Electrification of Regional Buses and Possibilities of Shared Charging with Other Transportation Modes

What impact does the electrification of transportation modes have on the electric grid? - A case study in Lysekil

Master's thesis in Infrastructure and Environmental Engineering [MPIEE]

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Abstract

To reduce emissions originating from the transport sector, electrifying long-range heavy transportation modes such as regional buses and trucks is crucial. However, an identified obstacle in the early phases of electrification is the lack of required charging infrastructure, to which shared charging has emerged as a possible solution. Therefore, the objective of this study is to investigate the possibilities of electrifying regional buses and examine the feasibility of shared charging with other transportation modes to accelerate implementation. Additionally, the impact of extensive electrification on the power grid remains uncertain. To address this aspect a case study was conducted in Lysekil, examining the impact on a limited geographical area. The overall method used was a gap analysis which was applied to the case study of Lysekil, in turn consisting of three parts. Firstly, the energy consumption and necessary charging infrastructure for electrifying a regional bus were estimated. Secondly, other transportation modes that could potentially share charging in the area were identified, and their respective charging demands were assessed. Finally, the charging demands from all transportation modes were compiled and added upon current electric consumption in Lysekil to evaluate the overall impact. Results indicate that it is possible to electrify a regional bus, where the most suitable sharing options for the examined route were with trucks charging overnight, or sharing grid connection with the locally operating electric ferry. The resulting charging demand from the electrification of heavy transport modes has a notable impact on the power grid, but to what extent depends majorly on the future share of electric trucks. In addition, the impact resulting from the electrification of personal cars and related charging will presumably have a large impact on the grid but was not taken into account due to uncertainties of the charging patterns. It is indicated that flexible solutions such as installing energy storage could reduce the required installed power output, and thereby reduce the load on the grid and risk of congestion. Therefore, to use the electrification of the transport sector as an asset, it is important to apply a system perspective.

Keywords: electrification, regional buses, electric trucks, charging demand, shared charging, charging infrastructure, electromobility.

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Marcus Edberg & Ellinor Wagnsson, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current
ACD	Automatic Connection Devices
ADT	Average Daily Traffic
AFIR	Alternative Fuels Infrastructure
BEB	Battery Electric Bus
BEC	Battery Electric Car
BET	Battery Electric Trucks
BEV	Battery Electric Vehicle
CCS	Combined Charging System
CO_2	Carbon Dioxide
DC	Direct Current
DREEMER	*Delade, Regional Energi- och Mobilitetsförsörjningssystem för Effektivt Resursutnyttjande.* Research project in the area of electromobility and resource utilization
EU	European Union
GHG	Green House Gas
HD-EV	Heavy-Duty Electric Vehicle
ICE	Internal Combustion Engine
IRI	International Roughness Index
LD-EV	Light Duty Electric Vehicle
MPD	Mean Profile Depth
QGIS	Quantum Geographic Information Software, a tool for analyzing geographical data
SOC	State of Charge
SVK	*Svenska Kraftnät.* Swedish power grid
TEN-T	Trans European Infrastructure Network
TIKK, TFK	Interactive maps for traffic flow and information
V2G	Vehicle to Grid

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1

Introduction

1.1 Background

European Union (EU) climate law states that it is an obligation to reduce CO_2-emissions by at least 55% by 2030 (compared with levels from 1990) and that net-zero emissions should be achieved by 2050 [1]. One of the largest emitters in the EU is the transport sector which accounts for approximately 27% of total CO_2-emissions [2]. As a consequence, the *Fit for 55* package has been introduced where the Alternative fuels infrastructure (AFIR)-regulation presents actions needed for the transport sector [1]. AFIR focus lies on replacing fossil fuels with e.g. electricity or electrofuels. It is further stated that to increase share of electric transportation modes, a convenient and user-friendly charging infrastructure that enables interoperability between EU-countries is a necessity.

In line with the EU climate law, Sweden has set up a national climate goal; to achieve net-zero emissions by 2045, with related milestones along the way [3]. Milestones for 2030 concerning transportation states that domestic transport-originated emissions (excluding domestic flights) must be reduced by at least 70% in comparison with levels of 2010, and that the non-trading sector (where transportation makes up around 50%) must reduce its emissions by 63%. But with the new proposal of a minimum fuel reduction requirement by the Swedish government, emissions will increase in close time and the 2030 milestone with its emission reductions is thus jeopardized [3]. Furthermore, according to the same prognosis, the goal of net-zero emissions by 2045 will therefore not be achieved. In modified scenarios (where the gap in 2045 is minimized and the goal will be achieved), the importance of a more rapid transition, from internal combustion engines (ICE) to electric transportation modes, is highlighted.

To pave the way and accelerate the electrification of heavy vehicles, the Swedish government has granted funding support for the construction of over 100 charging stations for heavy-duty trucks around Sweden, where one-third will be located in the region of Västra Götaland [4]. In addition, few chargers alongside roads and related range problems have made Volvo Trucks join a consortium investing in the expansion of charging infrastructure in EU and Sweden [5]. Similar actions can be seen regarding buses where Västtrafik is making large investments to electrify their bus fleet [6]. Currently, 300 electric city buses are operated by Västtrafik in the Gothenburg region, and during 2023 160 more electric buses will be introduced.

This will result in 2 out of 3 city buses being fully electric. Furthermore, new investments in electric buses are planned and by 2030, Västtrafik has set up a goal for all city buses (operating in both large and small cities in the region of Västra Götaland) to be fully electrified [6]. Although, the general goal for Västtrafik is that by 2030 all public transport shall be fueled by renewable fuels [7] which means that besides electricity, electrofuels, biogas, etc. are also included.

The introduction of electric city buses is a much more rapid process than for regional buses and coaches, where Gothenburg is at the forefront. A contributor to this modal shift has been a project called *ElectriCity* [8], a demonstrative research project, in which electric buses were developed and evaluated between 2015-2020. The demonstration project not only resulted in one of the largest purchases and rollouts of electric buses in Europe, but showed the potential of electric transports which has been transferred to other sectors (such as the construction sector). The project has moreover created a platform to develop public transport, aiming to speed up the electrification process. In line with ElectriCity and as a further development, a research project called DREEMER has been initiated and is on going. This thesis is in collaboration with the DREEMER project, with the goal of contributing by showing the potential in electrification of regional buses.

1.2 Aim

This thesis aims to investigate the electrification of regional buses in Västra Götaland and the geographical location of related charging infrastructure so that it can be shared between different transportation modes. Furthermore, the additional load on the power grid, resulting from electrifying transportation modes, will be estimated using a case study in Lysekil to limit the geographical area. This to evaluate the impact and whether the local power grid can handle such an increase. Furthermore, an overall aim is to present general guidelines and important findings to keep in mind when electrifiyng regional buses.

1.2.1 Research questions

1. **What is the charging infrastructure demand for a regional bus line if being fully electrified?**

2. **Is there a possibility of shared charging between regional buses and other transportation modes to increase the utilization rate of chargers?**

3. **What additional impact does the electrification of the transport sector have on the power grid in Lysekil?**

1.2.2 Limitations

This study will focus on buses with commuting characteristics and longer routes, no city buses will be included. Moreover, service and maintenance vehicles will also not be included. Other transport modes that are being electrified on a larger scale are personal cars, however, public charging accounts for a small part of overall charging, and evaluating the impact of home charging would require more refinement than possible and is therefore foreseen.

The financial aspect of investing in battery-electric buses compared to conventional buses is important, especially when the technology is still under development and prices are high compared to future assumed prices for electric buses. Although, the economic aspect will only be briefly discussed in this study.

2

Theory

2.1 Charger ownership

When charging BEVs there are different charging options depending on the form of ownership (private or public) which mainly affects who is allowed to charge, but also has an impact on price and power output.

- **Private charging stations** are owned by private actors and has restricted access to who is allowed to charge [9]. Chargers are usually located at homes or workplaces, resulting in longer charging times and use of lower power output. Using lower power tend to reduce costs for installation of chargers, and in combination with most private charging taking place during the night, private charging in general is the cheapest option. Moreover, the restriction of who is allowed to charge tend to reduce maintenance of charging stations since it gives full knowledge of users [9]. According to Energimyndigheten, 80-90 % of charging occasions take place at private charging stations in Sweden, and is therefore an important market when predicting future energy demands.

- **Public charging stations** are open for everyone to use and are located e.g. alongside roads, at shopping centers, and in parking garages [9]. Public chargers usually have higher power output since the stops in general are short. In addition, they are owned by companies that want to make profits from their customers, which results in higher charging costs and is a contributor to why only 10-20% of charging occasions take place at public charging stations [9]. Energimyndigheten further states that public chargers are vital to achieve a large share of electric vehicles since it enables charging when traveling longer distances and thus reduce range anxiety.

2.2 Charging Locations

Charging can take place at different locations depending on the vehicle's driving pattern. Focusing on BEBs and HD-EVs, following charging locations are the most common (illustrated in Figure 2.1 below):

- **Depot charging** takes place at the operator's depot and is the most common type of charging for HD-EVs today [10]. The chargers are privately owned to ensure that all operating vehicles have sufficient power when starting their route. Charging power and time differs depending on when the charging takes place. During night-time alternating current (AC) chargers with a power output of 50-150 kW are commonly used [11]. If the vehicles return to their depots during the day to charge (during driver breaks or peak hours), charging times are short and direct current (DC) charging can advantageously be used since it allows higher power output.

- **End-station-/destination charging** is used when complementary charging is needed during the operating route. Such charging is relevant for buses operating during long hours and/or long routes where depot charging is insufficient. This type of charging is also relevant for distribution trucks, enabling charging when loading/unloading. Charging times are usually short and therefore higher powers are used. For example, pantographs that are used for end station charging can have a power output of up to 600 kW [11].

- **On-the-way charging** is a key part of the public charging network and allows drivers to charge along the route. It is, as earlier mentioned, important to increase the number of electric vehicles and ensure great transport mobility [9]. For HD-EVs, on-the-way charging is mostly relevant for long hauling trucks with traveling distances >400 km [12]. In general, stops during routes are short and require high power/fast chargers, and for trucks, chargers with power outputs in sizes of megawatts are under development [13].

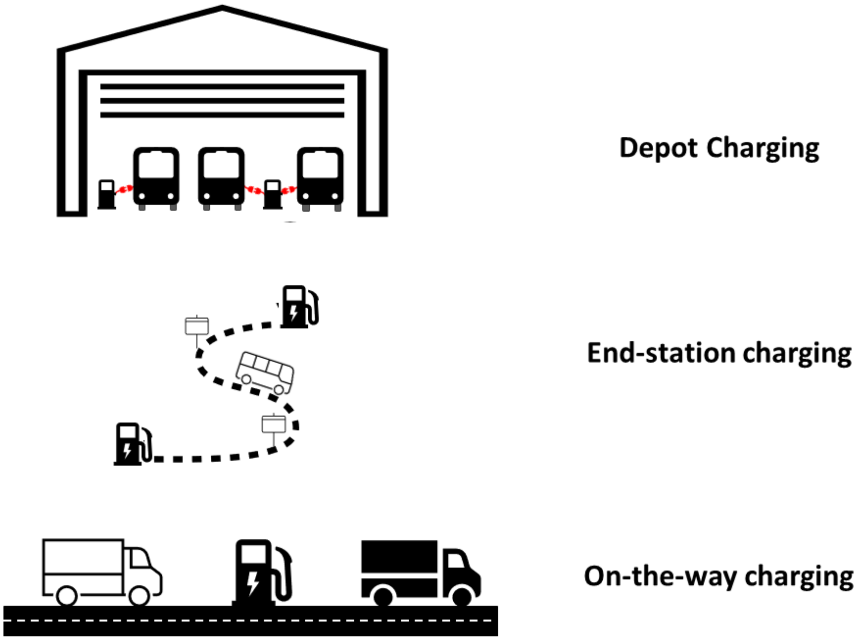


Figure 2.1: Illustration of different charging locations for BEBs and HD-EVs.

2.3 Charging technologies

Charging alternatives currently used or under testing are: Conductive/Contact charging or Inductive charging. Depending on desired power output different chargers are used.

- **Conductive charging** is the dominating technology where charging can be static or dynamic. Most commonly used are static chargers, which are either manually connected to the vehicle (plug-in chargers) or automatically using Automatic Connection Devices (ACD) [14]. Plug-in chargers are being standardized in Europe to ensure a consistent system where *Type 2* is the standard option when using AC at power below 50 kW [15]. For fast charging with power between 50-400 kW, Type 2 is still used but with an additional combined charging system (CCS) socket enabling DC charging. The different alternatives are illustrated in Figure 2.2 below, where (a) and (b) show two different types of pantograph charging (infrastructure mounted respectively roof-mounted), (c) is a ground mounted charging alternative, while (d) is the common plug-in charging alternative. Since plug-in chargers are currently limited to 400 kW, pantographs are used for charging at higher powers, up to 600 kW [11]. ACD's are moreover beneficially used for city buses since drivers do not have to leave the vehicle when charging at bus stops during operating times. Dynamic conductive charging uses catenary wires, where a vehicle mounted pantograph connects to overhead catenary wires and charges while driving.

- **Inductive charging** includes static or dynamic options, both using magnetic fields [14]. It is a technology still under development, not as prioritized as conductive charging since it proves to have less efficiency. However, it can in the future be used as a great complement to conductive charging since it can reduce battery sizes or increase range.

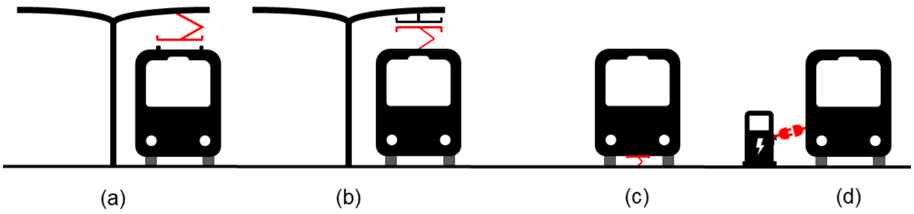


Figure 2.2: Illustration of different charging technologies: (a) infrastructure mounted, (b) roof-mounted, (c) ground-mounted, (d) plug-in.

2.4 Charging strategies

BEV charging can be divided into three options in terms of how to connect to the grid: Inflexible charging, Smart Charging and Vehicle-to-Grid (V2G) smart charging [16],[17].

- **Inflexible charging:** Vehicles are charged directly upon arrival when connected to the charger. Charging until the battery is full, or when leaving for the next drive.

- **Smart charging:** Based on the principle of maintaining balance in the power grid and requires communication between the vehicle and grid. Charging can be scheduled based on electricity prices and minimizes the total cost of the city's energy system. Vehicles are charged in a way that is beneficial to drivers and has sufficient power to meet driving needs.

- **V2G smart charging:** Vehicle batteries can discharge back to the grid and function as energy storage when not driving. Beneficial in terms of maximum utilization of renewable energy, e.g., vehicles can be charged by solar power during the day and discharge during peak hours, then recharge during the night when the grid is less stressed.

2.5 Battery technology

The battery technology used in battery electric trucks (BETs), BEBs is constantly being developed to become more adaptable to future demands and to be a more sustainable and viable option for HD-EV operations [10]. The areas that have a development potential are increased energy density, faster charging, and extending the life of the battery while at the same time maintaining the safe operation of the vehicle. The amount of power needed in HD-EVs to operate will significantly affect the battery's size and weight, which increase the total weight of the vehicle [18]. O'Leary further states that when operating the battery daily, a reliable control system is needed to increase the safety of the battery and its lifetime as the control system optimizes the condition of the battery. The condition of the battery is maintained when the temperature of the battery is not too hot nor too cold, and when the battery stays within the optimal operating capacity.

The battery chemistry commonly used in BETs and BEBs is the lithium-ion battery, where the battery consists of many smaller battery cells that are linked together, and enables the design of the battery to be optimized for every different vehicle type [18]. Furthermore, the lithium-ion battery has a high energy-to-weight (Wh/kg) ratio and a high power capability when the battery is charged or discharged which are important factors for a HD-EV.

Future energy storage systems are the foundation when fully electrifying the transport sector. As the batteries will get be more cost-efficient and at the same time enhance the energy-to-ratio it enables the transition to a fully electrified transport system to advance quicker [19].

2.6 Swedish power grid

An extensive electrification of our society is in the near future, which entails an increased electricity demand. The most significant increase in Sweden is expected to result from the industry sector, followed by the transport sector, where presented forecasts by *Svenska Kraftnät* (SVK) [20] predicts an energy demand of 290 TWh by 2045 (compared with today's consumption of ca. 140 TWh). At peak hours the grid already carries a heavy load and increased demand could result in congestion in the grid, resulting in insufficient power to the customers not extending. Therefore there is a need to extend the grid and flatten the curve, which means moving consumption to hours with less energy demand. The need for flexibility applies to all levels of the Swedish power grid, which consists of the Transmission grid and Distribution grid, that in turn consists of the regional and local grid [21].

- In the **Transmission grid**, electricity from large electricity producers is transported and very large consumers can be directly connected. It is owned by the state authority SVK and connects all parts of Sweden, and also contains international connections. To reduce transmission losses high voltages are used in the range between 400 kV to 220 kV.

- The **Regional grid** is the link between the transmission grid and the local grid. It allows for some large power consumers to connect directly to the regional grid and a voltage of 130 kV is usually used. The regional grid is owned by larger power grid companies.

- **Local grid** is the "last mile" transport to the major part of power consumers such as households and companies. In some cases, small electricity producers are also connected to the local grid. Voltage used in the local grid is approximately 40 kV and is owned by several small and local power grid companies.

2.7 Future charging infrastructure

- **TEN-T network:** The European Commission has introduced a policy stating that a widespread transportation infrastructure network (TEN-T) should be established across Europe [22]. This includes different transportation platforms such as railways, roads, shipping routes, and airports where the most important goal of the policy is to detect and remove bottlenecks and gaps in the transport system. Furthermore, there is a goal of installing several electric truck public charging stations, in relation to the TEN-T, by the year 2030 at each node displayed in Figure 3.1 to support the transition to fully electric regional transports [10].

- **Increase in charging infrastructure demand**
  The fast development and usage of both BEVs and HD-EVs globally require a fast and large expansion of the charging infrastructure as for today there are too few charging stations being installed. An estimated number from 2021 states there are around 375,000 public charging stations across Europe where an increase to 3.4 million public chargers is required to be in place by 2030 [12]. This would be an expansion of the charging infrastructure by approximately 900% and will demand an expansion not only in larger cities but across countries. The expanding charging infrastructure not only requires the electric grid to be upgraded to be able to distribute electricity but the production of renewable energy capacity to increase to cope with electrifying the transport sector [12].

3

Literature review

3.1 Shared charging

Previously conducted studies concerning optimization of charger locations and shared charging have mainly focused on personal vehicles and city buses, where each mode has been studied separately [23][24]. Ye et al. [24] have investigated shared charging hubs between battery electric cars (BECs) and battery electric buses (BEBs) with the intention of decarbonizing public transport within a regional area and reducing peak power demands. In the study, it was found that through coordinated shared charging in hubs between BECs and BEBs it is possible to: reduce peak-power demands, lowering investment costs for chargers, and significantly reduce greenhouse gas (GHG)-emissions. Moreover, Vehicle-to-Grid (V2G) charging was pointed out as a detrimental technology when sharing charging depots; without V2G charging, it is uneconomical for battery electric vehicles (BEVs) to charge at hubs when electricity prices are high [24].

An identified problem with shared charging infrastructure is separate systems being implemented in parallel in cities. For example, public transportation authorities plan their charging networks for buses, logistics companies have separate electric vehicle fleets, and city maintenance has its own system with electric vehicles unable to utilize previously mentioned actors' chargers. These problems were identified during a case study in Helsinki by Paakkinen et al. [25], which showed that the utilization rate of public city bus chargers is low, thus remaining time can be used to charge other vehicles and thereby increase utilization. Moreover, it was pointed out that the profitability of end-station city bus chargers can be increased by sharing chargers between modes, since end-station chargers that are serving only one route tend to have low utilization rates. But it must be taken into account that limitations arise when an external actor charges at a designated bus charger and thus blocks the charger, therefore two or more connections are needed to not disturb the bus schedule [25]. Finally, it was highlighted that a well-developed charging infrastructure can speed up the implementation process of electric vehicles in society.

3.2 Power grid capacity and future energy demands

Västra Götaland is one of the regions in Sweden that consumes the most electricity, but only produces about a third locally [26]. In the near future, more industries will be built in the region, in addition, the industries along with the transport sector will be electrified, resulting in a greatly increased energy demand. An extensive network expansion by Svenska Kraftnät is planned, and by 2035 the power output will have increased to 1200 MW, but the demand for the region will be even greater [26]. However, a large increase in energy demand is likely to be seen in the nearby time (before grid extensions have been carried out), putting pressure on local distributors to ensure sufficient electrical power. Therefore, to ensure sufficient electrical power and take the uncertainties of increased load due to electrification of transports; flexibility services and energy storage will be important solutions, based on personal communication with Charlotta Klintberg [27]. Thereby, electrification does not necessarily have to result in negative impacts on the grid, but can rather be of great contribution if using innovative and flexible solutions in combination with a system perspective.

A model simulating how the electric grid in Gothenburg will manage large-scale electrification of the transport sector has been developed in a project called *PussEL* [28]. The results showed that it will entail a significantly increased electricity demand and such action will create a risk of overload in some parts of the distribution grid. If the grid capacity is not extended, critical hours will be during mornings (before work and school) and in the evening when people return home and plug in their BECs for overnight charging. For the grid to handle an increased load, smart charging is recommended (and assumed when using the model) which allows a shift of peaks to hours with less base load [28]. Furthermore, an increased amount of BEVs in central parts of Gothenburg will presumably have an effect on the required charging infrastructure in surrounding municipalities, which is why charging stations will be needed to be developed in a widespread network.

To make shared charging infrastructure between BEBs and heavy-duty electric vehicles (HD-EVs) sustainable and well-functioning, a standardization of charging technologies is a necessity [14]. Charging technologies available are either dynamic or static, where the latter shows a greater efficiency potential and refers to pantographs or plug-in charging alternatives. Pantographs mounted on vehicle roofs are the most beneficial since this creates a more resilient system, e.g. if a vehicle-mounted charger is damaged, other vehicles can still use the charging infrastructure. However, it should be mentioned that it increases the weight of the vehicle and hence might not be considered an option [14]. Moreover, interoperability between vehicles and chargers of different manufacturers is pointed out as essential. According to Far et al. [14] strict charger standards reduce costs and ensure functionality, compatibility, and interoperability. However, interviews from the same study with end users, indicate that interoperability was considered more important between vehicles within the same category, while shared charging between different modes was considered less important.

3.3 Infrastructure planning and charger locations

One dilemma when examining charging infrastructure is whether the number of vehicles or the number of chargers is the detrimental factor [25]. For example, whether the charging network should be well established before the number of BEVs increase, or if BEVs need to increase in number to put pressure on the construction of chargers. From one perspective, vehicle development and the urgent need for CO_2-emission reduction speaks for the prior alternative, but from another perspective, a well developed infrastructure network is needed to remove the range anxiety problem and enable a somewhat similar driving pattern as for internal combustion engines (ICE) vehicles [5]. Since BECs and light-duty electric vehicles (LD-EVs) are already being used to some extent, and range anxiety has occurred, it is useful to use this insight when planning for HD-EV charging networks. In a study by ACEA and Fraunhofer ISI [29], charger locations for trucks in relation to the Trans-European Transport Network (TEN-T), seen in Figure 3.1, were investigated. For the chargers to be maximally utilized they should be placed along the TEN-T and where most trucks usually stop along their route (during night stops or breaks). The required charger powers are indicated by the average time at each stop (where longer stops would require less charging power and shorter stops would require higher charging power) [29].

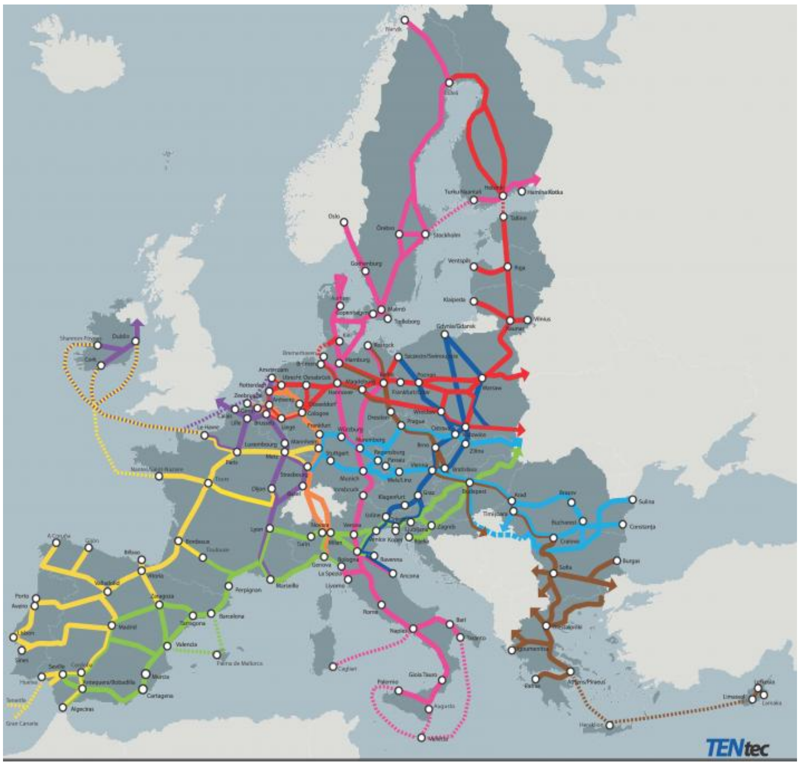


Figure 3.1: Map over the Trans-European Transport Network (TEN-T), showing the connecting nodes.

If looking at possible charging locations for buses, they have a strict operational schedule with fixed times, which becomes a limitation when planning shared charging infrastructure between modes where buses are included [24]. More specifically, possible charging times are time slots between routes, or at night outside operation times. As a consequence, the layout of the charging infrastructure networks has to be carefully planned to ensure sufficient battery power for buses during their routes. Therefore a large-scale electrification of the transport sector (using shared charging) will require a new hierarchy where scheduled modes are prioritized to prevent delays due to charging queues [25].

A detrimental factor when planning charging infrastructure for buses are battery capacity. Batteries suitable for end-station charging generally have smaller capacities since it is possible to charge regularly throughout the day [30]. Such infrastructure requires high-power chargers, and suitable batteries for this type of charging tend to be expensive and heavy. Batteries optimized for depot charging instead tend to have a larger capacity since they are aimed to be used in similar ways as traditional buses without needing to charge during the day. When charging during the night lower charger power is used since charging times are long [30].

An important aspect when installing chargers for electric buses is the utilization rate. To achieve a high utilization rate the location of the charger is essential according to Olsson et al [30]. The study states that end station chargers are more beneficial than placing them along the route, both in aspects of utilization rate and avoiding passengers waiting for the charging to be finished.

3.4 Research gap

Electrification of heavy vehicles is a developing area, with few vehicles in operation, resulting in insufficient information on mileage, charging demands, and charging locations. Continuing, the shift towards sustainable fuels and more electric vehicles comes with large investment costs for involved stakeholders when installing chargers and developing vehicles. A detrimental factor for the decision-making is the utilization rates of chargers, if it is too low the investment will be considered nonprofitable. In the early adoption phase with few vehicles and relatively low utilization rates, a possible solution can be to share charging infrastructure between different transportation modes. But as highlighted in the study by Ye et al. [24], shared charging between BEBs and HD-EVs is a limited area of research where further investigations are needed.

4

Method

A gap analysis was primarily used to estimate the demand for shared charging infrastructure between buses and trucks in Västra Götaland. The current situation serves as a base case, then a future scenario where all transport modes are fully electrified is assumed as the target, leaving the lack of charging infrastructure to get from the base case to the ideal scenario (with fully electrified transports) as the gap. In the analysis, both the visible charging infrastructure network (such as chargers) and the electric grid were considered when evaluating the possibilities and consequences of implementing shared charging infrastructure.

To create an overview of the impact electrification of transports has on a city's power grid, a case study was used as part of the method. Lysekil was chosen for the case study, believed to be a good representative because it has several different modes of transport in the area that can potentially be electrified in the future and in addition, has a fairly large seasonal activity variation.

When estimating charging infrastructure demand, each mode was treated separately because of different driving patterns, charging flexibility, and available information. The energy demand and charging possibilities for all modes of transport were compiled in the last part of the method, where load curves for future energy demand in Lysekil due to the electrification of transports were estimated. Figure 4.1 is a conceptual image of the process used in the case study.

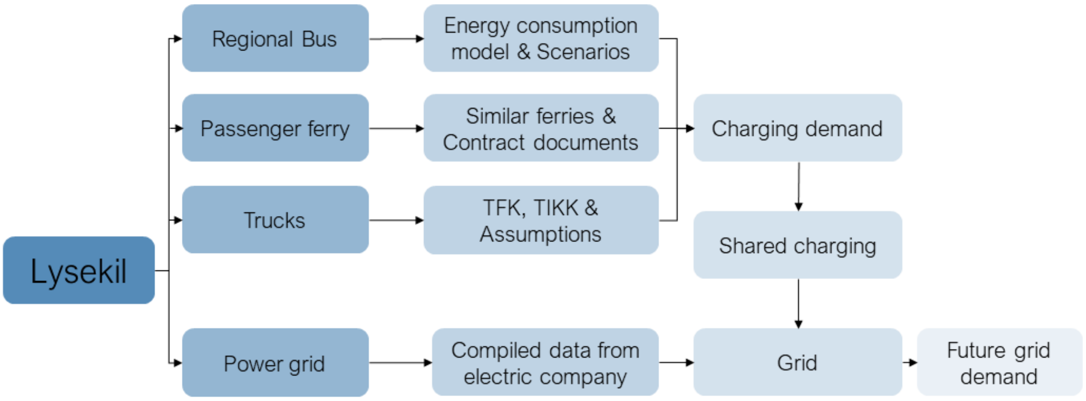


Figure 4.1: Conceptual image of how the case study in Lysekil was conducted with the different methods used for each transport mode and grid

4.1 Case study Lysekil

Lysekil is considered suitable for a case study investigating the possibilities of shared charging infrastructure since several different transportation modes passes through, take longer breaks, or stop overnight. Regional bus line **841** connects Lysekil with Gothenburg and additional local bus lines operate in Lysekil. The passenger ferry line **847** between Lysekil and Skaftö will be electrified at the end of 2023 and will charge at Lysekil harbor [31]. The industrial activity is rather large due to a building materials distribution center and other services located in the Lysekil harbor. Continuing, Lysekil was marked as a place suitable for truck charging in a study examining charging location with respect to the TEN-T network where a need for fast charging of trucks is indicated [29]. Figure 4.2 illustrates examined transport modes i in Lysekil.

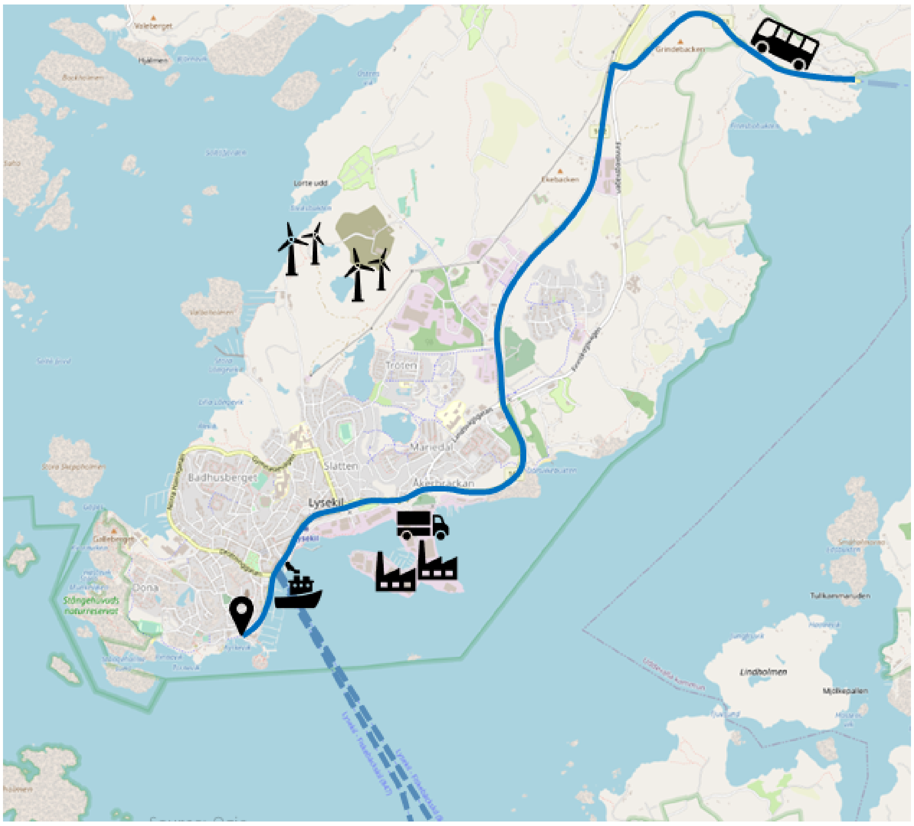


Figure 4.2: Map over Lysekil showing the different transport modes in Lysekil that were investigated in the case study

Overall activity in the city increases notably during summers due to tourism and summer residents, which can be seen in the interactive maps TFK from the Swedish Transport Administration [32], showing a 100% increase of traffic flow. The electric distribution in Lysekil is managed by LEVA i Lysekil AB [33] which is responsible for the local grid (with voltages up to 10 kV as well as low voltage connections of 400 V to villas etc.). Besides electricity distribution, LEVA has some local electricity production with two wind turbines and solar panels (producing approximately 15 GWh/year) that contributes to the electricity production, see location in Figure 4.2.

4.2 Battery electric bus

Bus charging infrastructure demand was estimated by first calculating the energy consumption for a bus during its route if being electrified. Moreover, seasons were taken into account when estimating the energy consumption for buses in the aspect of more energy consumption during hot/cold days due to cooling/heating, and battery performance. Secondly, different charging opportunities were identified from existing driving schedule. It formed a framework for charging scenarios that in turn were used to calculate energy demand for the bus line using different battery sizes, charging powers, and charging times. Finally, the needed charging infrastructure could be estimated for each scenario.

4.2.1 Bus line 841: Lysekil - Gothenburg

Bus 841 is a long-distance route with varying characteristics that affect the bus's energy consumption in different ways. The route between Gothenburg and Lysekil in total is 110 km and can be seen in Figure 4.3. This route was divided into two different sections (A and B) where the energy consumption varies. Section A between Torp and Lysekil contains frequent bus stops with a distance of 29 km, driving on smaller local roads "161" and "162". Section B between Gothenburg and Torp contains a few stops with a long distance of 82 km, driving mainly on the E6 highway.

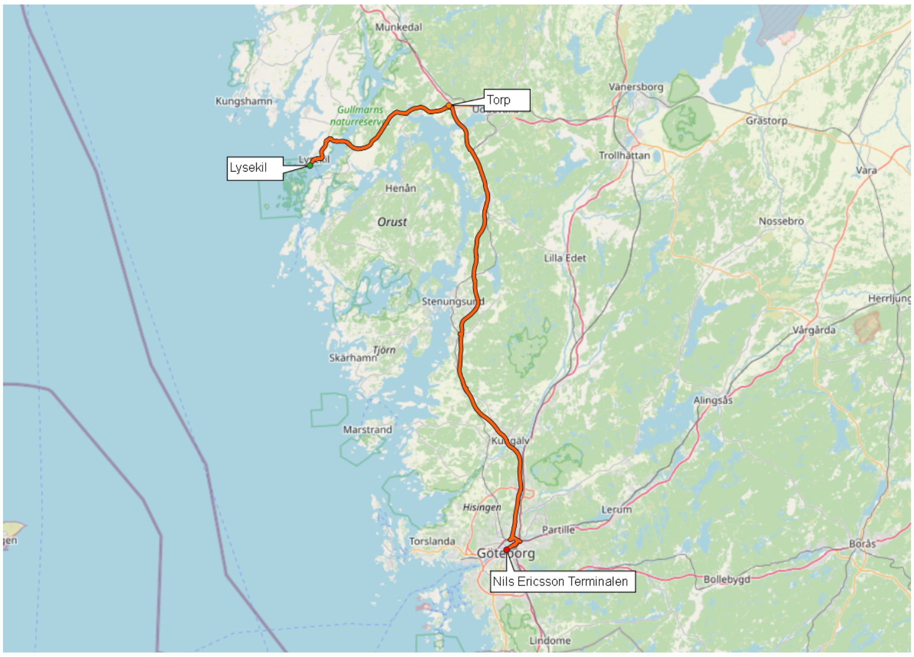


Figure 4.3: Bus route of Bus 841 from Lysekil to Nils Ericsson terminalen in Gothenburg passing through Torp.

Torp is an infrastructural node that is located along the E6 highway, where several transport modes passes by. It was mentioned during a meeting with Johan Bergek at VY Buss [34] that all different bus routes are adapted to seamlessly flow through Torp with as short layovers as possible for the commuters, leaving the slots to be too short to be suitable for charging at this location. Line 841 is operated by buses that also drive other routes as displayed in the timetable in Appendix A.1. According to this schedule, there is one bus (highlighted in the figure) that only runs the 841 line and this bus was used as a reference when electrifying bus 841.

4.2.2 Energy consumption

Based on a previously developed model the bus's energy consumption if being electrified was estimated. The model considers several different road and vehicle characteristics such as: route distance, height variations, speed limits, vehicle weight, acceleration/deceleration, and battery size [35]. A topographical profile was created using data from the Swedish Transport Administration and its interactive database "Lastkajen" [36]. The data was refined in QGIS to extract information relevant to line 841, in Figure 4.4 the topography for the route is presented.

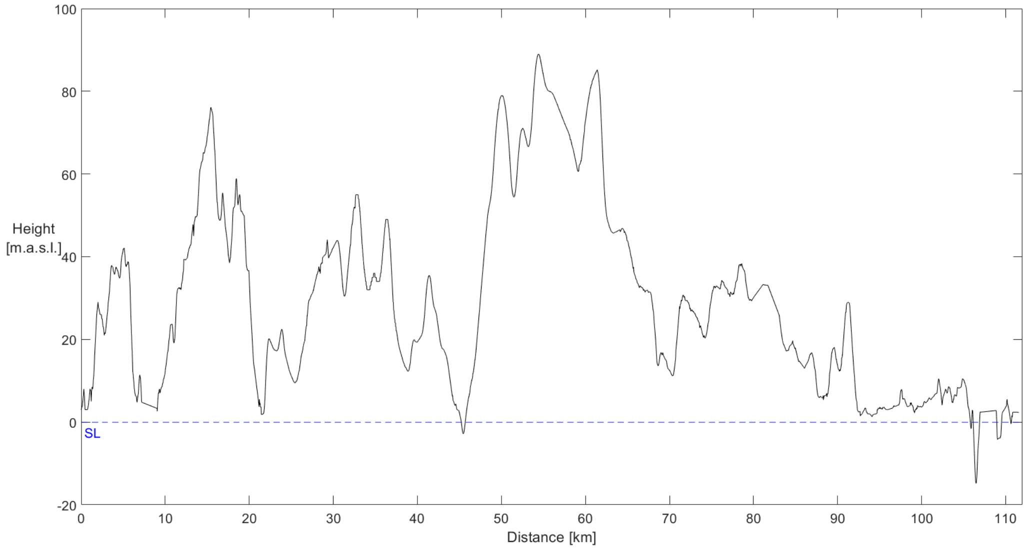


Figure 4.4: Height profile of route 841 between Lysekil and Gothenburg where the dotted blue line corresponds to the sea level.

Obtained topographical data (divided into segments) were further used as input in the model when calculating energy consumption, and energy gained using regenerative braking, during operation. The energy consumption model uses the following input data from Table 4.1 to calculate the energy consumption for the bus. Moreover, since these types of vehicles do not yet exist but are under development, the specific vehicle attributes were obtained through the DREEMER project as an estimation of future vehicle characteristics with a combination of similar features that were used in the previous study [35].

Table 4.1: Input values used as input in the previously developed energy consumption model.

Parameter	**Notation**	**Electric bus**
Total mass[a] [kg]	m	26500
Front area of vehicle[b] [m2]	A	7.2
Air resistance coefficient [-]	C_D	0.61
Rolling resistance coefficient[d] [-]	C_r	0.007
Accessory power[c] [kW]	P_{acc}	9
Acceleration[c] [m/s^2]	a	1
Deceleration[c] [m/s^2]	a	-1
Peak electric motor output[a] [kW]		350
Regeneration power limit[a] [kW]		350

[a] Based on personal communication with Henrik Bojö at Volvo Buses [37] and is an estimation of future vehicles.

[b] Area estimation based on similar vehicles operating today [38].

[c] From previously developed energy consumption model [35].

[d] Calculated based on IRI and MPD values from Trafikverket [36].

Estimation of energy demand for Bus 841 between Lysekil and Gothenburg if being electrified, was carried out using different scenarios to see what sort of charging infrastructure is needed. When forming the scenarios, the existing timetable for Bus 841 was taken into account to see how much time there was available for charging at the end stations. Different battery sizes were used when simulating the scenarios to optimize battery capacity. The simulated power output of the end-station chargers was 500 kW, and the utilization of the charger was observed to see the impact from charging on the grid. As the seasonal variations and temperature affect the energy consumption differently it is assumed to have a noticeable impact. Based on personal communication with Markus Sirnemark at Volvo Buses [39] the total energy consumption during the summer has an increase of 20%, and 50% during winter (compared to energy consumption during standard conditions).

Since the buses that are being simulated in the following scenarios are not operating on a larger scale, assumptions had to be made based on existing models and personal communication with Henrik Bojö at Volvo Buses [37]. The chosen battery sizes were:

- 350 kWh: battery size of currently operating city buses.
- 500 kWh: battery sizes the long-range buses currently under development will be equipped with.
- 650 kWh: battery capacity prototypes are stated to have [40].

The weight of the different battery sizes differs according to the energy-weight ratio [18]. The energy consumption model (used in the previous step of the method) uses the maximum weight of the vehicle as a parameter, therefore the different battery sizes (and corresponding weight increase) will only limit the cargo of the vehicle. In this case the number of people. In other words, a larger battery size is equal to less cargo/passenger to be carried.

4.2.3 Scenarios

Following presented are the used scenarios with motivations of why each scenario was used, with respective charging times listed in Table 4.2.

Scenario 1: The first scenario was performed according to the timetable, see Table 4.2, excluding any delays in the route. The scenario was performed to see if the bus would manage a whole day on only one charge (overnight charging) or how many trips the bus would manage before the battery was depleted.

Scenario 2: Second scenario was performed according to the timetable (excluding delays in the route), but the bus was allowed to charge as much as possible at both end stations (Lysekil and Gothenburg). Assumptions were made that the bus started to charge directly when entering the end station. The purpouse was to see if the existing timetable could still be used when using electric buses instead.

Scenario 3: For the third scenario the timetable was modified, allowing the bus to charge for one hour (between arrival and next departure) at the end station in Lysekil, simulating the use of at least one extra bus. Moreover, battery health was taken into consideration in the scenario, restricting state of charge (SOC) levels to a maximum of 90% and a minimum of 20%, based how existing electric vehicles operates. The charging stopped when the battery level reached 90%, and stood still for the remaining time before departing.

Table 4.2: Minutes available for charging at each location in the three scenarios.

Charging Location	Charging times Scenario 1 & 2	Charging times Scenario 3
Gothenburg	8	0
Lysekil	5	60
Gothenburg	32	0
Lysekil	5	60
Gothenburg	38	0
Lysekil	5	60
Gothenburg	38	0
Lysekil	5	60

4.2.4 Charging infrastructure demand

Resulting charging times from conducted Scenarios were used as input in further Matlab calculations to evaluate the need for charging infrastructure. The charging times were used for calculations of utilization rate for the charger, and together with the assumed charging effect, the resulting load on the power grid could thus be calculated.

4.3 Electric trucks

Charging demand for trucks was based on the traffic flow of heavy vehicles from measurements of average daily traffic (ADT) conducted by the Swedish Transport Administration's and published on their interactive databases *TIKK* and *TFK* [32]. The most recent data from Trafikverket available on the examined route is from 2021, but it was considered inaccurate due to COVID-19 (with less movement in the traffic compared to earlier years). Therefore, data from earlier measurements during 2017 was chosen to be further evaluated. The ADT-data was used to see the flow of trucks to/from Lysekil, and to estimate how many trucks stay during the night, thus needing overnight charging. Moreover, the ACEA study [29], identifying charging spots close to the TEN-T-network was also used as basis. The report identifies Lysekil as a place where fast charging for trucks will be the main demand, rather than overnight charging. In addition, this also leads to an assumption that every truck stopping to load/unload at the Lysekil industrial area will charge during the day.

To evaluate how the charging of electric trucks affects the electric grid the following aspects are taken into account:

- The number of trucks traveling to Lysekil that needs to be charged
- An average time the trucks spend in Lysekil loading/unloading the trucks
- The time of the day the trucks need to be charged
- The number of trucks spending the night in Lysekil

To get an additional indication of how the driving pattern for trucks is to and from Lysekil, local logistic centers, and distribution centers were contacted, and a study visit was made to Lysekil. According to Peter Sjöstrand at SDK shipping [41] from one of the largest logistic distributors in the Lysekil area, they process 18-20 trucks/day in the low season and 28-30 trucks in the high season (April-September). The time that the trucks spend loading and unloading is between 40 min to 4 hours and they have around 2 trucks that spend the night in the distribution center. Peter further mentioned that trucks operating for this specific logistic center come from all over Sweden and Northern European countries.

4.3.1 Trucks Charging in Lysekil

According to Bergman & Axelsson [42] the expected share of newly produced trucks that will be electric by 2030 is 50%, which is high but based on the fact that Sweden will probably be one of the leaders in the development. Keeping in mind that there are still ICE trucks in operation, the electric truck share is assumed to be 16 % of the traffic flow. Applying this on Lysekil, with data retrieved from Trafikverket [32] and personal contact with logistics companies [41], assumptions for the traffic flow of heavy trucks were made. In Figures 4.5 and 4.6 below the traffic flow is presented as it is today (with conventional trucks). Considering that the traffic flow data from Trafikverket is gathered from the main road to Lysekil, it is valued as reliable data of the flow. However what type of heavy vehicle is uncertain since local heavy vehicles such as garbage trucks and local buses are included in this data.

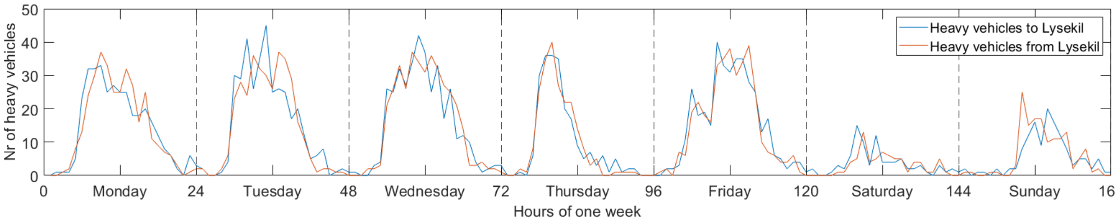
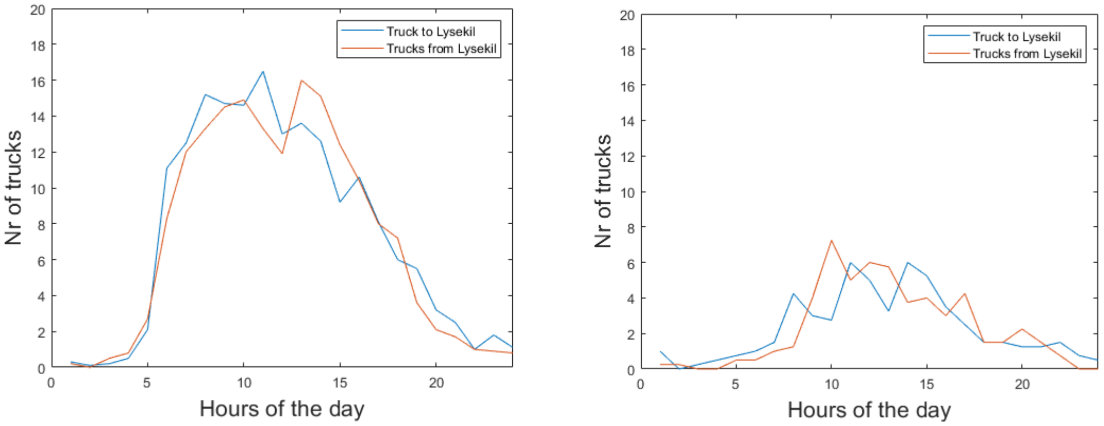


Figure 4.5: Heavy traffic flow to/from Lysekil weekly.



(a)

(b)

Figure 4.6: Average traffic flow of electric trucks to/from Lysekil on **(a)** weekdays and **(b)** weekends.

Estimated charging demand was based on the following assumptions: every truck entering Lysekil needs charging, the average time each truck spends loading/unloading is 1 hour, and the trucks are charging during this period with a charging power of 350 kW. This gave an indication of how the charging demand from trucks can impact the electric grid in the future. Moreover, the traffic flow from TFK also confirmed statements from the logistic company that there are few trucks staying in Lysekil during the night, which was important when examining night charging possibilities.

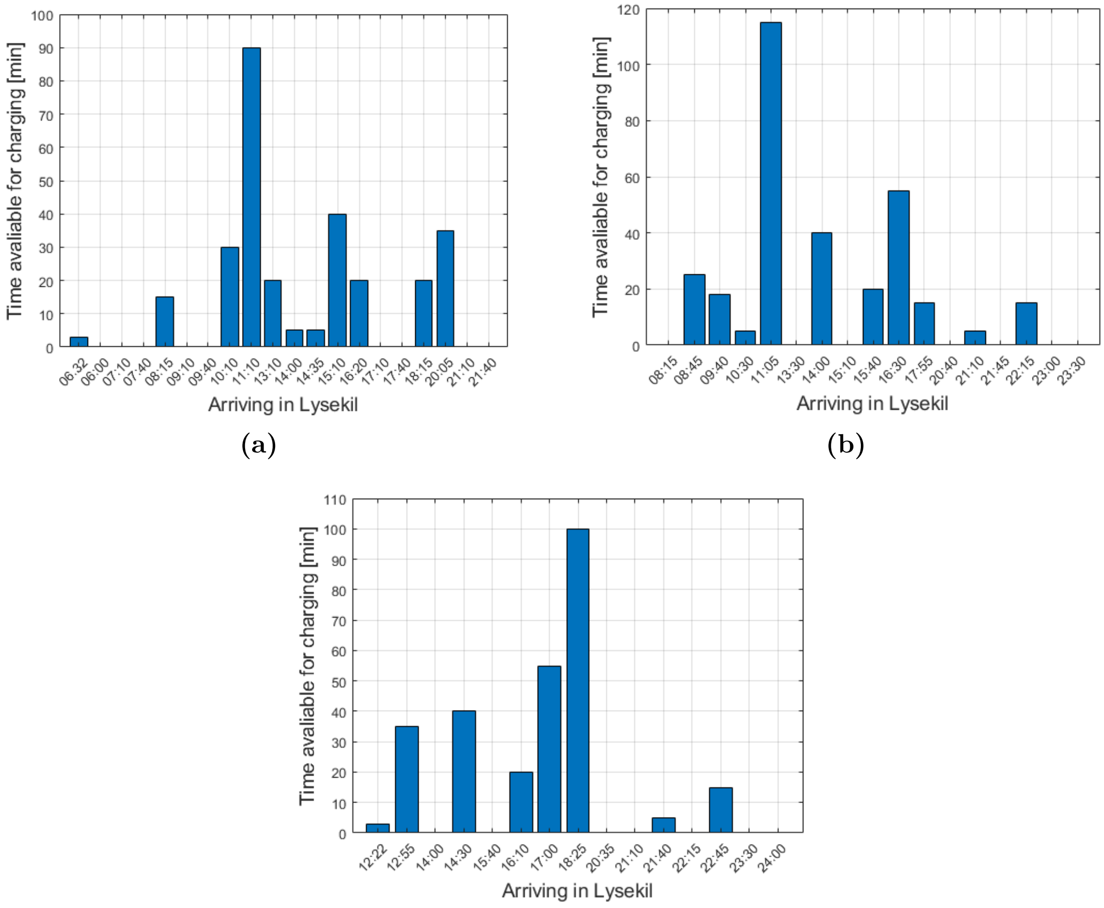
4.4 Electric passenger ferry

The passenger ferry that is operating today in Lysekil is line 847 between Lysekil and Skaftö displayed in Figure 4.7. This ICE ferry will be exchanged with a fully electric passenger ferry that will start operating by the end of 2023. Estimations regarding the ferry charging will therefore be based on Västtrafik's timetable request for the electric ferry in Lysekil, and hybrid electric ferries operating in Gothenburg (which are assumed to have a similar battery capacity and characteristics).

Figure 4.7: Passenger ferry line 847 between Lysekil, Skaftö and Fiskebäckskil.

The contract documents regarding the electric passenger ferry from Västtrafik include a timetable that the operator needs to fulfill. This is a general timetable that has not taken charging into account, therefore the driving schedule can change when the electric ferry is taken into traffic, but was however used as a basis when estimating charging demand. The charging demand for the ferry was based on personal communication with David Öberg [43] during a study visit to the hybrid electric passenger ferry *Eloise* that operates in Gothenburg. The study visit gave an indication of the characteristics such as battery capacity, energy consumption, and charging demand, found in Table A.1 of Appendix A.

According to the timetable, the ferry in Lysekil operates for as long as 18 hours in the summer which would require charging during the day. The time that is available for charging during the day is displayed in Figure 4.8. The charging of the ferry is limited to stops that are 20 minutes or longer since shorter charging is considered ineffective in this case. During the night the ferry will be charging with a lower power output from 20 % to 90% of the total capacity.



(a) **(b)**

(c)

Figure 4.8: Time available for charging i Lysekil **(a)** Monday-Friday, **(b)** Saturdays and **(c)** Sundays.

4.5 Electric grid

Since the activity in Lysekil has large seasonal variations it was of interest to examine the load on the grid during summer respectively winter when evaluating the grid's possibility to manage the future electrification of transports. Through personal communication with the electric distributor *LEVA i Lysekil AB* [44], information regarding energy bought in the municipality was obtained with an hourly resolution, see Figure 4.9. The data presented energy consumption during 2022 but did not contain information regarding self-produced energy. However, this information gave a good basis for calculating an average seasonal base load, as seen in Figure 4.10. The maximum capacity of the grid is 38 MW, which leaves space in the grid during both summer and winter on average. However, if looking at the worst week during winter in Figure 4.11, there is approximately 6 MWh left of the capacity during peak hour on the worst day (Thursday).

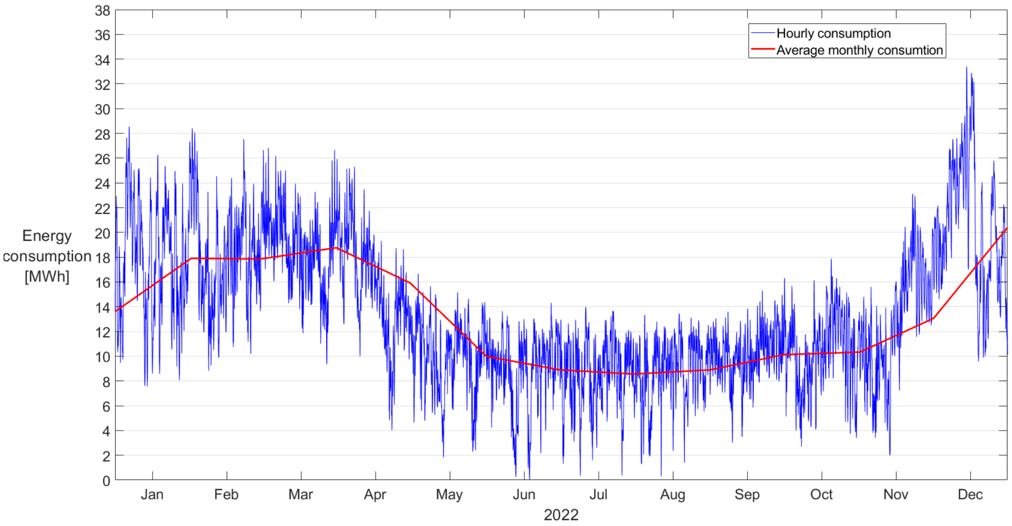


Figure 4.9: Electricity consumption in the Municipality of Lysekil during 2022, with an hourly and average resolution.

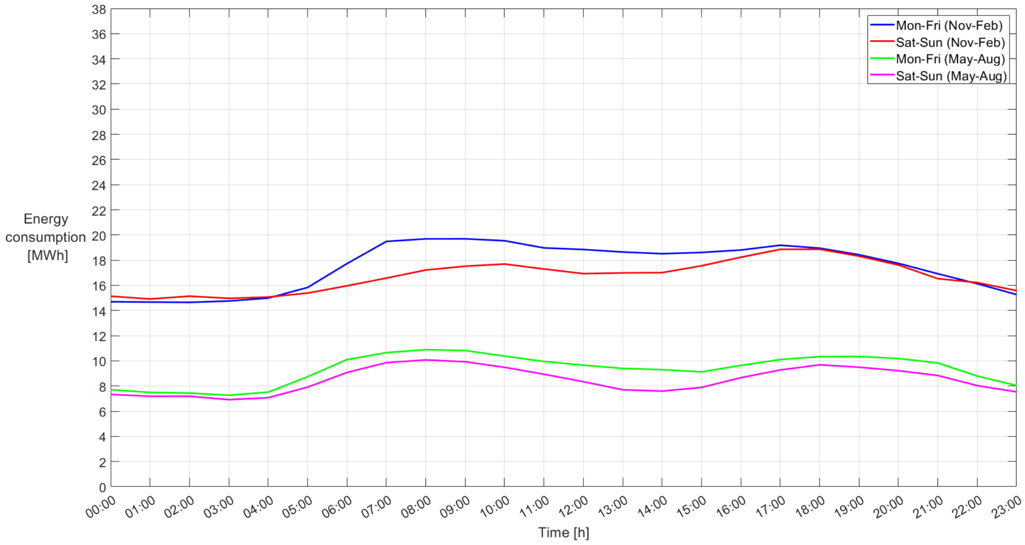


Figure 4.10: Average base load on weekdays and weekends during summer and winter in the municipality of Lysekil.

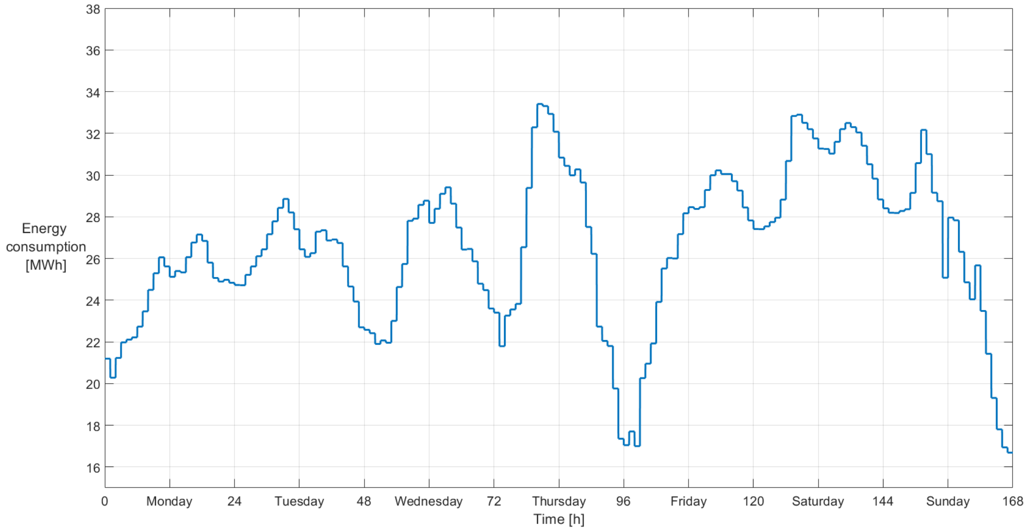


Figure 4.11: Energy consumption in Lysekil municipality during the worst week of the year 2022 in December.

Within the base load, home charging and public charging of BECs are included, where public charging was responsible for an electric consumption of 86 MWh in 2022, while the consumption from home charging is unknown. However, the share of electric personal cars during 2022 in Sweden was 4% [45]; therefore, the proportion corresponding to home charging in Lysekil is assumed to be small. But since the BEC fleet is expected to increase rapidly, future load from home charging will presumably have a significant impact on the grid, hence important to keep in mind when estimating future demands.

5

Results

This chapter aims to present and summarize the charging demands for each investigated transport mode and evaluate their effect on the power grid and aims to answer the research questions **(1)** and **(3)**. The results are commented on and briefly discussed to put them in context.

5.1 Charging infrastructure demand for regional electric buses

5.1.1 Energy demand

For one round trip on bus line 841 (Lysekil-Gothenburg-Lysekil) energy consumption and regeneration (through regenerative braking) are illustrated in Figure 5.1 below, where regeneration corresponds to the negative values. The energy consumption was calculated under standard conditions using a mean temperature in Gothenburg of 10.5 °C. If comparing the peaks in Figure 5.1 to the height profile presented in Figure 4.4, the energy consumption peaks occur when driving uphill while regeneration is at its largest when driving downhill.

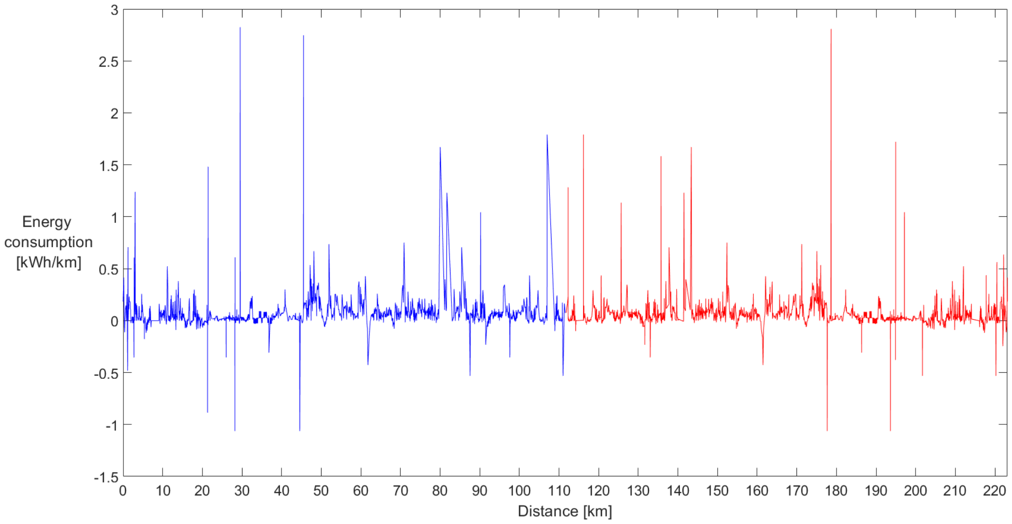


Figure 5.1: Energy consumption and regeneration during one round trip for bus 841 under mean temperature in Gothenburg.

With a driving distance of 220 km for one round trip, an average consumption of

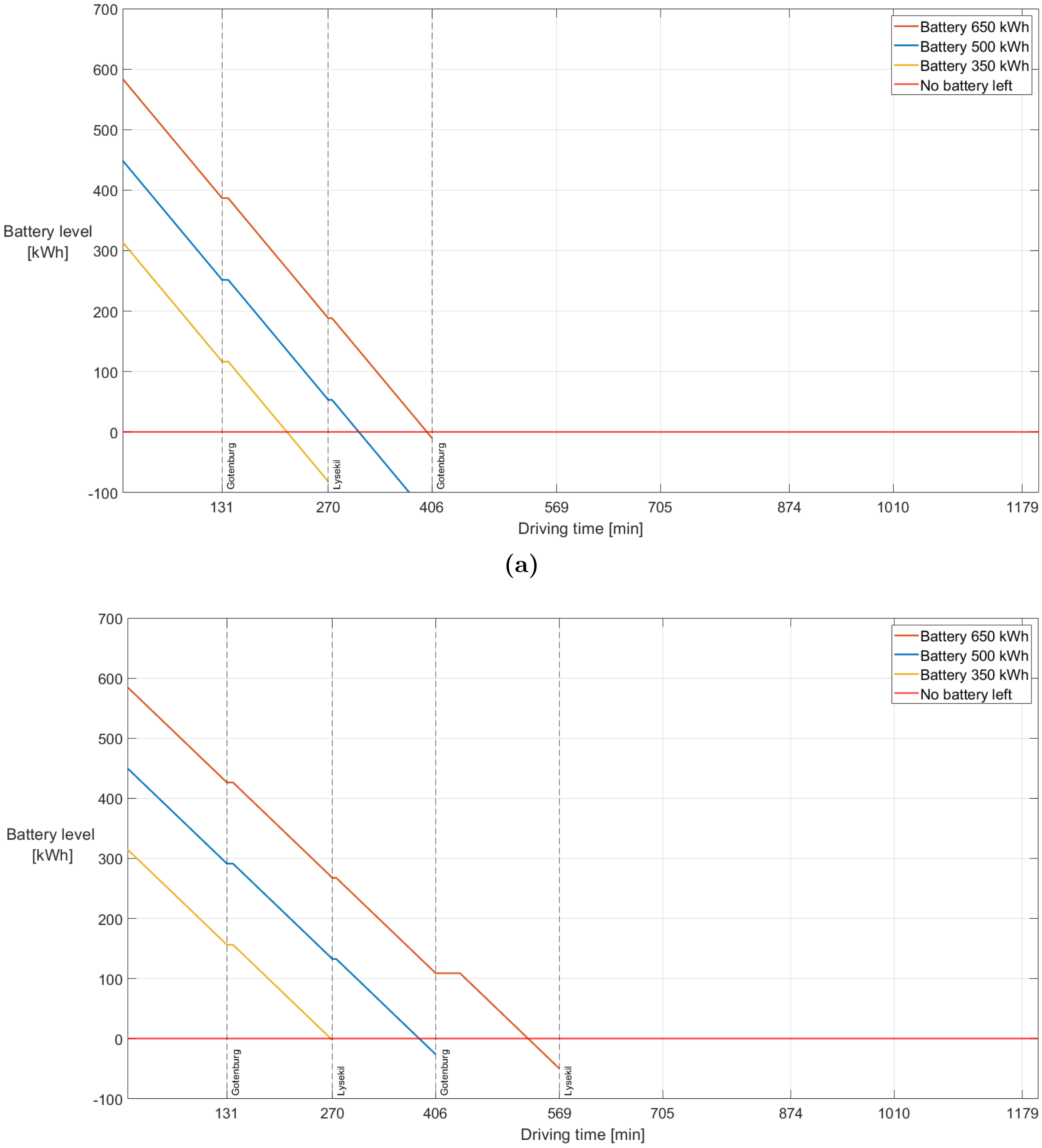
1.25 kWh/km was calculated, which with increased consumption during summer and winter resulted in 1.44 kWh/km and 1.80 kWh/km respectively. The energy consumption between seasons differ depending on increased accessory power for heating/cooling, and battery performance.

5.1.2 Regional bus charging infrastructure demand

For the three conducted scenarios, results when considering different battery sizes, required charging times, and charging infrastructure could be derived and are presented in following sections. A common denominator and decision-maker for whether the scenario was considered working or not was if the SOC stayed between the set limits of 90-20%, which are set considering battery health. For the graphs in Figure 5.2, 5.3 and 5.4, illustrating the battery levels, increasing parts corresponds to charging, descending parts to driving and flat parts when the bus is not charging but awaits the next departure.

5.1.2.1 Scenario 1

In Scenario 1, overnight charging was simulated to see if the bus could manage a whole operating day without the need for charging. It can be seen in Figure 5.2 (a) and (b) that for all three battery sizes, it is not possible to use only overnight charging, neither during summer nor winter, since the batteries are depleted before the day's end. To only use depot charging, a battery of approximately 2100 kWh would be needed (to manage operation during winter with corresponding consumption of 1.80 kWh/km). In Table 5.1 below, the SOC and battery levels at the end stations are shown in detail at each stop during operation.



(a)

(b)

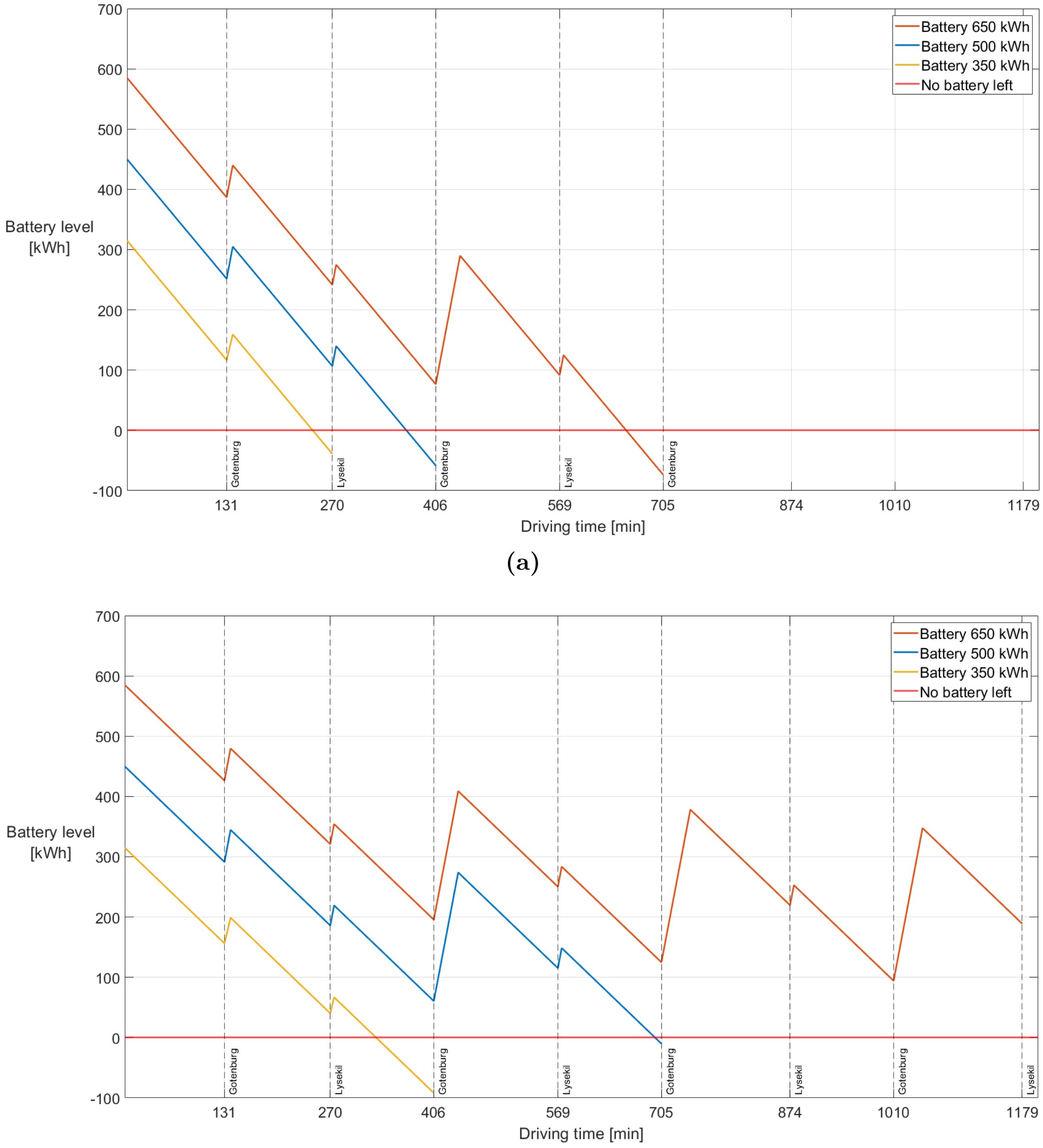
Figure 5.2: Battery level for examined battery sizes using only depot charging during **(a)** winter and **(b)** summer.

Table 5.1: Battery level and corresponding SOC for examined battery sizes in Scenario 1 at different locations and seasons.

	350 kWh				**500 kWh**				**650 kWh**			
	Summer		**Winter**		**Summer**		**Winter**		**Summer**		**Winter**	
Charging Location	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**
GBG	156	45%	117	33%	291	58%	252	50%	426	66%	387	60%
Lysekil	0	0%	0	0%	133	27%	53	11%	268	41%	188	29%
GBG	0	0%	0	0%	0	0%	0	0%	109	17%	0	0%
Lysekil	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
GBG	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
Lysekil	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
GBG	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
Lysekil	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%

5.1.2.2 Scenario 2

When charging as in Scenario 2, using a charging power of 500 kW (at every minute available in the existing timetable for bus 841, see Table 4.2), it can be seen in Figure 5.3 (a) that no battery option will manage such conditions during winter. For summer, a battery of 650 kWh could manage the conditions, see Figure 5.3 (b), but if looking at the specific values in Table 5.2 the SOC is reaching as low as 14%, which is under the desired limit of 20%. In addition, 14% left upon arrival is rather close to the battery being discharged which leaves a small safety margin. It could be a possibility to use a charger with higher power output (e.g. 1 MW charger) but since the longer charging times takes place in Gothenburg, where the power grid is at risk for congestion in the future, it is not desirable to put an even higher load on the grid in Gothenburg.



(a)

(b)

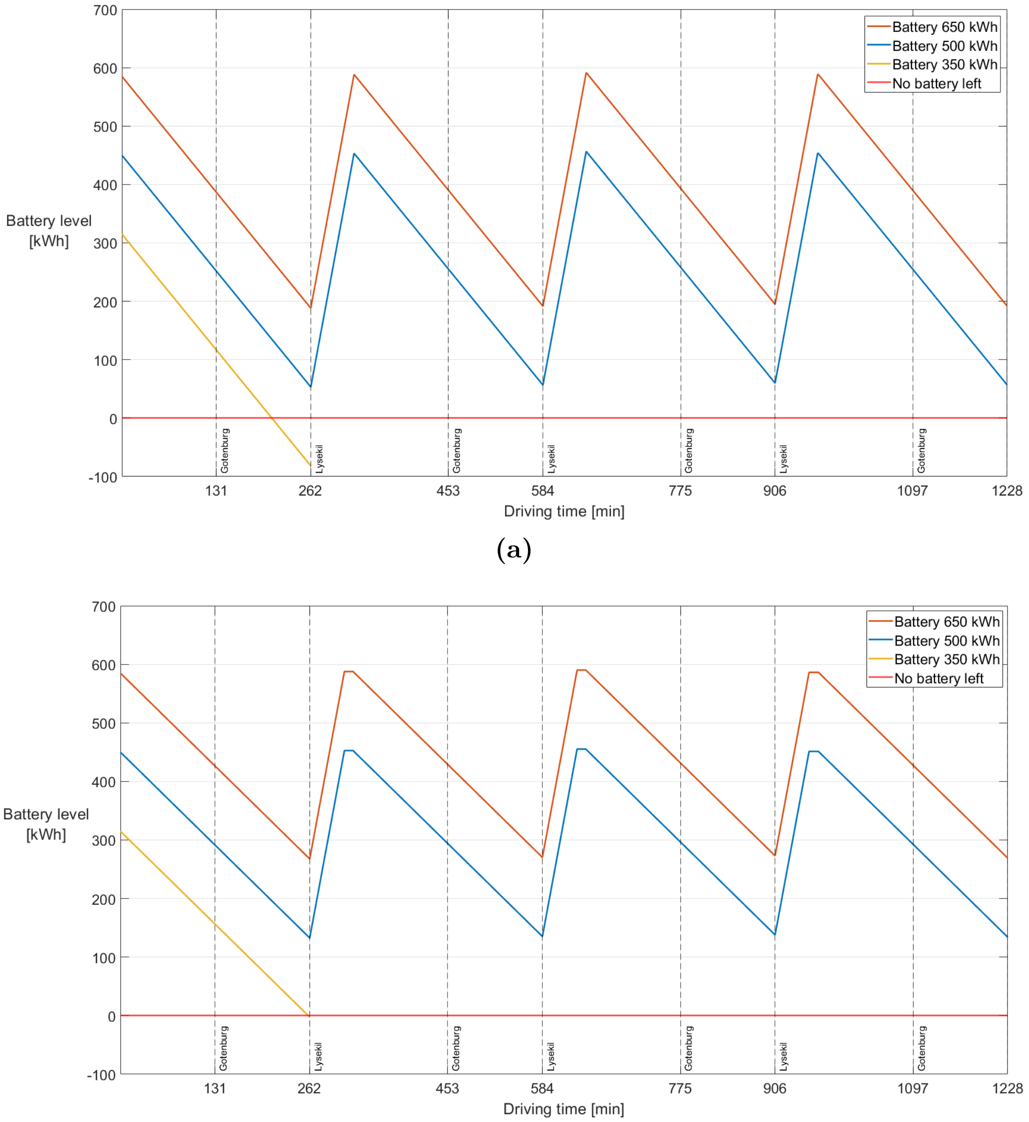
Figure 5.3: Battery level for examined battery sizes when charging at every minute available in the existing timetable during **(a)** winter and **(b)** summer.

Table 5.2: Battery level and corresponding SOC for examined battery sizes in Scenario 2 at different locations and seasons.

	350 kWh				**500 kWh**				**650 kWh**			
	Summer		**Winter**		**Summer**		**Winter**		**Summer**		**Winter**	
Charging Location	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**	**Battery Level**	**SOC**
GBG	156	45%	117	33%	291	58%	252	50%	426	66%	387	60%
Lysekil	40	11%	0	0%	186	37%	107	21%	321	49%	242	37%
GBG	0	0%	0	0%	61	12%	0	0%	196	30%	77	12%
Lysekil	0	0%	0	0%	115	23%	0	0%	250	38%	92	14%
GBG	0	0%	0	0%	0	0%	0	0%	125	19%	0	0%
Lysekil	0	0%	0	0%	0	0%	0	0%	220	34%	0	0%
GBG	0	0%	0	0%	0	0%	0	0%	94	14%	0	0%
Lysekil	0	0%	0	0%	0	0%	0	0%	191	29%	0	0%

5.1.2.3 Scenario 3

In Scenario 3 the timetable was modified to simulate a situation using at least one extra bus, and charging occurred upon arrival in Lysekil until the second next departure. Looking at the summer conditions, displayed in Figure 5.4 (b), both a battery of 500 kWh and 650 kWh would manage to operate according to Scenario 3 and stay within desired SOC range, see Table 5.3. For the winter conditions that can be seen in Figure 5.4 (a), the 650 kWh and 500 kWh batteries are not discharged during the route. However, if looking at the SOC for the 500 kWh battery option in Table 5.3, the values reach 11% when arriving for charging in Lysekil. This is considered too low, and therefore the only battery option to fulfill desired SOC is the 650 kWh battery. As a result, to electrify line 841 a battery of 650 kWh would be necessary, which is considered large as current models have batteries mainly in the range between 300-500 kWh. However, since the 500 kWh battery option can manage summer conditions, a possible solution is to use a 500 kWh battery with backup charging when critical weather conditions prevail. And as technology rapidly develops and energy densities increase (kWh/kg), it will enable greater ranges, and thereby a battery of 500 kWh could in the future also be an option that does not require extra charging.



(a)

(b)

Figure 5.4: Battery level for examined battery sizes when charging for 1h in Lysekil during **(a)** winter and **(b)** summer, using a power output of 500 kW.

Table 5.3: Battery level and corresponding SOC for examined battery sizes in Scenario 3 at different locations and seasons.

	350 kWh				500 kWh				650 kWh			
	Summer		Winter		Summer		Winter		Summer		Winter	
Charging Location	Battery Level	SOC	Battery Level	SOC	Battery Level	SOC	Battery Level	SOC	Battery Level	SOC	Battery Level	SOC
GBG	156	45%	116	33%	291	58%	252	50%	426	66%	387	60%
Lysekil	0	0%	0	0%	133	27%	53	11%	267	41%	188	29%
GBG	0	0%	0	0%	294	59%	255	51%	429	66%	390	60%
Lysekil	0	0%	0	0%	135	27%	57	11%	270	42%	192	30%
GBG	0	0%	0	0%	297	59%	258	52%	431	66%	390	60%
Lysekil	0	0%	0	0%	138	28%	60	12%	273	42%	194	30%
GBG	0	0%	0	0%	293	59%	255	51%	428	66%	389	60%
Lysekil	0	0%	0	0%	134	27%	57	11%	269	41%	192	30%

Continuing, if looking at the charging infrastructure in Scenario 3, the charger power assumed was 500 kW with an 80% efficiency due to transfer losses. When studying Figure 5.4, charging corresponds to the positive increment of the graphs and the flat part is when the bus is fully charged and awaits the next departure. With that, it can be seen in Figure 5.5 that during summer the bus is fully charged after 51 min, while during winter the full hour is needed (the additional blue part of the graph). Consequently, the charger will be occupied for all hours from the first bus arriving in Lysekil to the last bus leaving. Therefore, as indicated by Paakkinen [46], if chargers are to be shared between bus operators and external operators, the charging station would need two or more connections to avoid disturbing the bus schedule. In addition, this adds a delay sensitivity to the system. Hence, during winter there is no room for delays, and backup chargers along the route would be needed, while in the summer there is some space where delays can be earned. However, if looking at the shared charging from another point of view, it is only occupied during the bus' operating hours, leaving room for other vehicles such as trucks to charge at night.

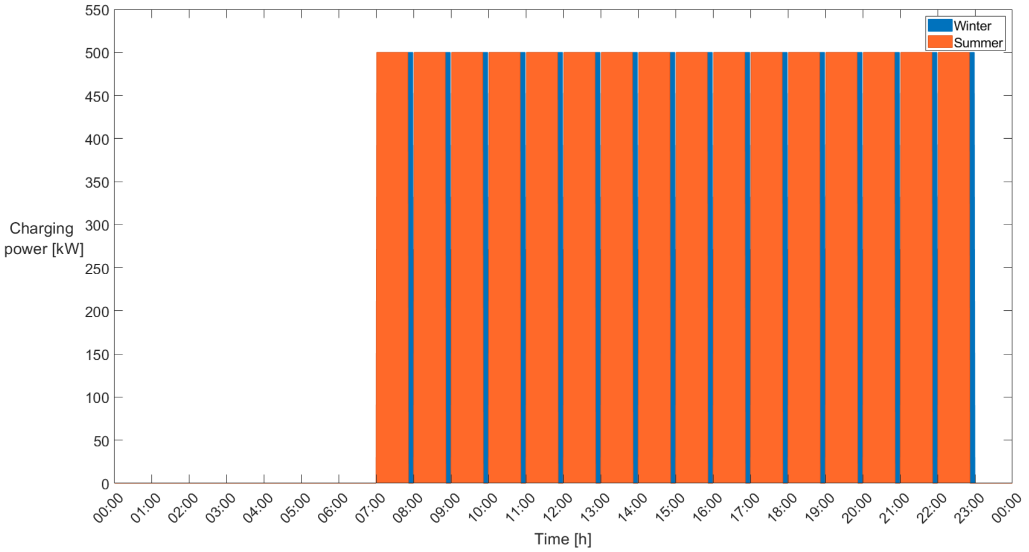
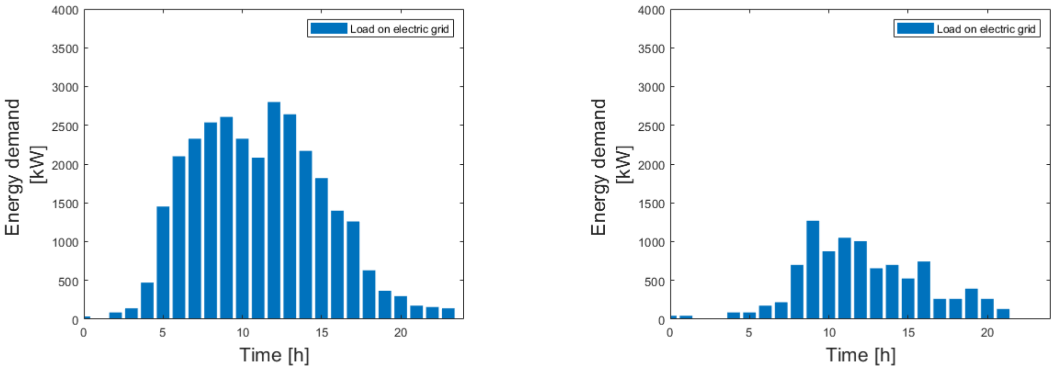


Figure 5.5: Charger occupation for one charger during winter in Scenario 3 when charging buses with 650 kWh batteries.

5.2 Charging infrastructure demand for trucks

This section presents the estimated future charging demand for BETs in Lysekil based on the traffic flow data in Figure 4.5 and assumptions that 16% of the truck fleet will be electric. In Figure 5.6 below, the average daily load from the charging of trucks on the electric grid is presented. The flow of heavy-duty vehicles to Lysekil is estimated to be evenly distributed over the year. It can be seen that the charging demand for BETs during the weekday (a) is significantly larger than during the weekend (b) (as expected due to a normal workweek).



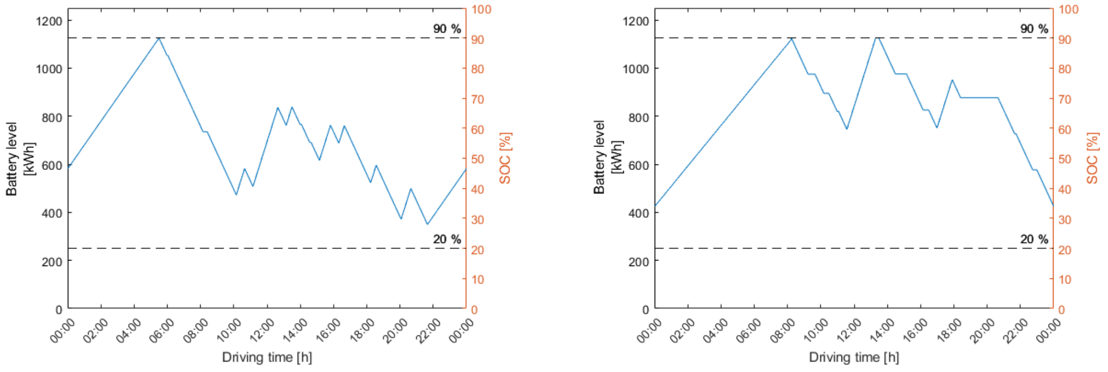
(a) (b)

Figure 5.6: Predicted daily load from charging trucks in Lysekil on an average weekday a) and weekend b) by 2030.

As there is one major road to the city center of Lysekil, the measured traffic flow of heavy trucks can be considered accurate. However, there are uncertainties regarding what exact type of vehicle is passing since measurements of heavy trucks also include service vehicles and other kinds of distributors (e.g. food distributors, considered non relevant to analyze in this study). To further investigate charging demand from trucks, more specific information is needed on truck driving patterns and information on the number of trucks that distribution centers are processing each day. In addition, the driving distances and cargo are relevant since long-hauling trucks or trucks carrying heavy cargo are assumed to want to have the opportunity to charge at every stop along their route, while more locally based distributors probably use charging at their depots instead.

5.3 Charging infrastructure demand for electric passenger ferry

Based on Figure 4.8 a), the electric ferry is required to charge when the stop is more than 20 minutes to maintain the optimal battery capacity level during the weekdays, this is displayed in Figure 5.7 (a). On the weekend Figure 4.8 (b) and (c) charging is only necessary two times during the day. Both the weekdays and weekends were evaluated with overnight charging with an 80 - 100 kW charger.



(a)

(b)

Figure 5.7: State of charge of the battery in the electric passenger ferry (a) weekdays and (b) weekends.

The charging demand for the electric ferry is presented in Figure 5.8, and display which times during the day the ferry needs to charge during an average week. Since the charging demand is based on the hybrid electric ferry Eloise operating in Gothenburg, and there is no exact operating schedule yet, the charging demand would need to be re-evaluated to get a more precise assumption of the charging demand and the load on the grid due to charging of the electric ferry.

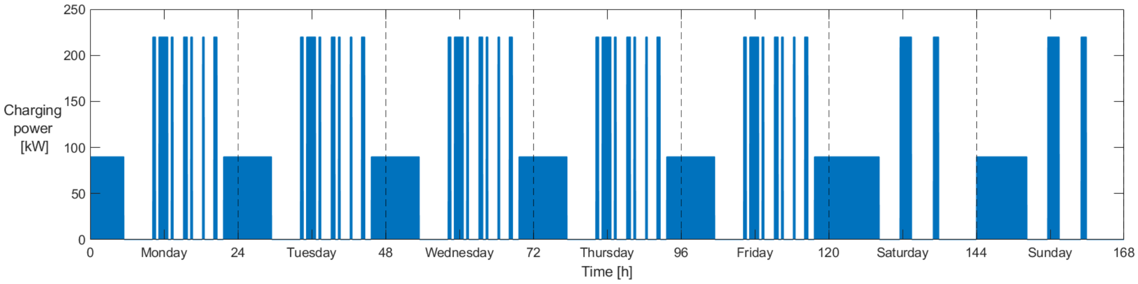


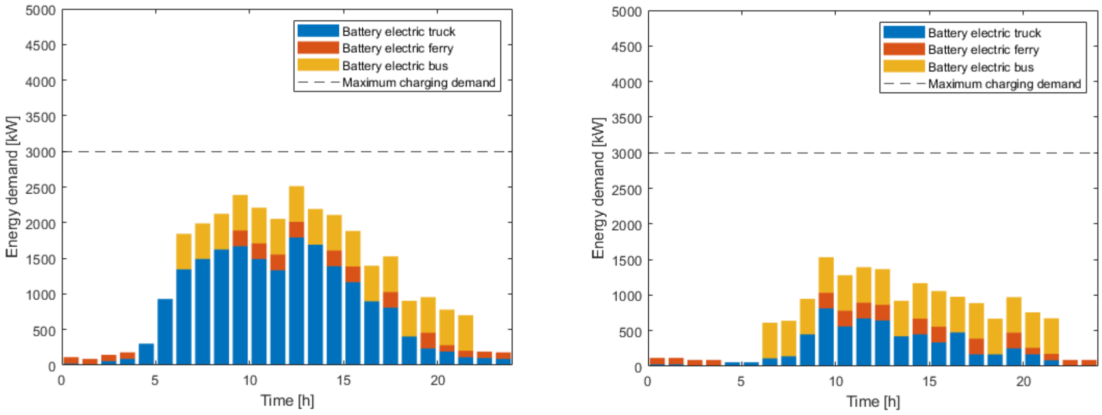
Figure 5.8: Charging demand for electric passenger ferry in Lysekil for a general week.

5.4 Impact on the power grid

Calculated charging demands for investigated transportation modes were summarized to see the total impact on the electric grid. This resulted in a maximum peak energy demand (during an average weekday) of 2.512 MW, as seen in Figure 5.9 (a), while for weekends the peak is 1.532 MW, Figure 5.9 (b). The demand during weekdays is higher and will therefore be the dimension value for installed charging power. With a maximum power demand of 2.512 MW, the power needed to be installed is assumed to be 3 MW (to leave some margin).

Looking at Figure 5.9, it is clearly visible that electric trucks account for the largest charging power output, but this result is based on assumptions that every electric truck arriving in Lysekil will charge. This can be an incorrect assumption, however, the need should be able to be met if such charging is needed. Therefore this result could be used as a guideline for future charging demands, but it is important to keep in mind that the uncertainties regarding how large a share the electric truck fleet will constitute has a great impact on the results. For example the used share of 16% electric trucks would need approximately 3 MW, but if the share would increase to 25% this would require an output of 3.5 MW, leaving 3 MW installed power to be insufficient. But installing charging power and chargers that are not utilized would be uneconomical.

Another aspect of the results presented in Figure 5.9 is the few trucks staying in Lysekil during the night. From personal communication with SDK shipping [41], approximately two of their trucks stay overnight. This indicates a great possibility of shared charging with the regional bus, that is assumed to charge between 07:00-23:00 (see Figure 5.5).



(a)

(b)

Figure 5.9: Predicted daily load from charging examined transport modes on (a) weekdays and (b) weekends.

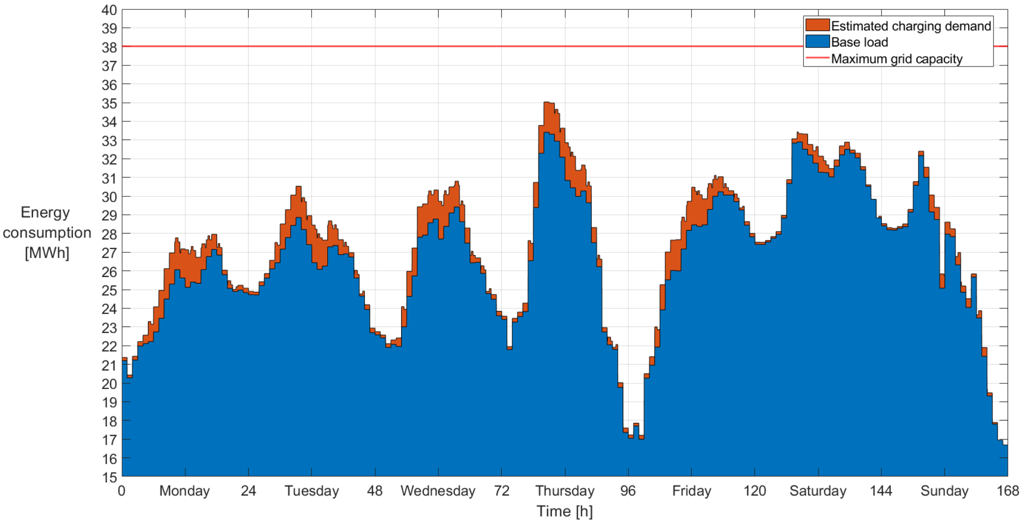


Figure 5.10: Energy demand for Lysekil municipality when adding estimated energy consumption from transports on the base load during the worst week of 2022.

When adding the estimated load from charging of examined transport modes on the week with the highest load during 2022 (in December), seen in Figure 5.10, the maximum value reaches 35 MW. Since the maximum possible power output is 38 MW there is still capacity left, see Figure 5.10. What else can be seen is that peaks in the grid occur during daytime, both for the base load and the truck charging. Remaining hours there is space in the grid that can be used for other purposes. For example, this can be used to charge batteries for energy storage, which in turn could be used to reduce peaks so that the grid can manage eventual higher peaks before the grid extension has been carried out. If installing the 3 MW as suggested to meet charging demands, the power available to use for e.g. energy storage would be as displayed in Figure 5.11 below.

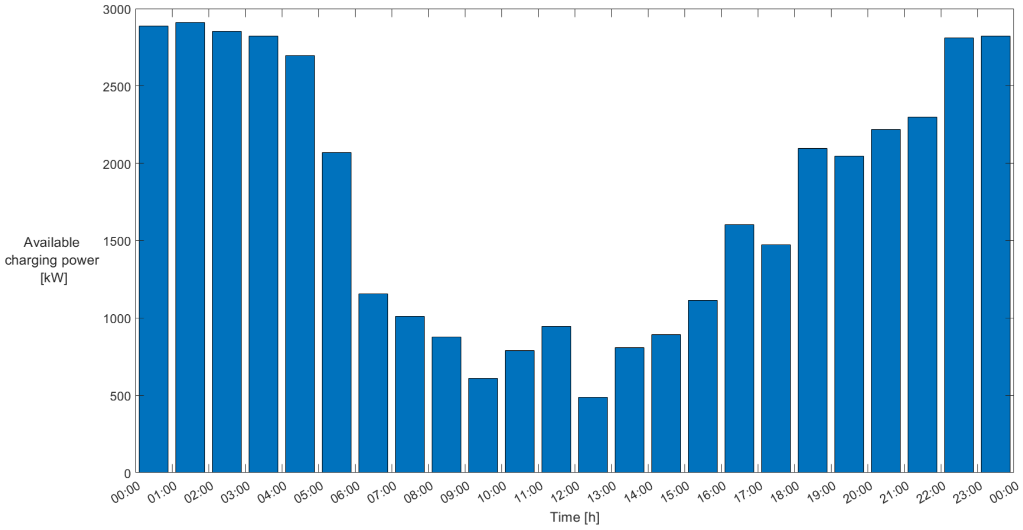


Figure 5.11: Available charging power if installing chargers with 3MW.

6

Discussion

In this chapter the results and related methods will be discussed, aiming to highlight possibilities discovered in the results while adding new perspectives and suggestions for further investigations. Subjects covered in the discussion are transport modes (both examined and others), shared charging infrastructure, the capacity and future demand of the power grid, and important economical aspects related to mentioned subjects.

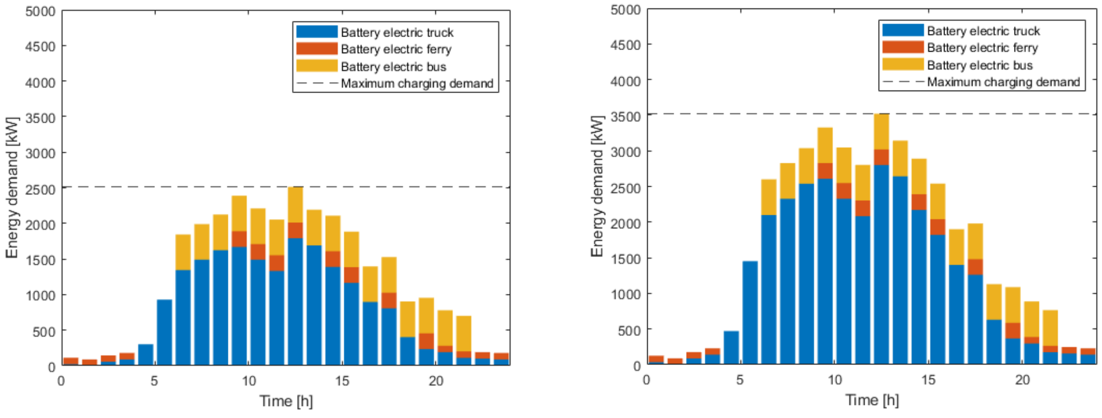
6.1 Battery sizes and operating schedules for electric buses

When developing regional buses, the ratio between capacity and weight of the battery is important. The optimal ratio could look different from situation to situation, depending on how a regional bus is operating. But for example, if choosing a smaller battery, a regional bus would need to charge more often and require chargers along the route, which could lead to higher infrastructure investment costs. This is indicated in conducted Scenario 3, where choosing the smaller 500 kWh battery would need backup charging during winter, while the larger 650 kWh battery can manage the whole route. Moreover, using a smaller battery in regional buses could result in passengers having to wait for the bus to charge during the travel. Therefore, regional buses are argued to need larger batteries to avoid charging on the route to the greatest extent possible. However, a larger battery increases the total weight of the vehicle, which leads to lower passenger capacity. In addition, batteries used contain scarce materials, and the extraction has a negative environmental impact [47]. Another future solution could be the implementation of electric roads (using inductive dynamic charging), which could reduce the needed battery capacity, but this would require even larger infrastructure investments and takes time.

During this study, one single route was isolated and examined. However, this is not a completely realistic situation but is necessary when showing the potential of electrifying regional buses. According to the bus operating schedule, found in Figure A.1 of Appendix A, it is not common that one bus is operating a single line for a full day. Taking this into account, and the charging needs for all bus lines, the operating schedule could be optimized after bus charging demands. This could allow for necessary charging in different ways than staged in conducted scenarios and could further possibly result in reduced required battery sizes.

6.2 Future share and driving patterns of electric trucks

This study presents that a rather small share of electric trucks, of 16%, has quite a large impact on the electric grid in terms of when peaks from charging of transport modes occur. As previously mentioned, an eventual share of 25% instead, would require approximately 1 MW more in peak power output. With expansion processes of the grid being a rather slow process, this would result in insufficient power output and need for flexible electricity solutions. Since Sweden is one of the leading actors in the electrification process of transport and is expected to take a large responsibility to increase the total share of electric trucks within the EU, it is not unrealistic that the share can exceed 16% by 2030 and thus exceed expected demands. For example, an increase of 9 percentage units, from the studied 16% to 25% of charging trucks, would result in increased electricity demand of 1 MW, see Figure 6.1.



(a) **(b)**

Figure 6.1: Difference in energy demand between (a) 16% share & (b) 25% share of electric trucks in the future truck fleet.

When predicting the driving patterns for trucks, one uncertainty has been the lack of data regarding driving ranges and stopping times for trucks, which is essential when evaluating the future charging infrastructure demand. Used data sets and predictions for charging locations along the TEN-T have given rough numbers and indications where it is needed, but to make more accurate calculations more data would be beneficial. The assumptions are also based on conventionally fueled trucks, therefore, how and if the driving patterns will change with an electric drivetrain is also an uncertainty.

6.3 Impacts from charging of personal vehicles

By 2030, 50% of the personal car fleet is assumed to be electric [48], which will supposedly result in a large impact on the power grid. The major part of charging will still be private, but if looking at the public charging demands for BECs [49], research indicates that the need for fueling/charging stations will be 2.3-4.5 times higher for electric vehicles compared to ICE vehicles.

Focusing on Lysekil, through personal contact with LEVA [44], it was discovered that public charging does not affect the grid notably today (but will presumably have a resulting impact on the grid in the future). Only approximately 0.07% of total electric consumption in 2022 resulted from the public charging of personal cars and in addition, the utilization rate of existing chargers is low. Contradictory, it was stated by LEVA that there are plans to increase public chargers from 10 to 20. This seemingly has to do with the large seasonal variations with 75% of charging occasions take place during summer. By that means, if the electric fleet will increase according to predictions, there will be an increased need for public charging in Lysekil that will probably result in a visible impact on the power grid. But to make accurate assumptions on how large the electricity demand resulting from charging of BECs is, more research would be needed.

6.4 Shared charging between transportation modes

When examining shared charging for regional buses based on the case study in Lysekil, the most suitable sharing option identified in the near future was the electric ferry (since it will be starting to operate by the end of 2023). There might not be an option to share the same charger, but it is rather the grid connection that can be suitable to share in the beginning if there are few electric regional buses in operation. However, if constructing a charger for the regional bus at its end-station it was seen in Scenario 3 that the bus will occupy the charger between 07:00-23:00, leaving space for trucks to night charge. This would increase the charger utilization rate notably, and investment costs thus could be shared by involved stakeholders. In addition, it could be of great use to offer a shared charging possibility for electric trucks, to pave the way in early adoption phases.

Prioritization of charging is an aspect that has not been investigated in depth in the study, yet it is an important question when suggesting shared charging since it affects charger location and willingness to share. For example: on the one hand, buses have strict operational schedules and need to charge according to timetables, on the other hand, logistic companies need to ensure sufficient power on their behalf so that the truck drivers do not have to wait for long times. If strictly scheduled modes, like buses, are to be prioritized the power output for other vehicles charging simultaneously would be reduced and the charging times increase. Furthermore, if buses occupy the chargers major part of the day, it might instead speak for alternative sharing options e.g. between trucks and other service vehicles such as garbage trucks.

6.5 Power grid capacity and estimations of future load

If analyzing grid capacity related to the electrification of society in general in the Västra Götaland region, it is already stated that the current transmission capacity in the transmission network will be insufficient to meet future demand. Extensions are being planned for and are to be completed by 2035. However, the extension is an expensive and slow solution to the problem and is why alternative solutions, such as locally produced electricity and energy storage, are of great importance. For example, wind power is a great asset along the coastline, and solar energy can be useful to reduce peaks, since peaks in the power grid tend to occur during hours when the solar radiation is at large, see Figure 6.2.

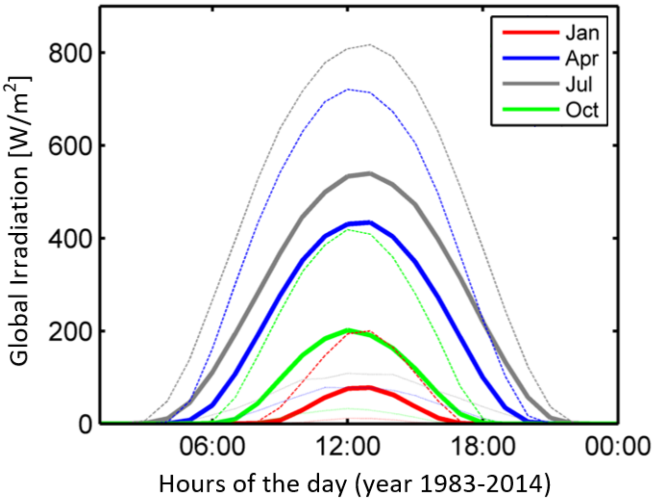


Figure 6.2: Solar irradiation curve for Gothenburg.

Furthermore, locally produced electricity could also be used to charge stationary batteries used for energy storage, they are then charged when the production is high and discharged when peaks occur in the grid. Applying this to the charging of transportation modes, batteries could be installed in connection to the chargers and are used when vehicle charging is needed during peak hours. It could also be feasible if two vehicles need charging at the same time with full power and there is not enough power available. But if this is to be used, the utilization of the battery, and hence mitigation of peaks should be notable, otherwise it will be uneconomical.

For Lysekil the grid capacity on average is considered sufficient and as previously presented, the average load is significantly lower during summer (approximately 7 MWh less, see Figure 4.10). For a place like Lysekil, this is beneficial since the activity increases notably during this time period. This will leave a margin in the grid capacity to utilize if the desired power output were to increase rapidly before a grid expansion. For another location with large seasonal activity, but during winter instead, additional load from charging of vehicles would occur simultaneously with other peak demands. Thus an extension and need for flexible electricity solutions would be more prominent. But with an increased number of vehicles in the area, a technology such as V2G could be beneficial. When the vehicles are not charging the batteries can be seen as an energy storage to exploit which could relieve load on the grid.

6.6 Trade-off when choosing battery sizes

Mentioned trade-off between battery sizes and installed charging infrastructure is a major aspect to consider in the planning stages. On the one hand, smaller batteries are cheaper but require more charging infrastructure and can result in a more sensitive system. On the other hand, the use of larger batteries requires fewer chargers and the system will be more stable, but the materials used will presumably be very expensive in line with large parts of society being electrified. Continuing, there are additional aspects to consider when evaluating battery sizes and that is the power grid and resources. Since the extensive electrification of society can create congestion in some parts of the power grid, it might be an option to choose larger batteries to avoid charging at some locations (as with this case study in Lysekil to avoid charging in Gothenburg). But that raises the question if it should be the grid company that accounts for the higher cost for a larger battery or the vehicle manufacturer. Furthermore, regarding resources, larger batteries require more materials, where some used in batteries are rare and will be at risk of shortage in the future. Therefore up-sizing to a larger battery option has to be sustainably viable as well.

7

Conclusion

From this study, it can be concluded that there are possibilities of electrifying regional buses with long commuting routes, and it is rather a question of when than if. What could act as an obstacle in the early adoption phases before there is a widespread charging network is that relatively large battery capacities are required. Furthermore, applying shared charging to increase charger utilization was found to be most suitable if shared with trucks needing overnight charging. This is based on that the examined route will probably need an extra bus and thus chargers will be occupied during operating hours. In the aspect of shared charging to reduce the load on the grid, it could be an option to use the same connection as the locally operating electric ferry in combination with battery energy storage if charging is required simultaneously.

The additional load from the electrification of investigated modes will in general be manageable for the power grid in Lysekil. However, during the week with the most load in 2022, the required power output is approaching the maximum value (with approximately 3 MW (8%) capacity left). Thereby, with additional transport modes being electrified (e.g. service vehicles, leisure boats, and cargo ships) along with the load from charging personal cars, it indicates a need for flexible solutions or extension of the local grid to manage future peaks.

To apply the results in a more broad perspective, the main findings are generalized and listed below:

- Electrifying regional buses could result in a sensitive system in the early phases in terms of charging times with little to no room for delays, where the delay sensitivity is found to be most prominent during winter. In consequence, this indicates a need for large batteries or backup charging along the route. Suitable locations for backup chargers are e.g. stops where other bus routes are passing or where longer stops for trucks take place so that other transport modes can use installed chargers to ensure utilization.

- The trade-off between battery sizes and the number of chargers needed is an important aspect when optimizing charging infrastructure, both from an economic and environmental perspective.

- Shared charging is a great possibility when combining night charging of electric trucks with electric regional buses operating during the daytime. For shared charging during the daytime, it could be more suitable between modes that are not as strictly scheduled as regional buses and with as large a charging demand. For example, between local buses/ferries, logistic companies, local distributors, and service modes (garbage trucks, etc.).

- Since peaks from charging only occur a few times, a solution can be the use of energy storage in combination with chargers to reduce peak power demand. This could reduce the needed charging power installed, or ensure that vehicles charging simultaneously get full power output if needed.
- By planning charging of public transportation modes in smaller cities, with capacity in the power grid, it could relieve the load on a more dense urban area where the power grid is at risk of congestion due to the overall electrification of society.

As a final note; to accelerate the electrification of regional buses, a pilot project similar to ElectriCity [8] could be a good contribution, where the listed general aspects could be useful. This could demonstrate the potential of electrifying regional buses, as well as contributing to the development of technologies useful for electric regional buses and shared charging.

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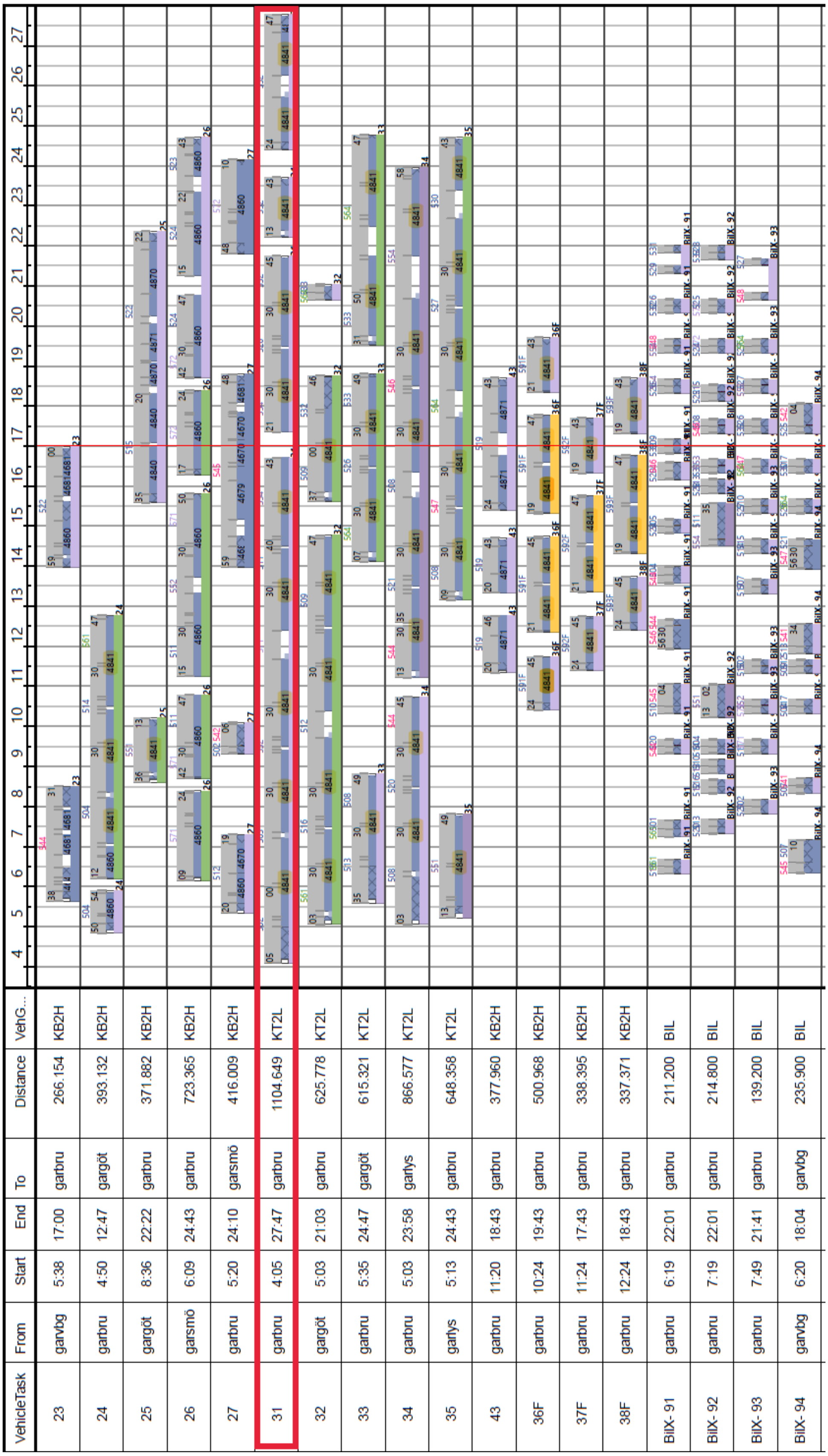
A

Appendix 1

Table A.1: Specifics for the electric ferry Eloise, operating in Gothenburg by Styrsöbolaget.

Operating information for Eloise (hybrid electric ferry)	
Battery Capacity	1250 kWh
SOC operation limits	90-20% (1125-250 kWh)
Energy consumption	100 kWh/h
Day charging power	220 kW
Night charging power	90 kW
Operation time without need for charging	8-9 hours



VehicleTask	From	Start	End	To	Distance	VehG...
23	garvbg	5:38	17:00	garbru	266.154	KB2H
24	garbru	4:50	12:47	gargöt	393.132	KB2H
25	gargöt	8:36	22:22	garbru	371.882	KB2H
26	garsmö	6:09	24:43	garbru	723.365	KB2H
27	garbru	5:20	24:10	garsmö	416.009	KB2H
31	garbru	4:05	27:47	garbru	1104.649	KT2L
32	gargöt	5:03	21:03	garbru	625.778	KT2L
33	garbru	5:35	24:47	gargöt	615.321	KT2L
34	garbru	5:03	23:58	garlys	866.577	KT2L
35	garlys	5:13	24:43	garbru	648.358	KT2L
43	garbru	11:20	18:43	garbru	377.960	KB2H
36F	garbru	10:24	19:43	garbru	500.968	KB2H
37F	garbru	11:24	17:43	garbru	338.395	KB2H
38F	garbru	12:24	18:43	garbru	337.371	KB2H
BilX-91	garbru	6:19	22:01	garbru	211.200	BIL
BilX-92	garbru	7:19	22:01	garbru	214.800	BIL
BilX-93	garbru	7:49	21:41	garbru	139.200	BIL
BilX-94	garvbg	6:20	18:04	garvbg	235.900	BIL

Figure A.1: Overview of driving schedule for buses operating bus line 841 during some part of its operating day, where the bus used for the charging framework in the thesis is highlighted.

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