high investment cost. For instance, a revenue stream from ancillary services could increase the profitability of the investment. Alternatively, such large capacities might be required if infrastructure supporting critical societal functions are required to operate in islanding mode for a set amount of time. Another interesting aspect is the future cost of batteries. An emerging availability of second-life batteries from electric vehicles could make for an ample supply of batteries and lower the investment cost significantly. The development of new battery chemistries suitable for ESS could also result in a lower cost.

5.4 Utilization

In this report, the users of the electric road are assumed to equal all the traffic currently driving on the road. However, this might not be very likely neither in the short nor long term. Short term, only a fraction of the traffic could be expected to use the ERS. To use the system, the vehicles need some form of equipment on board to connect with the ERS. It might take some time for vehicle operators to want to get the equipment and to get their hands on it. Additionally, the Project is limited in size, making it unlikely that neither all traffic nor all trucks using the highway will adapt to this local installation. Therefore, the "Low" scenario is set up in section 4.4. The rough power demand estimate for early adopters results in a peak of about 6MWh/h for All traffic and just above 4MWh/h for Trucks. Using around 5MWh of ESS capacity, these peak loads could be reduced by about 1MWh/h.

Long term, as more vehicles get the necessary equipment and as more ERS is installed, a larger share of the traffic might start using the system. Even so, all vehicles probably don't need to use it. Vehicles driving daily distances within the range of their onboard battery will probably be better off charging slower, but cheaper at home or some depot. Vehicles driving longer distances will likely benefit from, or even need, the ERS as reflected by the "Long-distance" scenario in section 4.4. The scenario estimates a peak power demand of around 24MWh/h for All traffic and about 14MWh/h for Trucks. The effect of an ESS installation becomes significantly different if cars are included or not. For All traffic, around 12MWh is needed to reduce the peak power by 4MWh/h. For Trucks, 12MWh reduces the peak power by around 2MWh/h.

Heavy vehicles are pointed out as the main priority for the ERS Project. Therefore, there is a real risk that the Project, and other ones to come, will focus solely on trucks and other kinds of heavy vehicles. This focus on trucks limits how many can benefit from the ERS and determines the dimensions of the installed power supply. Trucks make up about 40% of traffic's total peak power demand when considering the traffic flow in full and about 60% when considering the (theoretical) long-distance traffic.

The size and character of the power demand determine the dimensions of the ERS's power supply and a potential ESS. Allowing cars to use a system designed for trucks will quickly make the power supply inadequate because of the heavy afternoon peaks. However, as discussed in section 5.2, there is great potential for ESS to help reduce the increase in peak power if or when cars start using the ERS.

5.5 Future Work and Recommendations

The work carried out to produce this report comes with a number of limitations described in section 1.3. In summary, the limitations are: the choice of technology, the use of hourly average power demand and the focus on a specific project. The choice of technology mainly decides whether or not cars are able to use the system, the effect of which has been covered in depth. Maximum power draw is also a technical limitation and mainly affects to what extent power can be delivered for direct usage by the vehicle.

Considering only the hourly average of power demand means that potential power spikes have been neglected. These may have adverse effects on both the ERS and its power supply. Estimating traffic flow on a sub-hour scale would be desirable to examine the extent of such spikes in power demand. An effort to statistically estimate the traffic flow on a minute scale has recently been made by Lewis et al. (2022). Furthermore, an ESS installation could hypothetically make the grid unaffected by short-term power spikes.

It would also be desirable to investigate how the traffic flow considered in this report compares to that of other highways in Sweden and the world, both in character (pattern) and amplitude. If the highway considered here is generally representable, the results from this study might be applicable to most ERS installations for public use.

This study shows that there is little knowledge of how much critical traffic there is on the roads. To be able to design a backup system, knowing this is crucial. Therefore, a study on the flow of critical traffic would be desirable to enable the incorporation of adequate backup systems in ERS installations.

Finally, some recommendations for the Project have been compiled and can be seen below.

- Build feeding stations to deliver 14 MWh/h in total, i.e. the base case as well as demand from trucks driving long distances
- Include the possibility to upgrade the power supply to allow for cars to use the ERS. Consider letting ESS cover part of the additional peak power demand.
- Investigate the possibility to extend the usage of the ESS by providing ancillary services, this could heavily increase the storage system's profitability.
- Over-dimension the battery units with 20% to avoid charging the battery to 100% SoC as well as maintain the ability to peak shave at the targeted power limit during the lifetime of the battery
- Distribute the ESS between the feeding stations and place it on the DC side of the rectifier to use as much of the existing power electronics as possible.
- Perform a detailed cost analysis to determine the profitability of the ESS. Include cost reduction from reduced grid peak load, reduced cost of energy as less power is drawn during high-demand hours and revenue from ancillary services.

6. Conclusion

The aim of this thesis was to determine an ERS's power demand and how an integration of ESS in its power supply can be used for grid load alleviation and backup power. To perform the analysis, the Project "electric road E20 Hallsberg - Örebro" has been studied. Using the traffic flow from the Project area and the vehicle energy consumption, the power demand could be calculated. Subsequently, a number of set power limits and the power demand were used to determine the ESS capacity needed for peak shaving. Finally, an explorative approach was used to find the capacity needed for supplying critical transport with power during times of energy scarcity.

The ERS's power demand shows a variation in both time and space. The most significant variation in time occurs over the day where an afternoon peak can be distinguished. For cars, the peak is more prominent but of shorter duration compared to trucks. Generally, it was found that ESS is used best when the traffic flow, and subsequently the power demand, varies significantly over the day. Consequently, ESS has the most effect when cars are included as users of the ERS studied in this report. Critical transport was found to be a topic under investigation by the Swedish government. If the critical transport corresponds to 1% of the traffic flow, the battery capacities used for peak shaving can sustain the critical transport for 2-12 days. Alternately, 10% of the traffic flow be sustained for no more than 1-2 days with the capacities used for peak shaving.

Finally, it is unlikely that all of the traffic between Örebro and Hallsberg will use the ERS in its early days. Eventually, all vehicles driving daily distances surpassing the range of their battery distances could become customers. Therefore, ESS for peak shaving could provide a solution to meet all or a part of the increase in power demand coming from a higher adoption of the ERS.

7. References

Alsaidan, Ibrahim, Amin Khodaei, and Wenzhong Gao (2018). “A Comprehensive Battery Energy Storage Optimal Sizing Model for Microgrid Applications”. In: *IEEE Transactions on Power Systems* 33.4, pp. 3968–3980. DOI: 10.1109/TPWRS.2017.2769639.

Barać, Bojana et al. (2022). “Modelling and Evaluating Capability of Battery Storage Systems to Provide Extreme Event Services to the DSO: Case Study of Croatia”. In: *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*, pp. 34–39. DOI: 10.1109/MELECON53508.2022.9842864.

Bramerdorfer, Gerd and Edmund Marth (2021). “Computationally Efficient System-Level Evaluation of Battery Electric Vehicles”. In: *2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, pp. 311–317. DOI: 10.1109/WEMDCD51469.2021.9425674.

Domingues-Olavarría, Gabriel et al. (2018). “Electric Roads: Analyzing the Societal Cost of Electrifying All Danish Road Transport”. In: *World Electric Vehicle Journal* 9.1. ISSN: 2032-6653. DOI: 10.3390/wevj9010009.

Electreon (2022). *Our Technology*. URL: https://electreon.com/technology/faqs (visited on 12/21/2022).

Electric Vehicle Database (2022). *Tesla Model 3 Standard Range Plus*. URL: https://ev-database.org/car/1485/Tesla-Model-3-Standard-Range-Plus (visited on 10/21/2022).

Elonroad (2022). *Technology & Application Overview*. URL: https://elonroad.com/our-solution/ (visited on 11/21/2022).

Elways (2022). *Solution*. URL: https://elways.se/elways/solution/ (visited on 11/21/2022).

Energiföretagen (2021). *Så fungerar elnätet*. Permission to use and modify from customer service, phone call, 2022-12-20. URL: https://www.energiforetagen.se/globalassets/medlemsportalen-oppet/regional-verksamhet/gemensamma-dokument/sa-funkar-elnatet.pdf (visited on 12/20/2022).

Fiori, Chiara, Kyoungho Ahn, and Hesham A. Rakha (2016). “Power-based electric vehicle energy consumption model: Model development and validation”. In: *Applied Energy* 168, pp. 257–268. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2016.01.097.

Fyhr, Pontus et al. (2017). “Electric roads: Reducing the societal cost of automotive electrification”. In: *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, pp. 773–778. DOI: 10.1109/ITEC.2017.7993367.

GWL (2015). *LiFePO4 cycle-life based on depth of discharfe (convervative estimation)*. URL: https://shop.gwl.eu/blog/LiFePO4/FAQ-LiFePO4-cycle-life-based-on-DOD.html (visited on 12/13/2022).

Hammarström, Ulf et al. (2012). "Coastdown measurement with 60-tonne truck and trailer: estimation of transmission, rolling and air resistance." In: *VTI notat*. URL: https://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,uid&db=edsswe&AN=edsswe.oai.DiVA.org.vti.584&site=eds-live&scope=site.

Holmberg, Kenneth et al. (2014). "Global energy consumption due to friction in trucks and buses". In: *Tribology International* 78, pp. 94–114. ISSN: 0301-679X. DOI: 10.1016/j.triboint.2014.05.004.

Jansen, Gerard, Zahir Dehouche, and Harry Corrigan (2021). "Cost-effective sizing of a hybrid Regenerative Hydrogen Fuel Cell energy storage system for remote & off-grid telecom towers". In: *International Journal of Hydrogen Energy* 46.35, pp. 18153–18166. ISSN: 0360-3199. DOI: 10.1016/j.ijhydene.2021.02.205.

Kelly, Jarod C. et al. (2015). "Sustainability, Resiliency, and Grid Stability of the Coupled Electricity and Transportation Infrastructures: Case for an Integrated Analysis". In: *Journal of Infrastructure Systems* 21.4. DOI: 10.1061/(ASCE)IS.1943-555X.0000251.

Khizbullin, Robert, Boris Chuvykin, and Ronald Kipngeno (2022). "Research on the Effect of the Depth of Discharge on the Service Life of Rechargeable Batteries for Electric Vehicles". In: *2022 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, pp. 504–509. DOI: 10.1109/ICIEAM54945.2022.9787251.

Lantmäteriet (2022). *Geotorget beställning*. URL: https://geotorget.lantmateriet.se/bestallning/produkter (visited on 09/10/2022).

Lewis, Donovin D. et al. (2022). "Sizing Considerations for EV Dynamic Wireless Charging Systems with Integrated Energy Storage". In: *2022 IEEE Transportation Electrification Conference & Expo (ITEC)*, pp. 611–616. DOI: 10.1109/ITEC53557.2022.9813893.

Mallon, Kevin R., Francis Assadian, and Bo Fu (2017). "Analysis of On-Board Photovoltaics for a Battery Electric Bus and Their Impact on Battery Lifespan". In: *Energies* 10.7. ISSN: 1996-1073. DOI: 10.3390/en10070943.

Márquez-Fernández, Francisco J. et al. (2022). "Assessment of Future EV Charging Infrastructure Scenarios for Long-Distance Transport in Sweden". In: *IEEE Transactions on Transportation Electrification* 8.1, pp. 615–626. DOI: 10.1109/TTE.2021.3065144.

MSB (2022a). *Hemberedskap*. URL: https://www.msb.se/sv/rad-till-privatpersoner/forbered-dig-for-kris/hemberedskap---preppa-for-en-vecka/ (visited on 12/20/2022).

– (2022b). *Planeringsstöd för bortfall av energi*. Tech. rep. MSB2084.

Natanaelsson, Kenneth et al. (Feb. 2021). *Analysera förutsättningar och planera för utbyggnad av elvägar*. Tech. rep. TRV 2020/113 361. Trafikverket.

Preusser, Kiraseya, Wen Wei, and Anke Schmeink (2022). "Modelling Second-Life Batteries as the Energy Storage System for EV Charging Stations". In: *2022 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, pp. 199–205. DOI: 10.1109/SmartGridComm52983.2022.9961054.

Regeringen (Dec. 2020). *Inriktning för en sammanhängande planering för totalförsvaret*. Tech. rep.

– (June 2022). *Fastställelse av nationell trafikslagsövergripande plan för transportinfrastrukturen för perioden 2022–2033, beslut om byggstarter 2022–2024, beslut om förberedelse för byggstarter*

2025–2027 samt fastställelse av definitiva ekonomiska ramar för trafikslagsövergripande länsplaner för regional transportinfrastruktur för perioden 2022–2033 (rskr. 2020/21:409). Tech. rep. I2022/01294.

Rouholamini, Mahdi et al. (2022). "A Review of Modeling, Management, and Applications of Grid-Connected Li-Ion Battery Storage Systems". In: *IEEE Transactions on Smart Grid* 13.6, pp. 4505–4524. DOI: 10.1109/TSG.2022.3188598.

Serrao, Lorenzo et al. (2009). "A Novel Model-Based Algorithm for Battery Prognosis". In: *IFAC Proceedings Volumes* 42.8. 7th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, pp. 923–928. ISSN: 1474-6670. DOI: 10.3182/20090630-4-ES-2003.00152.

Shi, Jie and H. Oliver Gao (2022). "Efficient energy management of wireless charging roads with energy storage for coupled transportation–power systems". In: *Applied Energy* 323. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2022.119619.

Singh, Somendra Pratap et al. (2022). "Optimal management of electric hotel loads in mild hybrid heavy duty truck". In: *Applied Energy* 326. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2022.119982.

Strbac, Goran, Ioannis Konstantelos, and Predrag Djapic (Jan. 2016). *Analysis of Integrated Energy Storage Contribution to Security of Supply*. Tech. rep. Imperial College London.

Svenska Kraftnät (2022a). *Elområden*. URL: https://www.svk.se/om-kraftsystemet/om-elmarknaden/elomraden/ (visited on 12/12/2022).

– (2022b). *Sveriges elnät*. URL: https://www.svk.se/om-kraftsystemet/oversikt-av-kraftsystemet/sveriges-elnat/ (visited on 12/12/2022).

Swedish University of Agricultural Sciences (2022). *Digital maps and geodata*. URL: https://maps.slu.se/ (visited on 09/23/2022).

Szott, Marcin et al. (2021). "Battery Energy Storage System for Emergency Supply and Improved Reliability of Power Networks". In: *Energies* 14.3. ISSN: 1996-1073. DOI: 10.3390/en14030720.

Trafikverket (2018). *Nationell plan för transportsystemet 2018-2029 – Sammanställning och läshänvisning*. Tech. rep. TRV 2018/63947.

– (2021). *Transportsektorns samverkan inför samhällsstörningar (TP SAMS)*. URL: https://bransch.trafikverket.se/for-dig-i-branschen/samarbete-med-branschen/transportsektorns-samverkan-infor-samhallsstorningar-tp-sams/ (visited on 12/20/2022).

– (2022). *Fordonsflöden och hastigheter*. URL: https://bransch.trafikverket.se/tjanster/trafiktjanster/Vagtrafik--och-hastighetsdata/fordonsfloden-och-hastigheter/ (visited on 10/10/2022).

Uddin, Moslem et al. (2018). "A review on peak load shaving strategies". In: *Renewable and Sustainable Energy Reviews* 82, pp. 3323–3332. ISSN: 1364-0321. DOI: 10.1016/j.rser.2017.10.056.

Volvo AB (2022a). *Volvo FE Electric*. URL: https://www.volvotrucks.com/en-en/trucks/trucks/volvo-fe/volvo-fe-electric.html (visited on 09/26/2022).

– (2022b). *Volvo FH Electric*. URL: https://www.volvotrucks.com/en-en/trucks/trucks/volvo-fh/volvo-fh-electric.html (visited on 09/26/2022).

WSP Sverige AB (2021). *E20 Hallsberg – Örebro, Elväg, Brändåsen – Adolfsberg*. Tech. rep. TRV 2020/16183. Trafikverket.

Zhang, Yongzhi, Xiaobo Qu, and Lang Tong (2022). "Optimal Eco-Driving Control of Autonomous and Electric Trucks in Adaptation to Highway Topography: Energy Minimization and Battery Life Extension”. In: *IEEE Transactions on Transportation Electrification* 8.2, pp. 2149–2163. DOI: 10.1109/TTE.2022.3147214.