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On Electrification of Heavy-Duty Trucks

A Grid Impact Analysis of a High-Power Charging Station

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Civilingenjörsprogrammet i system i teknik och samhälle

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Abstract

The Swedish transport sector will need to undergo a major restructuring to achieve the established climate and environmental goals. The biggest change is that fossil fuels will be phased out and a larger part of the vehicle fleet will be electrified. This study deals with the electrification of heavy-duty trucks and how high-power charging stations affect the local electricity grid. Charging of heavy-duty trucks depends largely on the logistics of the transport system, which reduces the demand flexibility of power. High-power charging entails a risk of increased power peaks, which can affect the bus-voltage profiles, losses and loads on grid components.

This thesis has been conducted as general study based on the case with the high-power charging station at Vädermotet in the area Hisingen of Gothenburg. The purpose was to build a generic model of the electricity grid at Hisingen and then investigate the consequences of high-power charging for the grid for two charging scenarios: the first scenario with four ABB Terra 360 chargers, and the second scenario with six ABB Terra 360 chargers and one MCS. The electricity network model and simulations were performed in PSS®SINCAL. The two charging scenarios, as well as the scenario before chargers were installed, were then simulated for three different system-load cases: maximum, average, and low load.

The results showed that high-power charging of trucks had the biggest impacts for the voltage profiles during the case of low load. For the medium load and maximum load cases, the effect of the high-power charge decreased. Furthermore, electricity network losses increased for the low load case, but decreased slightly for the average and maximum load case. The reason was a more even load balance between the bus that connected the charging station to the grid and the rest of the network for the average and maximum load cases. In summary, the study indicated that grid implementation of a high-power charging station will have consequences for the local power system. However, the magnitude of the effects is not validated and can therefore only be regarded as indications. The outcome can be partly explained by the assumptions and simplifications of the model compared to the real system.

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Populärvetenskaplig sammanfattning

Aldrig förr har hotet från klimatförändringarna varit så påtagliga som idag. För att motverka klimatförändringarna har både globala och nationella mål satts upp, exempelvis FN's klimatmål i Agenda 2030. En av de främsta åtgärderna som måste till är att minska utsläppen av växthusgaser, framförallt koldioxid. Sverige har ett nationellt mål där nettoutsläppen av växthusgaser ska vara noll år 2045. I Sverige står inrikes vägtransporter för ungefär en femtedel av Sveriges totala utsläpp av växthusgaser. För att nå klimatmålen är det alltså viktigt att minska utsläppen från växthusgaser från transportsektorn. Av de totala utsläppen från transportsektorn står utsläppen av tunga lastbilar för ungefär sju procent. Tunga lastbilar är en viktig del i transportsystemet av gods. För att ha gröna transporter, drivna på el, vätgas eller biogas, av vår mat, mediciner och råmaterial i framtiden så måste alltså de tunga lastbilarna gå från att drivas på fossila bränslen, till att drivas på gröna drivmedel.

Detta projekt handlar om elektrifiering av tunga lastbilar. Målet med elektrifiering är att minska utsläppen av växthusgaser, men vägen dit är nödvändigtvis inte enkel. Elektrifieringen av bland annat tunga lastbilar bidrar till Sveriges ökade elbehov, men det ställer även ökade krav på transportsystemet och logistiken kring det som gör att alla leveranser kommer fram i tid. Alltså, den första utmaningen som elektrifieringen medför är att två stora och komplexa system behöver samverka. Elsystemet behöver leverera tillräckligt mycket effekt, även när behovet av laddning är högt. Behovet av laddning bestäms i sin tur av logistiken bakom transportrutterna. Dessutom så beror placeringen av laddningsstationer dels på vägnätets uppbyggnad, men också på var det finns tillräckligt mycket överföringskapacitet i elnätet tillgängligt så att en ny effektkrävande anslutning kan godkännas av elnätsägaren.

En central del i utmaningen med elektrifiering av tunga lastbilar är att Sveriges elnät åldras, samtidigt som att fler sektorer i samhället elektrifieras och befolkningen ökar vilket ökar behovet av el ytterligare. Transmissionsledningarna i Sverige har begränsningar i hur mycket effekt de kan överföra, något som beror på hur ledningen designades när den en gång i tiden byggdes. Men när effektbehovet nu ökar i samhället, så blir begränsningarna märkbara i elnätet och när effektbehovet är stort så kan ibland inte tillräckligt mycket effekt överföras. I dagsläget är detta ett problem i framförallt Stockholm och Uppsala, men det väntas bli ett problem även i Göteborg år 2030. En annan utmaning för elnätet är att fler förnybara energikällor integreras när fossila energikällor fasas ut. Detta leder till en ökad mängd intermittent effektproduktion vilket bland annat påverkar frekvensstabiliteten i elnätet.

Vid Vädermotet på Hisingen i Göteborg byggs just nu en laddningsstation med högeffektsladdare för tunga lastbilar. Denna planeras att tas i drift i juni 2022. Det maximala effektbehovet för laddningsstationen är 1,44 MW, vilket gör Vädermotet till Nordens hittills största publika laddningsstation för tunga lastbilar. Redan 2023 planeras en expansion av laddningsstationen, då kommer det maximala effektbehovet uppgå till ungefär 3 MW. Men vad har detta med elnätet att göra? Högeffektsladdning kräver stora mängder effekt från elnätet, variationer i hur mycket effekt som tas ut beror i sin tur på logistiken bakom transportsystemet. Detta projekt undersöker hur högeffektsladdning av tunga lastbilar påverkar elnätet och dess förutsättningar att fungera inom vissa ramar för stabil operation av elnätet.

I projektet byggdes en elnätsmodell som kunde användas för att simulera integreringen av laddningsstationen på Hisingen. För att göra simuleringarna mer realistiska erhölls lastprofiler med timvis effektkonsumtion från Göteborg Energi Nät AB, denna skalades sedan för att bättre matcha det uppskattade effektbehovet på Hisingen. Eftersom laddningsstationen inte tagits i drift än så simulerades även flödet av lastbilar till och från stationen. Detta behövdes för att beräkna effektbehovet för laddningsstationen vid olika tillfällen. Eftersom elbehovet varierar över året, framförallt som en konsekvens av utomhustemperaturen, var det även av intresse att undersöka elnätskonsekvenserna av laddningsstationerna för tre olika dygn under året. Därför valdes en dag i februari, när effektbehovet var som störst, en dag i juni där effektbehovet var som minst och en dag i september som motsvarade en dag med medelförbrukning. Elnätssimuleringarna utfördes i PSS®SINCAL, en programvara där elnätsmodeller kan skapas och simuleras. Lastprofiler för laddning av lastbilar, samt funktion för att hitta dagar för de tre lastfallen, skapades i MATLAB.

Slutsatserna som drogs från resultatet var att det fanns indikatorer som visade att högeffektsladdning av lastbilar har en effekt på det lokala elnätet. Framförallt i form av ökande förluster i elnätet, ökade spänningsfall, samt ökad risk för överbelastning av transmissionsledningar och kablar i elsystemet. Resultaten visade att effekterna av laddningsstationen hade störst konsekvenser för elnätet under lastfallet i februari, när lasten var som högst. Det bör dock nämnas att resultaten enbart kan ses som indikatorer. Studien baseras på flera antaganden på grund av brist på data, men även sekretess kring mer specifik data för elnätet på Hisingen. Det saknades även material för att kunna validera resultaten. Istället jämfördes resultaten mot liknande tidigare studier för att kunna säga något om deras rimlighet. För att kunna säkerställa resultaten från studien skulle modellen behöva bearbetas ytterligare, samt jämföras noggrannare med det verkliga systemet. Trots detta är det viktigt att understryka vikten av denna typ av elnätsanalyser för att förstå hur nätet påverkas av när laddningsstationer integreras. Men även när fler förnybara energikällor integreras i nätet. Elnätet står inför en stor förändring de kommande åren, vi måste förstå de olika komponenterna i förändringen och hur de samverkar med varandra.

Executive Summary

This master thesis study investigated the grid impacts on a local power grid with different voltage levels, in terms of voltage stability, active power losses in the system, and power capacity of conductors, when implementing a high-power charging station to the grid. The local grid model was a generalised model, with some modifications to resemble the grid at Hisingen.

However, several assumptions were made to create the scope of the study, but also to simulate the parts where data were missing. In the study the following assumptions were made:

- All electric trucks that weigh more than 3.5 ton were included to get a larger scope for the study.
- The distribution grid at Hisingen was assumed to be radial, with one main feeder from the transmission system down to the distribution level.
- The grid model did not consider individual loads, instead areas were aggregated to loads and the grid model stopped at the grid stations on 0.4 kV-level and 10 kV-level.
- The voltage levels in the power system model were assumed to be 400 kV, 130 kV, 10 kV and 0.4 kV.
- Charging hybrids were not considered in the thesis.
- A first-in-first-served principle was applied on the queue to the chargers at Vädermotet.
- When a battery electric truck (BET) is charging, it charges at constant power for some time and the battery was assumed to be fully charged at departure.
- Freight traffic and long-haul transports has the same driving pattern night and day.

A grid model was created and simulated in PSS®SINCAL for the three cases, representing days when the load was high, low, or on an average level respectively. The main finding of the grid impact analysis was that a high-power charging station do have effects on a local power grid. Furthermore, the results also indicates that a future expansion of the charging station may jeopardise, or at least reduce, the margins for stable operation of the local power grid.

However, the results of the study lacks validation and there are large simplifications of the real system that affects the results. To verify the results, the grid model needs to be processed further and the results would need to be compared to the real power system on Hisingen.

Förord

Med detta arbete knyter jag ihop mina år vid Uppsala universitet och civilingenjörsprogrammet i system i teknik och samhälle. Arbetet utfördes vid institutionen för elektricitetslära vid Uppsala universitet.

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Jag vill även tacka min familj och mina vänner för ert stöd och den värme ni gett mig under mina studieår. Här återstår det bara att tacka min partner och ständiga stöttepelare, David.

Maria Arvidsson
Uppsala, 17 maj 2022

Abbreviations

AC – Alternating current
BET – Battery electric truck
BESS – Battery energy storage system
CHP – Combined heat and power
DC – Direct current
DSO – Distribution system operator
EV – Electrical vehicle
GENAB – Göteborg Energi Nät AB
GHG – Greenhouse gases
MW – Megawatt, unit for active power.
kW – Kilowatt, unit for active power.
LCI – Line capacity index
LV – Low voltage
MCS – Megawatt charging system
MV – Medium voltage
MVA – Megavolt-ampere, unit for apparent power.
PLI – Power loss index
P – Active power
PV – Photovoltaics, i.e solar power.
Q – Reactive power
SOC – State of charge
SVK – Svenska Kraftnät
S – Complex power
TSO – Transmission system operator
VD – Voltage deviation
V1G – Vehicle to grid, power flows in one direction, only charging the vehicle.
V2G – Vehicle to grid, power can flow in two directions - to or from the grid.
VPI – Voltage profile index
VSF – Voltage sensitivity factor
WC – With charging stations
WOC – Without charging stations

Definitions and Explanations

Bus – A node in the power system, which several components of the power system like generators, loads, and transmission lines are connected to. In a system model, they are marked as bold lines.

Charging profile – The total power consumption at a charging station over a period of time.

Depot chargers – Charges at low voltage (AC), charging of BETs during nighttime. Often located at logistics centers or at truck garages.

Electric vehicle – A vehicle powered by electricity from batteries or fuel cells.

Load profile – The total power consumption of the end users in one area.

Public chargers – Charging BETs at high voltage (DC), during short periods of time (30-60 minutes), placed along roads to make fast charging available for long-haul transports.

Semi-public chargers – Medium voltage, charge during 2-4 hours. Often located at logistics centers.

Utility rate – Describes the utilisation of a charger. A high value indicates a high utilisation.

Contents

1 Introduction

Freight systems, including trains and trucks, are of great importance to freight necessary products such as food, products for industry and our everyday life. Today, 97 % of the heavy trucks runs on fossil fuels, mainly diesel [1]. In Sweden, all road transports stand for 18.98 % of the total Swedish green house gas (GHG) emissions, where 6.4 % comes from heavy trucks [2, 3]. As a response to climate change, Sweden has a goal that states that the GHG emissions shall be net-zero by 2045 [4]. To reach the goal, several changes are needed throughout the whole society, where a large part consists of switching to renewable energy sources to reduce the usage of fossil fuels and increase energy efficiency. Within the transport sector, it is mainly done by replacing fossil fueled vehicles with battery electric trucks (BETs), but also biogas-, and hydrogen-driven trucks. Thus, electrification of the heavy trucks is one of the keys to reduce GHG emissions [5, 6]. However, charging of BETs requires a lot of electrical power, which puts new demands on the power system that needs to be examined.

Electrification of heavy-duty trucks is still in the beginning of its expansion. The share of BETs is still quite low, but is expected to increase to 20 % of the total number of heavy-duty trucks by 2030 [7]. The development is necessary to reduce the GHG-emissions, both in Sweden and in the global transport sector. However, switching to a larger share of BETs creates a complex connection between the logistics behind the road freight transport system and the operation of the power system. Charging of BETs requires large amounts of electric power during short periods of time, which may be problematic during high-load hours (weekdays between 6 am to 10 pm, from November to March) [8]. To solve the challenges, solutions that create a more flexible and resilient power system and electricity markets are needed [9, 10]. Moreover, the Swedish power system must also be physically expanded to handle an increased power demand in the future [11]. Charging of electric heavy-duty trucks are a relatively new type of load that may affect load profiles, voltage profiles and power flows within the area where the charging station is placed [10, 12, 13, 14, 15]. It may also have consequences for the voltage stability and system losses. To conclude, the power system as we know it today is ageing and changing, therefore it is important to investigate which effects that charging of BETs may bring.

In June 2022 the largest public charging station for long-haul heavy-duty trucks in Scandinavia will be put into operation at Vädermotet in Gothenburg [16]. Thus, the study was based upon the situation at Vädermotet. The charging station will have a total charging power capacity of 1.44 MW separated on four chargers, ABB Terra 360 [17]. Furthermore, the station is supplied with power from two transformers, rated at 1.6 MVA, which opens up to a future expansion of the charging station. The overall purpose of the study was to investigate the grid impacts of a high-power charging station, in terms of effects on voltage stability, power flows and system losses. However, to perform such analysis, a generic grid model for simulations had to be constructed and a charging profile for the charging station had to be simulated. Thus, the study relies on several assumptions and simplifications of the real system. Hence, the results from the thesis shall not be regarded as an absolute truth, but rather as an indication of the challenges that high-power charging of BETs may bring to a distribution grid. To get an overview of how the effects may vary over the year, three cases were selected for simulations and a charging profile was simulated both for the current situation, but also one where a future expansion was considered.

1.1 Aim

The aim of the study was to build a model of a generic power system that contained elements that resembled the electric grid at Hisingen. The voltage levels vary from LV (low voltage) to HV (high voltage). Then, load profiles for high power charging of BETs was implemented in the grid model to simulate how the grid was affected by the charging load. Furthermore, the grid impacts were evaluated for three load cases: maximum, average, and low load. The results of the BET integration was investigated in terms of voltage stability, system losses and potential changes in power flows for different operating states of the local power system. More specifically, the following research question and sub-questions were ought to be answered,

- Which effects does high power charging of heavy-duty BETs have on the power-grid model of Hisingen in terms of voltage stability, power flows, and system losses?
  - How do the grid impacts vary for the three cases, both for the current size and a future expansion of the charging station?
  - What challenges may a future expansion bring to the electrical system on Hisingen, based on the simulation model?

1.2 Limitations

This study is geographically limited to only investigating the situation in Gothenburg, more specifically at Hisingen. Thus, the grid model was created as one feeder from 400 kV-level, to 0.4 kV. This approach had an impact on the results, as only the higher levels of the power system were considered, and larger residential areas were aggregated as loads connected to the 0.4 kV-level in the grid model. Hence, the study did not consider individual households, smaller industries or cable cabinets at the 0.4 kV-level. This limitation of the study was necessary as more detailed information about loads or the grid structure was not available. Moreover, a radial grid structure was assumed with respect to the conditions at Hisingen.

The simulations were run under the condition that it was operated at balanced three-phase steady-state conditions to facilitate the computations. This assumption is common when analysing the effects on a power grid when adding for example a BESS (battery energy storage system) or charging stations [18]. In this study, the purpose was to analyse the effects on a functioning grid to make more general conclusions. However, a fault study could be carried out, but that was out of the scope for this study.

Limitations were also made regarding the charging profiles for the BETs. Foremost, there was no available information regarding the driving routes or the state of charge for the BETs. Mainly because the charging station has not been put into operation yet. Thus, assumptions based on open data from Volvo and Scania were made to make as realistic simulations of the charging profiles as possible. A more extensive description of the assumptions can be found in section 4.2.

2 The Studied System

The share of EVs on the roads are increasing, which also increases the requirements on the power system to deliver enough power to meet the demand at all times [19, 20]. It is often suggested that this development with changes in consumption will affect power flows, losses and voltage profiles of local power grids considerably [20, 12, 14, 15]. This section will provide the reader with necessary background information, such as the current situation, the structure of the power system, power consumption and production, information about the charging station at Vädermotet, concluding with some potential challenges associated with BET integration in an electrical power grid. The scope of this study combines both the power system, but it also accounts for some characteristics of the transport system. Therefore, it is important to understand both the power system, and the basics behind the transport system.

2.1 Current Situation Description

The electrification of the Swedish transport fleet of trucks are still in an early phase [19, 7]. The adaption is still low but is expected to increase in the coming years. The ongoing electrification in society will increase the power demand, creating challenges for the power system. Moreover, the transport sector will also need to adapt as the long-haul heavy-duty trucks are being electrified. Thus, the current electrification rate in the transport sector will be presented in this section, as well as the transport system. Regarding the transport system, focus lies on possible placements of charging stations with respect to the road placement, but also the challenges that the Swedish transport system are facing.

2.1.1 Electrification of the Long-Haul Transport Sector

In the Gothenburg area, there were about 22,655 light and heavy trucks on the roads in the end of the year 2020 of which 226 were powered by electricity [21], see Figure 1. This corresponds to a share of 0.14 % of electric trucks in the Gothenburg area, which is the same as the national share of electric trucks [7]. In 2018, the share of BETs was 0.10 % of the total truck fleet in Gothenburg, so there has been a slight increase between 2018 and 2020. However, the electrification rate of trucks is expected to increase and by 2030 the share of BETs is predicted to be around 20 % of the total truck fleet. Apart from electricity, fuels such biofuel and hydrogen will also become more common, see Figure 2. By 2040 the goal is that 60 % of all heavy-duty trucks will run on electricity to reduce the GHG emissions by 85 % and fulfil the Swedish climate goals [22, 23]. Another profit of BETs, besides reducing GHG-emissions, is that noise and air pollution from road transports will be reduced, which is important in urban areas.

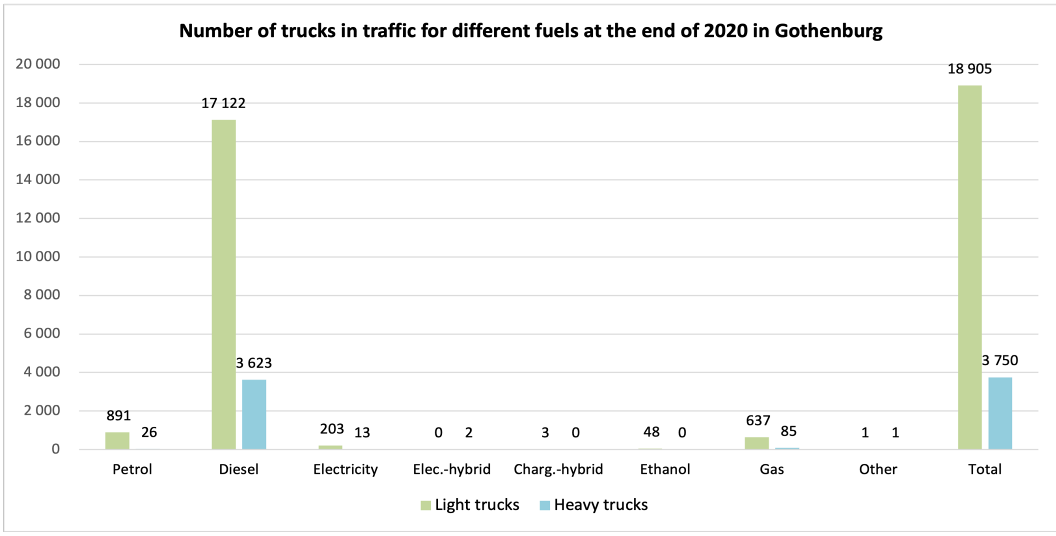
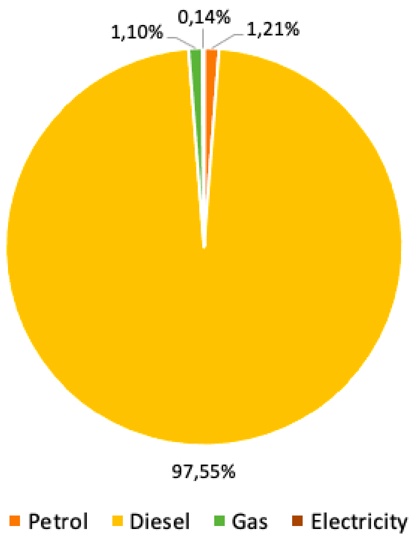
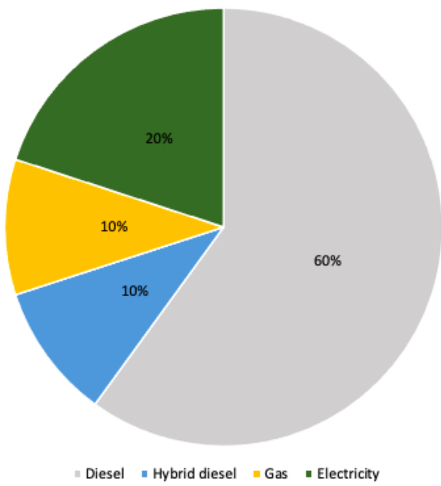


Figure 1: Number of trucks per fuel type in Gothenburg in the end of 2020. [21]



(a) Fuels used in heavy trucks in 2018 [1].



(b) Distribution of fuels for heavy trucks in 2030 [7].

Figure 2: Distribution of fuels for heavy trucks in Sweden in the years 2018 and 2030.

Both Figure 1 and 2 shows that the dominating fuel type for both light and heavy trucks is diesel, both on a regional and national level. Most likely, that will continue to be the situation until at least 2030 [7]. The electrification of the road transport sector is still in an early phase, but the share of electric, gas, and hydrogen driven trucks will increase. Thus, the amount of electricity used in the transport sector will increase by the next 10 years. However, due to electrification of the industry and other parts of society, as well as an increasing population, the power demand is expected to increase drastically in the next 5 to 10 years and be doubled by 2045 [11, 24].

2.1.2 Swedish Roads and Possible Placement of Charging Stations

There are several main roads in Sweden where most of the transports run, these are shown in Figure 3 [25].

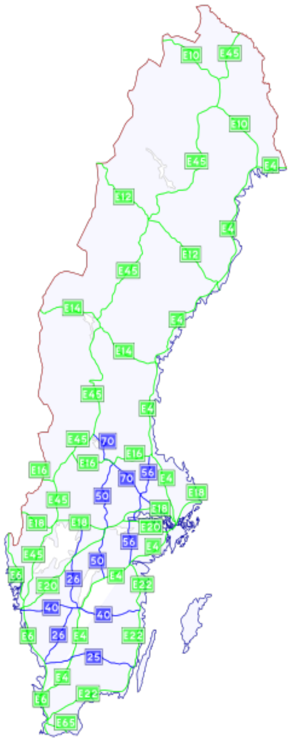


Figure 3: Swedish regional roads. [25]

The roads shown in Figure 3 connects regions and creates patterns for long-haul transportation routes. This also gives the possible locations of charging stations. The roads mainly determine the placement of public and semi-public chargers, while depot chargers are often located at logistic centres. As public and semi-public chargers are preferably placed along the roads, charging stations also requires that there are stable grid connections in the area so that enough electrical power can be delivered. Thus, the placement of charging infrastructure along the roads depends on both the transport system and its logistics, but also the power system and its reliability [13, 36].

As the rest of the society, the transport system is also changing. There are five trends in the development of the transport system, which also relate to the current societal changes. The trends are:

1) digitalisation and automatisation of the transport system.
2) net-zero GHG emission climate goals,
3) demand for available and flexible transports,
4) the transport system is more integrated with other complex systems, and
5) increased demands for safe and robust transports. [7]

Finally, there is a large potential in electrification of long-haul transports. To reach the potential, the current transport system will need to change, and the traditional transport system needs to be integrated with stationary charging stations [23]. However, solving this challenge still requires more research on batteries for BETs, MCS and the effects of an increased power demand on the power system.

2.2 The Power System

Most of the activities in society demand access to electric power, for example healthcare, manufacturing, construction, or rail transports. For every customer to always have access to electric power, we need a strong, flexible, and reliable power grid. The power grid is divided into three levels, depending on voltage levels. It consists of the transmission grid, regional grid, and the distribution grid (see Table 1) [18, 24, 26]. In Sweden, the transmission grid is governed by SVK, the Swedish TSO. On regional level there are some major grid owners, for example Vattenfall, Fortum and, E.ON, while the distribution grid can also be owned by local actors, for example GENAB. Table 1 gives an overview of the different levels in the power system with its corresponding voltage levels.

Table 1: Overview of the Swedish power system and its voltage levels [27].

Grid level	Standard voltage level [kV]	Active power [MW]
Generation	10-25	No load
Transmission	220-400	1000
Regional distribution	40-130	100
Local distribution	40-130	10
Consumption	0.4/0.23	0-1

One of the main tasks for SVK is to keep the grid frequency within 50 ± 0.1 Hz to ensure a stable and secure operation of the power system [11]. The grid frequency will decrease if a large load is connected to the grid as the generators slow down, and it will speed up if a large load is disconnected [18, 27]. This is often described as the grid power balance, as the grid requires balance between power production and consumption.

In Sweden, a majority of the power production is in the northern parts, while there is less production in the far south [11, 24]. To transmit the power from north to south, or from generator to consumer, several high-voltage transmission lines are needed. To supply loads with power, step-down transformer stations are used. Then, the power can be transmitted on a regional and local level at lower voltages. An illustration of the power system from production to consumption is shown in Figure 4. Most of the loads are connected to the distribution system, but some consumers with a high power consumption, for example larger industries, may be connected directly to the regional power system [18].

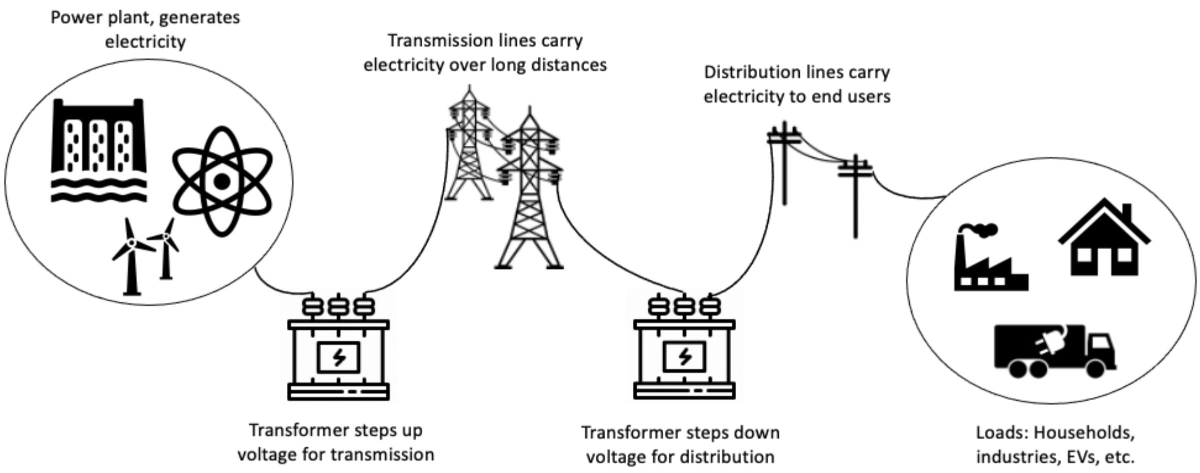


Figure 4: Illustration of the power system.

At generation level, the voltage is lower to protect the power components. A step-up transformer increases the voltage to transmission level, that way, the power can be transmitted over long distances with low losses. On the way to the consumers, the power is transmitted on the regional grid, at MV-level. At this level, larger loads such as large industries can be connected. However, most of the consumers are connected to the distribution grid, at a LV-level. Most of the losses in the power system occurs in the regional- and distribution grids. [27, 28]

2.2.1 Power Production and Consumption in Sweden

The annual electricity production is normally around 160 TWh in Sweden [19]. The dominating energy sources are hydropower, nuclear power, and wind power. Today, the Swedish energy system is going through a transition to meet the national and global climate goals [4]. Furthermore, the power consumption is expected to increase as a result of electrification of industries and transports [11, 24]. The Swedish electricity production over time is shown in Figure 5, where it can be seen that the share of renewable energy sources is increasing, mainly from wind power production [29].

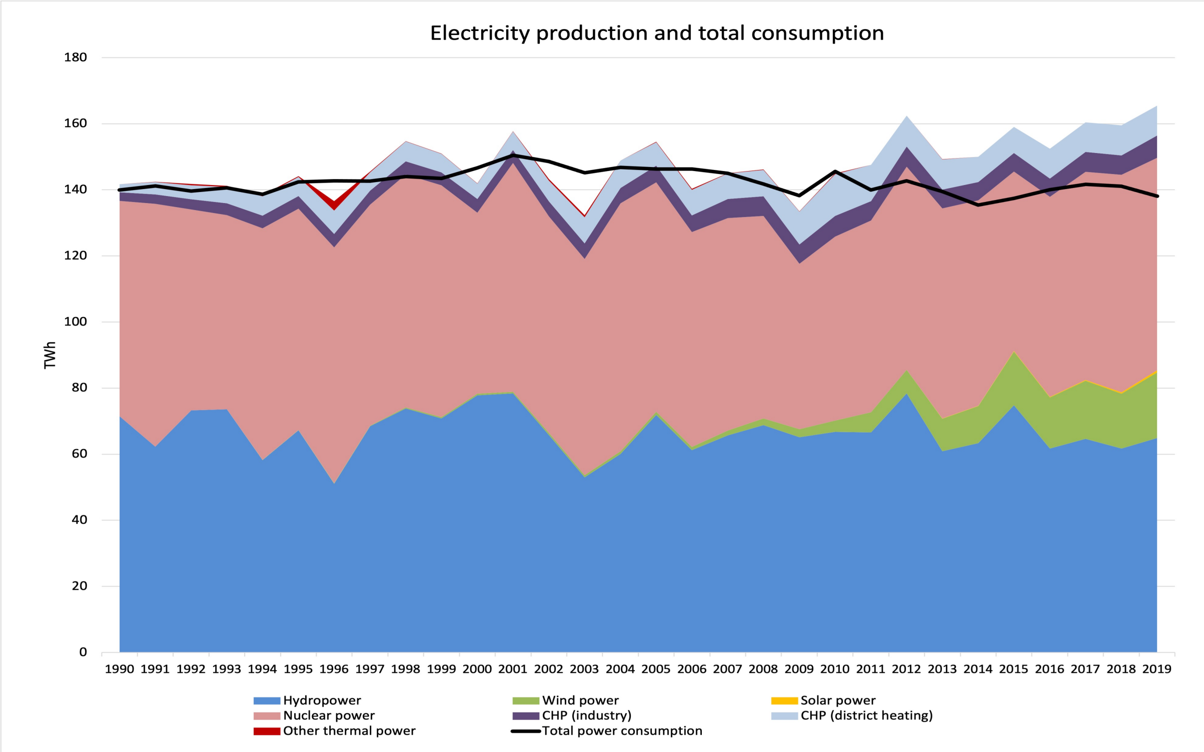


Figure 5: Electricity production from the different energy sources during the years 1990 to 2019. [29]

2.2.2 The Distribution Grid in Gothenburg

The local distribution grid in Gothenburg is owned and maintained by GENAB [10]. Due to safety and city planning, 95 % of the power is delivered to its end-consumers by underground cables [30]. The delivery reliability of the grid is 99.99 %, as there are still shorter interruptions occasionally. One disadvantage of underground cables is maintenance and difficulties with fault detection. Over time, the cables will be worn by movements in the earth. Hence, the cables need to be replaced every 40-50 years. Furthermore, more cables will be needed as the power consumption is increasing in Gothenburg as industries and transports are electrified [9, 10]. Furthermore, the distribution grid in Gothenburg is connected to the regional grid and the total transfer capacity is currently 900 MVA [30]. As the city expands, so must the grid capacity. By 2030 the estimated grid capacity is 1160 MVA.

In many parts of the local distribution system in Gothenburg, the capacity limits of the cables are not yet reached and there are good opportunities to increase the number of power demanding loads. However, parts of the 10 kV- and 130 kV-power system will need to be replaced or expanded. Today around 900 MW is transmitted through the distribution system in Gothenburg, which has a maximum theoretical capacity of 1500 MW. However, as the population increase and with a higher electrification rate, the maximum capacity is expected to be reached in the near future. This means that new investments needs to be done in the power system to be able to meet the increased power demand. [10]

The power consumption follows a yearly, weekly, and daily pattern. During one year, the power consumption is generally lower during summer and higher during winter. The scaled yearly power consumption profile for the Gothenburg area is shown in Figure 6. Furthermore, the weekly and daily load profile variations are also of importance to grid impact analyses. As shown in Figure 7, the consumption normally increases in the morning between 06:00-08:00 when people start their household machines, i.e. turns the light on, makes breakfast. Around 06:00-08:00 the industries also start up, then the industry load is more or less constant during the day. Then the power consumption increases in the afternoon around 16:00-18:00 when people get home from work and start to use different household appliances. The power consumption decreases during nighttime, because of less ongoing activities. Figure 7 shows the aggregated consumption that was used in the system model. However, the characteristics of the load profile applies for any load.

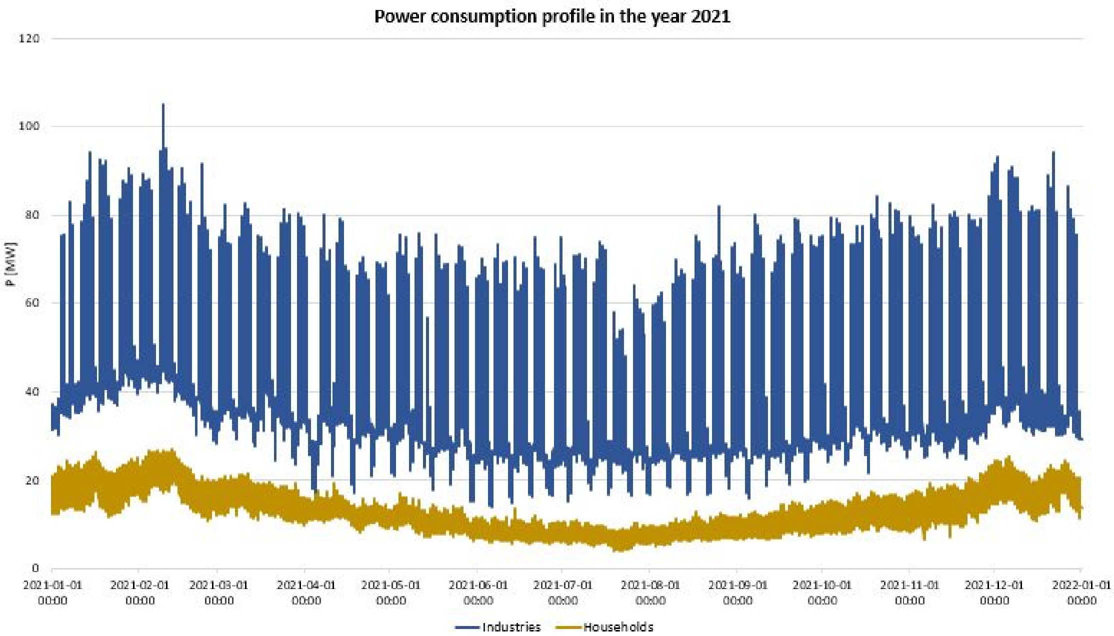


Figure 6: Generic load profile for Hisingen in 2021.

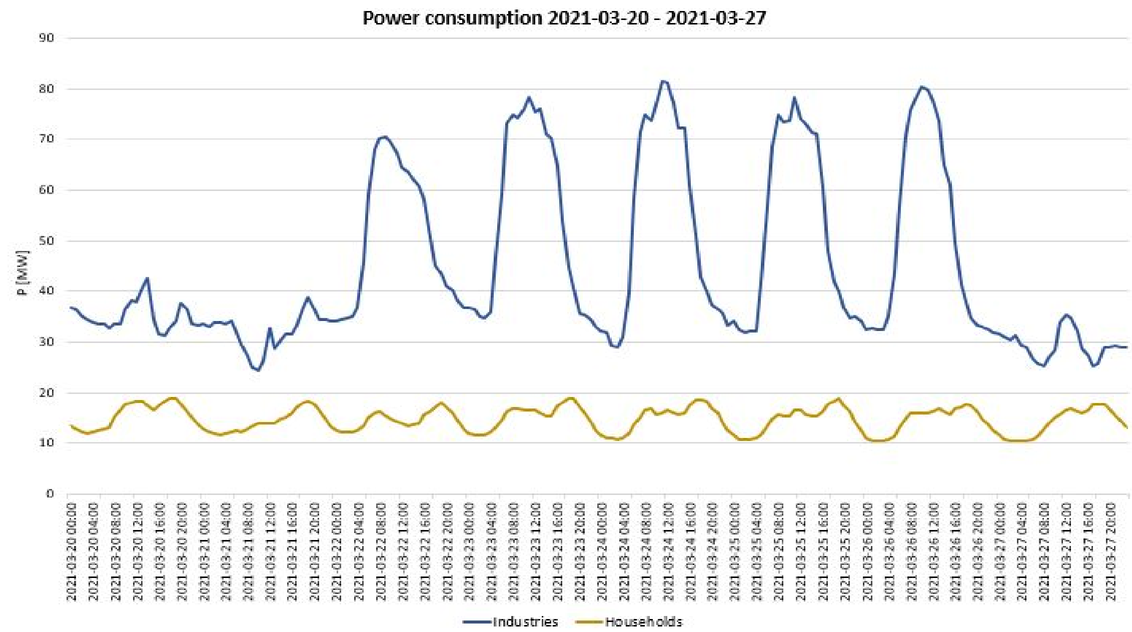


Figure 7: Load profile during a typical winter week for one feeder in the Gothenburg area.

Finally, there is a district heating system at Hisingen, and in the rest of the urban Gothenburg area. Thus, synergies between the district heating system and the power system could be used to for example reduce power peaks [9, 10]. Moreover, another challenge for the power system in the Gothenburg area is the placement of Northvolt's new battery factory [37]. It will be located in Torslanda at Hisingen, but more importantly the factory is estimated to require up to 200 MW. That is, about twice of the current power demand at Hisingen.

2.3 The Charging Station at Vädermotet

To have a reference in terms of size and placement, the charging station at Vädermotet was chosen as a reference for the study. The charging station is owned by Circle K and is the first public charging station for heavy road transports in the Nordic countries. The placement of the station is strategic since it is located near the highway (E6), Hisingsleden, Volvo's factory in Torslanda, and the harbour in Gothenburg, meaning that many heavy-duty transports passes through this area. The investment in charging infrastructure is in line with the Swedish climate goals, but also the local goals set by the harbour of Gothenburg to reduce GHG-emissions from transports with 70 % by 2030. [16]

Today, four ABB Terra 360 chargers are installed at Vädermotet and is planned to be put into operation by the summer of 2022 [16]. Each charger has a capacity of 360 kW. Two of the chargers will have two charging outlets and the other two will have one charging outlet, making it able to charge up to six electric cars at the same time [17, 31]. The limit of charging six BETs simultaneously takes the requirements on charging times into account. To ensure the power supply to Vädermotet two new transformers has been installed, with the ratings 1.6 MVA at 10 kV/0.4 kV. Where the 10 kV-side is connected to the grid, and the BETs charges at 0.4 kV.

There are plans to expand the number of chargers at Vädermotet in the near future. First two more ABB Terra 360 chargers are about to be installed, then there are also plans to implement one MCS, which would increase the charging power at Vädermotet [31]. However, it is not yet determined when this will happen. Furthermore, it will be possible for heavy-duty trucks to refuel with hydrogen from 2023-2024. The future goal is that Vädermotet will be a hub for renewable refuelling of heavy-duty trucks, which also puts new demands on the logistics of both local and regional transports. An illustration of Vädermotet as it is planned to be operated in the near future can be seen in Figure 8.

Figure 8: Illustration of the charging station at Vädermotet in operation. [16]

2.4 Potential Problems Associated with BET Integration

The energy transition combined with an increased power demand is the core of the problem, posing different challenges for the energy and the power system. These are mainly connected to power quality, voltage and frequency stability, and power balance [32, 33]. The challenges entail new requirements on components in the power system, services to increase flexibility on electricity markets, and measures to increase energy efficiency [9, 20].

As mentioned, the electricity demand is increasing as industries and transports are going through an electrification process, but also as a result of increasing population and a more energy-consuming lifestyle [20, 32, 33]. The ongoing electrification of heavy-duty trucks may cause problems such as voltage deviations, decreased power quality, and power balance problems [14]. A large share of EVs will affect the power demand pattern, but could also be used as flexibility services for the grid by using V2G services [9, 32, 34]. Furthermore, high-power charging of BETs may also affect voltage profiles in the nearby area of the charging station [35].

Another urging challenge in the Swedish power system are bottlenecks due to undersized transmission lines, due to uneven production and consumption between the north and south parts of Sweden [24, 36]. Today, several cities, mainly Uppsala and Stockholm as mentioned before, are affected by these bottlenecks, which causes power shortages during peak load hours [11, 19]. Bottlenecks in the transmission system is not an issue in Gothenburg today, but there are predictions that suggest that it will occur by 2030 [11, 30]. Based on the situation in Gothenburg, GENAB have identified some important areas to handle the future challenges. The two main areas are smart communication within the system to enable better usage of the distribution system and investments to strengthen the power system infrastructure. One example of smart communication could be smart charging of EVs, or to use BESS to store energy when the electricity price is low and use during peak load hours. To avoid bottlenecks in the grid to become a problem in Gothenburg in the near future, the following measures should to be taken:

- coordination and smart communication for smart charging of EVs to avoid peaks in power demand and to use the available capacity in the power system as efficient as possible,
- early dialogues in construction projects that include all stakeholders, and
- a common understanding of how electrification within different sectors affects the electricity grid. [10]

Moreover, GENAB has also handed in a suggestion to SVK to build another 18 km long 400 kV-transmission line between Hisingen and the mainland [38]. The investment would increase the grid capacity in the Gothenburg area with 1 GW. However, it is yet only a suggestion, and it would take at least 10 to 15 years until the line could be put into operation due to legislation and construction time [19]. On a short term scale, the measures presented above are a good way to secure the grid capacity and power deliverance in the Gothenburg area [10].

3 Theory

In this section, the theory that this thesis is based on is presented. It involves different aspects that need to be considered when investigating the effects of high-power charging on the power grid. To begin with, results from previous authors regarding grid implementation of BETs will be presented, followed by theory to simulate charging profiles and how to compute the utility rate of a charging station. The theory behind the grid impact analysis is presented, finalising with indexes to compute measurements of the grid impacts.

3.1 Grid Implementation of BETs

The placement and geographical distribution of charging stations are of great importance for the power system [15, 20]. The power system is complex and dynamic, meaning that it does not work in the same way at every point. The grid operation depends on the local load, loading of the line, and, power transmission capacity etc. Furthermore, the consequences on the power grid also depends on the type of charger (depot, public or semi-public charger), as semi-public and public chargers has higher peak-power than depot chargers in general [5, 12]. Furthermore, high peak-demands can reduce the reserve margins, cause voltage instability, reliability problems, transformer overloads, and increased system losses of the power system [12, 14, 39, 40].

Lopez et al. [20] has shown that voltage deviations are the main limiting factor for higher levels of EV integration, including BET integration. Usually, the problems are caused by the transmission lines and cables. This problem is related to an increased peak demand due to high-power charging [12]. Thus, Lopez et al. [20] suggests that grid improvements, for example building new transmission lines, must be done for higher shares of EV integration on the grid. Furthermore, the problems for the power grid becomes more severe for high-power charging stations (public chargers) since they cause extreme cases and the highest peak loads (P_{peak} > 1 MW) [14].

3.1.1 Charging Profiles

The load profile of a charging station naturally depends on when BETs are charging, thus by the arrival times, SOC (state of charge) at arrival, and the battery size. Arrival processes are often modelled as a Poisson process in traffic related problems [41]. The charging station can be considered a queuing system, where BETs arrive with a probability from the Poisson process, then checks if there is a non-occupied charger and thereafter starts to charge or waits in the queue [42]. There are several ways to model the queuing process, this theory is based on a *first-come, first-served*-scenario, FCFS [41]. For this kind of systems it is common to investigate the load profile, and thus the arrival process, on one charging port at a time [15].

Given an average arrival rate, λ, the Poisson distribution gives the probability that a certain number of BETs, n, arrive during a given period can be expressed as

$$P(n) = \frac{e^{-\lambda}\lambda^{-n}}{n!} , \tag{1}$$

Thus, we can see that the arrival of BETs follows a Poisson distribution [41] [43]. If there are N BETs in the area, then the number of BETs that arrives to each charger can be calculated as

$$n = NP_n . \tag{2}$$

If the number of BETs, n, is larger than the number of BETs that the charger can charge at the time t, the remaining BETs are placed in a queue. P_n is the probability of n numbers of trucks arrives at time t. Then, this process can be repeated for every charger in the system and the chargers may charge both newly arrived BETs, but also take BETs from the queue.

Furthermore, the energy demand for the arriving BETs is calculated. The energy demand of a BET depends on how long it has been running, the average speed, the energy consumption and the SOC at arrival [15, 40, 44, 45]. The energy demand of the battery in the BET is calculated as follows

$$E = TvE_{cons}(1 - SOC_{arrival}) , \tag{3}$$

where T is the running time (h), v is the average speed (km/h) and E_{cons} is the energy consumption per kilometer for the truck (kWh/km) [46]. $SOC_{arrival}$ ca be computed as $SOC_{arrival} = 1 - \frac{D}{L}$, where L is the maximum range of a BET and D is the driven distance in kilometres [33]. The charging time is determined by

$$T_{charging} = \frac{E_{cons}}{P_C} , \tag{4}$$

where P_C is the rated charging power of the BET. Finally, the battery size and range are important for long-haul road transport vehicles. Normally, long-haul BETs requires a battery size to be able to run for 2.5 to 4.5 hours [43]. Such range requires battery sizes between 250 kWh up to 540 kWh [44, 47, 48].

3.1.2 Utility Rate

It is of interest to know the utility rate of the charging station, that is, how much of the time that the chargers are being used [42]. The utility rate can be computed as

$$F_{utility} = \frac{\sum_{i=1}^{T} n_i}{sT} \ ,$$

where n is the number of BETs that are charging at an hour t, T is the simulation time, and s is the number of chargers. The utility rate was used when simulating the charging scenarios in order to make sure that the simulations were run with the same to simulate scenarios with the same utility rate. This was of importance when comparing the results of the charging scenarios.

3.2 Grid Impact Analysis

When conducting a grid impact analysis, the power flows in the network needs to be calculated. The power flows are needed to compute other grid impacts, such as voltage stability, grid losses, and load factor. This section will provide the needed theory to conduct a grid impact analysis to fulfil the purpose of the study.

3.2.1 Power Flow

Within any power system the power flows from generators, trough transmission lines to supply loads with power. Thus, when conducting analyses of power systems, it is of great importance to know how the power, both active and reactive, is flowing through the system. Hence, the method to perform these calculations is called power flows, or sometimes load flows. The power flow problem aims at computing the voltage magnitude and the phase angle at each node in a power system. Knowing voltage and phase angle, active and reactive power flows in the system, as well as losses can be determined from the power flow results. Here, it is important to keep in mind that there are different types of buses, which also affect the power flows. The three types are:

- **Slack bus**: There is often only one slack bus in a system, and it is a reference bus with $V\angle\delta$ where δ the voltage angle between the real and imaginary part of the voltage, it is typically 0° and the voltage magnitude is 1 p.u. The power flow computes P and Q at the reference bus. These are used to maintain the power balance in the modelled system.

- **Load (PQ) bus**: Here, P_k and Q_k is input data for each bus and the power flow computes V_k and δ_k. It is often called swing bus. Note that k denotes each bus in the system.

- **Generator (PV) bus**: This is the type of bus that is connected to generators, switches, transformers with tap-changers or any other bus that has an upper or lower limit for reactive power. These buses take P_k and V_k as input data, and the power flow equations give Q_k and δ_k. [18, 27]

The power that is being delivered to the system is defined as positive, while power that is consumed by loads is considered as negative. However, the power flow problem is not linear, and the equations are computationally heavy. A common way to find results using fewer calculation cycles is by the Newton-Raphson method. It will not be discussed in detail, but the method is numerical and an iterative process that uses Taylor series to solve the problems [14]. Furthermore, when computing the power flow, the bus admittance matrix, Y_{bus}, is constructed, the elements of Y_{bus} are:

- Diagonal elements Y_{kk}: The sum of all admittance's connected to bus k.
- Off-diagonal elements Y_{kn}: - (The sum of all admittance's connected between bus k and n), if $k \neq n$. [18]

Hence, the system can be written as

$$I = Y_{bus} V \ , \tag{6}$$

on matrix form, where I is a vector of size n with all currents injected to each bus and V is the voltages at each bus of the same length as I [18]. Thus, at bus k the current can be computed as

$$I_k = \sum_{i=1}^{n} Y_{ki} V_i \ , \tag{7}$$

where $k = 1, 2, ..., n$. The complex power delivered to each bus is given by

$$S_k = V_k I_k^* = P_k + jQ_k = V_k \sum_{i=1}^{n} Y_{ki} V_i e^{(\delta_k - \delta_i - \delta_{ki})} \ . \tag{8}$$

Then the power balance equations is written as

$$P_k = V_k \sum_{i=1}^{n} Y_{ki} V_i cos(\delta_k - \delta_i - \delta_{ki}) \tag{9}$$

$$Q_k = V_k \sum_{i=1}^{n} Y_{ki} V_i sin(\delta_k - \delta_i - \delta_{ki}) \ , \tag{10}$$

on polar form. In an AC power system, reactive power (Q) flows from a higher bus voltage magnitude towards a lower bus voltage magnitude, while active power (P) flows from the bus with the higher voltage angle towards the bus with the lower voltage angle [18]. Note that these equations represent one phase, in general we have a three-phase system, meaning that the expressions will be multiplied by three.

3.2.2 Voltage Stability

The voltage stability problem describes the power system's capability to maintain steady and acceptable voltages at all buses in the system during normal operation and when a disturbance is added, such as increased load or lapse of load [49]. If there is voltage instability, the bus voltage of the power system will decline in an uncontrollable way, which may make the system unstable for faults or changes in load. There are several methods to calculate the voltage stability. A commonly used measurement is the voltage sensitivity factor (VSF). It can be calculated as

$$VSF = \left\| \frac{dV}{dP} \right\| , \tag{11}$$

for all $P < P_{max}$ [12]. Thus, it is simply the ratio between change in voltage and active power. The VSF is sometimes illustrated by the PV-curve (power-voltage curve) [12, 13]. A high VSF-value indicates that even for small changes in load, the change in voltage can be large, which indicates a weakness of the system [13]. Note that this is not a local measurement, as a small change in one part of the system may have severe consequences in another part of the grid. However, there are some margins for what load every bus can handle, this is called the realistic loading margin, which affects the power flows [12]. Another thing that affects how much active power that can be transmitted for certain voltage levels is the length and thermal limits of the transmission line [49].

As the VSF gives a brief indication of the ratio between voltage and power changes, it is also of interest to determine voltage deviations between buses in the network. Voltage deviation (VD) measures the stability of a power system. The criterion for voltage stability is that the voltage must be within certain limits at every bus in the system, normally 0.95 p.u to 1.05 p.u (read about the per unit system in Appendix A) [12, 13, 14]. It is common to calculate the voltage deviations throughout the system when adding or removing loads to the system. Voltage deviation is computed as follows

$$VD = \sum_{i=1}^{n} \left(\frac{V^{ref} - V_i}{V^{ref}} \right)^2 , \tag{12}$$

where V_i^{ref} is the reference voltage of the network voltage level (1.0 p.u) and V_i is the actual voltage at respectively load bus. Furthermore, to prevent over-voltages and keep the bus voltage as stable as possible, power lines are in general not operated to deliver their maximum theoretical power [18]. The theoretical maximum is based on the rated terminal voltages and an angular displacement of $\delta = 90°$ across the line, which is an extreme operating point. Normally, the fraction between the sending side voltage and the receiving end voltage, $\frac{V_R}{V_S} \geq 0.95$, and the angular displacement should be $\delta = 30°$-$35°$ across the line. That is a necessary condition to keep the system stable even during transient disturbances [50]. For long transmission distances, the line loadability is normally depending on the thermal rating on the line, voltage drops, and stability considerations [28] (p. 685). To have a good voltage quality in the system, it is assumed that the bus voltage should be between 0.9 to 1.1 p.u from the nominal voltage of the network level [50]. For short transmission lines, < 80 km, the thermal limits of the lines dominates the transfer capacity [28] (p. 686).

Overloading of the power system results in larger voltage sags, that is, lower bus voltages in the system. This leads to lower transfer capability of the system, increased temperature in lines and cables, hence it lowers the margins for stable operation of the system. [28] (p. 684)

3.2.3 System Losses

Active power losses are a great problem for both TSO:s and DSO:s. As mentioned before, the system losses may increase when adding more charging stations to the power system [12, 14, 20]. When considering the losses of active power, there are both technical and non-technical losses, here we consider the technical losses. The most significant factors that affect the technical power losses are the network configuration, temperature, and the power transmitted over the lines [51]. Moreover, losses are generated in all grid components, but the main contribution comes from lines and cables [24, 52]. The active losses are in direct proportion to transmitted energy, an increased percentage of local production would reduce the losses in the local grid [24]. However, for increased demand the utilisation of the lines increase and thereby the losses if the difference between the nominal generation and consumption is large. The power loss in one line can be computed using the following expression

$$P_{loss} = I^2 R \ , \tag{13}$$

where R is the line resistance and I is the line current. For the whole system the losses can be computed as the sum of all line losses, that is

$$P_{loss,tot} = \sum_{i=1}^{n} P_{loss} \ . \tag{14}$$

It is clear from equation (14) that an increased load demand on one bus will contribute to increase the total system losses as well [12]. The main factor that influence the grid losses is the length of the power lines and cables, the cable dimensions (the thicker the conductor, the lower the losses), voltage level (higher voltage, lower losses) and the phase angle between voltage and current (reactive power) [24]. Finally, as the power demand is expected to increase in the future, the line capacity will decrease and thereby increase the transmission losses. Therefore, investments from both the TSO and DSO's are needed to reduce the losses in the future.

3.2.4 Load factor

Implementation of charging stations for heavy-duty BETs may cause large power variations at the charging station based on the number of BETs at the charging station and their charging power. High-power charging of BETs may increase the load variance in the system, which leads to a decreased load factor (LF) [53, 54]. However, it is possible that by applying smart charging or implementation, BESS increase the load factor. The load factor is a measurement of the system's utilisation rate, or efficiency of electrical energy usage. A high load factor indicates that loads are using the power system more efficiently, on the contrary, a low load factor indicates a less efficient energy usage. Note that large fluctuations may cause a lower load factor, which may cause energy losses [14, 20]. The load factor is defined as the average load divided by the maximum load during a given time period, it calculated as follows

$$LF = \frac{\frac{1}{n}\sum_{i=1}^{n} P_i}{\max(P_i)} , \tag{15}$$

where n is the number of hours in the given time period, and P_i is the system load at every hour. In this study, it was of interest to investigate how the load factor differed for the three cases and the different utility rates of the charging station, as it gives an indication of the overall system performance.

3.3 Measuring Grid Impacts

In this study, a modified generic grid structure was used to simulate the grid impacts of integration of BETs. Thus, it was of interest to investigate the overall system performance, rather than effects on single buses. To get an analytical overview of a system's performance, indexes may be used. Indexes are beneficial when comparing operation before and after system changes, but they may also be used to optimise the location or size of the suggested changes [55]. To analyse the effects on the system losses, a real power loss index (PLI) may be used. The PLI can be expressed as follows

$$PLI = \frac{|P_{loss,WC}|}{|P_{loss,WOC}|} \cdot 100 . \tag{16}$$

The lower the PLI value, the fewer impacts of BET integration and charging stations. The index can be used to compare the losses for different locations and share of BETs [55]. Furthermore, the effects on the voltage profile were of interest in this thesis. A voltage profile index (VPI) can be calculated using

$$VPI = \max_{n} \left(\frac{|V_1| - |V_n|}{|V_1|} \right) \cdot 100 , \tag{17}$$

thus, taking the maximum voltage drop between a chosen bus and the bus causing the largest voltage drop [55]. A lower VPI value indicate better network performance. Another common index to use when conducting grid impact analyses is the line capacity index (LCI), which is a measurement of the level of power flows, or currents, flowing through the lines with respect to the maximum capacity of the lines. A lower LCI value indicated that more capacity is available. Furthermore, it can be expressed as

$$LCI = \max_{m,n} \left| \frac{S_{mn}}{CS_{mn}} \right| \cdot 100 \ , \tag{18}$$

where S_{mn} is the complex power and CS_{mn} is the maximum complex power between bus m and n.

4 Methodology

In this section, the method behind the work of the thesis will be presented. The section is ought to give the reader an understanding of how and why certain assumptions were made, how the power grid was modelled and how the charging profile were simulated based on the case for the charging station at Vädermotet. As several simulations were made to create a scope for the thesis, a literature study was carried out. Both to find methods to conduct simulations and build models, but also to find results from previous studies to be able to discuss the reliability and validity of this thesis. Moreover, the section provides information on how the load cases were chosen, how the grid model was created, the load profile modelling, and simulations of charging profiles for the charging station.

4.1 Literature Studies

As for any scientific study, this thesis is based upon earlier studies within the field of electrification and its challenges. To collect relevant previous studies, a literature study was carried out. The collected material mainly comes from scientific articles, but also recent similar projects where the grid impacts of integration of BETs has been investigated. However, how BETs affect the power system is not yet completely determined. It is a complex challenge, and the results may vary as the conditions of the power system varies between different areas within Sweden, but of course also between different nations. The complexity of the power system makes it hard to draw general conclusions about BET integration, and can therefore not be found in the available research today. Furthermore, the attitude against BETs also depends on who is making the study or project, as the topic of EVs and its consequences on the power system may be considered controversial. The controversy is mainly regards who will profit from it or not, a well-known similar example is the question of BESS and its profitability. Some argues that it is only a temporary solution, while others argues that it is the future.

Moreover, the main purpose of the literature study was to get a sufficient overview of previous research and to find relevant theoretical concepts, but also methods to perform grid impact analyses. However, being aware of possible bias in the sources and that the power system in two different areas cannot be directly compared, the results from previous studies were handled with care. In general, trends and more general effects of the results were considered as reliable, while the magnitude of the effects in other studies was not considered when evaluating the results from this thesis. To make the thesis as transparent as possible, all assumptions and limitations are stated and motivated, as well as the data sources. It is important that both advantages and disadvantages of BET integration is discussed and that the results are not biased.

4.2 Assumptions

Several assumptions were made in the thesis. Detailed information about the power system on Hisingen was confidential and therefore not available. Also, charging data from the charging station at Vädermotet was not available, as the charging station at Vädermotet will not be in operation until June 2022. Thus, several assumptions had to be made to model grid implementation of a BET charging stations and perform a grid impact analysis. Assumptions are motivated throughout the thesis, but it is important to remember that there are a lot of assumptions and that it affect the results. The assumptions in the thesis will be briefly presented below.

- All electric trucks, both light and heavy, were included to get a larger scope for the study.
- The distribution grid at Hisingen was assumed to be radial, with one main feeder from the transmission system down to the distribution level.
- The grid model did not consider individual loads, instead areas were aggregated to loads and the grid model stopped at the grid stations on 0.4 kV-level and 10 kV-level.
- The voltage levels in the power system model were assumed to be 400 kV, 130 kV, 10 kV and 0.4 kV [9, 24].
- Charging-hybrid vehicles were not considered in the thesis.
- A *first-in-first-served* principle was applied on the queue to the chargers at Vädermotet.
- When a BET is charging, it charges at constant power for some time and the battery was assumed to be fully charged at departure.
- Freight traffic and long-haul transports has the same driving pattern night and day.

All these assumptions most likely had an effect on the results of the thesis. Based on this, it is important to keep in mind that the results of the thesis should not be regarded as the absolute truth, but rather as an indication of how BET integration can affect a local power system, in this case on Hisingen. However, these assumptions were necessary to the study as a lot of information was not available due to security and confidentiality aspects. Making well-motivated assumptions was therefore necessary to conduct the study and create a reasonable scope.

4.3 Set up Cases

The aim of the thesis is to determine the grid impacts of the high-power charging based on the station at Vädermotet. Thus, it was of interest to examine the impacts throughout a year, to understand how the impacts may vary for different load conditions. Hence, three cases were constructed. Firstly, the maximum load case had to be investigated. The hypothesis was that by examining the maximal load case, the maximum grid impacts of different utility rates of the charging station could be obtained. In opposite, it was also of interest to examine the case when the load was at minimum. In relation to other loads, the power requirement for Vädermotet will be greater at times of low power demand. How this affect the system is also of importance to illustrate. The third and last case that was simulated was when the system had an average load. The last case is more representative for most of the year, and is therefore important to include in the study to understand how BET integration affects the local power system throughout the year, and not just at the extreme cases. Finally, for future studies, it could also be of interest to combine these cases with different shares of intermittent power production. Gothenburg is the municipality with the highest share of installed PV-modules in Sweden, and there are also some wind power plants in the area [56]. Hence, that aspect should be taken into account, even though it was out of the scope of this thesis.

The time period for each case was 24 hours, since it was of interest to investigate the grid impacts and stability in the system it was a reasonable time frame for this thesis. The available data contained hourly measurements of the power consumption, thus the time step was one hour in the simulations. However, to see the long-term effects of BET integration a simulation could run over the course of one week to one month, or even more, this could give better results for some applications [40]. To find the three cases, the load profile for 2021 was used. The data were obtained from GENAB, as one feeder for industry loads and one for household loads. However, the load profile had to be scaled to match the total power consumption, how this was done is shown in Appendix C. Furthermore, the three load cases were found using a MATLAB-script. For the two extreme cases, the days that contained the maximum respectively minimum load were chosen. For the average day, the mean value for a whole day was calculated. Thus, the mean values for the whole days were stored and from them the median was found. Then, based on the number of the day that had the median value, the day with an average load for 2021 could be found. The script for finding the three cases is shown in Appendix B. Based on this, the three days found to be interesting for the thesis project were 2021-02-12, 2021-06-29 and 2021-09-23, which corresponds to the highest, lowest and most average power consumption in 2021 in the Gothenburg area.

4.4 PSS®SINCAL Simulation Methodology

The grid model that was used for simulations was built in PSS®SINCAL, a simulation software for power system analysis developed by Siemens [57]. The model was based on geographical information about the power system at Hisingen, design manuals, load data for one feeder and general background knowledge about distribution systems. The network structure for Hisingen, as well as power consumption data for specific areas, is covered by GENAB's confidentiality and could therefore not be used in this study. This is one of the main drawbacks of the study, since the accuracy of the simulation model could not be validated towards the real system. The data that was obtained from GENAB was the consumption for two feeders in the Gothenburg area, more information was not available since the security for GENAB's costumers must be prioritised.

Even though the simulation model was based on background knowledge about power systems and assumptions rather than real data, the simulations were conducted according to the method presented in Figure 9. The input to the model was the hourly power consumption profiles for the three cases and the hourly charging profiles for the three different utility rates of the charging station. However, to model the charging profile data about the trucks and requirements for the charging station was needed. The model data that was used was the grid structure, ratings for the conductors and other characteristics of the components in the power system. The output of interest was bus voltages and voltage deviations, power balance, power losses and the line loading.

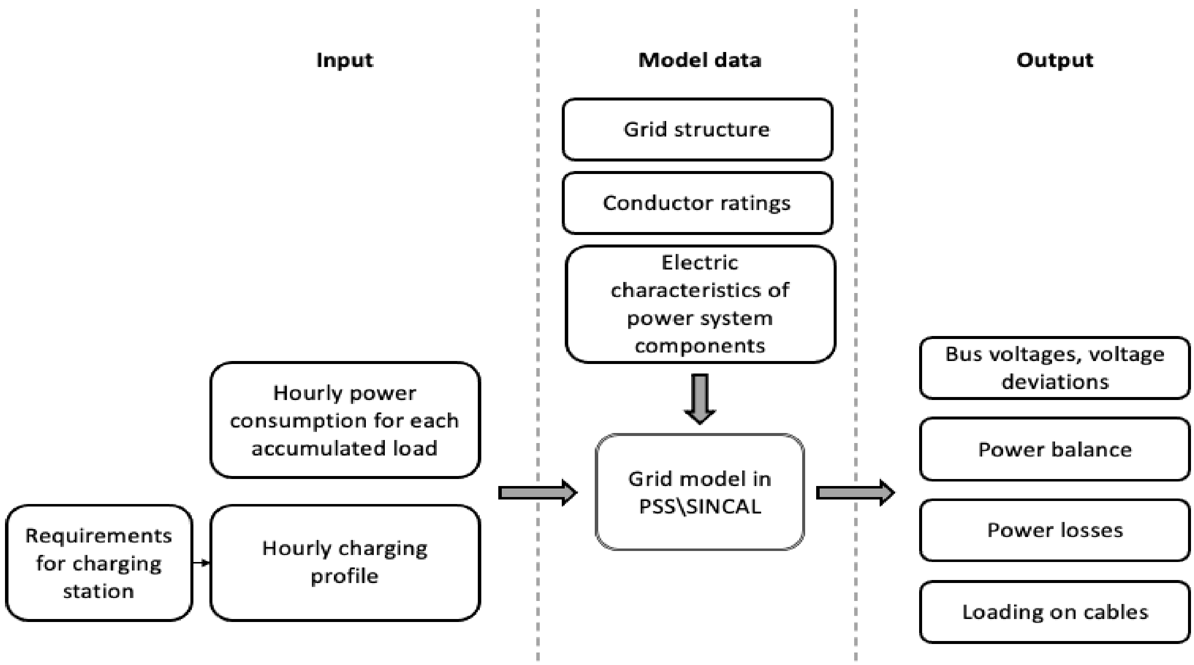


Figure 9: Diagram of the input, model data and output that was used to simulate the local power system at Hisingen.

4.4.1 Grid Structure

The grid structure was based on an IEEE-standard system with 37 buses [58, 59], see Figure 10. The system was used since it contains one main feeder that distributes power to smaller branches, which was also assumed to be the case at Hisingen. The feeder has been modified in previous studies and tested for different cases of renewable energy integration [59]. Furthermore, geographical information about Hisingen was used. On maps of Hisingen one main air transmission line could be seen, while the rest of the branches were underground cables. The loads were aggregated to represent different areas on Hisingen, as shown in Figure 11. Besides the overhead lines, the distribution of industry and residential load areas could also be seen from maps. Furthermore, the size of the network, 37 nodes, was a suitable size for a distribution network for a place as Hisingen. However, loads had to be aggregated, so for example housing areas and neighbourhoods as well as several smaller industries were aggregated as one load connected to one bus.

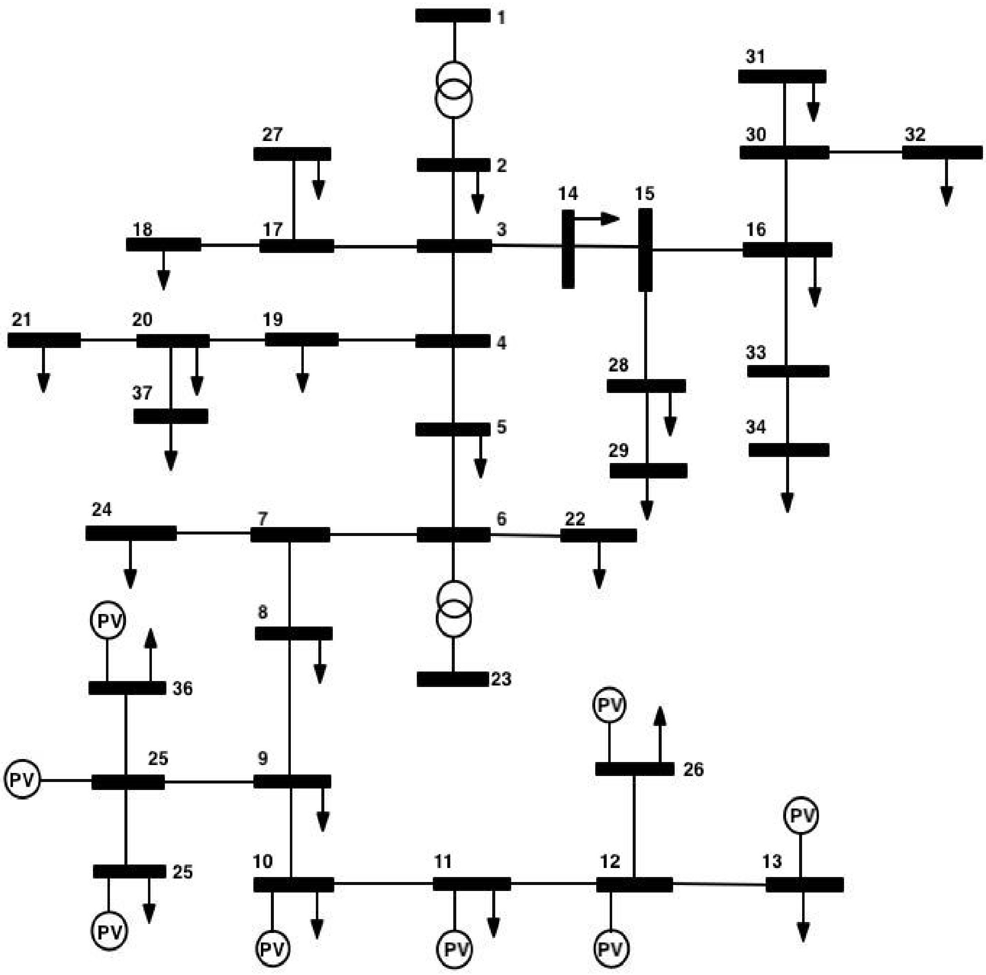


Figure 10: The original IEEE 37-bus system, where the bars represent the buses, the line represent three-phase transmission lines, the loads are marked with arrows and the generators are represented with circles. [58, 59]

Figure 11: Map of Hisingen, where aggregated residential loads are marked as blue areas and aggregated industry loads are marked as orange areas. The charging station at Vädermotet is marked as a red circle. Map from Google Maps.

When building the grid model, the loads were placed to the left or to the right side of the bus, depending on if the load was a residential load or industrial load. The convention for load placement that was used in the thesis is shown in Figure 12.

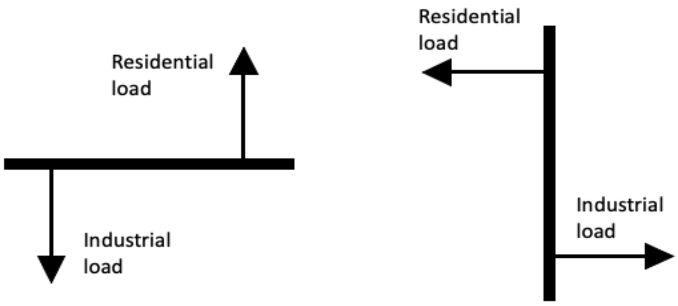


Figure 12: Load placement on buses.

To make the model truer to reality, some changes of the IEEE 37-bus system were made. First, some loads and lines were moved to match the geography of Hisingen better, see Figure 11 and 13. In addition, it was assumed that two of the residential areas with villas on Hisingen had some PV power production, which was modelled as smaller generators . Moreover, some more buses were added as more voltage levels were included on the feeder, as well as more loads. In the modified version of the test feeder, there were 46 buses.

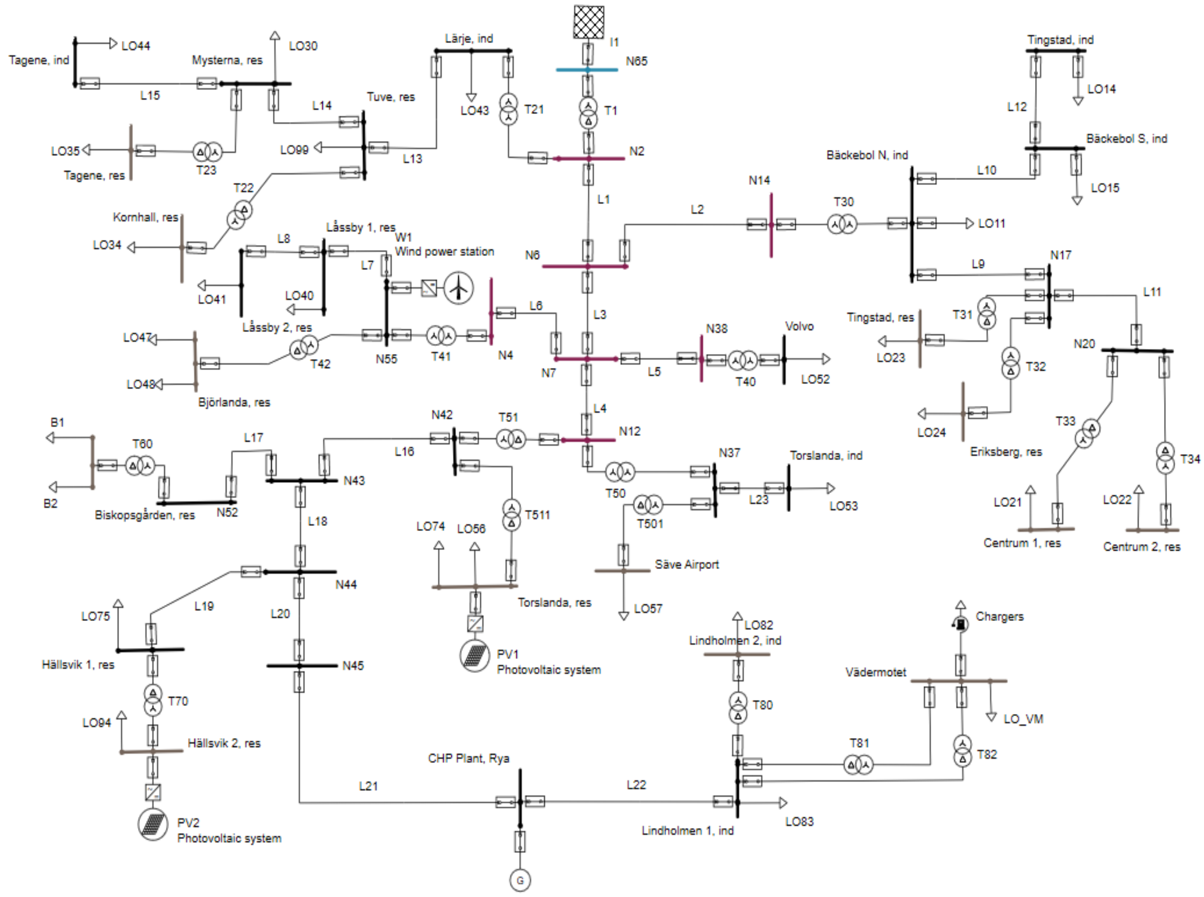


Figure 13: The modified grid used in the thesis. The colour denotes the different voltage levels, and each bus is assigned to a certain area of Hisingen.

To separate the different voltage levels, the nodes were assigned different colours. Blue buses denote a voltage level at 400 kV, purple denotes 130 kV, black denoted 10 kV and brown buses denoted the 0.4 kV-level of the system. Furthermore, the loads were separated into residential loads and industry loads, thus the loads were assigned with 'res' respectively 'ind' to separate the types in the model. Also, there was one slack bus in the system, one generator bus (the CHP plant at Rya) and 25 load buses. As the grid configuration strongly affects the results, and large parts of the configuration is based on motivated assumptions, it is important to keep in mind that this should be regarded as a test feeder, or a simplified model to resemble the true system, but it can not be compared with the real system.

4.4.2 Transformers

The simulation model contains 22 transformers. The transformers are used to connect the different voltage levels in the system. All transformers are modelled as two-winding transformers [60]. As no information was available about the transformers, the network design manual from E.ON was used. The voltage and apparent power ratings for the transformers in the thesis is shown in Table 2.

Table 2: Ratings of transformers.

V_1 / V_2 [kV]	S_{rated} [MVA]
10 / 0.4	1.6
10 / 0.4	2
10 / 0.4	5
10 / 0.4	10
130 / 10	15
130 / 10	20
130 / 10	30
400 / 70	20
400 / 70	30

According to E.ON's manual for network design, different types of transformers are used for different voltage levels [60] (p. 13-16). These types were used in the thesis. The transformer types can be seen in Table 3.

Table 3: Types of transformers. [60]

Voltage [kV]	Ratings	Trafo. type	Comment
400	400 kV / 130 kV	YND1	Step-down transformer.
130	130 kV / 10 kV	YNYN0	On-load tap-changers for voltage control.
10	10 kV / 0.4 kV	DYN11	Off-load tap-changers for voltage adjustment.

4.4.3 Generators

It is known that there are both wind power plants and solar power plants at Hisingen. However, how many or what power they deliver is unknown. In the model, it was assumed that the total production from renewable power sources was 2 MW. The number was an assumption based on the fact that there are some wind-power plants on Hisingen, some smaller solar power plants, and that some of the households has PV-modules installed on the roofs [9]. The power plants are aggregated and modelled as converters to the built-in modules that represent solar power plants respectively wind power plants. The wind power plant was installed at the node 'N55' and the solar power plants were installed at the nodes 'Hällsvik 2, res' and 'Torslanda, res'. Medium-sized wind power plants connected to distributions grids usually use induction generators, which absorbs reactive power from the grid. Thus, the wind power plant were modelled as an induction generator.

Furthermore, the CHP plant at Rya was modelled as a synchronous generator, as it is a larger power production plant [9]. The plant is in operation during 7-8 months every year, during winter time. It is expected to produce 1.25 TWh electrical power, corresponding to an average of 1.427 MW [61]. The generator was assumed to deliver twice the average power during the maximum load case, its average power delivery for the average case, and it was assumed to be out of operation during summer, thus during the minimal load case.

4.4.4 Transmission Lines

It was known that around 97 % of the transmission lines in the distribution system in Gothenburg are underground cables. Thus, it was assumed that the share of cables was the same on Hisingen since it is a part of the power system in Gothenburg. The lines at 130 kV was assumed to be overhead lines, as they were the only ones visible on existing maps of Hisingen. Moreover, it was assumed that the conductor lengths was not longer than 80 km on Hisingen, thus the assumptions regarding short cables were used and capacitance and inductance were neglected for the overhead lines [27]. An illustration of the pi-equivalent for a short transmission line is shown in Figure 14. Note that the capacitance was neglected for the overhead lines at 150 kV.

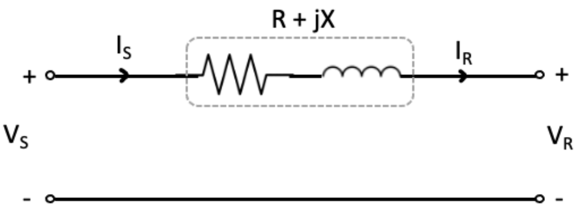


Figure 14: Illustration of the pi-equivalent for a short overhead transmission line, where the capacitance is neglected. [27]

For the rest of the system voltage levels, that is 10 kV, it was assumed that cables was used. The pi-equivalent for a short underground cable is shown in Figure 15. To find suitable data for underground cables on the voltage levels of interest, the design manual from E.ON was used [60]. The assumption regarding the length of the cables were based on the geography of Hisingen, it is a rather small island with short distances and most of the loads are located closely. However, for underground cables the capacitance could not be neglected. The grid model used in the thesis contained 21 lines and cables. The ratings and impedance's of the conductor types that were used in the thesis is shown in Table 4.

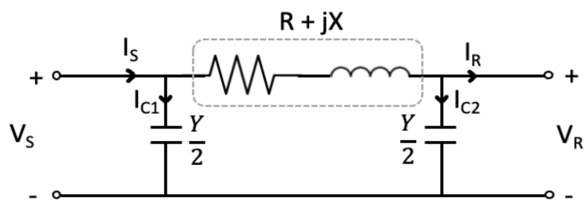


Figure 15: Illustration of the pi-equivalent for a short underground cable. Note that the capacitance is included. [27]

Table 4: Data for transmission lines in the distribution system.

Rated voltage $[kV]$	Resistance [Ω /km]	Reactance [Ω /km]	Capacitance $[nF/\text{km}]$	Thermal-limit current $[kA]$	Cross section $[mm^2]$
150	0.198	0.434	0	0.715	450
10	0.0557	0.099	558	0.662	400
10	0.105	0.111	406	0.456	185
10	0.0814	0.106	456	0.526	240

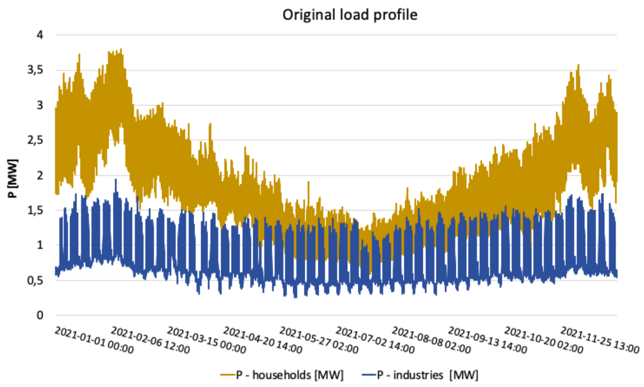
4.4.5 Loads

There are 29 loads in the grid model, 28 loads were residential and industry loads, while one load represented the charging station at Vädermotet. The loads were distributed at 25 load buses, representing grid stations (aggregating several smaller industries or residential areas). In reality, the grid does not stop at that level, instead radial feeders are connected to the grid stations which then delivers the electricity all the way to the end-consumer. However, in this system the total power consumption was 125 MW. The loads were modelled as hourly constant P and Q consumers as the available data was given on an hourly basis.

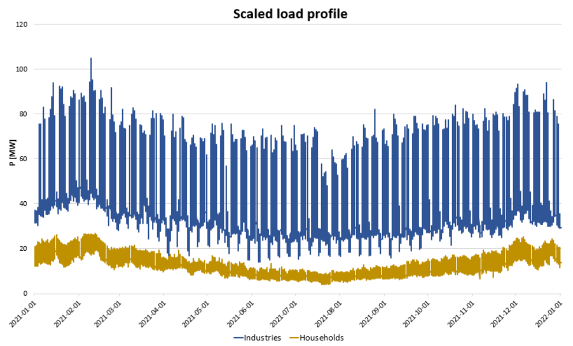
As mentioned, the loads were grouped into either residential or industrial loads. This was a broad generalisation to make the thesis more comprehensible. This generalisation was based on the demography and placement of different buildings, industries and residential areas. However, the residential load covers both commercial loads and transportation (private EVs). The industrial loads covered both transportation (not trams), utility systems and Säve Airport.

4.5 Scaled Load Profile for Hisingen

A load profile with hourly power consumption was obtained from Göteborg Energi AB. The data represented two feeders in central Gothenburg, covering a lot of the cities power demand, but not all. Due to confidentiality, all power consumption data from Gothenburg could not be obtained. To cover all of Hisingen's power consumption, the original load profile was scaled (see Figure 16), which was done using E.ON's standards for loads in power system and population data for Hisingen [60, 62]. As the shape of the load profile was known, a bottom-up methodology was used when scaling the load profile. That is, the total load at every load area in the model was estimated by taking the different industries and types of households into account. More information about how the load profile was scaled is found in Appendix C. However, the load profile before and after the scaling is shown in Figure 16.



(a) Original load profile.



(b) The scaled load profile that was used for simulations.

Figure 16: The load profile before and after scaling.

4.6 Charging Profiles Simulation

To simulate the system behaviour when implementing a charging station to the power system, charging profiles for the charging station is needed. The charging profile consisted of hourly power data with the aggregated loads for the number of BETs charging at the same time at Vädermotet. The charging station at Vädermotet has currently a total of four ABB Terra 360 chargers and a total of six BETs may be charged at the same time, meaning that four of the BETs has to share a charger, yielding a maximum power out-take of 180 kW to each BET instead of 360 kW. However, since the charging station at Vädermotet is expected to be put into operation by June in 2022 no real-life data about the usage of the charging station was available. Thus, it had to be simulated based on the knowledge about the station. For the future charging profile scenario, two ABB Terra 360 chargers were added and one MCS rated at 1 MW [31]. The future charging scenario (scenario 2) is planned to be put into operation by 2023 or 2024.

The arrival of BETs was assumed to be the same both during night- and daytime. This assumption simplified the model, but it is also reasonable to assume that freight transport runs around the clock. When talking about heavy-duty transports the limiting factors are not the time of the day, rather the fact that chauffeurs are not allowed to drive for more than 4.5 hours, and then they must have at least a 45 minutes break. The following driving data was used to calculate the energy demand (see Table 5). Furthermore, knowledge about electrical trucks from Volvo and Scania was used to calculate the energy demand [17, 48] (see Table 6 and 7).

Table 5: Driving data for the BETs.

Property	Abbreviation	Unit	[Value from - value to]
Consumed energy	E_{cons}	kWh/km	[1.2 - 1.7]
SOC at arrival	$SOC_{arrival}$	%	[0.2 - 0.5]
Driving time	T	h	[2.5 - 4.5]
Average speed	v	km/h	[70 - 90]

The values presented in Table 5 were used in the MATLAB script, where numbers used in the calculations were randomised based on the given intervals in Table 5. The randomisation made the simulations more true to reality, since it gives every arriving BET a different energy demand. The equations that were used to compute the energy demand were presented earlier in section 3.1.1.

To determine the charging time and the charging power, the truck's battery size was needed. There are several manufactures of BETs, but in this thesis BETs from Scania and Volvo were considered since they are a part of the project E-Charge. The model of the BET determines the battery size, and charging power. This, combined with how much energy the BET has consumed while driving, determined the charging time at the charging station. Every BET that arrived to the charging station was assigned a type by chance between the models in Table 6. Furthermore, the designated charging levels are shown in Table 7.

Table 6: Data for the batteries considered within this project [47] [48].

Company	Model	Range [km]	Battery size [kWh]	Designated charging level
Volvo	Model 1	300	450	2
Volvo	Model 2	300	450	2
Volvo	Model 3	350	540	3
Scania	Model 1	250	300	1
Scania	Model 2	200	165	1

Table 7: Data for charging depending on the charging level [47] [48].

Charging level	Rated voltage/current	Type	Rated charging power [kW]
1	620 V / 200 A	Public	130
2	600 V / 420 A	Public	250
3	750 V / 330 A	Public	250

This data was used to calculate the energy demand for every BET arriving to the station, a process that were assumed to follow a Poisson distribution with $\lambda = 2$. The BETs that could not charge directly when arriving were placed in a queue. The simulations resulted in two charging profiles, one for the current scenario and one for the future scenario considering an expansion of the charging station. Two simulated cases that had approximately the same utility rate were chosen to make the results comparable. A utility rate of 1 means that all chargers at the charging station runs at maximum charging power every hour, while a utility rate of 0 means that all chargers are out of service. Here, $F_{utility} \approx 0.75$. The charging profiles for the current and future scenario can be seen in Figure 17. In the first charging scenario 112 BETs were charged, and in the second charging scenario 164 BETs were charged during the 24 hours long time period. Meaning that a sufficient part of the electrical truck fleet in the Gothenburg area could use the public charging station, which implies that the simulations are reasonable. The MATLAB code for simulation of charging profiles is available upon request.

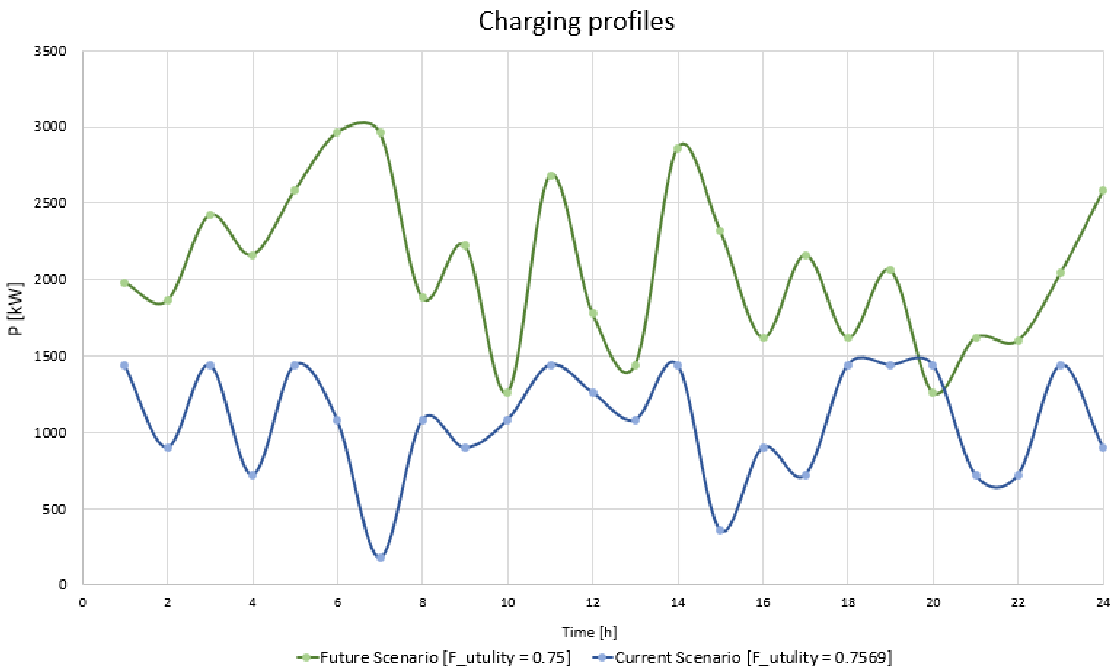


Figure 17: Charging profile for Vädermotet charging station.

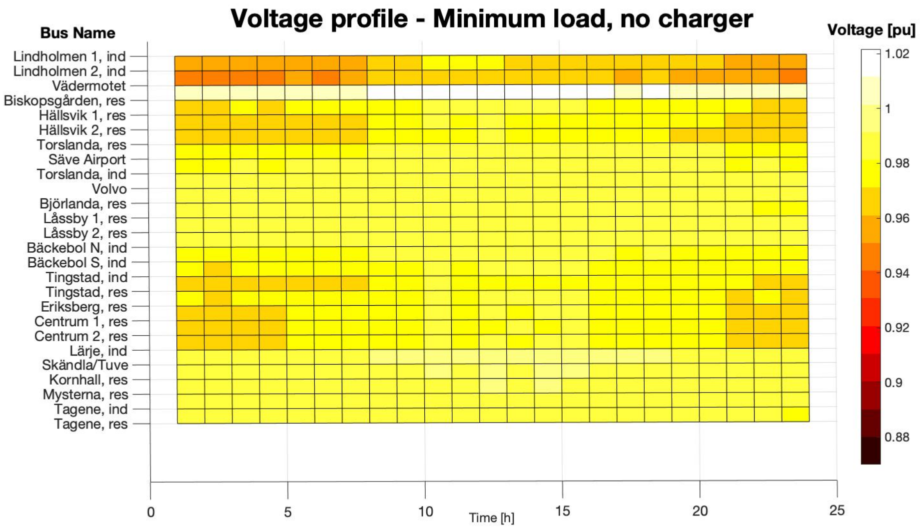
5 Results

This section will provide the results of the thesis. The results are primarily presented in figures and tables, followed by some shorter comments. A more thorough discussion will be carried out in section 6.

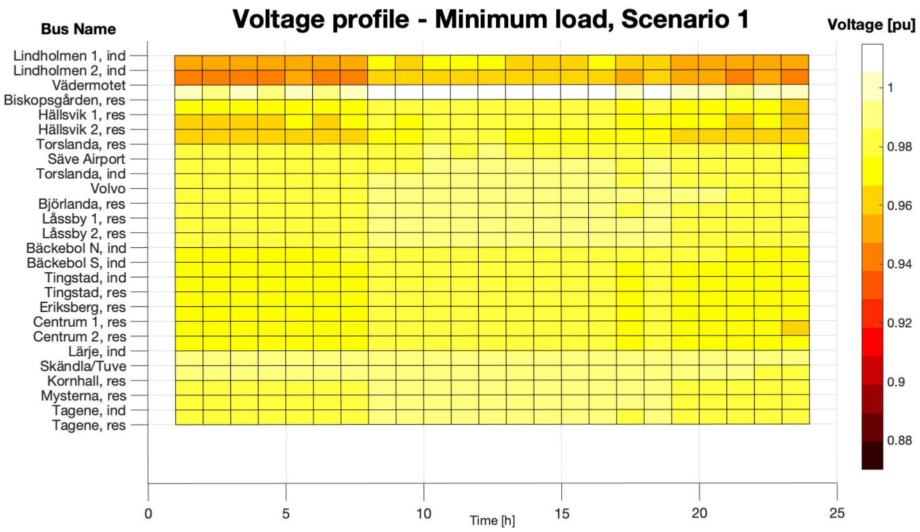
5.1 Impact on Voltage

To begin with, the overall system impacts were illustrated by plotting the bus voltages, in pu, at every bus of the system. This is often called the voltage profiles of the system. The results gave a better understanding for how the voltage sags and voltage deviations varies for the three load cases and the two charging scenarios. The voltage profiles for the minimum load are shown in Figure 18. Note that the scenario with no chargers installed was simulated, and then the scenario with four ABB Terra 360 chargers (scenario 1) and the scenario with six ABB Terra 360 chargers and one MCS (scenario 2) were also simulated. Furthermore, the different charging scenarios during the average load case is shown in Figure 19. Thirdly, the simulations of the maximal load case and the three charging scenarios are shown in Figure 20.

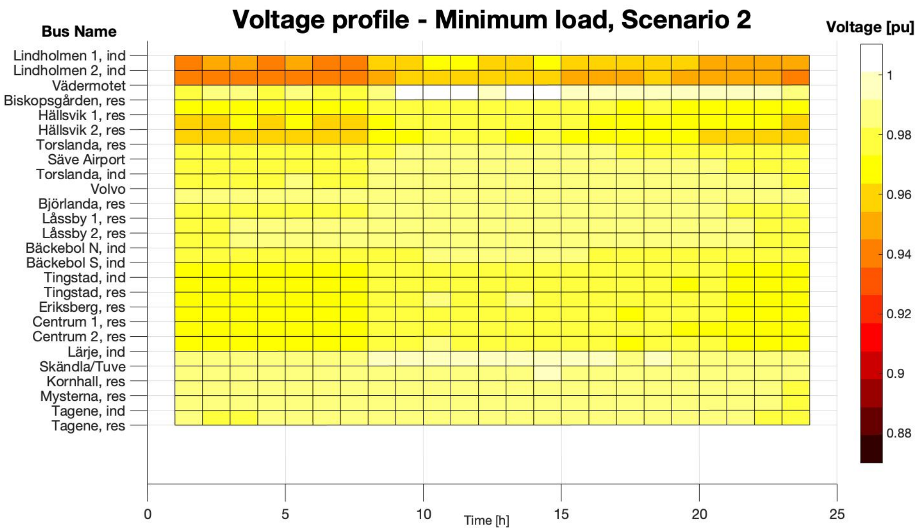
For the minimum load case, the results show that it was mainly the bus voltage at Vädermotet that was affected when installing chargers, both for scenario 1 and 2. Charging scenario 2 caused a voltage drop at the bus that is connected the charging station to the grid. The voltage drop was a result of the increased load on the bus. As the loading of the system increases, the larger the voltage drops. Apart from that, the rest of the bus voltages in the system were not too heavily affected by the increase of charging load. Moving on to the average load case, the voltage sags during high load hours increased at the buses in the system. The voltage dropped slightly at Vädermotet, but the largest voltage drop occurred in another part of the system. For the average load case, the voltage sags were still within acceptable limits for charging scenario 1, but for scenario 2 the voltage sag was below 0.90 pu. For the maximum load case, the system had some voltage sags to start with, but the sags grew larger as the charging load increased.



(a) Minimum load case, no chargers installed.

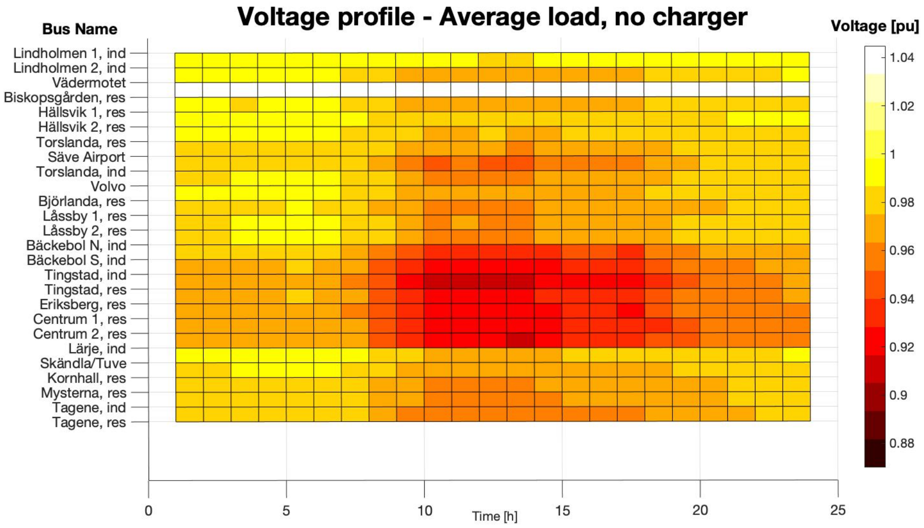


(b) Minimum load case, 4 ABB Terra 360 chargers.

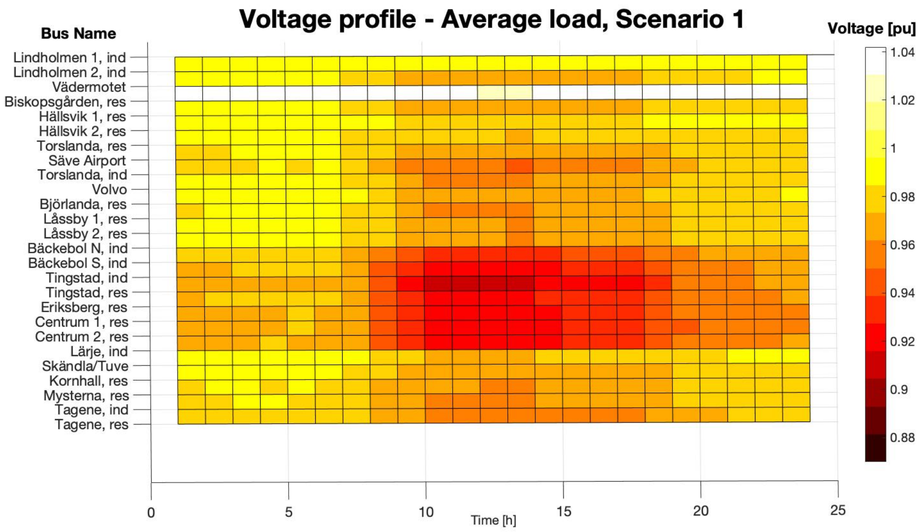


(c) Minimum load case, 6 ABB Terra 360 chargers, 1 MCS.

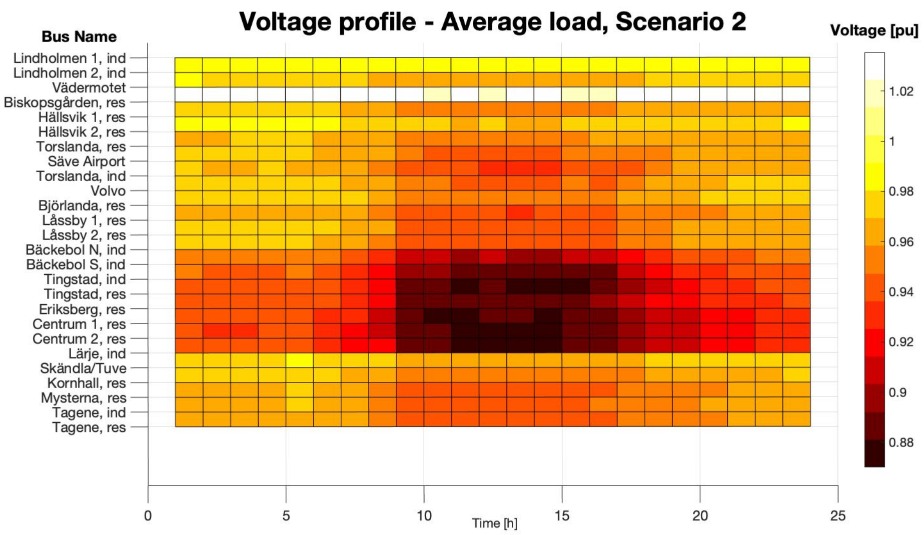
Figure 18: Voltage profiles with no chargers at Vädermotet.



(a) Average load case, no chargers installed.

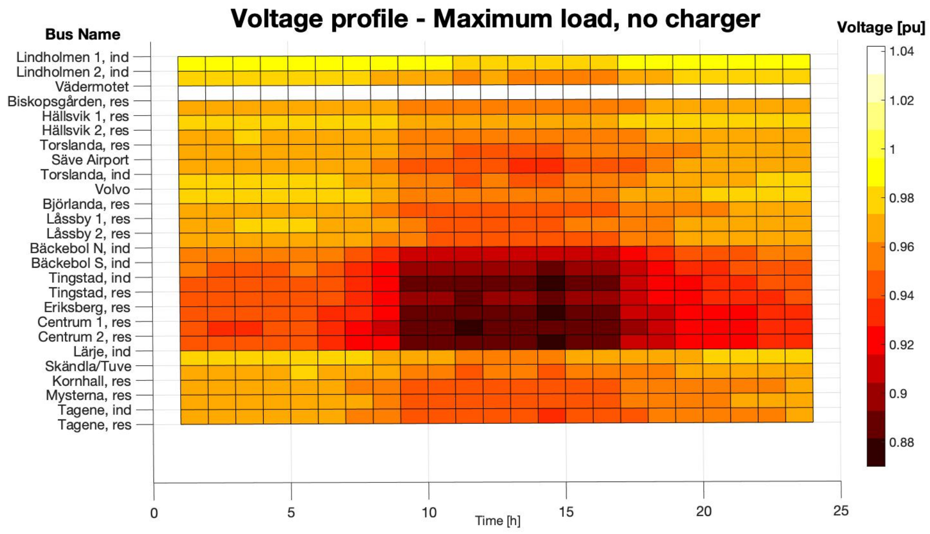


(b) Average load case, 4 ABB Terra 360 chargers.

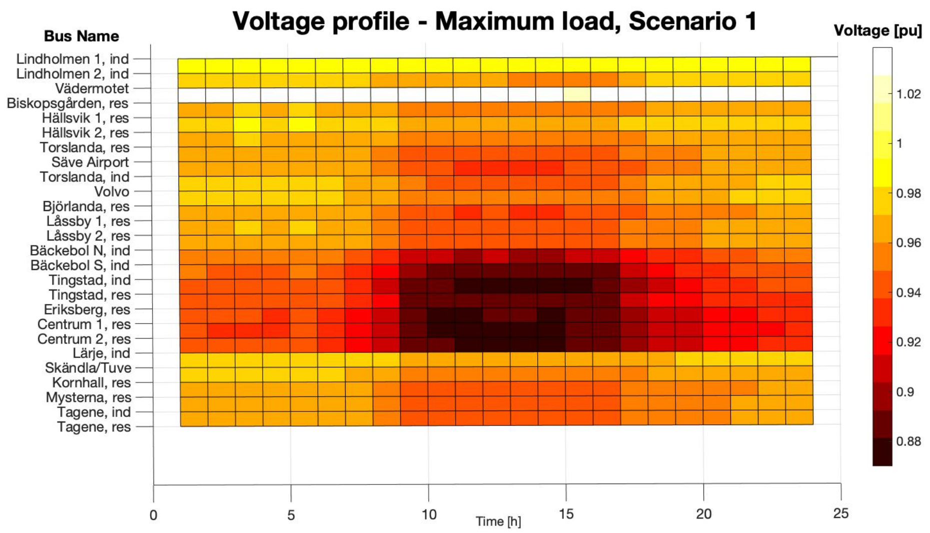


(c) Average load case, 6 ABB Terra 360 chargers, 1 MCS.

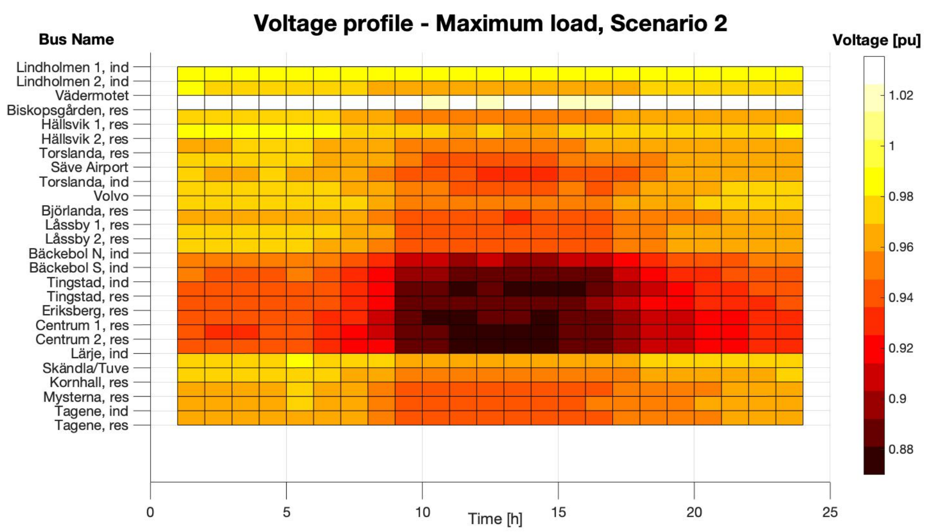
Figure 19: Voltage profiles for scenario 1 at Vädermotet.



(a) Maximum load case, no chargers installed.



(b) Maximum load case, 4 ABB Terra 360 chargers



(c) Maximum load case, 6 ABB Terra 360 chargers, 1 MCS.

Figure 20: Voltage profiles for scenario 2 at Vädermotet.

5.1.1 Voltage Stability

The voltage stability of the system gave an overview of the impacts of the increased load at the charging station. Thus, the VSF and VD were calculated, the results are shown in Table 8 and 9. As the simulations relies on several assumptions, the results should not be regarded as the absolute truth. However, the results indicates that the VSF and VD increased for the minimum load case for the charging scenarios, but for the average and maximum load case the differences were not that big.

Table 8: The voltage sensitivity factor of the system for the simulated cases.

Case	$VSF_{Scenario1}$ [kV/kW]	$VSF_{Scenario2}$ [kV/kW]
Minimum load	148.89	165.12
Average load	7.78	7.75
Maximum load	7.78	8.14

Table 9: The voltage deviation in the system for the simulated cases.

Case	VD_{WOC}	$VD_{Scenario1}$	$VD_{Scenario2}$
Minimum load	0.01885	0.02031	0.02496
Average load	0.01194	0.01152	0.0112
Maximum load	0.0399	0.0395	0.0393

It was notable that the VSF was much higher when adding the charging load for the minimum load case. In general, the VSF value was much higher for the minimum load case than for the other two cases. A high VSF value indicates that the change in voltage is high when changing the load, here more load was added. This indicates that the system is more sensitive to load changes in the system during the minimum load case. However, as the system load increases for the other two load cases, the VSF decrease. That is, an additional increase of charging load has less impact on the system performance when the system load is higher. However, it could also be seen that the voltage sags were larger for the average and maximum load case due to a high load.

The BET charging load at a charging station is strictly dependent on the demands of the transport system and its logistical schemes, making the charging load less flexible. Thus, the load may vary from low to high very drastically throughout the day. A higher system load, but also charging load, causes larger voltage deviations (see Table 9), which is a consequence of high loading and hence increased voltage sags. The results indicate that an increase of charging load may make the system more sensitive when adding more load, mainly for the minimum load case. For the average and maximum load case the VD decreased slightly, however it is hard to validate the significance of those results.

Moreover, it could be observed in PSS®SINCAL that the grid impacts in terms of voltage deviations from the slack bus were largest at the buses close to Vädermotet. However, at more distant parts the consequences were not as apparent.

5.1.2 The Load Factor

As the charging load at Vädermotet increased, the load factor increased for the three load cases. This indicates that the average power consumption increases, while the maximum power out-take is heavily affected by the charging load. For scenario 1 the maximum charging power was 1.44 MW and for scenario 2 the maximum charging load was 3 MW. However, in contrast to the peak power in the system it was not that much, even though the charging load increased the average power consumption of the system. Thus, the load factor increased, see Figure 21. The load factor increased, but it was not necessarily a positive consequence. The results indicate that the charging load at Vädermotet do have an impact on the overall power profile of the electrical system.

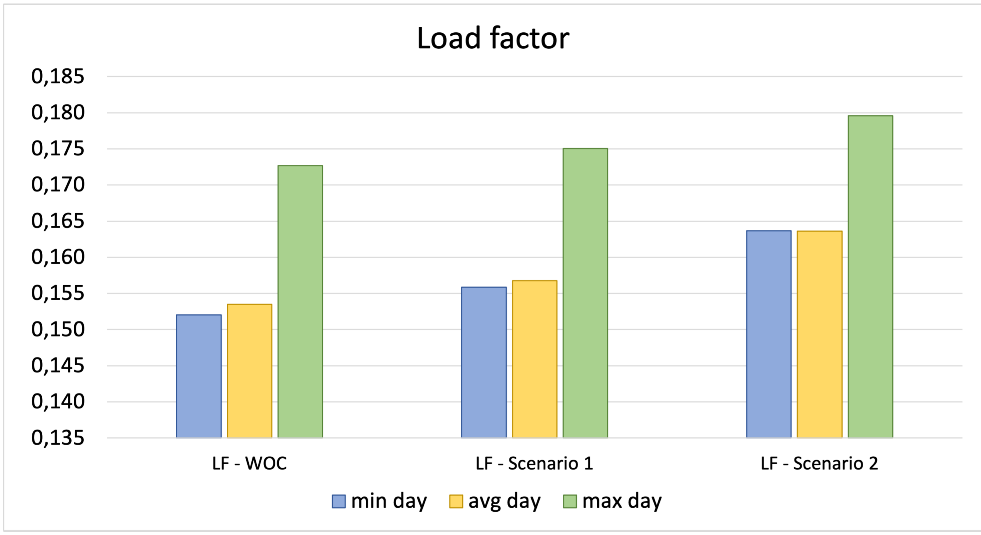


Figure 21: Load factor for the simulated cases.

The load factor increases, meaning that the increased load profile became more even as the charging load increased. This is most likely a result of the fact that the load "Volvo" dominates the system load profile. If the different charging scenarios had been simulated on a more local level, for example, only the feeder that supplies Vädermotet and nearby loads with power would have been simulated.

5.2 Line loading

The results for the most heavily loaded lines are shown in Figure 22-24. It could be seen that the lines near Vädermotet were impacted the most, meaning that the line loading increased for the charging scenarios for all three load cases. For more distant parts of the system, it was shown that the loading of the lines were not that heavily affected.

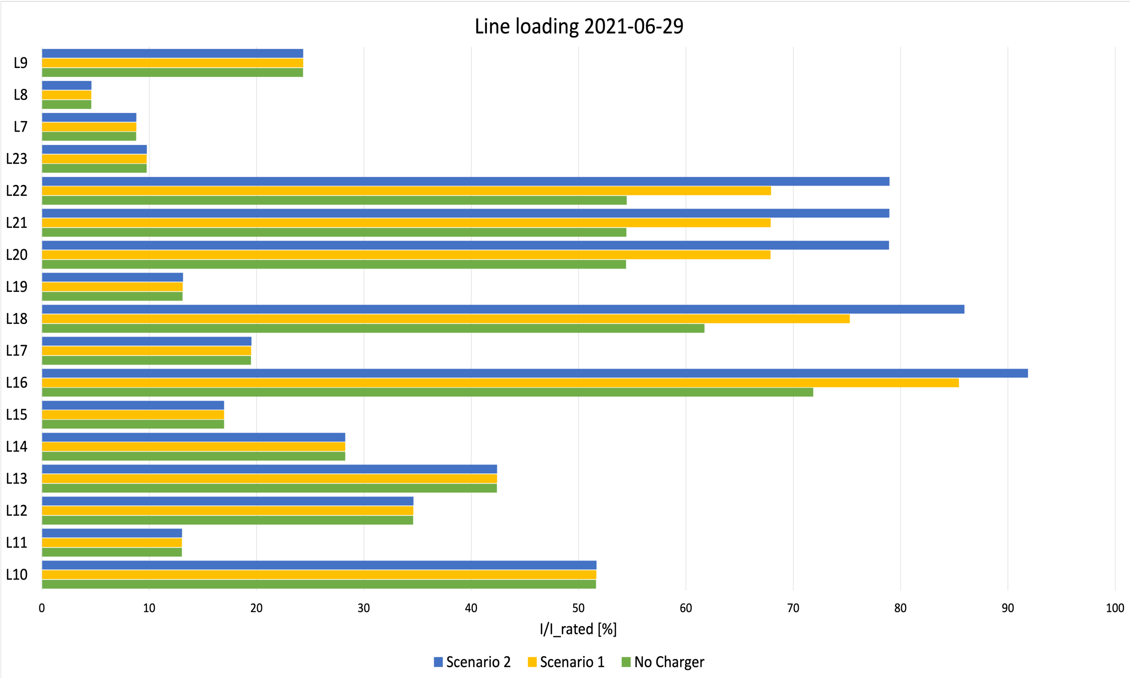


Figure 22: Maximal line loading for the minimal load case for the three charging load scenarios.

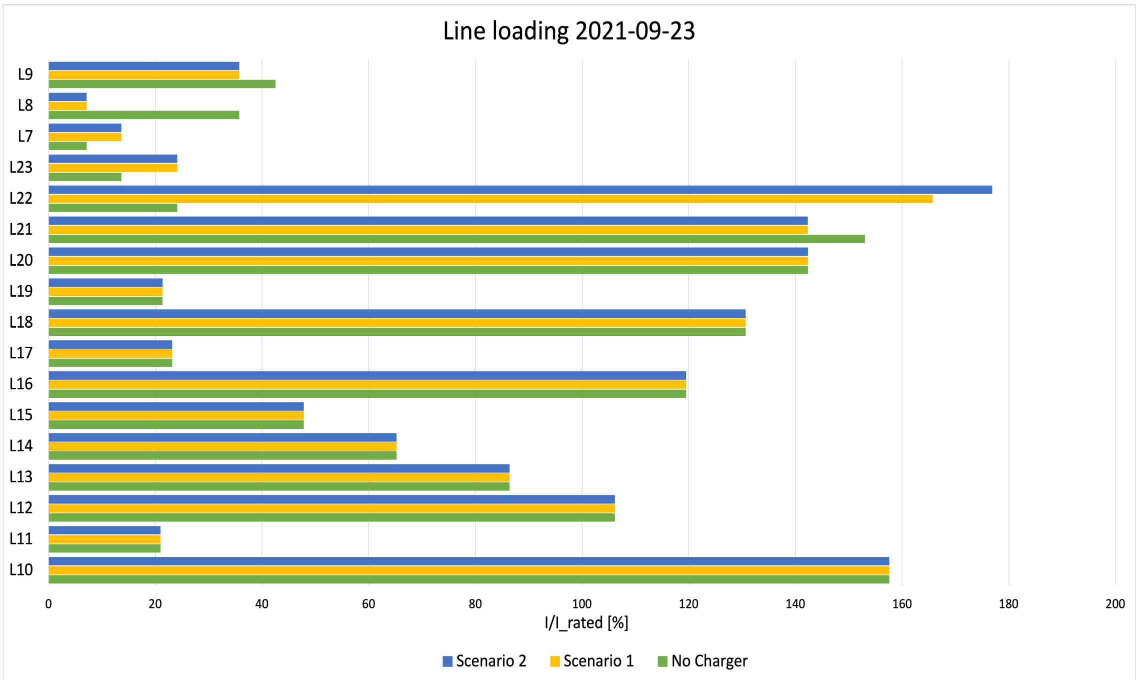


Figure 23: Maximal line loading for the average load case for the three charging load scenarios.

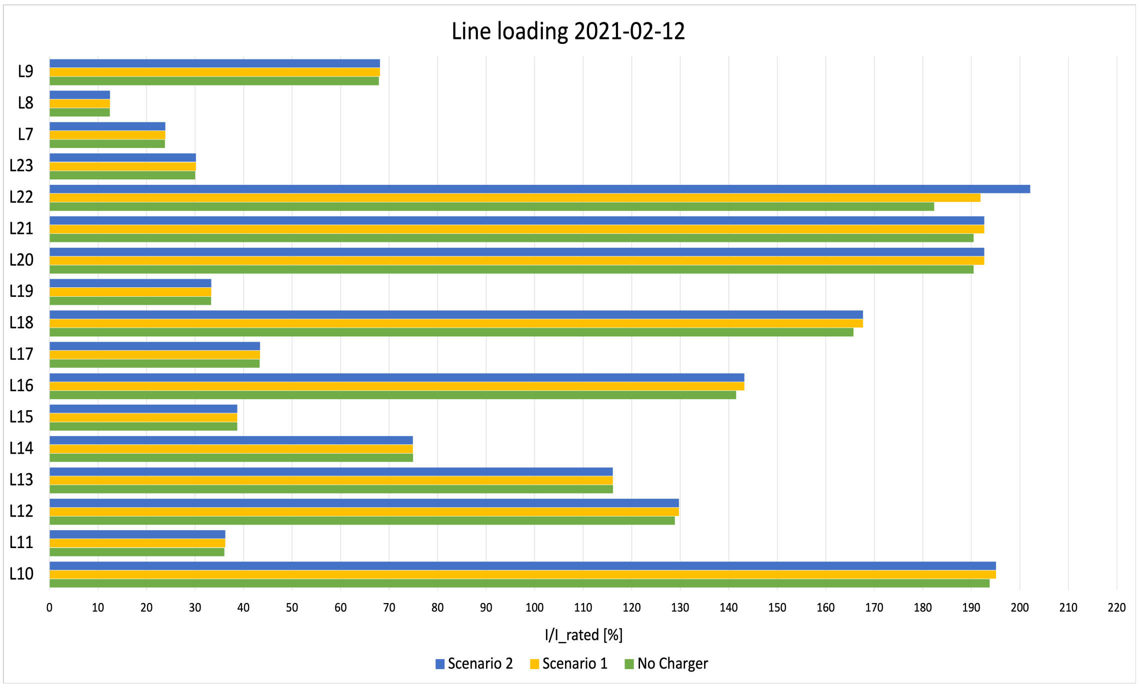


Figure 24: Maximal line loading for the maximal load case for the three charging load scenarios.

An increase of line loading was expected as the charging load increased, which also caused higher currents in the lines. This behaviour is strongly connected to the active power losses in the system. However, it must once again be mentioned that the results should be regarded as an indication of possible grid impacts, but regarding the line loading the results show that the loading increases drastically for the charging scenarios at the maximum load case. The line loading results shows the most heavily loaded conductors in the system at the peak load hour for the three load cases. For the average load case there are some strange results on the line loadability, which is a result of lacks in the grid model. Yet, it could also be a result of load balance in the network for that specific load case, as the load balance throughout the system also affects the loading of conductors. In summary, the results implies that overloading of lines may become more severe as the system load increases in combination with an increased high-power charging load.

5.3 System Losses

The system losses changed for the simulated cases. In general, it was concluded that the losses increased as the loads increase, which was expected. The losses changed the most for the maximum load case and for the two charging scenarios. The system was heavily loaded and when adding charging load at Vädermotet it increased the losses even more. Higher loading of the system yields larger current (see section 5.2) which increases the system losses. The results are shown in Table 10. The system losses were the sum of all losses in the system, however, here the summed losses over 24 hours are presented.

Table 10: The sum of the system losses for the simulated cases.

Case	$P_{loss,NC}$ [MW]	$P_{loss,S1}$ [MW]	$P_{loss,S2}$ [MW]
2021-06-29	9.5417	11.0897	12.9485
2021-09-23	33.5695	34.0017	34.6180
2021-02-12	62.3529	68.3859	69.1143

The losses are directly dependent on the current squared. Thus, as the load increases the currents in the system increases, and hence the losses. In Figure 25 the hourly active power losses are shown. Note that the losses increase the most for the maximum load case, but also that the losses increases the most during peak load hours when adding the charging scenarios. This is a result of system overloading, causing higher losses.

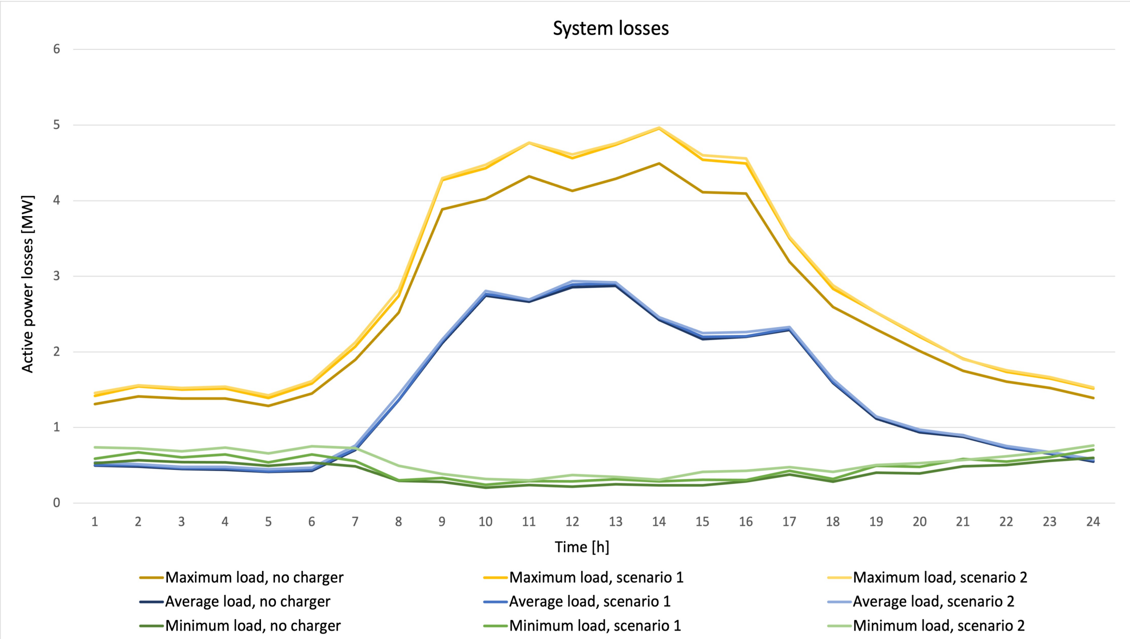


Figure 25: System losses for the simulated cases.

5.4 Grid Impact Indexes

Finally, the grid impacts were analysed using the following indexes; PLI, VPI, and LCI. The results are shown in Figure 11. The PLI increases as the system load increases, but also for the two charging scenarios. This was expected with respect to the results in section 5.3 and 5.2. Regarding the VPI no significant differences between the two charging scenarios could be observed, but it increased between the three load cases. As VPI can be regarded as an indicator of the overall grid performance, this shows that the system loading is of greater importance, rather than the specific load at Vädermotet. Finally, the LCI also increased for every load case, but also for the two charging scenarios. An increased LCI means that there is less line capacity as the charging load increases.

Table 11: Results for PLI, VPI, and LCI.

Case	PLI	VPI	LCI
Min. load, Scenario 1	116.2238	7.3888	85.4056
Min. load, Scenario 2	135.7043	7.3546	91.8475
Avg. load, Scenario 1	101.2873	12.6813	165.6696
Avg. load, Scenario 2	103.1233	12.3572	176.8244
Max. load, Scenario 1	109.6757	15.8669	192.6148
Max. load, Scenario 2	110.8438	15.6076	202.0715

6 Discussion

This section aims at discussing the results to draw some conclusions about the grid impacts when installing a high-power charging station. The discussion will also address issues such as the reliability, and disregarded aspects of the thesis. Note that the results that will be discussed are regarded as indicators for possible consequences of the real system.

6.1 Grid Impacts

The grid impact analysis showed that the consequences of the charging station were most apparent during the minimum load case. The reason was that the charging load at the charging station becomes larger in relation to the system load, thus, the charging load has a larger impact on the grid. However, no stability or loading limits of grid components were reached during the minimum load case for both charging scenarios. The fact that the general grid impacts were the largest during the minimum load case were revealed by the VSF value and the voltage deviations (VD) throughout the system. It could also be seen that the line loading increased the most for the two charging scenarios during the minimum load case. However, no violations occurred during the minimum load case. Yet, the results indicates that the fast varying charging load may be a dominating factor for the system behaviour during the minimum load case. The main problem is the high load variations. To avoid such problems in the future, a smaller BESS could be installed at the charging station to shave the power peaks and henceforth make the charging load more even, which could improve the overall system behaviour. Mainly by reducing the overloading of lines and cables at peak load hours.

For the average and maximum load case, the changes in voltage deviations decreases. However, as the system load increases in combination with the charging load, there are more severe voltage sags throughout the system. This is partly a result of the loading of the system, as high load increase the voltage sags in the system, but the sags keeps increasing when adding the charging station at Vädermotet. This behaviour was most apparent for the average load case, where the voltage sags increased for the two charging scenarios. For the maximum load case, the voltage sags were large for the no load case, but the sags increased even more for the two charging scenarios. However, as the system load was higher, the charging load at Vädermotet was smaller in relation to the other loads in the system. This caused fewer changes in the grid impact indexes, but also fewer changes on the line loading. The losses increased for the average and maximum load case. The increase of active power losses were largest for the maximum load case, and increased even more for charging scenario 1 and 2. This was a result of the high loading of the system, causing line overloading and more thermal losses. This is what the LCI shows, namely that the line capacity decreases as the system load and charging load increases. When the line capacity decrease, the thermal losses increase.

The results of the thesis indicates that the charging station will affect the local power system. The implementation of the high-power charging station will likely cause overloading of components in the system during average and high load days. It is also notable that the charging station mainly had an impact on the voltage profiles and loading of components in the grid area near the charging station. As the consequences seems to be more apparent on a local level, near the charging station, it could be of interest to investigate the possibilities of BESS installation or expanding the grid to avoid problems related to the high-power charging. Moreover, the shape of the load profiles are also important when considering the grid impact. Large fluctuations in the charging load will cause more severe grid impacts. Thus, it is recommended that the logistical schemes behind the charging times will be planned as smart as possible with respect to the grid capacity.

6.2 Reliability of the Study

This thesis was based upon several assumptions and simplifications of the reality. In addition, there are no similar studies or standards that this could be strictly compared against. However, the trends of the results that previous authors has proved also validates the results of this thesis. For example, previous studies has proven that system losses increases, voltage sags increases, and that the bus voltages in the system becomes more sensitive when installing a high-power charging station to a distribution grid [5, 10, 12, 14, 15, 20, 32, 39].

Even though the results seem to be reliable with respect to previous results from other authors, it must be kept in mind that this thesis is based on several assumptions. One main assumption is the grid configuration. Firstly, the grid was modelled as one main feeder at high voltage, from which radial feeders were connected to the loads through several transformer stations. This configuration was not based on information about the real electrical grid, but rather of the geography and demography of Hisingen. However, one thing that strengthens the results of the study was the choice of original test feeder. The IEEE 37-bus system. The model has been tested by other authors, both for connecting charging loads, and for integration of renewable energy sources. Moreover, the system has also been run on similar voltage levels, even though they were modified to suit the Swedish standards.

Another assumption regarding the loads were also made. A charging profile for one industrial load feeder, and one for residential loads, was obtained from GENAB. However, the original load profiles needed to be scaled. To do this, several assumptions were made about residential areas, but also about the number of industries and their sizes in different industry areas. A bottom up perspective was used, as well as data for average household consumption and power consumption for different types of smaller industries

[60]. Then, the shape of the load profiles was contained, but some white noise were added to the charging profile for every load area to give every load its own characteristics. The estimated maximum load was about 130 MW after the load modelling. This number was confirmed by Dennis Ossman at GENAB in a mail conversation, as it was a reasonable size of the total system load. So even though each individual load is based on assumptions and estimates, for example the load at 'Volvo', the total load profile for the system appeared to be quite accurate.

Moreover, the charging load at Vädermotet was also modelled as no data was available as the charging station is not yet in operation. The modelling was based on information about the number of chargers and their rated charging power at Vädermotet, but also the transformer ratings of the transformers that connects Vädermotet to the distribution grid. Furthermore, data about the BETs was obtained from Volvo and Scania, as their BETs seemed to be representative for long-haul duty BETs. Then, standard data about BET energy usage, $SOC_{arrival}$, average driving speed, and driving time was used [46]. Then, the arrival-, charging-, and departure processes were modelled, resulting in the charging profile in Figure 17. With a utility rate of approximatley 0.75, 112 BETs were charged at Vädermotet during 24 hours for the first charging scenario and 164 BETs were charged during the second charging scenario. This is reasonable numbers when taking the total number of trucks in the Gothenburg area into account.

All the assumptions that have been made throughout the study has been done carefully. However, the model should not be regarded as a model of the true system, but rather as a general model for a distribution feeder. For this study the placement of loads and load profile modelling was based on the situation at Hisingen. Thus, the results are partly a result of the assumptions and limitations that has been made throughout the study, and the final model gives a generalised overview of the grid impacts. However, the generalisation of the model is also a strength of the study. It facilities changes in load and generation. For example, a larger load such as Northvolt's factory could be added, different charging scenarios may be studied, and more renewals could be integrated without having to make large changes in the model.

6.3 Disregarded Aspects

Several aspects were disregarded in the study to keep the scope within reasonable limits. Firstly, charging load from private EVs was not considered. EVs may be used as a flexibility service to the power system, as V2G services can be used. That is, power can be discharged from the EVs to the grid when not in use and when the grid needs local power support. In Sweden, there are about 8,100 MWh of battery capacity in EVs that could be used to balance the power grid [34]. To investigate the possibilities of V2G services at Vädermotet would be interesting, even tough the charging ports will be occupied in accordance with a logistical scheme. Thus, only V1G services was considered in the study. However, it is possible that V1G will be most common for heavy-duty trucks even in the future. Even though Power Circle highlight the possibilities of V2G services to balance the grid.

Furthermore, there is also a district heating system in Gothenburg, and on Hisingen. When creating a more flexible local power market, it is important to consider the synergies between the power system and district heating system to optimise the performance and reduce the load factor for both systems. However, this would require more information about both systems, and it was out of the scope of the thesis. Most likely, some synergies between the systems are already being used today, for example during peak load hours to reduce the power peaks. If that property of the system had been taken into account, the results of the grid impact analysis would have been different. Probable with lower system losses and less voltage sags for the high load cases.

In the thesis, the renewable energy sources were assumed to deliver almost the same amount of power in all cases. However, as their consumption do vary a lot in reality, it would be of interest to investigate how that affects the grid performance when the charging station is put into operation. What will happen with the grid stability if the renewable sources do not deliver power while all charging ports delivers maximum charging power? That is an important question, especially since we know that the share of wind power will increase, but also electrification of transports and industries.

Finally, Northvolt will open a new battery factory in Torslanda at Hisingen. A strategic location as it is close to Volvo Cars industries. However, the factory's power demand is expected to be around 200 MW, which is about the same size as the total consumption of the city of Örebro [24]. Knowing that the total power consumption on Hisingen is currently around 150 MW, then an addition of 200 MW will have effect on the power system on Hisingen. Most likely, the factory will require a new line at high voltage to supply the factory with power. This increase of the system load will most likely affect the grid impacts of the charging station at Vädermotet, but also other types of charging loads at Hisingen. Since the 'base power' of the system will increase, there is a chance that smaller fluctuations in charging load will have fewer impacts on the overall system performance. However, components may be overloaded and there may occur voltage sags in the near area around the charging station.

7 Conclusions

The aim of the thesis was to build a general grid model, implement as much data from the real system as possible, and then perform a grid impact analysis for two charging scenarios based on the case of the charging station at Vädermotet. The thesis indicates that the high-power charging station do have effects on the local power system. Regarding the voltage stability, the thesis indicates that the charging station will cause larger voltage sags at buses in the system. There are also indicators that reveal that the voltage sensitivity and voltage deviation increases in the system, mainly for the minimum load case. Regarding the power flows, the increased load at the charging station causes larger power flows throughout the whole system, which increases the loading of components. This also increases the system losses. The system losses increase as the load increase, and for the maximum load case and charging scenario 2 the losses increased a lot in proportion to the previous losses. This means that the increased charging load at the charging station result in violations of line loadability, hence the thermal losss increase a lot.

Moreover, the thesis indicates that the grid impacts of the charging station is within the limits for a stable operation during the minimum load case, and for the average load case. However, for the average load case, it could be seen that the violations became more severe for the future charging scenario. Indicating that an increased charging load may be problematic for the system to handle. For the maximum load case, the system was heavily loaded even with no chargers installed. As charging load were added to the system the losses increased even more, as did the line overloading, the voltage sags got worse, and the VPI revealed that the system became more unstable. Or to put it in this way, the reserve to keep the system within stable operation decreased. In conclusion, the grid impact became worse as the system load increased, but also when more charging load were added. This was an expected result.

A future expansion of the charging station at Vädermotet will bring challenges to the local power systemMainly in terms of line overloading in the near area, but also in the form of increased active power losses. Moreover, the increased load and potential large load variations at Vädermotet will most probably cause more severe voltage sags in the local distribution system. However, it must be kept in mind that the system will be able to operate even with an increased load. But to use the power system as efficient as possible it needs to be operated without too large voltage sags, and the losses needs to be minimised. This could be done, but it requires an understanding of how the grid operates and how that knowledge could be integrated in the planning of routes for the BETs. In that way, all goods can still be delivered on time, causing as little grid impacts as possible. Furthermore, there are a lot of potential in grid integration of high-power charging stations. We are still in the beginning of finding them, but it will get better.

7.1 Suggestions for Future Research

As this study disregarded a lot of aspects that affect the distribution, a good start is to include those aspects. Electrification of the transport sector is a complex challenge, we have the technology, we have the knowledge, but one important aspect is cooperation, and finding synergies between different systems. For example, high-power charging stations causes large power out-takes, which may increase the power peaks for some days. To avoid increased power peaks, synergies between district heating systems and the power system need to be investigated. But also, the possibilities of flexible local electricity markets, there has already been pilot projects such as CoordiNet in Uppsala or Sthlmflex in Stockholm. This types of projects facilitates cooperation between different stakeholders. This would further facilitate investigations of the possibilities of electrification of heavy-duty BETs.

Moreover, the power out-takes are strictly dependent on the logistical schemes of the long-haul transports. It is also of importance to use the charging station as efficiently as possible, that is, to have a high utility rate. To achieve this, all BETs that passes through the area need to be considered, not just trucks from some freight forwarding company. Moreover, if one charger is not used at some moment, the possibilities of fast charging of personal EVs or light trucks could be investigated. A high utility rate is needed to maximise the return of investment for Circle K, whose large investment facilitates electrification of long-haul transports in the western parts of Sweden.

This study has risen several questions, some of them are presented in the list below:

- How will the system handle an increased charging load in combination with more renewables?
- How can a BESS be used to reduce the grid impacts and maintain voltage and frequency stability, even for high power peaks due to high-power charging? Where should the BESS be connected to the grid to maximise its potentials?
- How could synergies between the district heating system and power system be used to reduce the power peaks and increase the load factor for both systems?

As it is a complex challenge, it is natural that more questions have risen. Within the scope of this study it was not possible to answer all of them, but with future studies these questions will be answered. However, this is the time of cooperation and research, that is the only way forward to reach the climate goals and proceed with the electrification of the long-haul transport sector.

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Appendices

A The per unit System

When analysing power systems, per unit (p.u) values are often used. It is a convenient way of expressing true values as normalised values. It also makes it easier to get a quick understanding of voltage levels, how transformers are operating, and it also makes it easier to compare loads and generators. The per unit value is defined as

$$\text{per unit} = \frac{\text{true value}}{\text{base value}} \tag{19}$$

where a base power, S_b, are chosen for the whole system and base voltages, V_b, are chosen for sections between transformers depending on the transformer ratings. Note the base power (for one phase) can be calculated from

$$S_b = \sqrt{3}V_b I_b. \tag{20}$$

Which can be used if or example the base current is unknown.

B Code for Setting up Cases

```
% Find the days with maximum and minimum power consumption

[P_max, I_max] = max(P_tot);      % Find the maximum value and its index
[P_min, I_min] = min(P_tot);      % Find the minimum value and its index

max_day = P_households(1009:1032) + P_industries(1009:1032);
t_max = Time(1009:1032);      % Get the day that contains the maximum value
min_day = P_households(4295:4318) + P_industries(4295:4318);
t_min = Time(4295:4318);      % Get the day that contains the minimum value

%% Find average day
n = 24;      % Number of elements to create the mean over
s = size(P_tot, 1);      % Find the next smaller multiple of n
m = s - mod(s, n);
y = reshape(P_tot(1:m), n, []);      % Reshape x to a [n, m/n] matrix
Avg = transpose(sum(y, 1) / n);      % Calculate the mean over the 1st dim
common_day = median(Avg);      % Find the most common day from the average days

for i = 1:1:365
    if Avg(i) == common_day
        index = i;      % Find the index of the median of the average day,
                % the index corresponds to day of the year
        break
    end
end

% index = 266 (day # of the year) –> 2021-09-23 (thursday)
avg_day = P_households(6360:6383) + P_industries(6360:6383);
figure;
plot(t_max, [max_day, avg_day, min_day])
ylabel("Power consumption [MW]")
xlabel("Time [hours]")
legend("Max power", "Agerage day", "Min power")
```

C Load Profile Modelling

Two load profiles were obtained from GENAB. One feeder for household loads and one for industry loads. There was no information about where in Gothenburg the data was collected. What was important in this study was the shape of the load profile, as it is important for the system operation. Moreover, the total original load profile only covered 3-4 MW, which was not enough to cover all the loads in the simulation grid model for Hisingen. Several load profiles were created for every residential and industrial load.

When calculating the residential loads, the population of Hisingen was taken into account, which was about 158,000 people in 2019 [62]. It was assumed that two thirds of the population lives in flats and one third lives in villas. Furthermore, it was assumed that there are two people in every flat and three people in every villa on average. Based on that, the number of flats respectively villas were calculated. This resulted in approximately a total of 70,000 households (52,700 flats and 17,500 villas). Then, it was assumed that a villa consumes 20,000 kWh in one year and a flat consumes 2,000 kWh [63] [64]. Based on that, the total power consumption was calculated. Then, the original load profile were scaled to get a more correct estimate. However, the shape of the original load profile was conserved. This was done in an Excel sheet.

Furthermore, the total load profile were divided into smaller profiles to represent every residential area on Hisingen. The size of every residential load were determined by the demography of Hisingen and if the area were dominated by villas or flats. Finally, every load should have its own fingerprint. Thus, white noise signals in the range of ± 50 kW were generated and then added to the load profiles. Thus, the shape and characteristics of the load profiles were contained, but every load profile was a bit different.

For smaller industrial loads, the grid design manual from E.ON was used [60] (p. 23). The number of smaller industries were approximated by looking at the map of Hisingen. For larger industries it was known that Preem consumes 20.4 MW on average, ST1 consumes 1-2 MW, Volvo consumes 38 MW [65]. The industries were also scaled in such manner that the characteristics of the original load profile were contained. Then, the total industry load profile was separated with respect to the different industry areas on Hisingen. Finally, white noise were also added to the industry loads to give every load profile its own fingerprint. The load profiles that were used in the study are shown in Figure 26-31.

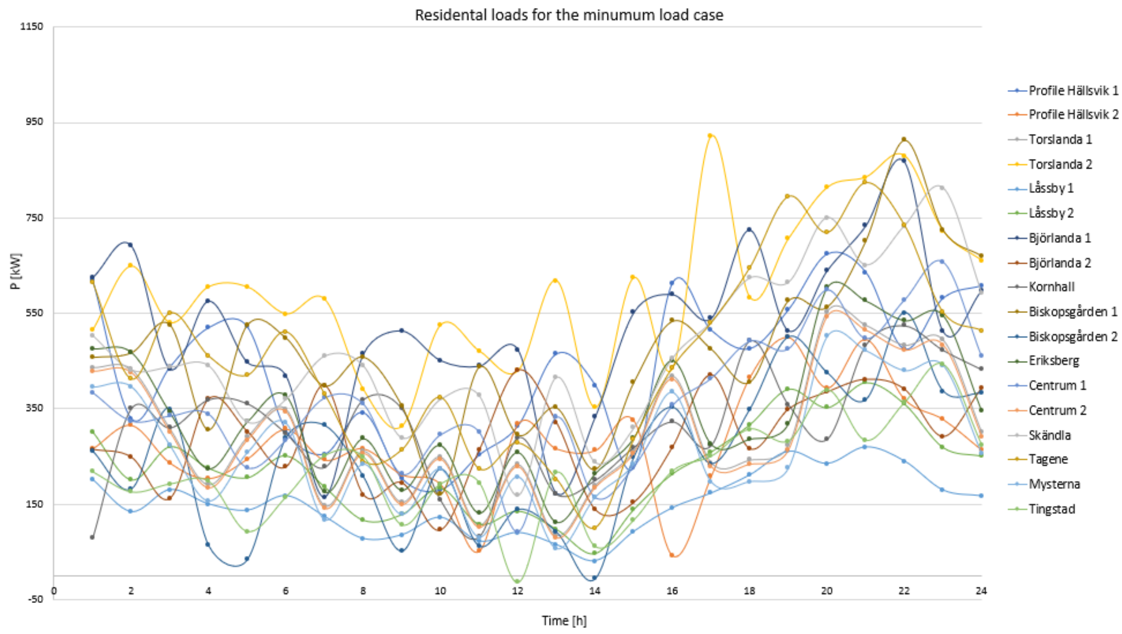

Figure 26: Residential loads for the minimum load case.

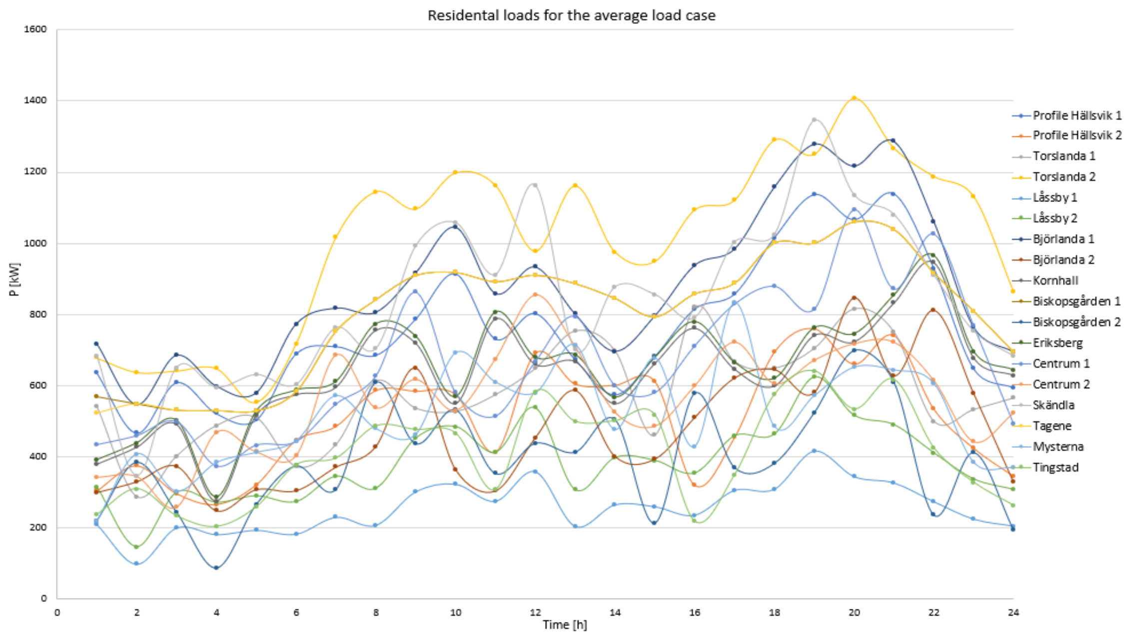

Figure 27: Residential loads for the average load case.

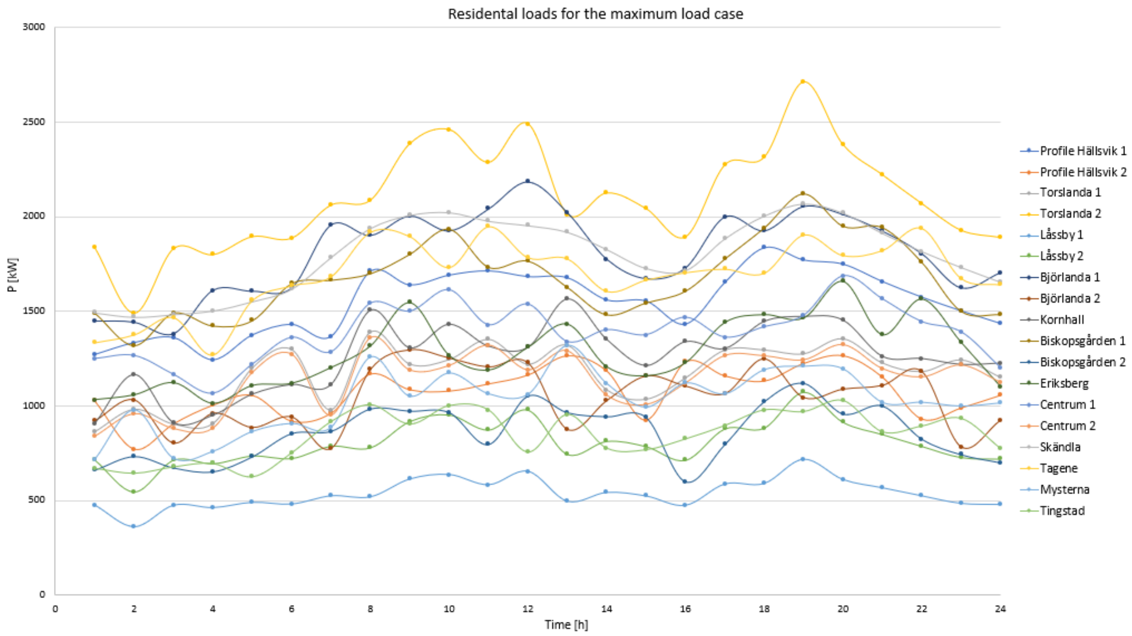

Figure 28: Residential loads for the maximum load case.

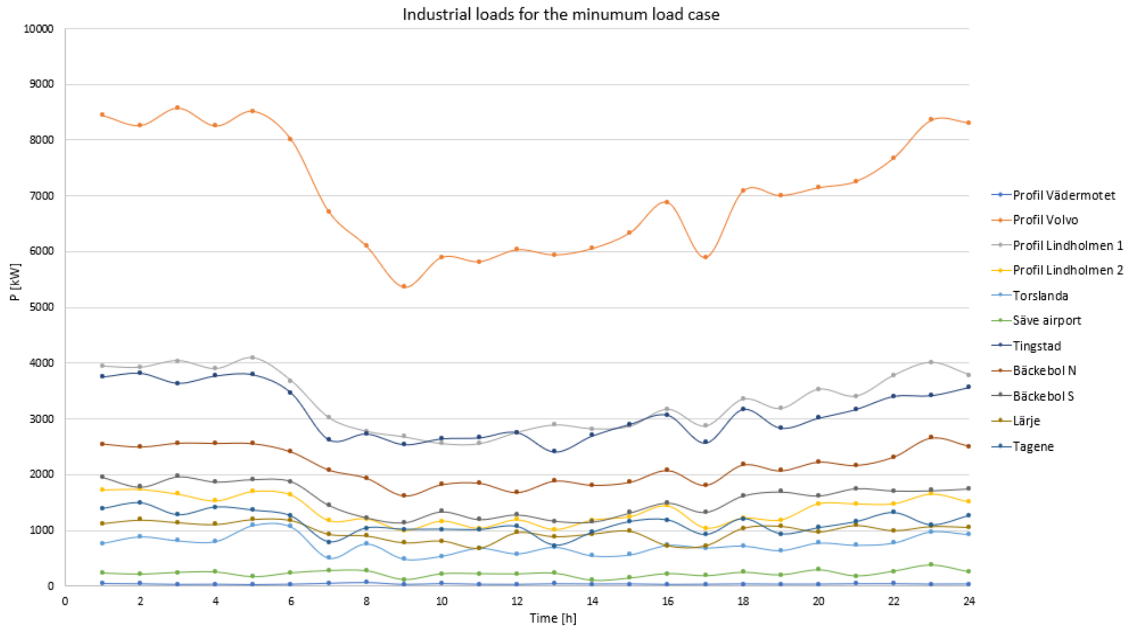

Figure 29: Industrial loads for the minimum load case.

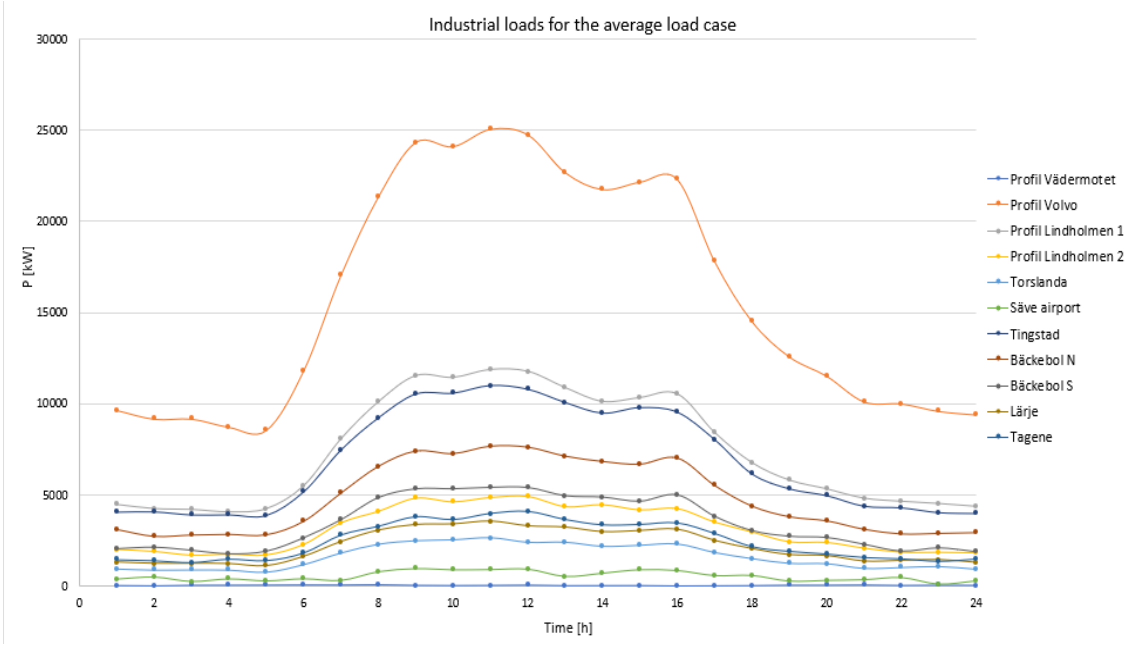

Figure 30: Industrial loads for the average load case.

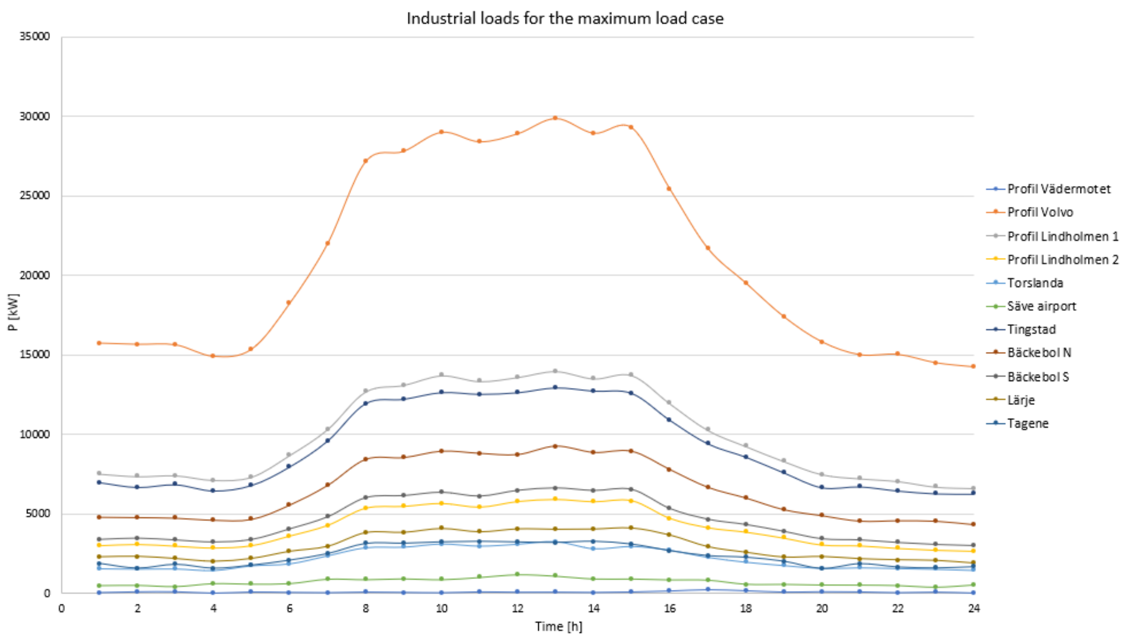

Figure 31: Industrial loads for the maximum load case.