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Battery Electric Multiple Unit trains on Kinnekullebanan

A study regarding charging infrastructure on non-electrified railway lines

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Abstract

This thesis investigates replacing diesel trains with battery trains on routes where fully electrifying entire lines is not possible due to protections by law or that it is economically unjustifiable. Having battery trains operating at such distances can contribute to sustainable railway traveling. Calculations of energy consumption for market-available Battery Electric Multiple Unit (BEMU) trains and simulations for charging infrastructure at various points along the railway line are conducted, considering charging time, train characteristics, and local grid suitability.

Data was collected for BEMU trains to simulate their energy consumption over Kinnekullebanan using Python, accounting for a worst-case scenario with winter conditions in Sweden and nearly end of life battery packs. Additionally, charging infrastructure calculations were performed in Python using designated points along the route for energy requirement analysis. The studied infrastructure methods were extending the overhead line onto the railway line, constructing an overhead line island for charging while traveling, and stationary charging at the platform.

The results showed that all infrastructure methods were feasible for Kinnekullebanan. Stationary charging at the stations in the two larger cities offered the best grid capability and the longest charging times. A single stationary charging station in a rural area mid-route, had weaker grid support and comparable charging times to the two-station setup. Overhead lines in both scenarios resulted in minimal or no charging time at the stations.

BEMU trains with larger installed battery capacities had a lower impact on the local grid, as they retained more energy upon arriving at the station. The proposed charging infrastructure could be used by all trains, although the installed battery capacity varied depending on the location of the charging stations.

In conclusion, battery capacity is crucial for compatibility with potential charging infrastructure locations and methods. The characteristics of BEMU trains must be investigated alongside the charging infrastructure to ensure the trains can reach their end stations successfully.

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Populärvetenskaplig sammanfattning

Större delen av Sveriges järnvägsnät är idag elektrifierat, men det finns sträckor där elektrifiering antingen är ekonomiskt oförsvarbar eller rentav omöjlig på grund av att områden är skyddade som naturreservat enligt lag. På dessa sträckor behövs tåg som kan köra utan direkt anslutning till kontaktledningsnätet som förser tåg med elektricitet. För att göra transportsektorn mer hållbar kan dieseltåg på dessa sträckor behöva bytas ut. Genom att istället använda förnybar el kan systemets utsläpp av växthusgaser minska med upp till 90 %.

Under resor på Kinnekullebanan, som ibland kallas Sveriges vackraste järnvägssträcka, passeras Kinnekulle, ett stort naturreservat längs Vänerns kust. På denna sträcka är det omöjligt att helt elektrifiera banan, både på grund av naturreservatet och eftersom resandet längs Kinnekullebanan har mindre volymer än andra sträckor i Sverige, vilket gör investeringen i kontaktledningar alltför kostsam. För att skapa ett hållbart resande och gynna miljön behöver dagens dieseltåg som färdas längs banan bytas ut mot eldrivna tåg. Eftersom elektrifiering inte är möjlig, kan batteritåg vara en lösning.

Examensarbetet undersöker hur hållbart resande kan införas på sträckor som Kinnekullebanan. Nya tekniker som möjliggör drift av batteritåg har studerats och olika metoder har jämförts för att förstå hur tågen och infrastrukturen behöver anpassas till varandra. För att kunna jämföra reseupplevelsen har laddningstider för tågen studerats, och hur detta påverkar resans totala längd.

Slutsatserna ger en inblick i hur batteritåg kan bidra till att fasa ut fossila bränslen i Sveriges järnvägssystem och hur bytet till batteritåg skulle påverka trafiken och det omkringliggande samhället. Genom att studera resultaten från examensarbetet kan riktlinjer för hur liknande sträckor kan implementera batteritåg undersökas, vilket i framtiden kan skapa en mer hållbar järnväg i Sverige.

Med stationär laddning kan tågen behöva stanna längre på stationerna, vilket kan förlänga resan för de som reser längs hela banan. Samtidigt sänks investeringskostnaderna, vilket möjliggör investeringar på andra områden i samhället. Genom att använda laddningsöar, där kontaktledningar installeras på kortare sträckor, oftast cirka tio kilometer, kan tågen ladda batteriet medan de kör. Detta kan kräva stora investeringskostnader men gör samtidigt att resan blir nästan lika kort som med de dieseltåg som idag trafikerar Kinnekullebanan.

Resultaten visar att flera alternativ för laddinfrastruktur kan möjliggöra batteridrift längs Kinnekullebanan. Lättare tåg krävde mindre energi, vilket gör att laddningstiderna kunde vara mycket korta då väldigt lite energi behövde laddas i batterierna för vidare resande. Detta för alla typer av infrastrukturslösningar. Men när antalet resenärer ökar, behöver tågen vara större vilket drar mer energi och resulterar i längre laddningstider. Med större batterier minskar laddningstiderna samtidigt som investeringskostnaderna ökar. I slutändan kan man överväga om det är mer hållbart att ha långa restider under kalla vinterdagar, som undersökts i ett värsta fall-scenario, eller om en högre investeringskostnad skapar de bästa förutsättningarna för järnvägssträckan.

Att ladda i kommunerna gav en liten påverkan på hur mycket el som används från det lokala nätet. Ökningen var särskilt liten i de scenarier där antalet platser för laddning ökade, vilket innebär att påverkan på kommunens totala behov av el var mindre. Högspänningsladdning kräver att elnätet behöver vara bra byggt med transformatorer som klarar de höga laster som laddningsstationerna för batteritåg skulle innebära. På Kinnekullbanan var dessa platser relativt få då tågen passerar både mindre städer och små orter vilket begränsade antalet lämpliga platser för stationär laddinfrastruktur.

Energiförbrukningen för typiska batteritåg på dagens marknad har beräknats genom simuleringar i Python, för att identifiera områden på banan som är mer energikrävande, såsom platser där tågen behöver stanna oftare eller där det finns fler backar. Dessutom krävs mycket energi för att driva ventilation och värme på tågen, vilket är särskilt viktigt i ett samhälle där det kan bli mycket kallt på vintern. När energiförbrukningen kan beräknas mer exakt, blir laddinfrastrukturen och tågen bättre anpassade gentemot varandra och de korresponderande laddningstiderna mer verklighetstrogna. Detta möjliggör skapandet av realistiska scenarier för framtida batteridrift.

Exekutiv sammanfattning

Studien undersöker möjligheten att ersätta dieseltåg med batteritåg på sträckor där elektrifiering antingen inte är möjlig på grund av skyddade områden enligt lag eller där elektrifiering med kontaktledning är ekonomiskt oförsvarbar. Genom att studera olika tågmodeller på marknaden och genomföra simuleringar av deras energibehov i ett värsta fall scenario, där batteriet nästan nått slutet av dess livstid under en kall vinterdag, har behovet av att bygga ut laddinfrastrukturen för att möjliggöra batteridrift utretts. Tre huvudfrågor har undersökts: Vilken typ av tåg krävs för att trafikera sträckan, hur påverkar valet av tåg den nödvändiga infrastrukturen och hur påverkar valet av infrastruktur det lokala elnätet?

Resultaten visar att fyra olika infrastrukturalternativ är möjliga: att förlänga den befintliga kontaktledningen in på banan från två riktningar, att bygga en laddningsö för att möjliggöra laddning medan tågen färdas längs banan, samt att använda stationära laddstationer vid plattformarna. Stationär laddning var tidskrävande och för tåg med kapacitet för 120 personer behövdes cirka 18 minuter laddning, samtidigt som investeringskostnaden för denna infrastruktur var lägst. Att använda delelektrifiering kan möjliggöra att den installerade batterikapaciteten i tågen kan vara mindre, samtidigt som den tidigare tidtabellen hålls någorlunda intakt. Investeringskostnaderna för ett sådant system var dock väsentligt högre än för stationär laddning. Genom att jämföra hur dessa förändringar i laddinfrastrukturen påverkar tågens behov av batterikapacitet, tidtabell och investeringskostnad, kan avvägningar göras för att avgöra vilket alternativ som fungerar bäst för den undersökta sträckan och om batteritåg skulle kunna användas effektivt.

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Tilda Andersson
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Dictionary

AC	Alternating Current.
Axle load	The train's total weight distributed over the number of axles. The axle load is the weight supported by one axle.
BEMU	Battery Electric Multiple Unit.
Bimodal	A train that can operate using two distinct power sources.
BTMS	Battery Thermal Management System.
C-DAS	Connected Driver Advisory System.
Catenary	The system of overhead wires used to supply electric power to trains.
CC	Constant Current.
CV	Constant Voltage.
DC	Direct Current.
DOD	Depth of Discharge, the extent to which a battery is discharged compared to its maximum capacity.
EoL	End of Life, when the battery reaches 80% of its initial capacity.
GHG	Greenhouse Gases.
HVAC	Heating, Ventilation & Air Conditioning.
OHL	Overhead Line.
OHLE	Overhead Line Extension.
OHLI	Overhead Line Island.
Pantograph	Current collector on a train that draws electricity while in contact with the catenary.
RCC	Rail Charging Converter.
SOC	State of Charge.
Stationary charger	A charging method that requires the train to be stationary at the station.

Abbreviations

v	Speed of the train
v_{ref}	A reference speed of 100 km/h
ρ	Air density
g	Gravity
a	Acceleration
m	Total mass of the train
L	Total Length of the train
A_f	Front area of the train
C_d	Air drag coefficient
F_R	Rolling resistance Force
F_D	Aerodynamic drag resistance Force
F_G	Grade resistance Force
F_C	Curve resistance Force
F_a	Acceleration Force
F_{Tr}	Total resistance Force
C_R	Rolling resistance coefficient
θ	Railway slope
k	Circular curve resistance coefficient
R	Radius of a circular curve
P	Power
E	Energy
η	Efficiency
d	Distance
V	Voltage
I	Current
t	Time
SOC_{max}	Maximum State of Charge
SOC_{min}	Minimum State of Charge
$C_{battery}$	Installed battery capacity

Contents

1 Introduction

The Swedish railway network is, to a large extent, electrified, but there are exceptions where fully electrifying entire lines is not reasonable from an economic perspective. One of these examples is Kinnekullebanan, a 121 km railway line without a catenary where diesel trains today are in use. A catenary system is a component of the Swedish railway power supply system, consisting of overhead wires that provide electrical power to rail vehicles. Västtrafik, whose trains travel on Kinnekullebanan, is investigating an investment in battery trains that can be powered both from the catenary and from batteries mounted on the trains. On non-electrified lines, the battery will power the train, making it possible to travel without a catenary.

Battery trains can travel in different ranges depending on the characteristics of the trains. The trains must be built with a larger battery capacity than what is realistic, due to the conditions of the railway line and the ambient temperature, for traveling the full distance of Kinnekullebanan. Trains with high battery capacities are often longer and heavier and they have a higher seating capacity, which would not be reasonable for Kinnekullebanan. At Kinnekullebanan, the amount of travelers differs throughout the day, with around 80 people in the morning and evening hours and around 20-30 people during low-demand hours.

The speed and slope of the railway line are significant factors that affect the maximum distance the trains can cover. Aerodynamic drag resistance increases at higher speeds, leading to a higher energy demand. Additionally, shorter trains may be used during off-peak hours, potentially comprising only a single car. This limitation further restricts the distance these trains can travel before requiring a recharge, depending on the installed battery capacity. For shorter trains the installed battery capacity is typically smaller, however they also require less energy for traveling. To utilize battery trains on Kinnekullebanan, investigations regarding charging infrastructure as a complement to the battery trains are required. Various recharging methods are available, including extending the existing catenary system to available traveling without recharging on the non-electrified distance, implementing overhead line islands to available charging while traveling on a shorter segment of constructed catenary, and utilizing stationary charging stations at the platform.

To reduce the emissions from the Swedish railway network, it is important to consider vehicles powered by sustainable fuels. Compared to diesel trains, a battery train generates 90% less greenhouse gases (GHG) if green electricity is used (NOW GmbH, 2023). Replacing diesel trains with battery trains for traveling on Kinnekullebanan could be significantly more sustainable.

In this thesis, the energy consumption for Battery Electric Multiple Unit trains is calculated based on the properties of the battery trains available on today's market. Different charging infrastructure possibilities are researched and placed at suitable locations based on the calculated energy consumption. The infrastructure must be positioned so that the train can, with a realistic battery capacity, manage to travel to the end station in each direction. Ensuring the new infrastructure is compatible with the local electricity grid is crucial, as high loads can cause disturbances or necessitate further development to the local grid.

1.1 Purpose and & Research questions

This thesis aims to investigate how battery trains can replace diesel trains on railway lines without catenary in Sweden, lowering the emissions from railway traveling. The calculations are based on the trains characteristics, such as the capacity of the batteries mounted on the trains, the distance battery trains can travel with the conditions of Kinnekullebanan, and how different charging methods will affect factors such as delay times and required energy from the electricity grid. The research questions of this thesis are as follows:

- What infrastructure is required for battery trains to travel along the railway line?
- How can the characteristics of battery trains be adapted to suit feasible infrastructure development along the railway line?
- How does the existing local electricity grid affect the feasibility of implementing charging infrastructure for battery trains?

1.2 Research boundaries

This study focus on battery trains at the non-electrified distance in Kinnekullebanan. Therefore, the electrified distance that is part of the total route is left outside of the system. The battery trains can use energy from the catenary, meaning no energy from the battery needs to be used while traveling on the electrified distances. When the battery train starts its route on the non-electrified railway line, the batteries are expected to be charged to their maximum state within the state of charge limits.

The simulations of Kinnekullebanan have been conducted for a worst-case scenario. The solutions are made so that the trains can travel in colder temperatures where the battery capacity has degraded to the point before reaching its end of life within the system. Simulations regarding when the trains start traveling on the railway line are not included in this thesis.

2 Background

In this section, the background of Kinnekullebanan, along with constraints and related projects, will be presented.

2.1 Kinnekullebanan

Kinnekullebanan is a 121 km non-electrified railway line. As of 2025, the trains travel from Gothenburg to Håkantorp in the presence of a catenary, where the train then branches off and travels on Kinnekullebanan to Gårdsjö without the presence of a catenary. After reaching Gårdsjö, the train travels to Örebro, again in the presence of a catenary.

To cover the non-electrified sections, Bombardier Itino trains are currently in use. These trains are powered by diesel-hydraulic and have a maximum speed of 140 km/h. They partially operate on Västra stambanan, a high-speed railway line in Sweden, and this setup currently creates a bottleneck for faster trains (Järnvägar.nu, 2020). In the future, the trains are planned to travel a shorter route where Battery Electric Multiple Unit (BEMU) trains are being investigated to replace the current diesel trains[1]. The future route that the trains plan to operate on is depicted in Figure 1 (For distances between stations, see Appendix Table A1). Marked with a black line is the non-electrified distance studied in the thesis, and the yellow lines indicates that the trains can already travel in the presence of a catenary.

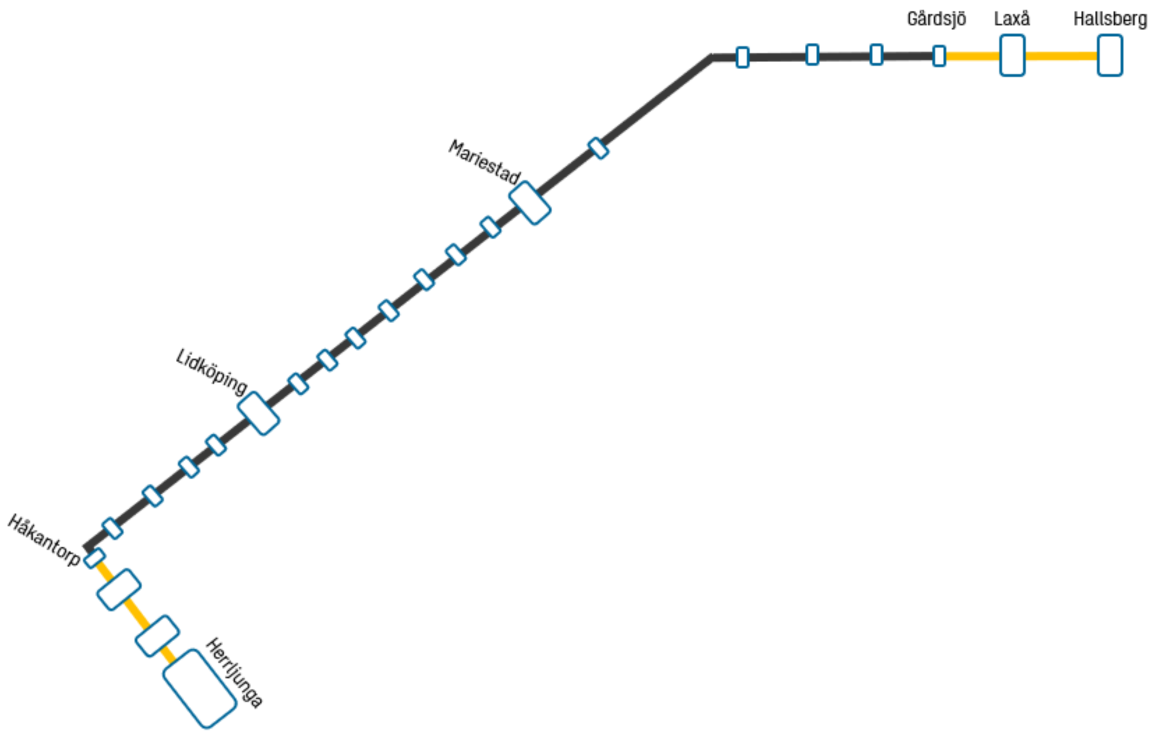

Figure 1: Expected future route that the battery trains will travel via Kinnekullebanan. Marked in black is the non-electrified distance studied in the thesis, and the yellow line indicates presence of a catenary.

[1]Pontus Gunnäs, Business Manager & Robin Griffiths, Business Development Manager, Västtrafik

BEMU trains make it possible to travel on non-electrified distances. However, the distance of Kinnekullebanan is longer than the potential range the BEMU trains currently on the market can travel. Therefore, it will be necessary to invest in charging infrastructure to allow the use of BEMU trains on Kinnekullebanan. The trains on today's market can sometimes travel 120 km in optimal conditions (Alstom, 2020). However, factors such as the slope of the rail, circular curves, ambient temperature, and the operating speed of the train are factors that, for Kinnekullebanan, decreases the possible traveling range. Currently, no BEMU trains are approved for traveling on the Swedish railway, and the trains must properly function in colder climates.

2.1.1 Electrification Plans and Operational Constraints

Extending the catenary has been researched for Kinnekullebanan. One investigated stage was electrifying the distance between Håkantorp and Lidköping (see Figure 1). In 2013, the cost of upgrading the standard of the railway as well as electrifying this distance was estimated to cost 377.5 MSEK (Trafikverket, 2014). Electrifying the distance, would today cost around 500 MSEK[1].

Extending the catenary over longer distances beyond Lidköping can be challenging since a large area, Kinnekulle, surrounding the railway line is designated a nature reserve (Naturvårdsverket, 2024). The protections in this area make it more difficult to construct new infrastructure. However, if additional electrification becomes necessary, the distances beyond Gårdsjö are not designated as a nature reserve (Naturvårdsverket, 2024), making it a viable alternative.

The limitations of Kinnekullebanan will restrict the selection of trains suitable for operating at non-electrified distances. On Kinnekullebanan, the maximum axle load must be less or equal to 22.5 tons. On the railway line, the maximum speed is 100 km/h. However, the speed can be lower on specific segments, such as near the route's urban areas. The speed profile on Kinnekullebanan that constrains the possible speed can be seen in Figure 2. Additionally, the railway is limited to a single track, which necessitates that the two trains pass each other at designated passing points or passing stations (Järnvägar.nu, 2020).

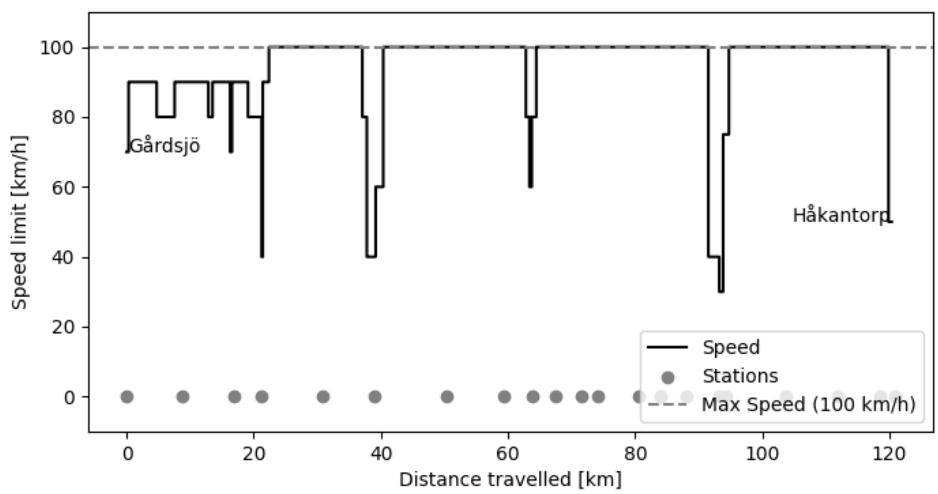

Figure 2: Speed variations for trains traveling on Kinnekullebanan.

[1] Robin Griffiths, Business Development Manager, Västtrafik, 28-03-2025.

2.1.2 Power Supply Constraints

The train traveling on Kinnekullebanan passes through cities as well as rural areas. In two larger cities and a smaller locality (Hällekis) in between, 132 kV regional transmission lines are drawn into the areas. These transmission lines can be seen on Open Infrastructure Map (OpenInfraMap, n.d.). The passing cities also have local energy production from combustion power plants where the produced vapor is used for electricity production (Lidköping Energi, n.d.; VänerEnergi, 2024). The presence of transmission lines in these cities indicates a well-developed regional grid that can have sufficient capacity for high-power infrastructure.

In the rural areas, there is no direct connection to high-voltage infrastructure. The power lines near the rural areas are marked as lower voltage than 10 kV (OpenInfraMap, n.d.). This may indicate limited electrical capacity, making these areas less suitable for high-power charging infrastructure. In rural areas, the electricity is mainly from pole-mounted substations. In Sweden, 61.5% of pole-mounted substations have power rating lower than 400 kVA for 20 kV, and for 10 kV, most substations have a transmission effect greater than 400 kVA (K.-J. Andersson, 2008).

2.2 Related projects

The Master Thesis *Efficiency of regional travel* by Cherine Colliander (2020) presents research on energy consumption for electric trains, among other vehicles, in Sweden. This thesis aims to optimize traveling for different factors, such as lowering the impact of traveling on the environment and traveling time. To investigate the environmental effects of trains, the energy consumption was thoroughly calculated by utilizing different models for resistive forces contributing to the energy consumption by the train. In addition to energy consumption, losses in the system are taken into account to provide an accurate value of the energy requirement from the system. The result was a comparison between different vehicles, where the train and the electric car had the lowest emissions per passenger. All vehicles' energy consumption per passenger was in the same order of magnitude.

3 Theory

The following paragraph explores the theory behind battery trains and the associated charging infrastructure.

3.1 Battery Electric Multiple Units

An Battery Electric Multiple Unit (BEMU) train is a bimodal train that can operate from two power sources. The BEMU train differs from other bimodal trains since both power sources utilize electricity. On the electrified distance, the catenary can power the train's movement and charge the installed battery packs (Mwambeleko & Kulworawanichpong, 2017). In Figure 3, the flow of energy from the catenary is marked with a yellow line. From the catenary, the current is transmitted through an DC-AC converter to provide the traction motor with alternating current (AC).

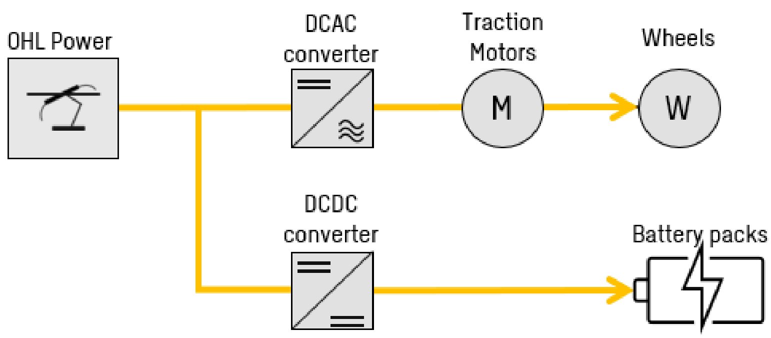

Figure 3: Train collecting power from the catenary via its pantograph to power the electric traction motor and recharge the battery packs.

Energy stored in the battery packs will power the train on non-electrified railway lines, meaning the batteries will discharge as the train travels (Mwambeleko & Kulworawanichpong, 2017). The current flow from the battery packs to the traction motor is marked with a yellow line in Figure 4. The battery's direct current (DC) is transmitted to the DC-AC converter, which supplies AC to the traction motor.

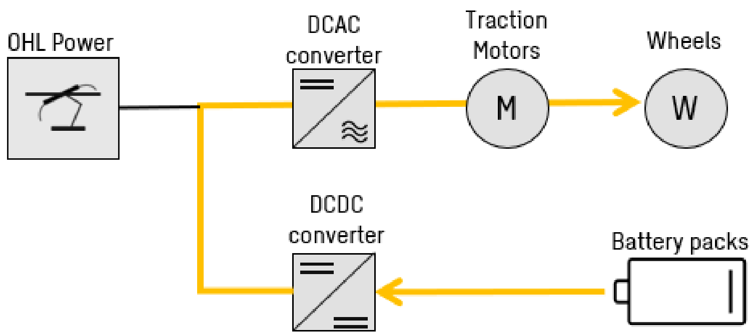

Figure 4: Stored energy in the battery packs providing the traction motor with AC.

BEMU trains can operate at varying speeds depending on the power source supplying energy. When powered directly from the catenary, they can typically reach speeds of 160 km/h (Končar, n.d.), surpassing the current maximum speed of 140 km/h for the Bombardier Itino trains operating on Kinnekullebanan. In battery mode, most BEMU trains can reach speeds up to 120 km/h (Končar, n.d.).

Unlike traditional trains, BEMU trains do not feature a separate locomotive; they are integrated into a multiple unit. Compared to the existing Bombardier Itino trains with a diesel engine, BEMU trains utilize an electric traction motor, which provides higher efficiency and reduced maintenance costs. Furthermore, diesel engines are less efficient for commuter rail services due to the frequent stops and shorter distances between them (Mwambeleko & Kulworawanichpong, 2017).

Several BEMU trains are currently available on the market. However, none of the existing trains are specifically customized for the Swedish climate, making them unsuitable for low temperatures in Sweden. The trains must, therefore, be customized to operate in the Swedish climate[1]. Characteristics of four BEMU trains available on today's market, which have been researched for this report, are summarized in Table 1 (sources: Alstom, n.d.; Stadler, n.d.; Stadler, 2024; Siemens Mobility, n.d.-b; Siemens Mobility, n.d.-a).

Table 1: Characteristics of BEMU trains on the market as of 2025.

Train	Axle load [ton]	Tare weight [ton]	Length [m, cars]	Seating capacity [seats, cars]	$V_{max}^{electric}$ [km/h]	$V_{max}^{battery}$ [km/h]
Alstom Coradia Conti-nental BEMU	22.5	114	57, 3	140–160	160	160
Stadler Flirt Akku	<20	–	65, 3; 81, 4	128, 1	160	120
Stadler RS ZERO	<18	–	27, 1; 53, 2	59, 1; 148, 2	120	120
Siemens Mireo Plus B	<20	96	47, 2	120	160	120

According to Alstom[1], a manufacturer of BEMU trains, the capacity of the batteries mounted on their trains could vary based on the request from the customer. One of these batteries can store 50 kWh of energy. The more battery packs, the longer the distance the train can travel. To maintain a long lifetime of the battery packs, it is recommended to charge the battery to 85% of its maximum capacity and not to discharge it under 20%.

[1] Johan Näreby, Tender Leader & Peter Mellberg, Alstom, interview 18-02-2025.

The expected lifespan of the batteries ranges from 7 to 12 years, significantly shorter than the train's overall lifespan of approximately 30 years. Furthermore, measures are being taken to extend the longevity of the trains beyond the initial 30 years. Since batteries are expensive to replace, handling them properly and adhering to the recommended guidelines for battery maintenance and usage is essential.

The end of life (EoL) for a battery is most commonly when the battery capacity reaches below 80% of its initial capacity, meaning if the battery initially could provide energy for one hour, it can, at the point before reaching EoL, give energy to the vehicle for less than 0.8 hours. Once the battery packs reach their EoL, they can transition into a second life phase, functioning as stationary storage devices. By recycling the batteries, it is possible to recover 70% of the components, including 95% of rare elements (NOW GmbH, 2023).

3.1.1 HVAC & BTMS requirements

A heating, ventilation and air conditioning (HVAC) system is necessary to provide a comfortable indoor climate for passengers during traveling. Due to requirements on today's trains, the energy consumption from the HVAC system itself can be 30% of the total energy consumption (Barone et al., 2020). The estimated, required power from the HVAC system can be determined using the following equation:

$$P_{HVAC} = n(-1.2T + 21.2)[kW] \tag{1}$$

Where n is the number of cars in the multiple unit and T is the ambient temperature in °C (Streuling et al., 2021).

A Battery Thermal Management System (BTMS) is a component commonly used in electric vehicles. Its primary function is to maintain safe operating temperatures, which helps ensure safe performance, prolonging the battery's lifespan and enhancing its operating efficiency. If the temperature within the battery tends to fluctuate, it can significantly affect the battery performance. The temperature within the battery is controlled through cooling and heating methods. These methods can, for example, be fans or other devices, making it possible to control the heat during the charge and discharge of the battery. By utilizing a BTMS in the battery train, the overall system efficiency can be improved (MokoEnergy, 2024).

3.2 Driving modes

A train travels with different driving modes: acceleration, constant speed, coasting, and braking mode. The various modes will consume different amounts of energy, and modes, such as braking and coasting modes, make it possible to regenerate some of the used energy. Acceleration mode is where the train increases it speed from the initial speed to the speed limitation of the railway line (Mwambeleko & Kulworawanichpong, 2017).

During constant speed, the resistive forces will affect the energy consumption. The provided energy must equal the force slowing down the train to maintain a constant speed. Coasting mode is where no acceleration or braking occurs, and the electric traction motor will provide close to zero energy. During coasting mode, the train will slow down due to the resistive forces from the railway conditions as well as from aerodynamic drag. During braking mode, the train will decrease its current speed to the desired speed (Mwambeleko

& Kulworawanichpong, 2017), often at a station where new passengers enter the train. The train's kinetic energy, together with its deceleration during braking, can be used to estimate the energy required to reduce its speed. The kinetic energy for a train is described as follows:

$$E_{brake} = \frac{1}{2}mv^2 \tag{2}$$

Where m is the total mass of the occupied train and v is the running speed of the train

The traction motor that drives the train can be switched to operate as an electric generator during braking and coasting mode. When the traction motors operate as an electric generator, regeneration of the provided energy for braking can be made to some extent (E. Andersson & Lukaszewics, 2006). This process is called regenerative braking. While the train is running in the presence of catenary, the regenerated energy can be provided back to the electricity grid, while in battery mode, it can be used to store energy in the battery for further use. Around 60 to 70% of the energy provided to de-accelerate the train can be regenerated as electricity (E. Andersson & Lukaszewics, 2006).

In Sweden, train drivers use a digital system called the Connected Driver Advisory System (C-DAS) to maintain punctuality in the timetable. The digital system is created to simplify communication between the traffic controller and the train driver. The system continuously updates the driver about the planned journey throughout the actual traveling. With C-DAS, the driver can see the planned route, which helps them maintain speed and optimize their driving pattern (Trafikverket, 2023b).

3.3 Catenary systems and Train power supply

A catenary system consists of overhead wiring designed to power trains and other rail vehicles. Its primary purpose is to enable the flow of electricity, supported by multiple components working together within the system (MacImpulse, 2024).

Key components in the catenary system include the contact wire, which is in direct contact with the pantograph, a device mounted on the top of the train to collect current. The messenger wire supports the contact wire, helping to maintain height and tension. Droppers are vertical wires that connect the contact and messenger wires, assisting in maintaining the correct height and tension of the contact wire. Insulators are used to prevent the flow of current into the supporting structure. Cantilever structures are poles that support the overhead catenary system, holding the wires at the required height above the tracks (MacImpulse, 2024). In Figure 5, the catenary system with the mentioned components is depicted.

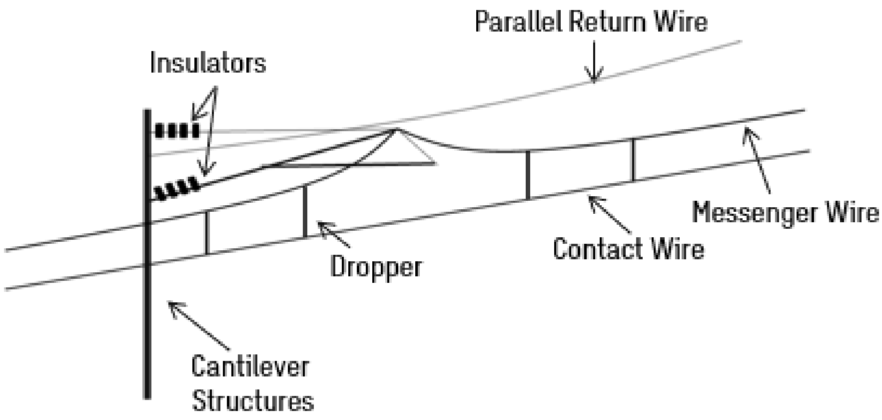

Figure 5: Main components in the catenary system.

Banverket mainly purchases green electricity from power companies, which is transferred at 132 kV in a three-phase system with a frequency of 50 Hz. This electricity is then converted to 16.7 Hz by frequency converters placed along the railway. These converters, which include rotating machines and static inverters equipped with power electronics, facilitate the conversion of electric power (Trafikverket, 2006).

Once this electricity is available, BEMU trains typically charge via their pantographs. The pantographs contact shoe makes contact with the overhead line (OHL), allowing the train to collect current from the wire to provide electric power to the traction motors and recharge the battery (CivEngTech, 2025).

Due to losses, the energy provided by the Swedish supply system will be higher than the energy charged. The losses occur in the converter stations and from the catenary. The efficiencies have a value of 91.5% and 96%, respectively, resulting in an 88% efficiency for supply to modern electric trains (E. Andersson & Lukaszewics, 2006).

3.3.1 Charging via catenary

Instead of electrifying entire railway lines, various recharging options can be implemented. One such option is the use of overhead line extensions (OHLE). This involves adding an extension to the existing OHL, which can typically utilize the existing substation for power supply (Dschung & Ludolf, 2021). The OHL operates at a voltage of 15 kV and a frequency of 16.7 Hz. If the additional power demand for the extended OHL exceeds certain thresholds, it would necessitate an increase in the capacity of the existing substation (Dschung & Ludolf, 2021). While the train is stationary, the maximum current on the pantograph is limited to 300 A to prevent overheating at the contact point. Delivering a high current is possible since the railway power supply system is dimensioned for such demand. When the train is in motion, the charging rate varies, and at speeds over 40 km/h, it can charge the battery as needed[1]. The contact point between the catenary and the pantograph shifts as the train moves, preventing overheating.

Another alternative is to implement overhead line islands (OHLI), which consist of shorter segments of OHL, typically around 10 km in length, where a new substation can be

[1] Johan Näreby, Tender Leader & Peter Mellberg, Alstom, interview 18-02-2025.

necessary to provide energy. If the frequency of the OHL matches the local grid frequency of 50 Hz, significant cost savings can be achieved (Dschung & Ludolf, 2021). Recharging a 1 MW battery via OHL would take approximately 7-10 minutes (International Railway Journal, 2023). Figure 6 illustrates the concept of an OHLI. The yellow lines represent electrified sections, while the black lines indicate non-electrified sections. The gray circles denote stations located along the electrified segments.

Figure 6: Overhead Line Island enables the charging of trains while they are traveling along electrified sections of the track.

While the train runs on the partially electrified line, it can be directly powered by the catenary and recharge the battery while traveling. The train's pantograph is pushed against to the OHL, collecting current which, when stationary at the station, mainly recharges the battery (NOW GmbH, 2023).

From an economic perspective, constructing an OHLI is more expensive per kilometer than an OHLE. In addition to the actual catenary, costs are influenced by establishment areas, work paths, installation of the OHL, and connections to the existing line network. The cost for the OHL itself is around 6,000 SEK per kilometer. Extending the catenary for ten kilometers would cost around 62.5 MSEK (€5.60 million), creating an OHLI for ten kilometers would cost around 86.5 MSEK (€6.14 million). Since the overhead line network in Sweden is a separate power system, it cannot be powered from a separate or different system. The cost of a separate power supply, such as if a new power station needs to be built, is not included in the cost for the construction of an OHLI[1].

3.3.2 Stationary charging

Another option is to utilize stationary charging, allowing the train to recharge at a station while passengers board and disembark the train. The recharging time will vary depending on the existing energy level in the battery. Figure 7 illustrates the concept of stationary charging. The gray circles represent the stations, while the yellow line that runs through the station indicates the potential for charging at that location. At the station, OHL is constructed, and its length cannot exceed the platform.

Figure 7: Stationary charging at the platform.

One example of a stationary charging station is the Voltap charging station, which utilizes

[1]Christian Albinsson, Calculator, Sweco, 03-03-2025.

local grid conditions to charge trains via their pantograph at a voltage of 15 kV and a frequency of 50 Hz. The recommended charging current for this station is 80 A. The smaller variant of the Voltap charging station has a power output of 1.2 MW, enabling it to transfer energy at a rate of 20 kWh per minute (Furrer+Frey, 2024). The energy transfer from the stationary charging station is slower than charging via the OHL, meaning charging the train with a stationary charger at the platform requires more time. The current is lower for the stationary charger as it depends on transformers and is designed for continuous operation.

Some advantages of the Voltap charging station are that it is significantly cheaper compared to the electrification of the railway line, it doesn't require power electronics, and it is compact (Furrer+Frey, 2024). In an email correspondence with Philipp Gerber from Furrey & Frey, a broad estimation of the costs for purchasing the charging station was approximately €1.5 million[1].

Another option for stationary charging is the Rail Charging Converter (RCC) from Siemens Mobility. The specifications for this charger are similar to those of the Voltap charger. Charging a BEMU train with the RCC would take approximately 20 minutes (Siemens Mobility, 2025). In the UK, the RCC has been purchased for £1.7 million (Railway Gazette, 2023).

A complete charging cycle of a battery most commonly consists of two stages. The first stage involves charging the battery from the lower SOC value to around 80% using constant current (CC). The second stage uses constant voltage (CV) to charge the battery to its full capacity (Sarda et al., 2024). Utilizing CV enables a greater portion of the battery capacity to be charged without exceeding the voltage limit. The current exponentially decreases during CV charging, leading to slower charging of the battery packs (Volta Foundation, 2022).

3.4 Common railway issues

In Sweden's railway power supply system, the primary issue in 2024 was the catenary being brought down by falling trees. Damage to the train can lead to derailments, resulting in the catenary being torn down and causing damage to both the track and the vehicle (Trafikverket, 2024).

Power outages or the destruction of the catenary can occur for various reasons, including heavy snow, birds causing short circuits, thunderstorms, or problems with the train's pantograph. Failures in components within the electrical system, such as supporting cables, can also contribute to these issues (Trafikverket, 2023a). In 2019, 25% of all delays were attributed to infrastructure-related problems, with 3% of these arising from catenary systems and electrical faults. The most common infrastructure issue was signal errors (Tågexperterna, 2023).

In winter conditions, the catenary can become heavier due to ice accumulation. The increased weight from the ice build-up can lead to a deterioration in the contact between the pantograph and the overhead line. Poor contact may cause an arc flash, a rapid release of energy caused by an electric fault, which is a significant reason why the catenary can be damaged during winter (Nielsen & Nilsson, 2013).

[1] Philipp Gerber, Team leader E-mobility, Furrey & Frey, 21-02-2025.

3.5 Model; energy requirement for traveling

When a train is in motion, it is subjected to several resistive forces that work against its movement. The total force slowing down the train can be calculated using Equation 3.

$$F_{Tr} = F_R + F_D + F_G + F_C + F_a \tag{3}$$

Where F_R is the rolling resistance, F_D is the resistance from aerodynamic drag, F_G is the grade resistance, F_C is the curve resistance, and F_a is the acceleration resistance force (Lindgreen & Sorenson, 2015).

The rolling resistance refers to the frictional force exerted by the rail, which will slow down the train. It is influenced by the rolling resistance constant C_R, the mass of the train, as well as the force of gravity (Lindgreen & Sorenson, 2015). The rolling resistance can be calculated using Equation 4.

$$F_R = C_R m g \tag{4}$$

The rolling resistance constant C_R is given by three constants (Lindgreen & Sorenson, 2015).

$$C_R = C_0 + C_1 \frac{v}{v_0} + C_2 (\frac{v}{v_0})^2 \tag{5}$$

In this context, v_0 represents a reference speed of 100 km/h, and the variable v represents the train's current speed. The constant C_1 and C_2 represent values for a passenger train, which are set as 0.25 and 0.50‰, respectively. C_0 is a calculated constant (Lindgreen & Sorenson, 2015) and for a BEMU train that can be estimated to a value of 3.5‰. This value is typical for trains with four axles and can be used to simulate multiple-unit trains, which resemble a locomotive more closely than a passenger car.

The aerodynamic drag force is determined by the train's traveling speed, with the train's frontal area being a significant factor contributing to high or low energy consumption. The force from aerodynamic drag is calculated using the following equation:

$$F_D = \frac{1}{2} C_d A_f \rho v^2 \tag{6}$$

$$C_d A_f = (8.3 + 0.057L)[m^2] \tag{7}$$

Where A_f is the area in the direction normal to the velocity and C_d corresponds to the air drag coefficient, and L is the length of the train (E. Andersson & Lukaszewics, 2006). ρ is the air density (Lindgreen & Sorenson, 2015). The parameters refers to a passenger train.

The grade resistance, F_G, is the force that will slow down the train or lower the energy requirement due to passing slopes on the railway line (Lindgreen & Sorenson, 2015). The grade resistance can be calculated with the following equation:

$$F_G = mgsin\theta \tag{8}$$

$$\theta = tan^{-1}(\frac{slope}{1000}) \tag{9}$$

Where the *slope* can be replaced by the track gradient, given in ‰. In addition to gradients, traveling through curved sections of the railway line also affects the energy demand. This is due to curve resistance, F_C, which arises when the train negotiates a bend in the track. It is given by:

$$F_C = k\frac{m}{R - 55} \tag{10}$$

Where k is a constant value of $6.5kg/m$ and R is the radius of the circular curve. Equation 10 can be used for a radius greater or equal to 300 m (Colliander, 2020).

The force required to accelerate the vehicle increases its energy consumption and adds to the total resistive forces that must be overcome.

$$F_a = ma \tag{11}$$

Here, a denotes the applied acceleration. Adding the resistive forces from Equations 4 to 11 and integrating the expression multiplied by the distance over each segment corresponds to the energy requirement. The full expression for the energy needed by the traveling train is presented in Equation 12.

$$E = \int_{x1}^{x2} Fdx = \int_{x1}^{x2} (m(C_R g + gsin\theta + a) + \frac{1}{2}\rho C_d A_f v^2 + k\frac{m}{R - 55})dx \tag{12}$$

4 Method

The following paragraph outlines the methodology employed to derive the results for the research questions. This paragraph will review the collected data and how the simulation parameters were chosen. Equation 12 for resistive forces, along with Equation 1 for HVAC and the formulation for BTMS requirements, were implemented in Python to compute the energy consumption for various train types.

4.1 Data

The data collection for this thesis was conducted in collaboration with Sweco. Information regarding the characteristics of battery trains was gathered through a literature study and from interviews with various manufacturers of battery trains and charging stations. Specific parameters relevant to the case were utilized to simulate traveling trains on Kinnekullebanan. The data collected included:

1. **Passing stations:** Stations and their corresponding placement along the railway line was collected from Trafikverkets NJDB website (Trafikverket, 2025) to be able to calculate the energy consumption for braking and accelerating before and after the stations.

2. **Weight:** The weight of the trains varies based on peak and off-peak hours, as shorter trains are likely to be used during low-demand hours, decreasing the weight. A comparison of available trains on the market was conducted to accurately simulate trains of different sizes to establish an average weight relative to passenger capacity. This data was obtained through a literature study and from interviews with manufacturers of BEMU trains.

3. **Length:** The length of the train is a critical factor as it directly impacts aerodynamic drag. A longer train will experience increased aerodynamic drag resistance, increasing energy consumption. This data was obtained from the literature study.

4. **Maximum speed:** The maximum speed along the railway line varies during segments and depending on the traveling direction. To analyze these variations, data from a RailSys file was collected.

5. **Slope:** Information about the slopes of the Kinnekullebanan was gathered from a RailSys file. The railway's slope was recorded alongside the corresponding distance for each segment. The slope will be reversed in the opposite direction, as what is downhill on the standard route will be uphill on the return journey.

6. **Circular curves:** Circular curves on the Kinnekullebanan were sourced from Trafikverkets NJDB website (Trafikverket, 2025). The radius and the length of the curve were collected, and a measurement of the location of the curve on the railway line was conducted.

7. **HVAC & BTMS:** Typical power consumption for HVAC and BTMS was gathered and applied in the simulations.

8. **Charging parameters**: Current, voltage, frequency, and power were collected through a literature study to calculate the charging parameters, such as the charged energy per minute for different charging infrastructure methods.

4.2 Train characteristics

Initially, a literature study of BEMU trains on today's market was conducted. In addition to the literature study, interviews with manufacturers of BEMU trains were made to collect further information regarding the characteristics of their trains. The train characteristics were then studied to choose the simulation parameters, such as the length of the train and its occupied weight relative to the seating capacity. Table 1 presents the collected data used to choose the simulation parameters. The collected data showed that all four trains could be used on Kinnekullebanan since the axle load of the trains did not exceed the maximum value of 22.5 tons.

4.2.1 Simulation parameters

Three different train sizes were selected based on the train characteristics obtained from the literature study. These sizes were chosen to simulate trains that meet varying passenger demand. Table 2 presents the three train sizes simulation parameters. The HVAC requirement was calculated with Equation 1, where the ambient temperature was set to -20°C corresponding to winter conditions.

Table 2: Train parameters for simulation.

Parameter	Occupied weight [tons]	Length [m]	HVAC [kW]
Long train	129	57	113
Middle-length train	108	47	90.4
Short train	60	27	45.2

The lowest temperature recorded around Kinnekullebanan was -32°C in Skara in 1918. In contrast, the average temperature for January 2020 was -12.4°C (SMHI, 2024). To ensure that the train could operate effectively in winter conditions, a temperature of -20°C was chosen as a reasonable benchmark, as it allows for a buffer above the extreme lows while still accounting for typical winter temperature.

The system was simulated with some constant parameters. The constant simulation parameters are presented in Table 3. The simulation parameters were used in Equation 12 and in the charging infrastructure calculations.

Table 3: Constant simulation parameters.

Parameter	Value
ρ	1.395 kg/m^3
k	6.5
g	9.82 m/s^2
η	90%
SOC_{max}	85%
SOC_{min}	20%
v_{ref}	100 km/h
C_0	3.5‰
C_1	0.25‰
C_2	0.50‰

The air density, ρ, was set to 1.395 kg/m^3, corresponding to the air density at -20°C (Engineers Edge, n.d.). This value was selected because aerodynamic drag resistance at high speeds had the greatest impact on the train. During winter, the air density is higher, leading to an increase in this resistive force.

For charging, the parameters differed between stationary and OHL charging. Table 4 presents the simulation parameters used for the charging calculations.

Table 4: Constant charging parameters for simulations of charging methods.

Charging method	Voltage [kV]	Current [A]	Power [MW]	Energy transfer [kWh/min]
Stationary	15	80	1.2	20
OHL	15	300	4.5	75

4.3 Energy requirement calculations

The energy requirement for the three train sizes was calculated using a Python script based on a RailSys file. The total distance of approximately 121 km was divided into segments with varying parameters in the resulting Excel file gathered from RailSys. The gathered train parameters, presented in Table 2 and 3, were incorporated into Equation 12 in the code.

Using Python loops, the dataset was iterated to calculate the energy requirement for each segment. Figure 8 illustrates an example of energy consumption influenced by variations in railway parameters. The top graph displays the energy required to overcome slopes, while the bottom graph highlights the exponential increase in energy consumption caused by aerodynamic drag. The example plot for slope is simulated for a speed of 100 km/h, and the plot for aerodynamic drag is simulated for a slope of 0 ‰.

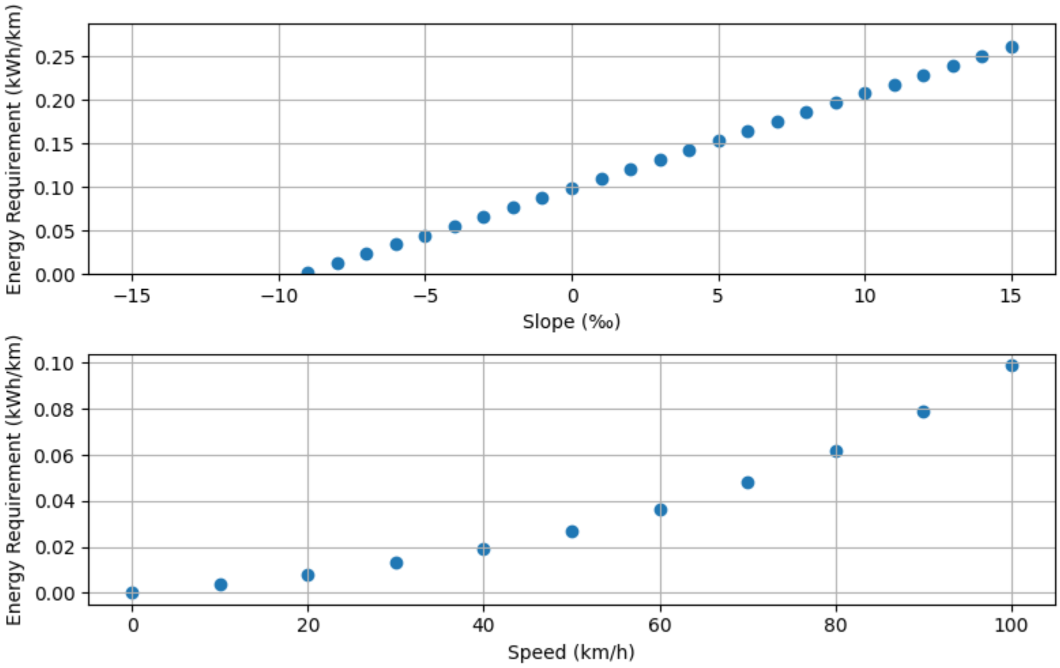

Figure 8: Energy consumption due to grade resistance and aerodynamic drag.

The energy consumption from grade resistance was close to zero before passing -10 ‰. For slopes with energy consumption smaller than 0, braking and coasting were applied not to exceed the speed limitation.

In the energy calculation, the driving pattern was taken into regard. All four described driving patterns in Section 3.2 were used in the calculation. When the following segment had a higher speed than the current speed, acceleration was applied using Equation 11. When the speed was lower in the following segment, coasting was applied instead; for larger differences in speed, braking was used to complement coasting mode to lower the speed to the limitation quicker, for example, before reaching a station. When braking the train, Equation 2 was implemented with Equation 11 to find how long the train had to be in braking mode to lower the kinetic energy to the kinetic energy for the speed limitation of the next segment.

For braking and coasting, regeneration was applied. A conservative estimate of 60%, the lower value from the literature study (see Section 3.2), was used for regeneration. The lower value was chosen to ensure the train could reach the charging location without overestimating the possibility of regenerating energy to store in the battery. Regeneration was only applied to the energy used to drive the train since the energy consumption from the other components cannot be regenerated.

HVAC and BTMS were incorporated into the code during the total traveling time of the train. The two system were important since it ensured a comfortable indoor climate and safe operating temperatures for the batteries to optimize the performance. The power calculated for HVAC presented in Table 2 was included in the Python script as a function of time over the total distance.

The sizes of the batteries were used to determine the energy requirement for the BTMS system. A reference battery was used to create an equation for the BTMS system, where the battery had an installed capacity of 1,000 kWh and a BTMS system of 50 kW[1]. The BTMS for other battery capacities was then calculated using the following formula:

$$P_{BTMS} = \frac{50}{1000} C_{battery} = 0.05 C_{battery} [kW] \tag{13}$$

The losses from the battery supplying energy to the traction motor were considered by dividing the energy consumption by an efficiency of 90%:

$$E_{tot} = \frac{E_{req}}{\eta} [kWh] \tag{14}$$

All energy calculations were made separately and were then converted to a common x-axis using the *union1d* function in Python. The function made it possible to summarize all separate energy calculations over the total distance.

4.4 Charging calculations and locations

Different charging methods were simulated to study possible charging solutions for a traveling train. In addition to the different cases, the number of stations varied to study how this would affect the delay. The battery capacity was chosen so that the train would reach the charging station at the battery EoL. The SOC limits used under EoL conditions can be seen in figure 9. Of the remaining 80% of the initial battery capacity, 65% of the energy could be used by the train without exceeding any SOC limits.

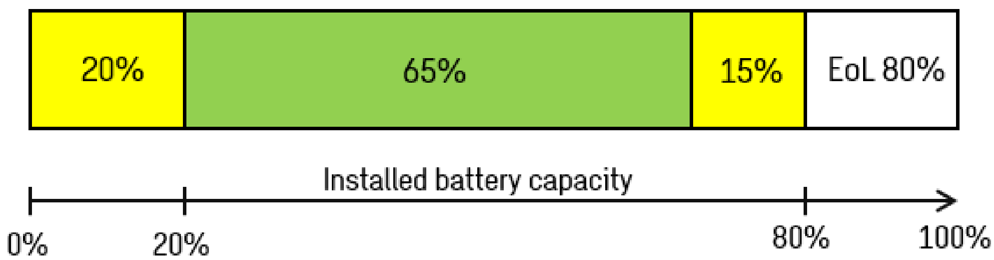

Figure 9: Installed battery capacity compared to the potential energy usage in simulations where the battery is nearing its EoL.

4.4.1 Stationary Charging

The studied locations for stationary charging along with the start and end stations can be seen in Figure 10.

[1] Johan Näreby, Tender Leader & Peter Mellberg, Alstom, interview 18-02-2025

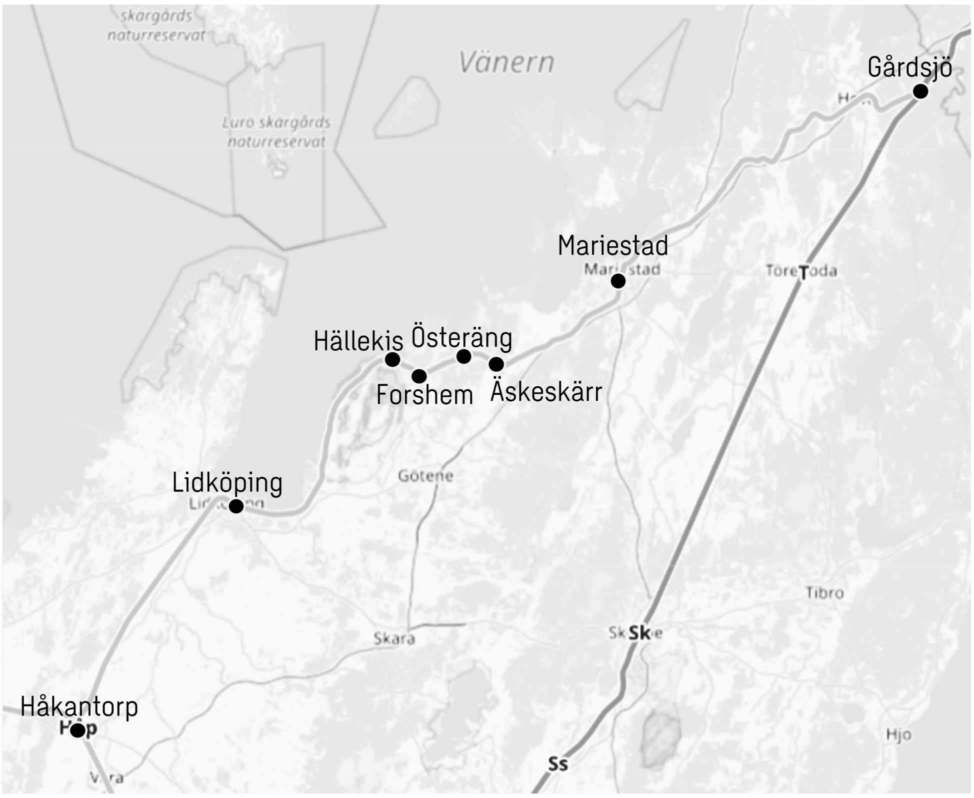

Figure 10: Charging locations investigated, including start and end stations along the route. Based on an extract from OpenRailwayMap, with added markings. Screenshot taken on June 17, 2025. Own elaboration.

The first scenario involved stationary charging at two stations. Two stations were significant because they would allow shorter charging times at each station where charging is possible. In this case, passenger flow was considered, as a higher volume of passengers likely leads to longer stop durations. Therefore, the two largest cities, Mariestad and Lidköping, were chosen, as the flow of passengers is expected to be higher.

Similar projects were researched to identify the characteristics of stationary charging stations. One common charging method identified was the Voltap charger, which exhibited characteristics similar to those of other stationary charging stations for trains. The simulation aimed to calculate the energy requirement needed to reach each station by utilizing the *interpolate* function in Python. This allowed for the determination of the energy consumption from the battery prior to arriving at the charging location from either direction, providing insights into the remaining battery energy upon reaching the station.

$$E_{battery} = E_{capacity}0.52 - E_{d1}[kWh] \tag{15}$$

$E_{capacity}$ is the installed battery capacity, and 0.52 is the stored energy that can be used from the battery, taking SOC limits and battery EoL percentage into regard. E_{d1} is the energy requirement to travel from the starting point to the first station.

By subtracting remaining energy in the battery from the energy requirement for the next segment and dividing the result with the energy input from the stationary charger (20 kWh/min), the charging time at each station was determined.

$$t_{charge} = \frac{E_{d2} - E_{battery}}{E_c}[min] \tag{16}$$

The battery sizes were tested for the three train sizes to ensure enough energy was stored to cover the full distance while being charged at the designated locations.

Figure 11 illustrates a traveling train charging at two platforms. The energy charged at each station corresponds to the energy needed to cover the subsequent distance.

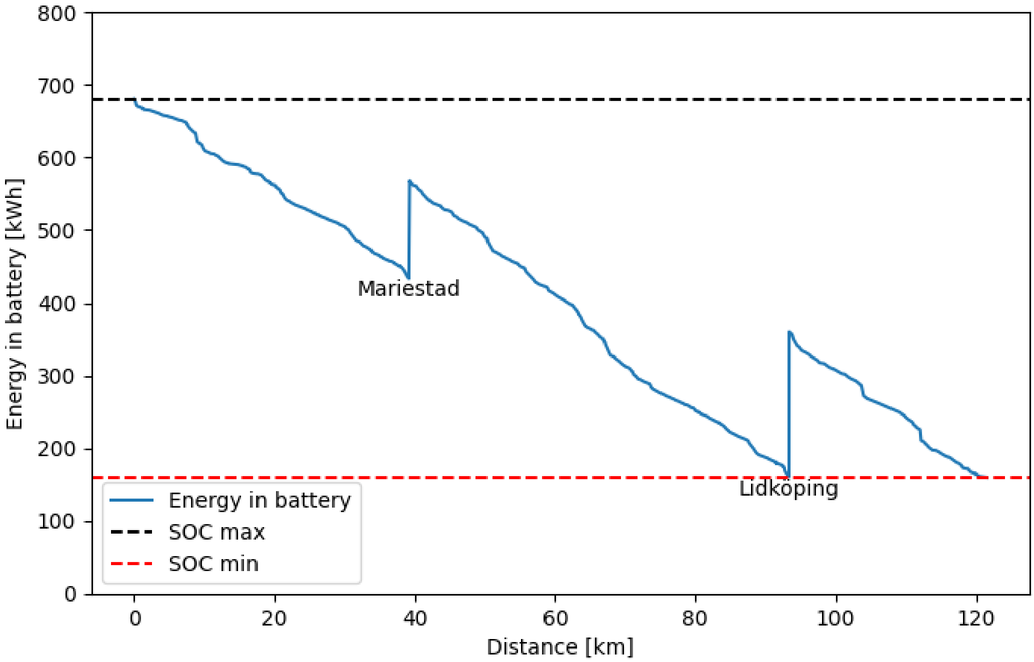

Figure 11: Traveling train stopping in Mariestad and Lidköping to charge its battery.

The second scenario for stationary charging simulated a single charging station to reduce the overall costs of installing charging infrastructure. Suitable locations were identified by plotting energy calculations alongside battery sizes to determine effective charging stations along the route. It was found that all battery trains with realistic battery capacities could reach a station positioned in the middle of the distance. Therefore, four stations located at the midpoint (see Figure 10) were tested to analyze the necessary increases in battery size compared to the two charging locations scenario. To calculate the charging time at the placed stations, Equation 16 was used, where E_{d2} was the distance between the charging location and the end station in both directions.

4.4.2 Overhead Line Extension

The length of the railway that needs to be electrified for trains to travel along Kinnekullebanan without charging was determined using a method similar to that for identifying charging station locations. The maximum distance the trains could travel without charging was calculated by simulating energy requirements and battery capacities for three train sizes. Since battery trains cannot recharge on non-electrified sections, the required electrification extension is the maximum distance the train can travel without recharging subtracted from the total distance.

$$d_{electrified} = d - d_{reached}[km] \tag{17}$$

d is the full length of Kinnekullebanan, and $d_{reached}$ is the distance the train can travel on a full battery charge, within the SOC limits, before reaching EoL.

The reverse route is also considered since the train operates from two starting points. The extended distance should be based on the train's direction, which requires more energy. The chosen distance was tested to validate that the trains could reach the electrified path from both directions since different segments required different amount of energy.

4.4.3 Overhead Line Island

As in the scenario with one stationary charging station, the OHLI was placed in the middle of the route. This was chosen since all trains could reach this position with realistic battery capacities. While traveling on the electrified section, energy is provided directly from the catenary, and the battery charges simultaneously.

From a cost perspective, the OHLI should be as short as possible. Therefore the OHLI was located with one station along the route. This setup allows for shorter charging times at the station if necessary while ensuring the distance is sufficient for battery trains to reach the OHLI in both directions.

During travel on the electrified path, a recommended current of 300 A was utilized. Charging while traveling could utilize even higher currents; however, the maximum current while stationary was utilized to avoid rapid charging of the battery. The typical voltage and current for the catenary was used to calculate the energy that could be provided to the battery per minute, using the formula in Equation 19.

$$P = VI[kW] \tag{18}$$

$$E_c = \frac{VI}{60}[kWh/min] \tag{19}$$

The necessary charging time while traveling on the electrified segment was calculated using Equation 16. The total length of the OHLI was computed by analyzing the current speed and the distance the train needed to travel or stop at the station to attain the required charging time.

4.5 System simulations

A logistical calculation was conducted to assess the demand for Kinnekullebanan. It is anticipated that 10 trains will travel in each direction during a typical day[1]. To determine when the trains would return to their starting station in each direction, a timetable for Kinnekullebanan (Västtrafik, 2025) was examined.

In Table 5, the travel time from Hallsberg to Herrljunga is presented (see Figure 1). These locations were the expected start and end stations in the future where the electrified

[1]Pontus Gunnäs, Business Manager & Robin Griffiths, Business Development Manager, Västtrafik.

distance was included. Additionally, a turnaround time of 20 minutes was included before the train could resume its journey. This turnaround time could be longer, but it was determined based on an analysis of the timetable to see when the train could start its next journey.

Table 5: Traveling time.

Parameter	Value [min]
Traveling time	168
Turnaround time	20

To simulate the system accurately for all four scenarios, the charging time with stationary charging was incorporated as a delay, which varied according to the battery capacity and the size of the train.

For the last two journeys of the day, it is assumed that one car can be disconnected from the train traveling in each direction. This results in a shorter train that matches the demand during these hours. This assumption is only made for the later hours of the day, as a middle-length train is likely needed again during subsequent trips during the earlier hours. For a detailed overview of the two traveling systems, see Table A2 and A3 in Appendix A.

The total energy consumption from the power stations takes losses into regard. The efficiency for energy transfer from the power station to the battery trains was calculated with the value of 88%, which was the typical losses from the Swedish supply system for electric trains (E. Andersson & Lukaszewics, 2006) found in the literature review.

To get an idea of the effects of the traveling system on the current infrastructure, power peaks from the system were plotted alongside the hours of the day. This was made to see how the peaks could be problematic for the location and to see if more exact time scheduling would be required to lower the economic costs and the effects on the local electricity grid. The locations were analyzed using a map showing grid connections to the studied locations (OpenInfraMap, n.d.).

4.6 Validation of energy calculations

An average value for multiple unit trains was utilized to ensure the energy calculations were close to the energy requirement for a real system. The compared average value was 53.9 Wh/ton-km for multiple unit trains (Colliander, 2020). To compare this with the simulated system, the total energy consumption of the traveling train was divided by the total distance of Kinnekullebanan. The compared value was multiplied with the occupied weights of the three simulated trains as shown in Table 2.

In an email correspondence with Rikard Tegnevi from Siemens Mobility, a broad estimate for the average energy consumption to use in studies for their Mireo Plus B train was provided as 5 kWh/km[1]. This value was used only when comparing the middle-length

[1]Rikard Tegnevi, Siemens Mobility, 05-03-2025.

train since this train served as a reference when choosing the simulation parameters for the middle-length train.

5 Results

The following paragraph presents the simulation results described in Section 4. Simulations were made to investigate the researched questions in Section 1.1. All simulations were made for winter climates with an ambient temperature of -20°C and for a battery at the point before reaching EoL. More detailed information regarding the presented figures and tables can be found in *Appendix A*.

The figures show the values for both the standard and reverse routes. The standard route refers to trains traveling from Gårdsjö to Håkantorp, while the reverse route refers to trains traveling from Håkantorp to Gårdsjö.

5.1 Energy consumption

The total energy consumption for the short train, middle-length train, and long train over the distance of Kinnekullebanan is shown in Figure 12.

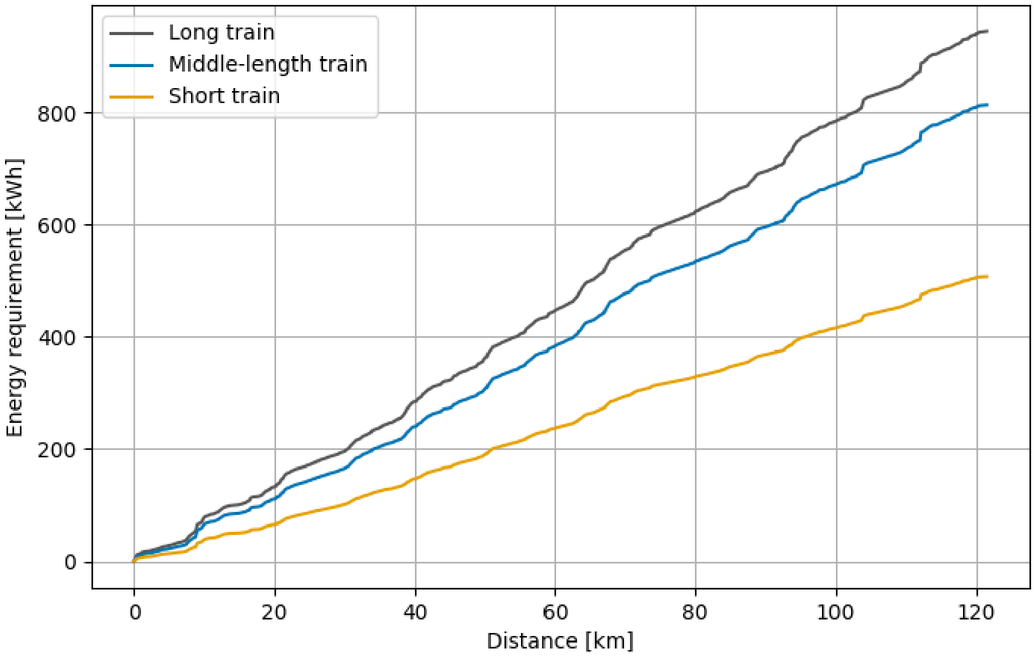

Figure 12: Energy consumption for a long, middle-length, and short train traveling from Gårdsjö to Håkantorp.

The energy consumption simulation revealed that the longest and heaviest train, with the highest seating capacity, had the highest energy usage. Accelerating and braking the train demanded more energy, as did maintaining the speed limit and driving uphill. Conversely, the shorter train exhibited the lowest energy consumption, with the driving pattern less impacting the total energy consumption. The energy consumption was higher for all train sizes for the reversed journey from Håkantorp to Gårdsjö. The parameter contributing to the higher energy consumption was mainly the slope of the railway as well as different speed limitations depending on the direction of travel.

For the three different train sizes with varying battery capacities, the achievable distance on a full charge is illustrated in Figure 13. The values presented represent the shortest distance the train could travel in either direction.

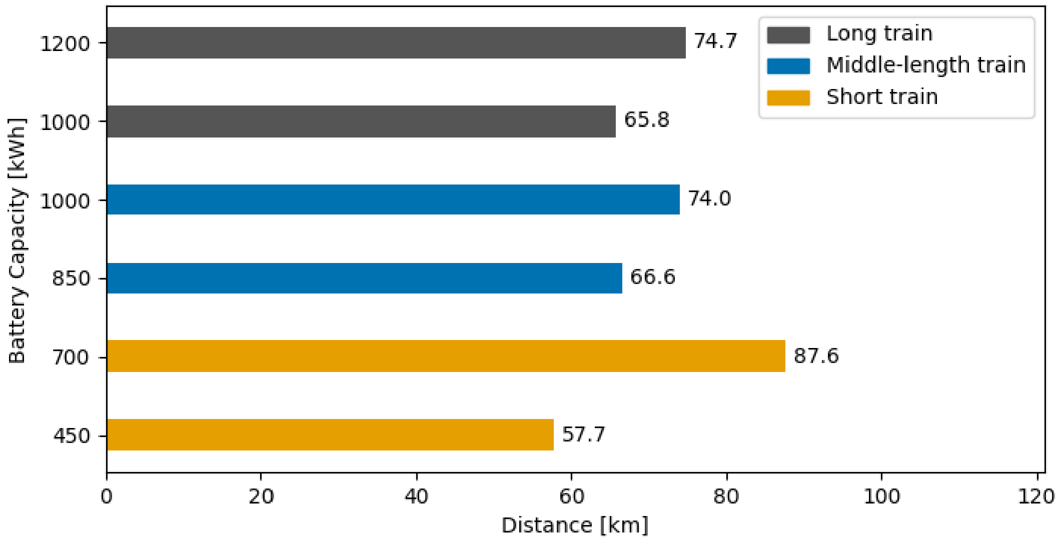

Figure 13: Traveled distance for three train sizes with varying installed battery capacities at their end of life.

The 27 m, 60 ton train with an initially installed battery capacity of 700 kWh could travel the longest distance, 87.6 km, during the simulated conditions.

Table 6 shows the possible distance the trains can travel with the remaining 20% of the stored energy in the battery in case problems occur on distances where charging is not possible.

Table 6: Distance the train can travel using the remaining 20% of the stored energy if problems occur.

Direction	Train size	Battery capacity [kWh]	Buffer distance [km]
Standard	Long train	1,200	19.5
Reversed	Long train	1,200	19.8
Standard	Middle-length train	1,000	20.1
Reversed	Middle-length train	1,000	20.0
Standard	Short train	700	20.0
Reversed	Short train	700	22.2

The table's results show that all trains can travel around 20 km with stored energy below the lower SOC limit in both directions.

5.2 Charging results

Three cases were studied for the charging infrastructure: stationary charging with two stations, stationary charging with one station, and an overhead line island. Additionally, one scenario was considered in which the catenary was extended, eliminating the need for charging.

5.2.1 Stationary charging: 2 stations

For stationary charging with two stations, one was placed at the platform in Mariestad and another in Lidköping. The more battery capacity installed on each train size, the shorter the corresponding charging times. Figure 14 presents the resulting charging times for larger battery capacities. The darker color shows the standard route, while the lighter shows the reversed route.

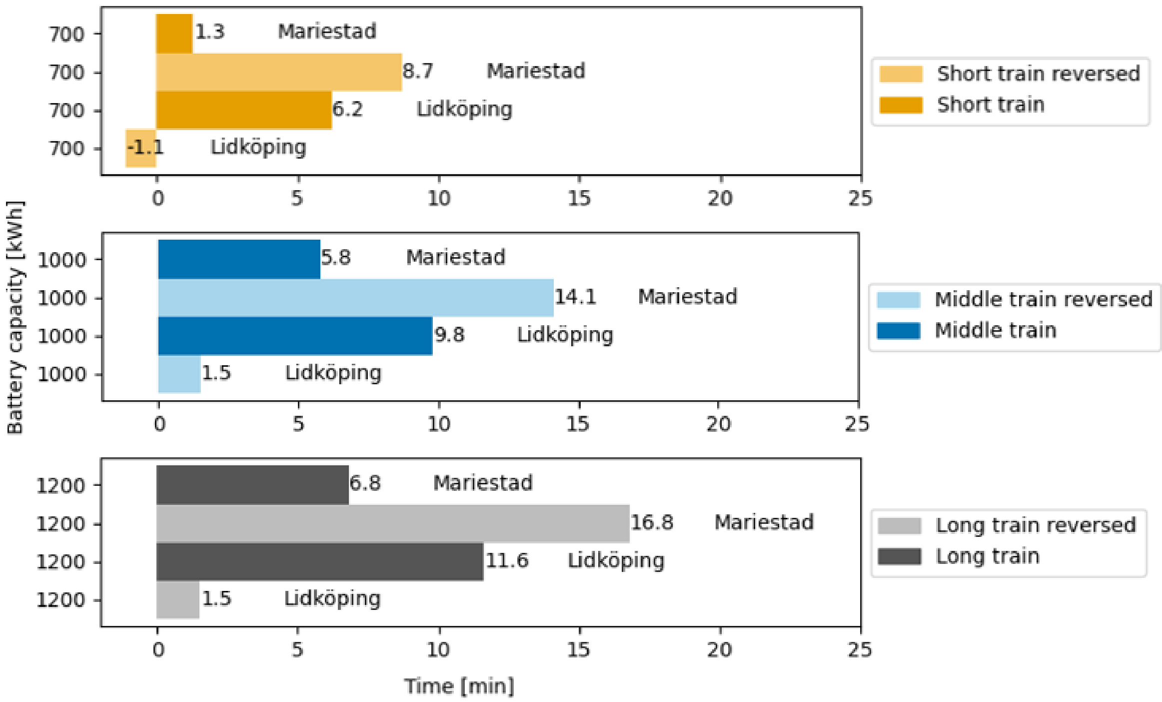

Figure 14: The shortest charging time for the three train sizes at two stationary charging stations.

The total delay in charging for the short train was 7.6 min for the reversed route, which required more energy. For the middle-length train, the longest total delay was 15.7 min for the reversed route, and the long train had a delay of 18.3 minutes. The negative section shown in the figure for the short train on the reversed route indicates that, with the installed battery capacity, the train does not need to recharge in Lidköping. In Appendix Table A4, the smallest possible battery capacity with corresponding charging time can be studied.

For the charging times shown in Figure 14, the corresponding charged energy at each station is presented in Figure 15.

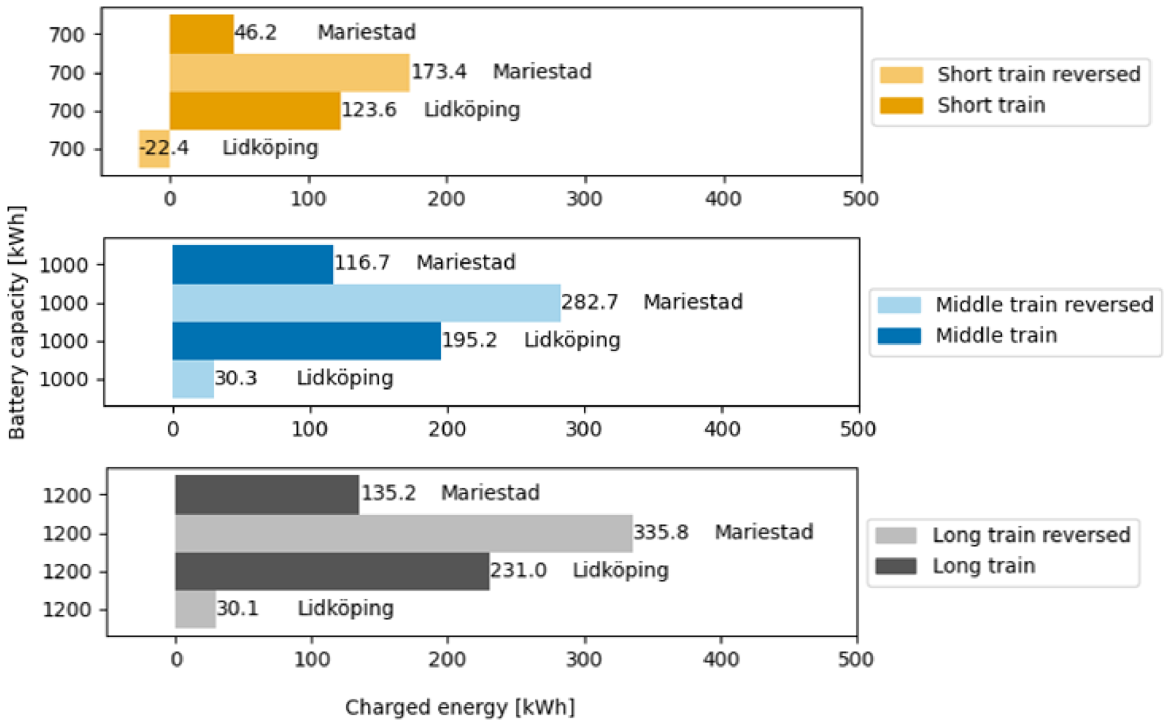

Figure 15: Energy charged for the three train sizes at two stationary charging stations.

5.2.2 Stationary charging: 1 station

In Figure 16, the charging times with one station for the smallest possible battery capacity as well as for bigger battery capacities to lower the charging time are shown.

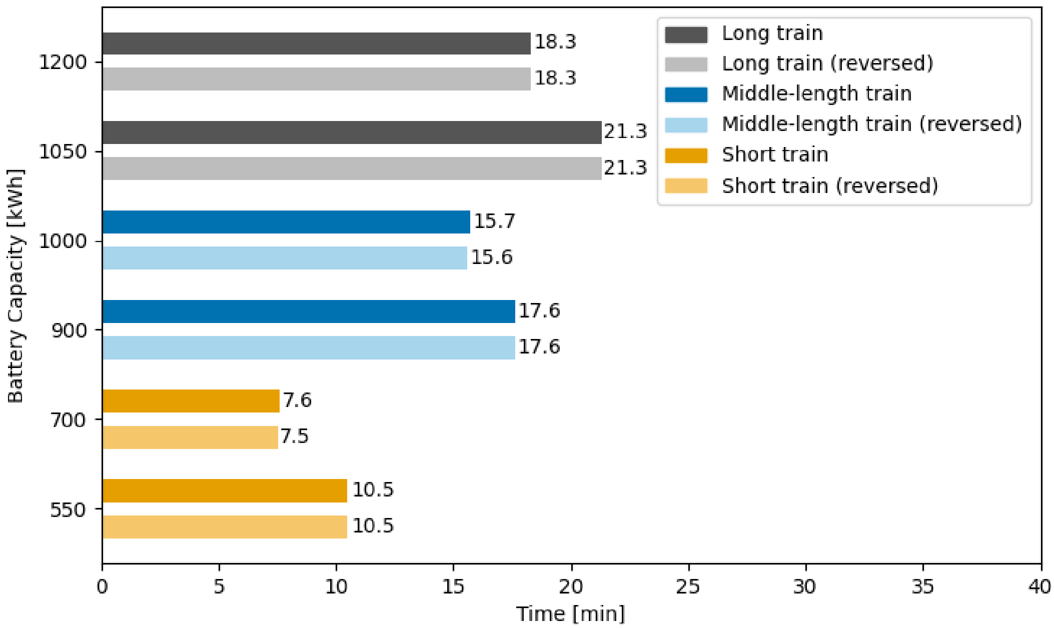

Figure 16: Charging time with stationary charging at one charging station.

For one charging station located in Forshem, in the middle of the total route (see Figure 10), the battery capacities for the middle-length train and the long train could be smaller than those of the other locations. The middle-length train could travel successfully with a 850 kWh battery, and the long train travels with a 1,000 kWh battery capacity. The lower value presented in the figure is the minimum battery capacity for the other stations and for the short train for all stations.

5.2.3 Overhead Line Island

The results of the OHLI project included the creation of a 6 km electrified segment passing through the station Österäng (see Figure 10), one of the four stations located in the middle of the total route. The charging times required to provide the necessary energy during travel on the electrified path are illustrated in Figure 17. The dashed black lines indicate the time trains can charge while moving along the electrified segment.

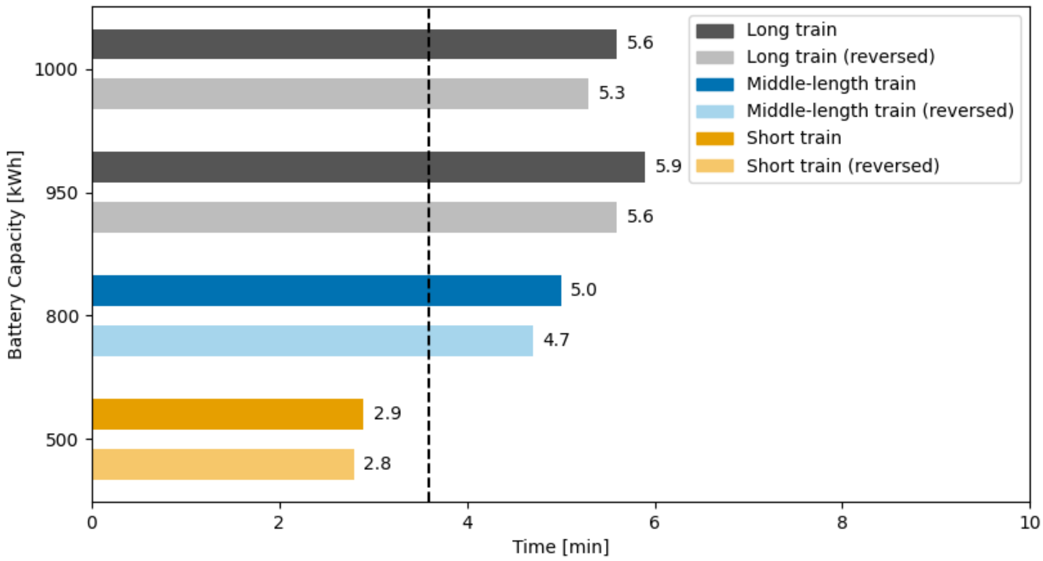

Figure 17: Charging time while traveling on the OHLI.

The results showed that the short train did not require a stop at the station, allowing for a reduction in the electrified distance. In contrast, both the middle-length train and the long train required a short stop at the station to charge the battery to store the required amount of energy for traveling the full distance of Kinnekullebanan. With OHLI, the battery capacity of the trains could be smaller than for one charging location.

5.2.4 Overhead Line Extension

For the OHLE simulation, the reachable distance the trains can travel was subtracted from the total distance shown in Figure 13, resulting in the required electrified distances shown in Figure 18. The dashed black line shows the discussed electrified distance between the stations Håkantorp and Lidköping.

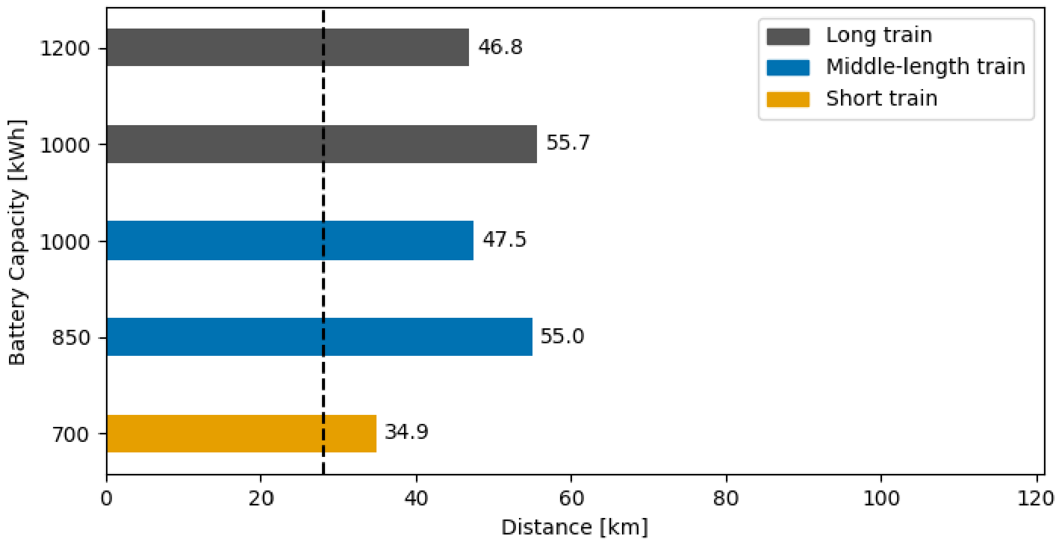

Figure 18: Required extended electrified distance for the trains to reach the end station.

The result showed that a short train with a battery capacity of 700 kWh required an additional electrified distance of 6.76 km, to the distance investigated by Trafikverket, for the trains to be able to travel the full distance of Kinnekullebanan. Using only trains of this size required the shortest OHLE.

5.3 Battery capacity comparison

The results indicate that the preferred battery capacity depends on the chosen charging solution. To facilitate comparison, Table 7 presents the total installed battery capacity per available passenger for each train configuration.

Table 7: Installed battery capacity per seating capacity of the trains.

Scenario	Seating capacity	Battery capacity [kWh]	Specific battery capacity [kWh/pass]
Stationary & extended	150	1,200	8.0
	120	1,000	8.3
	59	700	11.9
OHLI	150	1,000	6.7
	150	950	6.3
	120	800	6.7
	59	500	8.5
Minimum battery capacity	150	900	6.0
	120	750	6.25
	59	450	7.6

The comparison showed that the short train, with a maximum seating capacity of 59 passengers, had the highest specific battery capacity in all scenarios. The battery capacity for the final system equipped with an installed OHL was lower per passenger compared to the solution using stationary charging combined with extended OHL. For the scenario where the smallest possible battery capacity where installed, using two stationary charging locations, the lowest specific battery capacity was achieved.

5.4 System: Energy Grid

The analysis indicates that, with trains traveling ten times in each direction per day, six trains will be required to meet the demand. This calculation accounts for the delays associated with charging while the trains are stationary. Specifically, it was determined that four of these trains should be middle-length trains, while two should be short trains to fulfill operational requirements adequately.

5.4.1 Grid Energy; Two Charging Stations

Table 8 presents the total energy consumption for charging the train at the two charging locations. Also, the daily energy consumption for the two locations is described with a percentage increase in energy use for the municipality per day from the new charging infrastructure.

Table 8: System energy consumption and percentage increase of the daily energy consumption for the two charging locations.

Location	Grid energy [MWh]	Municipality daily consumption [MWh]	Percentage increase in consumption [%]
Mariestad	7.0	816	0.9
Lidköping	3.7	1,222	0.3

The energy consumption for charging the battery trains had less than a 1% increase compared to the daily energy consumption.

Figure 19 and 20 shows the charging occasions according to the current timetable, where blue marks train to charge in Mariestad and Lidköping, respectively, starting from Gårdsjö, and orange marks charging of trains traveling in the reversed direction starting from Håkantorp. The low peaks in each color indicate a short train traveling in that direction.

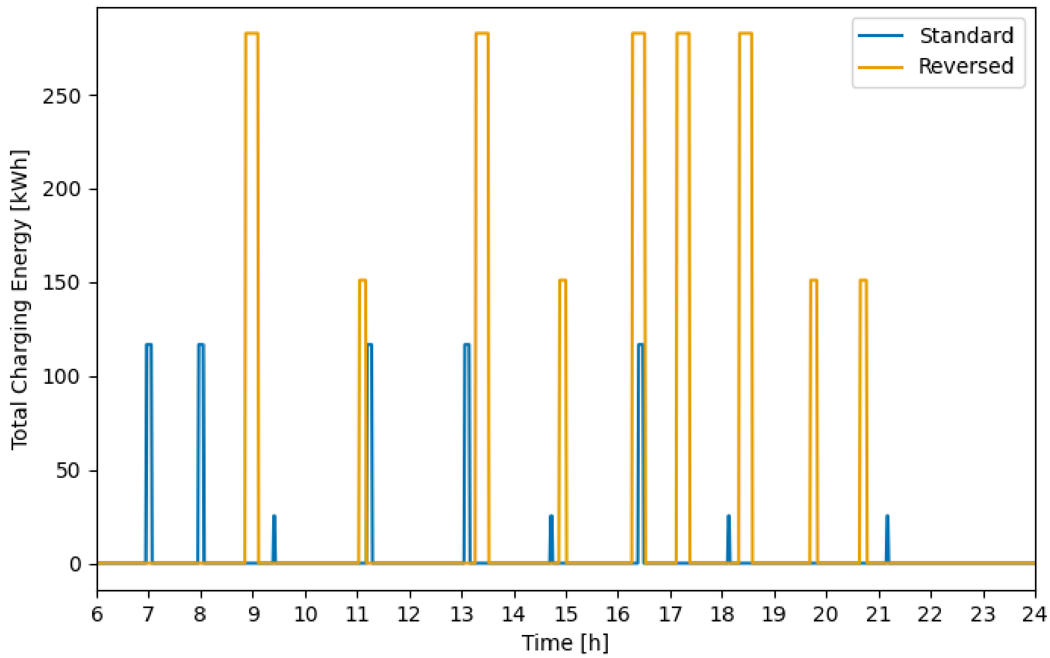

Figure 19: Charged energy from stationary charging in Mariestad for the scenario with two charging stations.

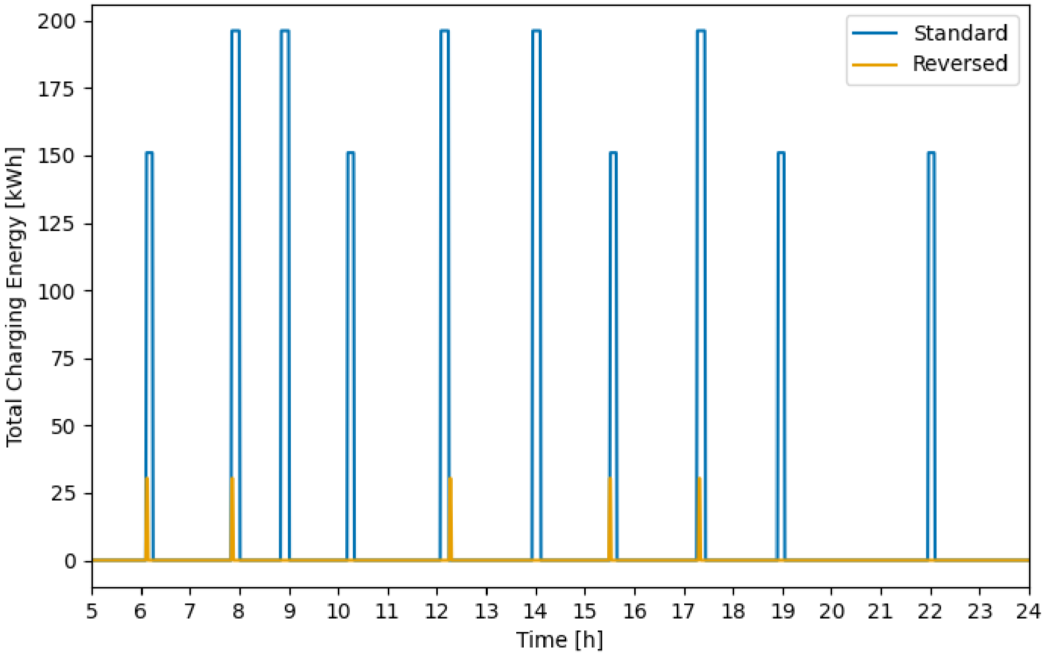

Figure 20: Charged energy from stationary charging in Lidköping for the scenario with two charging stations.

With the current timetable, two trains are required to be charged at the same time for both charging locations.

5.4.2 Grid Energy; One Charging Station

In Table 9, the total energy consumption for charging trains at a single station for the four charging locations located in the middle of the route (see Figure 10), all in the municipality of Götene, is presented. Alongside the total charged energy per day, the table includes the average energy consumption for Götene during 2023. The percentage indicates a rough estimate of the increase in local energy usage resulting from the development and utilization of this infrastructure.

Table 9: Energy Consumption and Percentage of Daily Energy Consumption for One Charging Station.

Parameter	Grid energy [MWh]
Short train (700 kWh)	1.7
Middle-length train (1,000 kWh)	3.6
Total energy consumption	5.3
Municipality daily consumption	818
Percentage increase in consumption	0.6%

The results showed that the increased energy consumption was less than 1% of the municipality's daily energy consumption.

In Figure 21, the charging occasions and the charged energy per occasion for the full system, including both short and middle-length trains, are shown. The lower peaks indicate short trains charging at that platform.

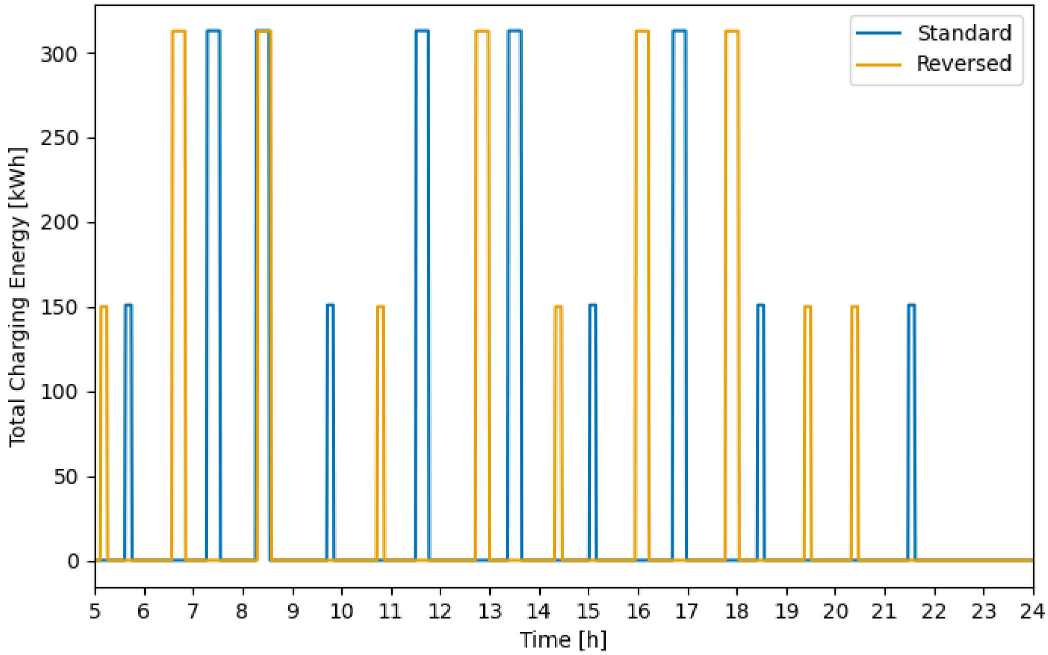

Figure 21: Charged energy from charging the trains with one stationary charging station.

The current timetable requires two charging occasions simultaneously during peak hours, resulting in a power peak greater than 600 kWh while middle-length trains charges at the station.

5.4.3 Total energy consumption OHLI

In Table 10, the total energy consumption for an average day is presented, during which 10 middle-length trains and 10 short trains operate daily. The energy consumption includes the charged energy in the battery and the energy directly used for traveling the electrified distance. The selected battery capacities were 500 kWh for the short train and 800 kWh for the middle-length train, the smallest possible batteries capable of reaching the OHLI from both directions.

Table 10: Energy consumption and percentage of the daily energy consumption for a charging from the OHLI.

Parameter	Battery capacity [kWh]	Grid Energy [MWh]
Short train	500	2.7
Middle length train	800	4.5
Total energy consumption	-	7.2

The total energy consumption from the electricity grid was higher than the required energy for one charging station, where a higher battery capacity was suggested.

5.5 Economics: Charging Infrastructure

Based on the system calculations, the presented costs for electrifying the railway line are for the two scenarios where OHL was constructed in the simulations, is shown in Table 11. The trains included in the final system are used to calculate the infrastructure costs.

Table 11: Calculated cost for catenary infrastructure.

Charging solution	MSEK	M€
OHLE	618.7	55.4
OHLI	44.5	3.99

The results indicate that an OHLI of 6 km will be more cost-effective than the total distance required for the extension of the catenary.

5.6 Validation of energy consumption

To validate the energy calculations for the three trains with installed battery capacity as in Figure 12, the average energy consumption was calculated and compared to other trains. This resulted in the values in Table 12.

Table 12: Validation of average energy.

Weight [tons]	Simulated train [kWh/km]	Comparison [kWh/km]
60 (short train)	4.24	3.68
108 (middle-length train)	6.85	6.63
129 (long train)	8.15	7.90

The result showed that the simulated train used more energy per km compared to the average value for multiple unit trains. The middle-length train, with an average energy consumption of 6.85 kWh/km, had a higher average energy consumption than the reference value of 5 kWh/km (see Section 4.6) for the Mireo Plus B train of the same size.

6 Discussion

The following paragraph discusses the results in relation to the research questions posed in this thesis. Specifically, the focus was on the characteristics that the trains should possess for the investment to be effective, how these train characteristics influenced the suitability of different charging infrastructure options, and the suitability of placing the charging infrastructure in an electricity grid perspective.

6.1 Energy & charging calculations

The traveling trains' energy consumption increased with the train's size. In addition to weight and length, the installed battery capacity also influenced whether the energy consumption was higher or lower. Across all simulations, the reversed route's total energy consumption was greater. This was likely due to slope variations or speed limitations that differed based on the train's direction. For larger and longer trains, the battery capacity had to be increased to travel the distance of Kinnekullebanan with the constructed charging infrastructure in all scenarios.

The results indicated that the shortest possible charging time for stationary charging occurred when short trains traveled the distance. For short, middle-length, and long trains, the maximum delay for stationary charging was approximately 7.6, 15.6, and 18.3 minutes, respectively. With two charging locations, the charging time could be distributed, effectively decreasing the charging times at each location. Passengers who do not travel the full distance may only experience one of the two delays, making traveling more comfortable for those who travel shorter distances. The minimum battery capacity was lower compared to the chosen values presented in the results. With the smallest possible battery capacity, the charging time was significantly longer, indicating inefficiency from a timetable perspective.

While the charging times for stationary charging may appear somewhat lengthy, it is important to note that the simulations are created for a worst-case scenario. The batteries have 80% of the installed capacity left, and the ambient temperature was set to winter conditions in Sweden, which increased the energy requirement from the HVAC system significantly. At higher temperatures, less energy would likely be consumed, resulting in more energy being stored in the batteries upon reaching the station. This would subsequently reduce the charging time. Additionally, the calculated charging times were designed to ensure the train could reach the next station with 20% stored energy in the battery. The strict upper and lower SOC value limits the amount of energy that can be utilized from the battery. However, it is not recommended to discharge or charge the battery outside of the SOC limits often since it would degrade the battery faster, meaning EoL will be reached earlier.

If the goal is to minimize charging time, it would be preferable to consider charging via OHL. The results showed that the charging times at the station could be significantly reduced by constructing an OHLI. It would not even be necessary for a short train to charge at the station, allowing the train to maintain its schedule as before. However, for middle-length and long trains, a brief stop at the station is required; still, the charging times at the station would be around 2 minutes, significantly shorter than the charging times associated with one or two charging locations. Since the train is likely already scheduled to stop at the station to allow passengers to board or disembark the train, these additional minutes for charging may not exceed the duration of the scheduled stop in the current timetable. To avoid the necessary stop, the train could travel slower during the electrified distance or use coasting longer to slower brake the train upon reaching the station. Other alternatives include constructing an additional kilometer of OHL or adding a battery pack with a capacity of 50 kWh. Increasing the battery capacity would result in slightly higher energy consumption, but approximately the 2 minutes of charging time would be eliminated. However, by extending the OHL further, the costs will increase.

The four different infrastructure measures required varying battery capacities. The stationary charging infrastructure with two stations allowed for the installation of smaller batteries; however, less energy can be stored with smaller batteries, resulting in longer charging times at the stations. For the OHLI, the smallest possible installed battery capacity could be utilized for all trains without significantly increasing the charging time. Meanwhile, for the OHLE, a larger battery capacity allows for shorter distances that need to be electrified for the trains to operate effectively, significantly reducing construction costs.

In the case of problems in power supply from the catenary in the scenario with the creation of an OHLI, all trains could, with the remaining 20%, travel around 20 km in both directions, according to the results. With this buffer, the trains could travel to Mariestad from the OHLI, one of the two larger passing cities. However, problems related to power supply had a small percentage of the common faults according to the statistics (see Section 3.4).

6.2 System analysis

From a system perspective, the logistics study indicated that for Kinnekullebanan, it would be advisable to use trains of short and middle-length to accommodate passenger demand. A middle-length train may be deployed even when only a short train is needed. This approach helps reduce the total number of trains in the system and prevents the need to disconnect a part of the multiple unit when it is utilized again as a middle-length train during peak load hours later in the day.

Since larger BEMU trains require more energy, it can be beneficial from both a system and economic perspective to invest in battery trains of optimal size to reduce electricity demand. High electricity demand not only leads to increased overall costs but also results in longer charging times, which are typically shorter for smaller trains, according to the results, since they require significantly less energy.

For charging, the total energy charged per day was significantly less than the average energy consumption at the charging infrastructure locations, indicating a relatively small percentage increase in electricity drawn from the local grid. This comparison is more interesting in the larger cities since the daily energy consumption for that municipality is probably the highest within the city itself. The results showed that the trains with the smallest possible battery capacities required more energy from the infrastructure. If larger batteries are used on the trains, there will be less reliance on the electricity grid at the charging infrastructure locations. Instead, the trains will be able to charge their batteries with electricity provided directly from the railway power supply system while traveling along the already electrified sections.

In a system that includes short- and middle-length trains, charging events for both scenarios, one with a single charging location and another with two, can coincide with the current timetable. During peak load hours, trains arriving from the standard and reverse directions may converge simultaneously at the same charging station. With the existing timetable, this situation would necessitate two charging stations at each location. All trains passing through must draw significant amounts of energy from the same chargers for stationary charging with only one station. Consequently, if two trains need to charge simultaneously, the electricity grid could experience a peak demand of more than 600 kWh, corresponding to two trains of middle-length. The charging infrastructure installed then has a load of 2.4 MW, which is very high. For smaller installed battery capacities, this power peak would be even higher. This would result in a substantial power peak in the daily load on the electricity grid. Along with the high power peaks, charging infrastructure costs will be twice as high.

A single charging station could be located at multiple sites. Based on the available battery choices, the optimal option was to place one charging station in Forshem, where a smaller battery capacity could be accommodated. Although the three train sizes must charge for the same duration, it would only occur at one station. Another important aspect is the study of the electricity grid and its connections to the sites. Hällekis has a direct connection to a 132 kV regional grid (see Section 2.1.2), which means there is a nearby substation where the connection with loads in megawatts can have less impact compared to other locations that only have local grid connections from this substation. Also, if two trains charges at the same time, this location would be more suitable to handle such load. Despite Forshem enabling smaller batteries when implementing one stationary charging station, the grid connections are significantly stronger in Hällekis, and the charger integration would likely have a lower impact on the local electricity grid.

To avoid high power peaks, a new schedule can be required. By distributing the charging occasions more evenly throughout the day, the new load in the infrastructure can have less influence on the electricity grid. In the scenario with two charging stations, it is easier to distribute the charging occasions more evenly than in the scenario with one charging station since the charging times at each station were shorter than the total charging time at one station. The scheduling time in the scenario with one charging location is tight since all of the trains have to charge more energy into their batteries, which increases the charging time at that location compared to the scenario with two charging locations.

For OHLE and OHLI, power supply from the railway power supply system is required since the catenary power supply is a separate power supply system in Sweden, and another or different system cannot be used. In the scenario where the catenary is extended onto Kinnekullebanan from the starting and end stations, it is likely possible to utilize the existing substations to provide energy for the new electrification. When the railway is partially electrified, new power stations for energy supply to the catenary may be required unless it is possible to utilize power stations from Västra Stambanan, which runs parallel to Kinnekullebanan. Further research could explore creating a charging island using the existing infrastructure.

Due to the stationary charger's dependency on the electricity grid, the study of Kinnekullebanan revealed that only three stations were viable locations. Building new electricity infrastructure and charging infrastructure would have been prohibitively expensive. Among these three stations, one was suitable for stationary charging with a single charging point, while the other two required additional charging stations to cover the entire railway line. With fewer charging points, trains require larger batteries to operate efficiently across longer distances without frequent recharging. Thus, requesting increased battery capacity becomes a critical aspect of the discussion when planning and implementing stationary charging solutions on Kinnekullebanan in combination with BEMU trains.

BEMU trains, being bimodal, can be used on various routes if other trains operated by Västtrafik encounter faults. Since BEMU trains can reach higher speeds than the current diesel-hydraulic Bombardier Itino trains, they would not face the same speed limitations on these routes. When powered by the catenary, BEMU trains can achieve speeds of up to 160 km/h (see Section 3.1), allowing them to be used more flexibly across multiple distances.

6.3 Economics

From an economic perspective, investing in stationary charging infrastructure would be significantly cheaper. The cost of installing a single stationary charging station, with an installed power of 1.2 MW, could cost between €1.5 million and €1.7 million (see Section 3.3.2). In comparison, the costs associated with OHL installations are much higher. The created OHLI of 6 km cost approximately €4 million, and this figure does not include the potential costs of a new power station, which could significantly increase the total expense if required. Extending the catenary over longer distances could be more expensive, with estimates reaching approximately €55.4 million with the additional 19.4 km to the investigated extension needed for the middle-length train to travel without recharge.

In addition to the high costs associated with infrastructure, there are also expenses related to managing delays and other operational issues. When considering BEMU trains, it is important to weigh the costs of experiencing long delays with a cheaper infrastructure against the potential for shorter delays accompanied by expensive infrastructure.

When comparing the charging infrastructure options, having two charging stations, which are more expensive than one, allows for smaller battery capacities. Operating with smaller battery capacities could result in cheaper trains. Since batteries are costly and need to be replaced more frequently than the train itself, it may be financially beneficial to have a lower battery capacity. This approach could contribute to cost savings overall.

The results for specific battery capacity showed that the short train consistently had the highest values across all scenarios. To cover the full route, the short train required a significantly larger installed battery capacity relative to its size and seating capacity. From an investment perspective, this suggests that the middle-length or long trains may offer better value due to their more efficient battery usage. The OHLI scenario demonstrated significantly lower specific battery capacities compared to those with stationary charging combined with extended OHL at the recommended battery capacity, indicating that OHLI is a more cost-effective option in this perspective. The lowest specific battery capacity was achieved in the scenario with the smallest possible battery capacities; however, this came with significantly longer charging times and a higher reliance on energy drawn from the local electricity grid at the charging locations.

6.4 Validation

The simulated energy consumption was higher than the average for multiple unit trains. Given that the average energy consumption for the simulated train on Kinnekullebanan takes railway conditions such as slope and driving patterns into account, it is reasonable for the value to be elevated. The slopes and the number of stops in the simulation can differ from those used for the average value for multiple unit trains. That the average energy consumption, in the simulations for the specific route, slightly differs from a general value can be expected. Furthermore, the energy consumption was calculated under an ambient temperature of -20°C, which contributed to higher energy usage due to higher HVAC requirements and an increased aerodynamic drag resistance, which for high speeds was the resistive force that contributed to the highest energy consumption.

Since the order of magnitude of the two average values is similar, the average energy consumption is reasonable. Compared to the average value of 5 kWh/km (see Section 4.6) for the middle-length train, the simulated energy consumption for the middle-length train was significantly higher. This comparison could be more reasonable, as it is based on an average value of an actual BEMU train, which was used to choose the simulation parameters for the middle-length train. The differences in values may be attributed to various factors, including the driving pattern, winter temperature, or the inclusion of specific railway parameters.

For the charging infrastructure, it is possible to compare the charging times with the understanding that it takes approximately 20 minutes to charge a BEMU train fully (see Section 3.3.2) Considering that the simulations were conducted based on the battery's EoL, which means that less energy can be stored due to battery degradation, it is reasonable to assume that stationary charging would take almost 20 minutes to fully charge the largest train with the highest battery capacity with a single charging station in the simulated scenario. The charging times for the smallest train were significantly shorter; this can be due to the smaller battery capacity or the battery's remaining energy upon reaching the station. This leads to less energy needed to be charged into the battery.

The validation indicates that the simulated values are comparable to a real scenario in which the energy consumption of an actual train would be tested. Similarly, the charging times appear reasonable compared to the established value of 20 minutes to charge the train.

6.5 Limitations and assumptions

During the simulations, the weight of the battery packs was kept constant. In reality, the train's weight would increase or decrease as the battery capacity varies. The limitation was set since the information regarding the weight of the batteries them-self on the studied trains was not available. If larger battery capacities are used on the trains, the total weight of the train will increase, and smaller batteries will entail a lighter train. If the increased weight of the batteries increases the energy consumption, the smallest battery possible in all scenarios might have to be increased to match the demand. The simulations serve as an example where different battery capacities are assessed to observe how charging times and the load on the electricity grid would change. Additionally, the potential charging locations for a specific battery capacity may vary based on real-world testing of the trains on the railway line.

The ambient temperature of -20°C may occasionally drop even lower, potentially causing the infrastructure or selected trains to operate ineffectively in such colder conditions. Conducting a more in-depth study of the temperature variations in the area is advisable to determine the necessary operational temperatures and create a battery capacity sufficient for the trains. Even though the temperature might be lower than 20°C on some occasions, the temperature most commonly is not lower than the chosen ambient temperature. In the future, as global warming can come to contribute to warmer winters in Sweden, this temperature might not even be reached.

The driving pattern was assumed consistent for all train drivers using systems like C-DAS. Different driving patterns can lead to varying energy consumption, and individual drivers are expected to have unique driving patterns due to human error. However, advanced systems that communicate recommended driving patterns to drivers could help create more uniform driving behavior. This consistency is crucial for battery-powered trains, where sufficient energy must be stored in the battery to complete the entire non-electrified railway line and to uphold similar time scheduling. In the thesis, the parameters are chosen so that the trains have a very small buffer for variations in driving patterns if choosing the smallest possible battery capacities. This is, therefore, a limitation that needs to be considered while studying the results.

If an investment in BEMU trains is made, the trains available on the market may have evolved, or specially manufactured trains might be acquired. The selected sizes of the trains do not account for the specific number of passengers; instead, they may be larger than necessary, as the trains analyzed are those currently available on the market based on the available information. In the real system, the middle-length train might be even smaller, decreasing the required extended distance or lowering the energy consumption from the local electricity grid in the chosen cities.

In addition to potential advancements in BEMU train technology, battery technology can develop to allow for greater energy storage capacity. In the future, it may be possible to use fast-charge batteries that enable more energy to be transferred to the train per minute without causing rapid battery degradation. Furthermore, improvements in battery efficiency could enhance various aspects, such as reducing the necessary length of the OHL and decreasing charging times.

6.6 Future research

Since driving patterns are a human source of error, it would be interesting to study different drivers' driving patterns and how human error contributes to increased energy consumption for battery trains. Given the system's sensitivity to high energy consumption due to the absence of a power supply during travel, systems like C-DAS or self-driving systems could be beneficial in a similar system. Investigating driving patterns for BEMU trains could be worthwhile for further studies, as these patterns likely contribute to operational issues. This would require a study on the differences in driving patterns among train drivers in a real system to examine the extent of these differences and their impact on energy consumption, as well as how effective a system like C-DAS could be in promoting consistent driving patterns.

In further studies, it would be interesting to investigate the possibilities of implementing OHLI on similar railway lines in Sweden to reduce the climate impact of railway travel and for other distances where partial electrification could simplify the catenary construction. OHLI, in combination with BEMU trains, can bring significant cost savings, as smaller sections of specific railway lines would not need to be electrified. Using OHLI and BEMU trains can simplify electrification plans in Sweden since segments such as tunnels would not need to be electrified. This approach would make construction easier and also be a cost-effective option.

Other routes in the Swedish railway network, like Kinnekullebanan, are not economically feasible to fully electrify. Investigating similar routes can be valuable for understanding the differences and evaluating how the studied solutions could work for other railway lines.

7 Conclusion

Short BEMU trains with low installed battery capacities required the least energy to travel the simulated distance. To meet passenger demand, shorter trains can be used, lowering the energy requirement for traveling. In the scenario with two stationary charging stations, the smallest possible battery capacity was achieved. For the scenario with the extended OHL, the largest battery capacity became more advantageous as it allowed for shorter extensions of the catenary system, resulting in significant cost savings. For OHLI, the smallest battery capacity proved to be the most advantageous, leading to the lowest overall battery capacity required in the entire system.

The four charging infrastructure constructions could enable BEMU trains to operate effectively on Kinnekullebanan. The stationary charger was the cheapest and most time-consuming method for charging the train, resulting in delays of a few minutes for all trains.

Extending the overhead line over the necessary distance was the most expensive option. However, it eliminates the need for charging altogether, enabling uninterrupted operations on the railway line. Additionally, it will not impact the local electricity grid, as the energy utilized comes from a separate power supply system.

Constructing an OHLI would lead to very short delays for charging. However, this option is significantly more costly than stationary charging and is the most complex due to the limited placement options caused by natural reserve areas surrounding the railway line. It can also become costly based on the possibility of utilizing the infrastructure from the end stations or stations on Västra Stambanan.

The stations where constructing charging infrastructure would have minimal impact on the electricity grid were limited. As a result, adjustments to battery capacity became essential to ensure the BEMU trains could travel the entire railway line efficiently.

Electricity restricted the viable locations for charging infrastructure. Two stationary chargers could distribute the load more efficiently. The two cities selected for the stationary charging stations had the strongest grid connections, making them the most suitable locations for high-power charging infrastructure.

In conclusion, battery capacity is crucial for compatibility with potential charging methods and locations. The characteristics of BEMU trains must be investigated alongside charging infrastructure to ensure the trains successfully reach their end stations from both traveling directions.

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Appendix A Supplementary Data for System, Energy and Charging

Table A1: Passing stations and corresponding distance.

Station	Distance [km]
Gårdsjö	0.2
Hova	8.9
Torved	17.2
Lyrestad	21.3
Hasslerör	30.9
Mariestad	39.3
Lugnås	50.5
Äskeskärr	56.5
Österäng	59.6
Forshem	64.0
Hällekis	67.7
Råbäck	71.8
Trolmen	74.3
Blomberg	80.6
Källby	84.2
Flisbäck	88.3
Lidköping	93.3
Framnäs city	94.4
Lovene	103.9
Järpås	112.1
Stora lovene	118.6
Håkantorp	121.5

Table A2: Timetable Kinnekullebanan from simulations, OHL.

Travel	Direction	Train	Size	Departure	Arrival
1	-1	1	L	03:53	07:01
2	1	2	L	04:10	07:18
3	-1	3	M	05:20	08:28
4	1	4	M	05:49	08:57
5	1	5	M	06:49	09:57
6	-1	6	M	07:04	10:12
7	1	1	L	08:15	11:23
8	-1	2	L	09:29	12:37
9	1	3	M	10:03	13:11
10	-1	4	M	11:29	14:37
11	1	6	M	11:55	15:03
12	-1	1	L	13:05	16:13
13	1	2	L	13:34	16:42
14	-1	5	M	14:43	17:51
15	1	4	M	15:15	18:23
16	-1	6	M	16:32	19:40
17	1	1	L	16:58	20:06
18	-1	2	L	18:08	21:16
19	-1	3	L	19:05	22:13
20	1	5	L	20:01	23:09

Table A3: Timetable Kinnekullebanan from simulations, Stationary charging.

Travel	Direction	Train	Size	Departure	Arrival
1	-1	1	L	03:53:00	07:08:33
2	1	2	L	04:10:00	07:25:33
3	-1	3	M	05:20:00	08:43:39
4	1	4	M	05:49:00	09:12:36
5	1	5	M	06:49:00	10:12:39
6	-1	6	M	07:04:00	10:27:39
7	1	1	L	08:15:00	11:30:33
8	-1	2	L	09:29:00	12:44:3
9	1	3	M	10:03:00	13:26:39
10	-1	4	M	11:29:00	14:52:39
11	1	6	M	11:55:00	15:18:39
12	-1	1	L	13:05:00	16:20:33
13	1	2	L	13:34:00	16:49:33
14	-1	5	M	14:43:00	18:06:39
15	1	4	M	15:15:00	18:38:39
16	-1	3	M	16:32:00	19:55:39
17	1	1	L	16:58:00	20:13:33
18	-1	2	L	18:08:00	21:23:33
19	-1	6	L	19:05:00	22:20:33
20	1	5	L	20:01:00	23:16:33

Short train

Table A4: Stationary charging results for 2 stations; smallest possible battery capacity.

Short train	**Point 1**
Battery capacity	450 kWh
Total energy requirement	482.81 kWh
Energy requirement Mariestad	134.83 kWh
Charge & time Mariestad	6.5 min, 130.07 kWh
Energy requirement between stations	229.25 kWh
Charge & time Lidköping	5.94 min, 118.74 kWh
Total delay	12.44 min
Short train	**Point -1**
Battery capacity	450 kWh
Total energy requirement	483.75 kWh
Energy requirement Lidköping	112.65 kWh
Charge & time Lidköping	4.3 min, 86.03 kWh
Energy requirement between stations	207.38 kWh
Charge & time Mariestad	8.19 min, 163.72 kWh
Total delay	12.49 min

Table A5: Stationary charging results for 2 stations; Shortest charging time.

Short train	**Point 1**
Battery capacity	700 kWh
Total energy requirement	514.06 kWh
Energy requirement Mariestad	145.11 kWh
Charge & time Mariestad	1.26 min, 46.17 kWh
Energy requirement between stations	244.08 kWh
Charge & time Lidköping	6.24 min, 123.64 kWh
Total delay	7.5 min
Short train	**Point -1**
Battery capacity	700 kWh
Total energy requirement	515.0 kWh
Energy requirement Lidköping	119.49 kWh
Charge & time Lidköping	-1.12 min, -22.41 kWh
Energy requirement between stations	222.1 kWh
Charge & time Mariestad	8.67 min, 173.42 kWh
Total delay	7.55 min

Middle-length train

Table A6: Stationary charging results for 2 stations; Smallest battery capacity.

Middle-length train	**Point 1**
Battery capacity	750 kWh
Total energy requirement	801.57 kWh
Energy requirement Mariestad	229.51 kWh
Charge & time Mariestad	11.08 min, 221.55 kWh
Energy requirement between stations	382.04 kWh
Charge & time Lidköping	9.50 min, 190.02 kWh
Total delay	20.58 min
Middle-length train	**Point -1**
Battery capacity	750 kWh
Total energy requirement	801.78 kWh
Energy requirement Lidköping	183.67 kWh
Charge & time Lidköping	6.94 min, 138.76 kWh
Energy requirement between stations	345.09 kWh
Charge & time Mariestad	13.65 min, 273.03 kWh
Total delay	20.59 min

Table A7: Stationary charging results for 2 stations; Shortest charging time.

Middle-length train	**Point 1**
Battery capacity	1 000 kWh
Total energy requirement	832.82 kWh
Energy requirement Mariestad	239.79 kWh
Charge & time Mariestad	5.83 min, 116.67 kWh
Energy requirement between stations	396.88 kWh
Charge & time Lidköping	9.81 min, 195.15 kWh
Total delay	15.64 min
Middle-length train	**Point -1**
Battery capacity	1 000 kWh
Total energy requirement	833.03 kWh
Energy requirement Lidköping	190.51 kWh
Charge & time Lidköping	1.52 min, 30.31 kWh
Energy requirement between stations	359.8 kWh
Charge & time Mariestad	14.14 min, 282.72 kWh
Total delay	15.65 min

Long train

Table A8: Stationary charging results for 2 stations; Smallest battery capacity.

Long train	**Point 1**
Battery capacity	900 kWh
Total energy requirement	952.76 kWh
Energy requirement Mariestad	274.33 kWh
Charge & time Mariestad	13.05 min, 261.08 kWh
Energy requirement between stations	454.75 kWh
Charge & time Lidköping	11.18 min, 223.69 kWh
Total delay	24.24 min
Long train	**Point -1**
Battery capacity	900 kWh
Total energy requirement	952.33 kWh
Energy requirement Lidköping	217.04 kWh
Charge & time Lidköping	8.01 min, 160.21 kWh
Energy requirement between stations	411.14 kWh
Charge & time Mariestad	16.21 min, 324.13 kWh
Total delay	24.22 min

Table A9: Stationary charging results for 2 stations; Shortest charging time.

Long train	**Point 1**
Battery capacity	1 200 kWh
Total energy requirement	990.26 kWh
Energy requirement Mariestad	286.67 kWh
Charge & time Mariestad	6.76 min, 135.22 kWh
Energy requirement between stations	472.55 kWh
Charge & time Lidköping	11.55 min, 231.04 kWh
Total delay	18.31 min
Long train	**Point -1**
Battery capacity	1 200 kWh
Total energy requirement	989.83 kWh
Energy requirement Lidköping	225.25 kWh
Charge & time Lidköping	1.50 min, 30.07 kWh
Energy requirement between stations	428.82 kWh
Charge & time Mariestad	16.79 min, 335.76 kWh
Total delay	18.29 min

Table A10: Stationary charging results for one station.

Train	**Battery capacity**	**Charging time 1**	**Charging time -1**
27 m	550	10.47	10.51
27 m	700	7.50	7.55
47 m	900	17.62	17.63
47 m	1 000	15.64	15.65
57 m	1 050	21.28	21.25
57 m	1 200	18.31	18.29

Table A11: Possible traveled distance for the trains without recharging.

Direction	Train	Battery capacity [kWh]	Traveled distance [km]
1	Short	450	62.59
-1	Short	450	57.74
1	Short	700	87.63
-1	Short	700	86.56
1	Middle-length	850	66.56
-1	Middle-length	850	66.48
1	Middle-length	1 000	73.96
-1	Middle-length	1 000	79.65
1	Long	1 000	66.26
-1	Long	1 000	65.80
1	Long	1 200	74.68
-1	Long	1 200	80.38

Table A12: Required electrified distance for overhead line extension.

Train	**Battery capacity**	**Electrified distance**
27 m	700	34.9
47 m	850	55.0
47 m	1 000	47.5
57 m	1 000	55.7
57 m	1 200	46.8

Table A13: Overhead line island results

Parameter	**Value**
Start point	57 km
End point	63 km
Total electrified distance	6 km
Energy transfer	75 kWh/min
Charging time while traveling	3.6 min
Short train [500 kWh]	2.92 min
Middle-length train [800 kWh]	4.98 min
Long train [1 000 kWh]	5.63 min