Bachelor's thesis

Bratlie, Frida
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Depot charging of electric buses in Oslo and Akershus

Designing and optimising the operation at Furubakken depot

May 2019

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Norwegian University of Science and Technology
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Report title: Depot charging of electric buses in Oslo and Akershus **Report title (Norwegian):** Depotlading av elektriske busser i Oslo og Akershus	**Project assigned:** 18.10.2018 **Number of pages/appendixes:** 77/5 **Submission deadline:** 24.05.2019
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Field of study: Renewable Energy Engineering	**Project Number:** FEN1901
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Preface

This bachelor thesis is written by a group of three students at Norwegian University of Science and Technology. The group (FEN1901) is attending the *Renewable Energy, Engineer* program at The Department of Energy and Process Engineering. The thesis is developed in collaboration with Tor Didrik Krog from Siemens AS and Elise Foss from Hafslund E-CO.

Based on the electrification of the transport sector and Ruter's tender round for route area 1 (Furubakken depot), this thesis focuses on implementing electric buses in Oslo and Akershus. We have simulated the demand of a full electrification of the bus fleet associated with Furubakken depot with the basis of the departure schedules. Different measures have been implemented in order to optimise the operation of the depot, with the aim of lowering the power peaks.

We want to give our gratitude to our internal supervisors, Professor Odne S. Burheim and Associate Professor Håvard Karoliussen at the Department of Energy and Process Engineering, for proofreading, productive discussions and providing us with sources of information. Also, we want to give our gratitude to our external supervisor Tor Didrik Krog for technical guidance, proofreading and providing us with a workplace at Siemens's offices in Trondheim. We want to thank Jon Stenslet from Ruter and Ragnar Ulsund from Hafslund Nett for enlightening interviews and providing us with key parameters. Finally, we want to give our gratitude to Atle Nesje for proofreading.

Trondheim 24.05.2019

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Abstract

As a part of the electrification of the Norwegian transport sector, electric buses are an important contributor in reducing greenhouse gas emissions. Oslo desires to be at the forefront of the electrification and was in 2019 awarded the European Green Capital title. Ruter AS, responsible for the public transport in Oslo and Akershus, had in 2018/2019 a tender round for route area 1 - ”Vestre Aker” and ”Østre Bærum”, where environmentally friendly solutions such as electric buses were highly valuated.

This thesis assesses a complete electrification of the bus fleet at Furubakken depot, associated to route area 1. The focus is directed towards how the operation of the depot can be designed and optimised to adapt to the power demand of the buses and available network capacity. In addition, the profitability of implementing a stationary battery for the purpose of peak shaving is evaluated.

A smart charging system for a worst-case consumption is developed in order to optimise the operation of the depot. This involves reducing the number of active chargers and using different prioritisation systems for the resulting charging queue at the depot. From the results of the simulation, the capacity-based prioritisation reduces the power peaks with 37 % and provides a monthly saving of 175.5 kNOK due to the network tariff.

The simulation of the stationary battery is developed with the intention of finding the minimum battery size and the corresponding profitability for each level of desired maximum power peak. The use of a stationary battery for further peak shaving is not profitable as the procurement cost is higher than the savings achieved by the network tariff. This is mainly due to the wide peaks of the load profile that occur when implementing smart charging. A stationary battery can also be used for network and economic purposes.

Electrification of a bus fleet requires a greater number of buses in operation, where the result of this thesis concludes with a 38 % increase for Furubakken depot. With a higher number of buses, the productivity, meaning the number of hours a bus is in operation during 24 hours, decreases. As an electric bus has a higher production emission, it requires a longer range before breaking even with a diesel bus. Lower productivity further reduces the profit of having electric buses. In order to increase the productivity, the energy consumption for each line should be accurately predicted to reduce the number of purchased buses. Another solution is to replace a portion of the bus fleet with e.g. biodiesel buses.

As some buses use a significantly amount of time and energy driving back and forth to the depot, opportunity charging could be beneficial for some lines. When implementing the pantographs, factors such as local grid capacity, strategic location and long-term technical architecture must be considered. In order to achieve sustainable solutions for the charging infrastructure, a well-defined role distribution between the owner and the operator is important.

Abstract in Norwegian

Som en del av elektrifiseringen av den norske transportsektoren er elektriske busser et viktig bidrag for å redusere klimagassutslippet. Oslo ønsker å være i toppen av elektrifiseringen og ble tildelt tittelen Europeisk miljøhovedstad i 2019. Ruter AS, som er ansvarlig for kollektivtrafikken i Oslo og Akershus, har hatt et anbud i 2018/2019 for ruteområde 1 - Vestre Aker og Østre Bærum hvor miljøvennlige løsninger som elektriske busser ble vurdert høyest.

Denne oppgaven tar for seg en helelektrifisering av buss flåten ved Furubakken depot, tilhørende ruteområde 1. Det er fokus på hvordan driften av Furubakken depot kan bli designet og optimalisert for å tilpasse seg både lastuttaket til bussene og nettverkskapasitet. Lønnsomheten ved å implementere et stasjonært batteri for å redusere effekttoppene blir også vurdert.

Et smart lade system for forbruk ved verste tilfelle er utviklet for å optimalisere driften på depotet. Dette innebærer å redusere antall aktive ladere og implementere ulike prioriteringssystem som rangerer ladekøen på depotet. Fra resultatene av simuleringen vil et kapasitetsbasert prioriteringssystem redusere effekttoppene med 37 % og gi en månedlig besparelse på 175,5 kNOK grunnet nettariffen.

Simuleringen av det stasjonære batteriet er utviklet med formål i å bestemme minimum batteristørrelse og tilhørende lønnsomheten for hver ønskelige effekttopp. Bruken av et stasjonært batteri til ytterligere lastutjevning er ikke lønnsomt da investeringskostnadene er høyere enn besparelsen oppnådd fra nettariffen. Dette er hovedsakelig forårsaket av de brede effekttoppene i lastprofilen som oppstår ved bruk av smart lading. Et stasjonært batteri kan også brukes til nettformål og økonomiske formål.

Ved å elektrifisere en bussflåte kreves det flere busser i drift sammenlignet med en dieselbuss løsning. For Furubakken depot konkluderes det med en økning på 38 %. Med en økning av busser vil produktiviteten, definert som driftstimene til en buss i løpet av et døgn, øke. Ettersom en elektrisk buss har høyere produksjonsutslipp kreves det en lengre kjøredistanse før den blir mer gunstig enn en dieselbuss med hensyn til klimagassutslipp. Lavere produktivitet reduserer ytterligere gevinsten av elektriske busser. For å øke produktiviteten bør energiforbruket nøyaktig predikeres for å redusere antallet av busser investert. En annen løsning kan være å erstatte en del av den elektriske bussflåten med for eksempel biodiesel busser.

På grunn av at elektriske busser bruker store deler av sin tid og energi på å kjøre fram og tilbake til depotet for å lade, kan det være gunstig at noen linjer bruker hurtiglading ved endestasjonene. Ved installasjon av pantografer bør det tas hensyn til faktorer som nettkapasitet, strategiske lokasjoner og langsiktig teknisk arkitektur. For å oppnå bærekraftige løsninger innen ladeinfrastruktur, er det viktig med en veldefinert rollefordeling mellom eierskap og drift.

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List of Terms

Active power	–	The real component of the power of an alternating current circuit; the product of the voltage and that part of the current that is in phase with the voltage
Change-over	–	Moving capacity from one line to another
CO_2 equivalent	–	A measure used to compare the emissions from various greenhouse gases based upon their global warming potential.
Cycle	–	The process of fully charging and discharging a battery.
Depth of discharge	–	Describes how deeply the battery is discharged.
Electrification	–	Transition from another form of energy to electricity.
High voltage distribution	–	Defined as voltage from 1 to 22 kV
Impedance	–	The amount of opposition faced by direct or alternating current when it passes through a conductor component, circuit or system.
Low voltage distribution	–	Defined as voltage from 230 V to 1 kV
Memory effect	–	A battery gradually loses its maximum energy capacity if it is repeatedly recharged after being only partially discharged.
Nord Pool ASA	–	Runs the leading power market in Europe.
OppCharge	–	An initiative aiming at establishing a common interface for opportunity charging of electrical vehicles.
Power peak	–	Power output that is higher than the average.
Reactive power	–	The power that is exchanged between reactive components, inductors and capacitors. It is the product of the voltage and the part of the current which is phase shifted 90°relative to the voltage.
Redundancy	–	Robustness to ensure availability in the event of component failure by having back-up systems.
Short circuit performance	–	A measure of how stiff the grid is.

Smart charging	–	Collective term used for various charging functions within the station that makes the charging process easier, cheaper and more efficient.
Specific energy	–	Energy content per unit mass
Specific power	–	Power per unit mass
State of charge	–	Defined as the percentage of the battery capacity available for discharge.
Substation	–	Station containing one or several distribution transformers, in addition to low-voltage and high-voltage switchboard plant.
Tap changer	–	A mechanism in transformers which allows for variable turn ratios to be selected in discrete steps.
Well-to-wheel analysis	–	An application that gives an overall picture of the utilised energy resources and its emissions from the point of primary energy source extraction (well) to the point of utilisation (wheels). Can be separated into well-to-tank and tank-to-wheel evaluations.

Abbreviations

AC – Alternating Current
BESS – Battery Energy Storage System
DOD – Depth of Discharge
DR – Demand Response
DSM – Demand Side Management
ES1 – End Stop 1
ES2 – End Stop 2
ESS – Energy Storage System
GO – Guarantee of Origin
HVO – Hydrotreated Vegetable Oil
ICE – Internal Combustion Engine
KILE – Kvalitetsjusterte Inntektsrammer ved Ikke Levert Energi
LCO – Lithium Cobalt Oxide
LFP – Lithium Iron Phosphate (LiFePO4)
LMO – Lithium Manganese Oxide
LTO – Lithium Titanate (Oxide)
NCA – Nickel Cobalt Aluminium
NMC – Nickel Manganese Cobalt
NVE – Norges vassdrags- og energidirektorat
PTO – Public Transport Operator
PTA – Public Transport Authority
SEI – Solid Electrolyte Interface
SoC – State of Charge
SVC – Static Var Compensator
TTW – Tank-To-Wheel
UNFCCC – United Nations Framework Convention on Climate Change
WTT – Well-To-Tank
WTW – Well-To-Wheel

Symbols

Symbols	Unit	Description
ΔU	%	Voltage drop
φ	-	Phase difference between current and voltage
$cos(\varphi)$	-	Power factor
$C_{electricity}$	NOK/month	Electricity cost
C_{energy}	NOK/kWh	Cost of the energy segment of the network tariff
$C_{energy,monthly}$	NOK/month	Monthly cost of the energy segment
C_{power}	NOK/kWh	Cost of the power segment of the network tariff
$C_{power,monthly}$	NOK/month	Monthly cost of the power segment
E	kWh	Capacity of a battery
E_B	kWh	Energy in the stationary battery
$E_{B,max}$	kWh	Capacity of the stationary battery
E_{demand}	kWh/day	Daily energy consumption for the bus fleet
$E_{necessary}$	kWh/day	Required size of the stationary battery with one charging cycle per day
I	A	Current through a battery during charge/discharge
L	m	Length
P	kW	Power output or input to a battery
P_B	kW	Power output or input to the stationary battery
$P_{B,charging}$	kW	Maximum charging power
$P_{B,discharging}$	kW	Maximum discharging power
P_{diff}	kW	Difference between the maximum power limit and the load profile of the buses for each minute
P_{load}	kW	Power consumption of the buses for each minute
P_{max}	kW	Limit of maximum power consumption
P_{tot}	kW	Total power consumption with peak shaving using stationary battery
P_{TX}	kW	Transmitted power
Q	Ah	Capacity of a battery
R_1	Ω/km	Resistance of the conductor
U	V	Effective voltage
X_L	Ω/km	Reactance

1 Introduction

As part of the Paris Agreement's goal of limiting global warming to 1.5 °C, a global focus on electrifying the transport sector has evolved. As the capital of Norway, Oslo desires to be at the forefront of the electrification and was in 2019 awarded the prestigious European Green Capital title from the European Commission. It is further expected a transport sector revolution in the coming years.

In this thesis, an electrification of Furubakken depot in Oslo is studied, with the purpose of optimising the operation. The thesis is written in collaboration with Siemens AS and Hafslund E-CO. The background and purpose of the thesis is elaborated in this section. In addition, the problem to be addressed, different delimitations and a brief overview of contributors are presented.

1.1 Background

The world is facing a climate crisis due to the increasing emissions of greenhouse gases. As a result, several political cooperation agreements have been established with the aim of reducing emissions locally and globally. Examples of agreements are the Kyoto Protocol and the UNFCCC, which both served as a part of the background for the Paris agreement, established in 2015. The central goal of the Paris Agreement is to limit global temperature rise in this century to well below 2 °C above pre-industrial levels and to pursue efforts to further limit to 1.5 °C.[1]

The Paris Agreement requires all parties to form nationally determined contributions. Norway aims to reduce their emissions to at least 40 % below 1990 levels by 2030. Their priority areas are transport, industry, carbon capture and storage, renewable energy and shipping. In addition, Norway has committed to becoming carbon neutral by 2030, meaning zero carbon dioxide emissions. They also have a goal of becoming a "low emission society" by 2050, meaning 80–95 % greenhouse gas emission reductions below 1990 levels.[1] A low emission society involves, among others; low-energy and low-emission buildings, low emission transport and mobility solutions, and safe and adequate supply of low carbon energy.[2]

The global energy consumption is constantly growing due to rising welfare and population growth. Worldwide, fossil energy sources dominate, and the transport sector is one of the largest contributors to greenhouse gas emissions. This also applies to Norway, where the transport sector in 2017 accounted for 17 % of the total emissions. Figure 1.1 illustrates the Norwegian emissions divided by sectors. In total, Norway was responsible for 52.7 million tons of CO_2 equivalents in 2017.[3]

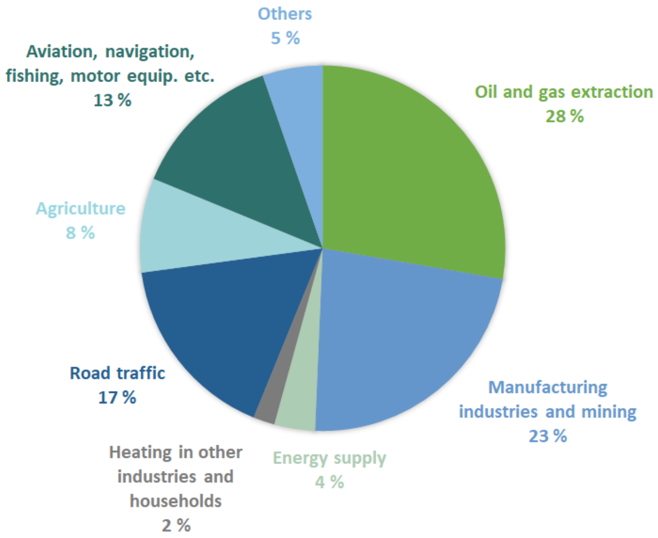

Figure 1.1: *The Norwegian emissions divided by sectors. The values are for 2017. Note: The figure is recreated based on the original and edited to improve the readability.[3]*

In order for Norway to fulfil the Paris Agreement and their climate goals by 2030, the transport sector must ensure a large proportion of the emission cuts. Conversion from fossil to emission-free transport will require extensive electrification. In the National Transport Plan 2018-2029, the Government presented the following plan for further work:

- New ferries shall use low or zero emission technology.
- New passenger cars and light vans shall be zero emission vehicles in 2025.
- New city buses shall be zero emission vehicles or use biogas in 2025.
- By 2030, new heavy vans, 75 % of new long-haul buses and 50 % of new trucks are to be zero emission vehicles.
- By 2030, commodity distribution in the largest city centres is to be approximately emission free.
- Government agencies shall, as far as possible, use biofuel, low or zero emission technology in their own and hired vehicles.
- By 2050, the transport shall be approximately emission-free/climate neutral.

By laying these assumptions at the basis of the further transport development, large parts of the transport sector can be electrified within 15-20 years.[4, 5] Several cities, both nationwide and worldwide, have already introduced or are planning to introduce electric buses. Among others, Oslo, Stavanger and Kristiansand have electrical buses in operation. Before the summer of 2019, 70 new electric buses are being commissioned in Oslo, making the capital Europe's foremost on electric buses.[6] By August 2019, 35 electric buses are planned to operate four lines in Trondheim. Bergen also plans to acquire up to 80 electric buses for start-up in 2020.[7, 8] In a report by NVE from 2017, it is assumed that all city buses in Norway's 30 largest cities are electrified by 2030. This corresponds to approximately 500 city bus routes.[4]

Ruter is the company responsible for public transport in Oslo and Akershus, which corresponds to more than half of the public transport in Norway. They have an ambitious environmental profile with an estimation of a fossil-free bus fleet in 2020. This is illustrated in Figure 1.2. From 2025 onwards, the proportion of electric buses is estimated to be dominant.[9]

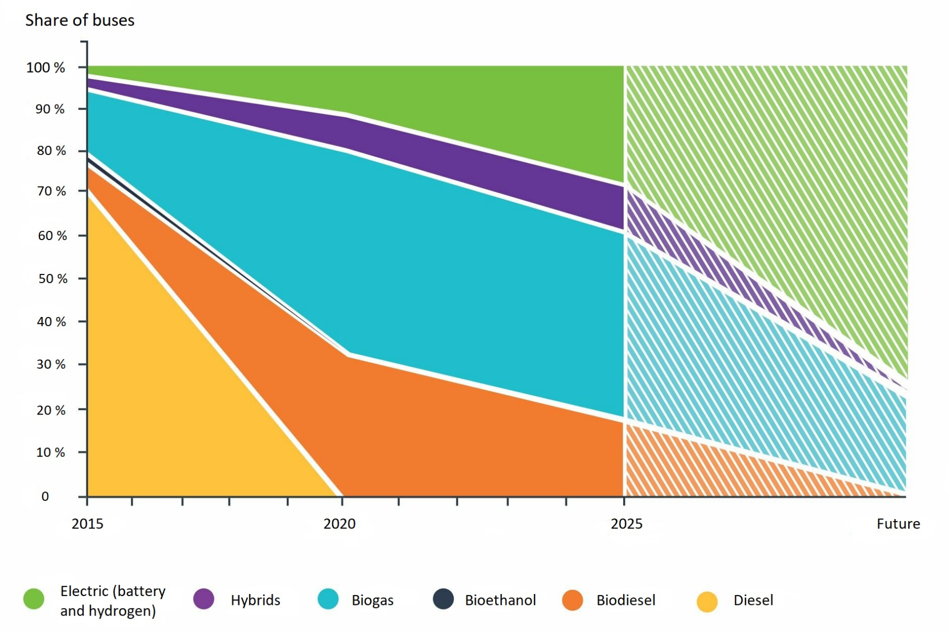

Figure 1.2: *Ruter's environmental goal for the Norwegian bus sector in 2025.[9]*

An electrification of the transport sector does however mean that a higher number of appliances are dependent on electricity from the grid. In a report made by NVE, it is concluded that extensive electrification of the transport sector in Norway can create challenges in today's distribution network, especially for transformers. However, as indicated by Figure 1.2, an absolute electrification is not expected to be completed before the next 20-30 years, and much of today's transformers and power lines in the distribution network will at this point have been replaced. In order to reduce the need for large expansions and reinvestments in the network, systems for smart charging and load levelling are relevant measures.[10]

1.2 Problem to be addressed

The problem that will be examined in this thesis is:

How can the operation of Furubakken depot be designed and optimised to adapt to the power demand of the buses and available network capacity? To what extent can the use of stationary batteries contribute to the reduction of power peaks?

In 2018/2019 Ruter had a tender round for route area 1 - ”Vestre Aker” and ”Østre Bærum”, that included the use and rent of Furubakken depot. The depot has 15 associated bus lines, all of which are assumed to be electrified in this thesis. The depot has to be modelled with respect to the capacity limitations of the grid. Other important criteria for evaluation are consumption, economy, emission and risk. The model must consider the number of buses, the charging frequency and the total charging power that is expected to be deducted from the network. In addition, this thesis will investigate the use of a stationary battery to reduce power peaks, mainly for economic reasons, but also with regard to grid stability and security of supply. The dimension of the battery will be modelled based on the power requirements throughout a day. When designing and optimising the depot, the perspective of the operator has been mainly in focus.

1.2.1 Delimitations

Several delimitations are done in this thesis because of limited time usage and the desire to simplify. The biggest delimitations regarding the simulations is that the impact of topography for each specific line and delays are not included. As it was an ongoing tender round at Furubakken depot when this thesis was written, a lot of information was restricted. Therefore, factors such as specific passenger demand and several buses per departure was not included.

Two other delimitations are made regarding power losses and economic assessments. It is not included losses in the components on the depot because there was not made a proper sketch over the depot. The calculations would therefore have been with great uncertainty. In addition, the losses would most likely not impact the conclusions of this thesis. Delimitations regarding economic assessments are also made as it was not an area of focus in the problem to be addressed.

1.3 Contributors

The list below mentions people that have contributed with valuable information for this thesis. The shared knowledge and answering of questions within their study of field is received with great gratitude.

Name	**Position**	**Company**
Eriksen, Andreas B.	Higher executive officer	Norges vassdrags- og energidirektorat
Foss, Elise	Business Developer & Strategic Advisor	Hafslund E-CO AS
Gaalaas, Glenn-Ivar	Project Manager	Unibuss AS
Haukaas, Vebjørn	Power System Analyst	Siemens AS
Krog, Tor Didrik	Head of Business Development & Strategy	Siemens AS
Reichel, Frank	Managing Director	VDL Bus & Coach Norway AS
Solberg, Sindre	Senior Engineer	Siemens AS
Stenslet, Jon	Material & Facility Manager	Ruter AS
Ulsund, Ragnar	Senior Engineer	Hafslund Nett AS
Ystanes, Svein	Advisor, Route Planner & General Manager of Design	Kolumbus AS

Siemens AS

Siemens AS is a global powerhouse that develops high-tech and innovative solutions for industry, energy, cities and transport. Their focus areas are electrification, automation and digitalisation.

Siemens AS is one of the employers for this thesis. They have an interest in the electrification of the transport sector as they play a pioneering role in infrastructure and industry solutions. With this thesis, Siemens AS desires to acquire increased knowledge on how challenges related to electrification of depots can be solved using sustainable solutions.

Hafslund E-CO

Hafslund E-CO owns Norway's second largest power generation company, E-CO Energi AS, and Norway's largest grid company, Hafslund Nett AS. Hafslund Nett AS owns and manages the regional network in Oslo, Akershus and Østfold, as well as a distribution network comprising 35 municipalities in Oslo, Akershus and Østfold.

Hafslund E-CO is one of the employers for this thesis. They want to map out future market potential of the following electrification of the public transport sector. They can potentially have a central role when the relative immature market of electric buses develops. In addition, they want to help and cooperate with students.

1.4 Information gathering

Relevant information for the thesis is collected mainly from books, reports and previous thesis written by students from various universities. The digital database for NTNU Library is the main resource used for obtaining information. In addition, several specialists have contributed with knowledge through conversations and discussions. A list of the concerned persons are given in Section 1.3.

Relevant information about the tender round is mainly gathered from Ruter. However, a lot of the desired information was only available for the competing public transport operators. The most important information gathered was which lines that are connected to Furubakken depot. Based on these lines, information about departure timetables was extracted from Ruter's homepage.

2 Power Grid

The power grid is critically important infrastructure. Secure power supply is essential for a modern society, where business, public services and households all consider safe access to electricity as a matter of course. For an electrified bus depot, security of supply is crucial for the operation. In order to ensure delivery reliability, factors such as good voltage quality and high degree of redundancy is important.

This chapter presents the structure of the Norwegian transmission network, as well as factors relevant to ensure grid stability and delivery quality. It also addresses the spot areas in Norway and the market price of electricity associated with these areas. Further, the network tariff, both in general and specific to this thesis, is described. Finally, various techniques of peak shaving are presented.

2.1 Structure

The Norwegian transmission network is divided into two stages: transmission and distribution. The transmission network is at a high voltage level, usually 300 to 420 kV, but in some parts of the country, lines of 132 kV are also included. The distribution network includes voltage levels from 230 V to 132 kV, where it is normal to divide between regional (33-132 kV) and local (0.23-22 kV) distribution network.[11, 12] Figure 2.1 illustrates an overview of the classification with corresponding voltage levels. The voltage is stepped-up from power plant to transmission lines, and conversely stepped-down from transmission to regional distribution. The distribution transformer transforms the voltage from regional to local distribution lines. Normally, an additional transformer provides the final voltage transformation from 22kV to 400/230 V, but this is not included in the figure.[12, 13, 14]

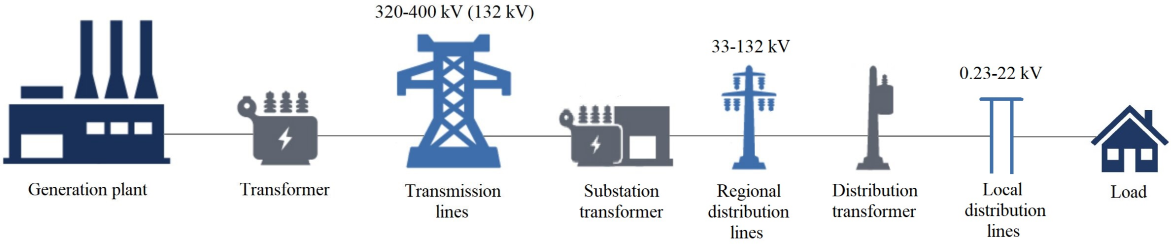

Figure 2.1: *Structure of the Norwegian transmission network.[15] Note: The figure is recreated based on the original and edited to improve the readability. Distribution lines are divided in regional and local and values for voltage levels are added.*

The transmission network connects large producers and consumers in a nationwide system, as well as including international connections. Most of the energy-intensive industry and production companies are connected to the transmission network or regional distribution network. The local distribution network represents the power grids that usually provide power distribution to smaller end users. Normally, 230 V is used in households, while services and small industries are connected to 400 V.[14]

In Norway, Statnett owns and operates the transmission network. They are the system administrator for the entire electricity grid, and has the overall responsibility for safe and stable power supply.[11] Municipalities and county municipalities own most of the distribution network.[14]

2.2 Grid stability

The electricity grid is facing several challenges related to the increase in variable renewable power generation, such as wind and solar, power trading between nations and an ageing AC transmission infrastructure. This, in combination with an increasing global demand for electricity, results in operation close to grid stability limits. To prevent damage to electric components in the network and at the consumer, it is important to maintain a stable and correct magnitude for both the frequency and the voltage.[16]

The Norwegian power grid operates at a frequency at 50 Hz. To avoid frequency deviations, it is essential to maintain the balance between production and import, and consumption and export. If the consumption and export of electric power is higher than production, the frequency will decrease below 50 Hz, and vice versa.[17]

As the network in Norway is interconnected with large parts of the Nordic region, large deviations in the frequency are rarely experienced. Higher fluctuations are normally due to unexpected disconnections of larger power plants, disconnections of heavy loads in the power system or forecast errors.[18] Statnett, as the system administrator, is responsible for the regulation of the frequency.[14]

2.3 Delivery quality

Delivery quality is a collective term that includes delivery reliability and voltage quality. Delivery reliability addresses the access to electric energy, while voltage quality defines the applicability of the electric energy.[19] Delivery quality is important for obtaining good functioning of electric equipment and appliances. Reduced delivery quality can lead to malfunction, casualty and financial loss for everyone who is affiliated with the power system.[20]

2.3.1 Delivery reliability

A measure of delivery reliability is the frequency and duration of interruptions, which is closely related to the degree of redundancy in the network.[21] In order to ensure delivery reliability, it is essential to have reserves at all times. Statnett's goal is to operate the power grid according to the N-1 principle.[22] N-1 redundancy ensures system availability in the event of a single component failure. The grid will therefore continue to operate in normal state following the loss of one generating unit, transmission line or transformer. Accordingly, component N will have at least one independent backup component.[23] In case of the N-2 criteria, the network is constructed to guarantee security even if one component is shut down for operational reasons and another should fail at the same time.[24]

The degree of redundancy the network is operated on can vary depending on the weather, and thus seasons of the year. During the winter season, the consumption, and thus also the load on the grid, is higher compared to the summer. The possibilities for change-overs in the event of interruptions, outages and maintenance in the grid are therefore fewer, resulting in lower delivery reliability in the period. Figure 2.2 illustrates the consumption in Bærum municipality in 2018, where Furubakken depot is located. The variations of this curve are a good representation for the consumption in most parts of Norway, which is particularly known for its cold winters. Accordingly, the power peaks occur during periods of low outdoor temperature, typically for the months of January, February, March, November and December. The average consumption value in MW throughout the year is represented by the red line. The values span from 68 to 392 MW, with an average value of 193 MW.[25]

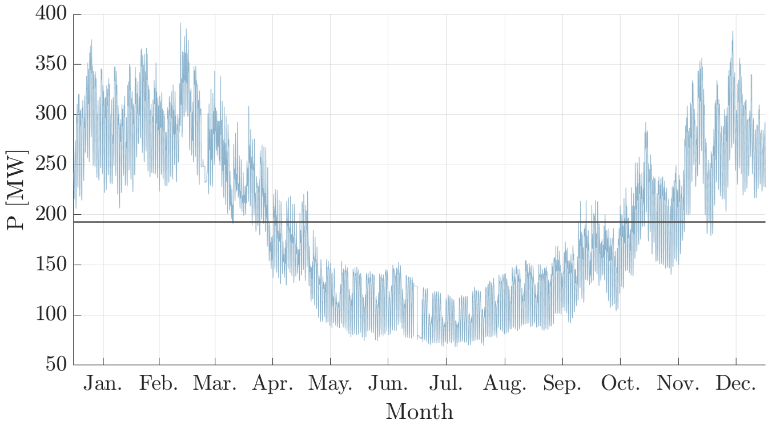

Figure 2.2: *Power consumption in MW in Bærum municipality for 2018. The red line represents the average power consumption for the period. The data is provided from Hafslund Nett.[25]*

The power consumption also varies from hour to hour of each day. For a 24-hour period, the demand for a household is higher in the morning and afternoon compared to the evening and during working hours. Industries, however, have higher consumption in the production hours, typically from 8.00 a.m. to 4.00 p.m.[26] The overall power consumption in Bærum municipality for 30th of January 2019 is shown in Figure 2.3. The two highest peaks are around 8.00 a.m. and 17.00 p.m., which corresponds well to the daily routine of most people. The peaks reach a value of approximately 380 MW, while the lowest value is slightly above 280 MW. The use of electricity and heating in the industry and at the working place is the main factors to why the curve remains above average in working hours.[25]

To ensure that network companies focus on maintaining good delivery reliability through secure facilities and operations, Norway has a KILE arrangement. KILE represents the customers' costs of interruptions and is included in the grid companies' corporate financial assessments. This entails deductions from the company's revenue ceiling, so that the company's permitted income is reduced as a result of non-delivered energy. The purpose of this arrangement is to give the network companies an incentive to build and operate the grid with an economically optimal delivery reliability. KILE is calculated using cost functions based on different customer groups, such as agriculture, household and industry. The costs depend on the duration of the interruption, as well as the time it occurs.[27]

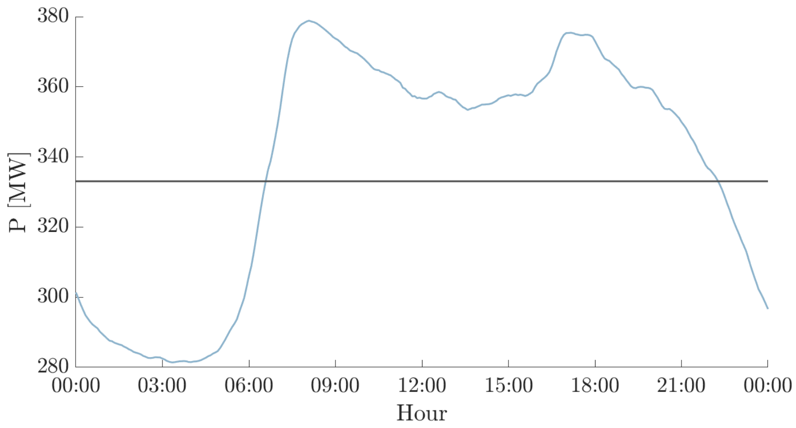

Figure 2.3: *Power consumption in MW 30th of January 2019 in Bærum municipality. The red line represents the average power consumption for the period. The data is provided from Hafslund Nett.[25]*

2.3.2 Voltage quality

Voltage quality is a characteristic of the voltage that is important for it to be used safely. Electric equipment used in the Norwegian electricity grid must be designed to function within a certain limit of variation. Short variations in the effective value should be within a range of ± 10 % of nominal voltage, normally 230V, for connections in the low voltage grid. In the high voltage grid, 11 kV and 22 kV, a maximum of 5 % stationary voltage drop is permitted when transmitting power. Good voltage quality is important to prevent failure or reduced lifespan of electric equipment.[28, 29]

Many electric appliances of today have high power consumption, which causes great demands on short circuit performance. The power grid can be considered as stiff or weak depending on this performance. A stiff grid will have high short circuit performance and low impedance, leading the voltage to remain approximately constant during changes in production and consumption. On the other hand, a weak grid will have low short circuit performance and high impedance, leading the voltage to be more affected by changes in the load. In Norway, approximately 40% of the grid can be considered as weak. For this approximation, a weak grid is assessed to have a short circuit performance of less than 1,000 A.[30]

The capacity of the transformer and the dimension of the transmission network are the main factors that determine the short circuit performance at each point in the network.[31] In order to determine the voltage drop, and thus also give an indication of the short circuit performance, Equation 2.1 can be used. As the equation describes, the voltage drop increases with the cable length, L, and the amount of transmitted power, P_{TX}. By using this equation, it is possible to ensure that the voltage drop remains within the 5 % limit of variation.[32]

$$\Delta U = \frac{= 2P_{TX} \cdot L \cdot (R_1 \cdot cos(\varphi) + X_L \cdot sin(\varphi))}{U^2 \cdot cos(\varphi)} \cdot 100\% \tag{2.1}$$

The voltage drop along a cable will accordingly vary depending on the distance from the transformer. The greater the distance between the load and the transformer, the weaker the network is. Problems with low voltage far from the transformer will particularly be experienced in the winter period with high load. As for a bus depot, it is essential to be located near a transformer to maintain good voltage quality.[29, 32]

Voltage regulation

Voltage regulation is a key factor in ensuring delivery quality. The need for voltage regulation can occur with large stationary voltage variations over the year, or over short intervals such as voltage dips. Short variations can be problematic with regard to the electrification of the transport sector, especially as fast chargers for electric vehicles and ferries produce relatively frequent and high in- and outputs. High integration of unregulated power generation in the distribution network could also lead to large voltage variations, for example by solar cells in varying cloud cover.[33] Consequences of voltage variations can be malfunction and disconnection, which in turn can cause consequential damage and production losses. In some cases, it can also cause equipment failure or reduced lifespan.[34, 29] Current measures to prevent voltage variations are the use of transformers with tap changers, compensation of reactive power or implementing amplification of the network.[34]

The use of transformers with tap changers causes the turnover ratio to change automatically in order to regulate the output voltage of the transformer. Accordingly, the voltage variation in the high voltage distribution network will not propagate to the low voltage network. A larger voltage increase in the high voltage distribution network, as a result of the input of distributed production, can therefore be allowed.[35] In periods of low load and high production, the transformer will reduce the voltage to prevent customers from experiencing too high voltage, and vice versa. Consequently, all customers can get acceptable voltage conditions.[36].

Use of reactive components is another method of voltage regulation. In the case of inputs or disconnections of large loads, reactive power can be supplied or absorbed to quickly regulate the voltage. In the transmission network, static components such as capacitor batteries and static Var compensators (SVCs) are used to increase reactive production during undervoltage. Conversely, inductive components, such as reactors, are used to absorb reactive power during overvoltage.[37] In the distribution network, batteries can contribute to regulation of active and reactive power, as an alternative to traditional network investments.[33] If amplification of the network is necessary, cables can be made more robust and effective with the purpose of reducing line losses. This can be done by adding new cables or replacing old with new and thicker ones.[38]

2.4 Market price mechanisms

Customers that are connected to the grid are required to pay for two products. They have to pay for the cost of the energy purchased from the power supplier, in addition to network tariff to the local utility company for transport of the power.[39] The market price of electricity depends on supply and demand. It is calculated daily by Nord Pool ASA based on the participants' total purchase and sales reports for the next 24 hours. Consequently, the market determines the price.[40] In 2018 the electricity price span between approximately 0.30-0.50 NOK/kWh.[41]

There are several factors that influences the marked. Power exchange makes it possible for the power to move from low cost areas to high cost areas at all times. During high demand and low production, it is desirable to import cheaper power from abroad. Conversely, it is common to export power when local electricity prices are low. Variations in precipitation and temperature causes the electricity prices to vary widely; both throughout the day and through seasons and years.[42]

The prices are also dependant on transfer conditions, between areas and countries internally in the Nordic countries, and between the Nordic countries and the rest of Europe.[42] The Nordic region is a common power market divided into different elspot areas.[43] The boundaries of these areas are determined based on transmission limitations in the Nordic network, also called bottlenecks. These bottlenecks occur when the transmission capacity in or out of a region is less than the demand, causing the region to become a separate temporary market with a separate temporary price.[44] Norway is divided into five price areas (NO1-NO5), illustrated in Figure 2.4.[45]

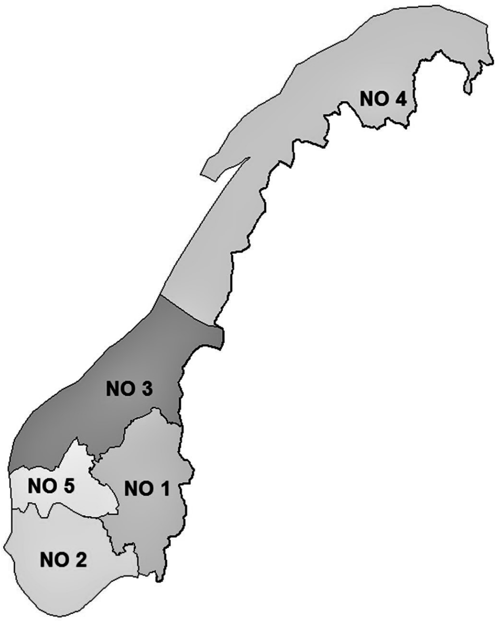

Figure 2.4: *Map of the five elspot areas (NO1-NO5) in Norway. Note: The figure is edited based on the original.[45]*

2.5 Laws and regulations

In addition to the raw material electric power, the customer must also pay for connection to- and use of the grid.[42] This is a part of the network tariff, which gives the grid companies income to cover the costs of transporting electricity, given efficient operation, utilisation and development of the network.[39]

The network tariff contains of an energy segment and a fixed- and power segment. The energy segment is variable and reflects the costs associated with the electric losses when transmitting power through the network. Most of the network tariff is, however, fixed client-specific costs, i.e. costs for measurement, settlement, invoicing and similar, as well as capital and maintenance costs. The fixed segment is a defined amount per year. The power segment provides a reasonable return on investments in the network, and is calculated from the power consumption of the customer in a defined period. It is common to use the maximum power consumption per month. This is illustrated in Figure 2.5, where the power tariff is given by the highest peak of the specific month, in this case equal to the first peak. Some, however, use the average power of several measurements over the same period instead. The power segment is mainly used by business clients.[39, 46]

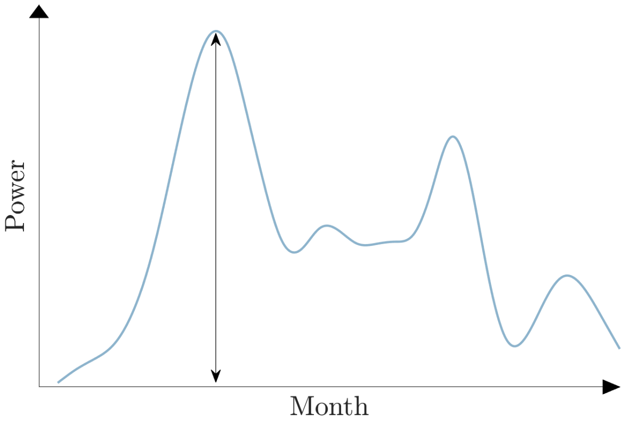

Figure 2.5: *An illustration used to describe the concept of power tariff by maximum peak. The figure is made using modified values from Hafslund Nett.[25]*

Transmission of electricity is a monopoly business as it is not economically viable to allow several network companies to build parallel lines in the same geographical area. NVE annually determines an individual revenue ceiling for each network company. The ceiling has an upper limit on how large income the network companies can collect through the network tariff. NVE has also a set of defined principles on how to determine the tariffs, however the network companies can themselves choose the specific design.[39]

Hafslund Nett operates with separate network tariffs for corporate customers. They are categorised as low-voltage or high-voltage customers. Low-voltage customers can choose between a energy tariff, which only consist of a fixed and an energy segment, or a power tariff, which uses automatic time measurements and is settled for consumption of power and energy, as well as a fixed amount. For the power tariff, a distinction is made between low-voltage and high-voltage customers, as well as joint measurement (e.g. shopping centres and housing co-operatives). The energy and power segments have different prices depending on summer and winter season.[47, 48]

The load on the distribution network is changing in line with more self-production, increasing use of power-consuming equipment, in addition to "plus customers" who delivers power back to the network. This creates a need for extensive network development in order to dimension the grid according to consumption peaks.[49] To counter this, NVE suggest that the network rent should, to a greater extent, reflect the costs the individual customer imposes on the grid. In 2017, they issued a proposal for changes in the regulations in how network companies should design the network tariff. NVE proposes that all network companies introduce an arrangement for "subscribed power", where customers subscribe to a specific energy consumption per hour (kWh/h). Consumption over the subscription will be charged extra. This concept is illustrated in Figure 2.6.

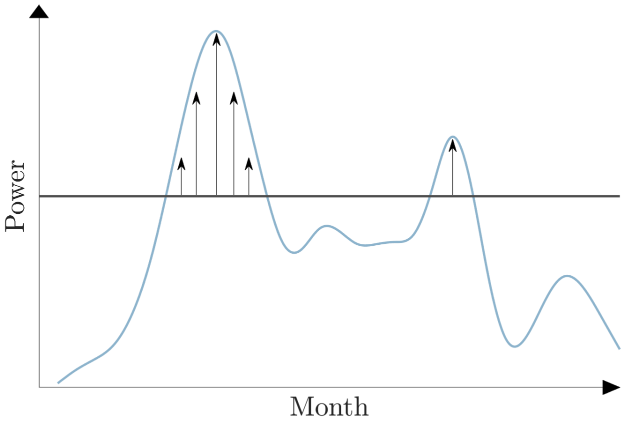

Figure 2.6: *An illustration of the concept proposed by NVE. The red line represents the subscribed power consumption per hour. The figure is made using modified values from Hafslund Nett.[25]*

The cost of electricity will thus depend on the load profile of the customers and should therefore work as an incentive for the customers to change their demand profile. If the network rent reflects the structure of the costs related to consumer patterns, the costumers may be motivated to use the grid more efficient. The purpose is to even out the customers' power consumption throughout the day. Lower consumption peaks will reduce the need for future network investments, and thus the costs of the network companies, resulting in a lower network tariff for customers over time.[50, 51] Due to several inputs to the proposed model from 2017, NVE has decided to arrange a new hearing in the first quarter of 2019.[52]

2.6 Peak shaving

Peak shaving is a technique used to reduce power consumption during high peak periods. For an energy system, it is desirable to reduce consumption peaks for several reasons. From the perspective of the operator, peak shaving is desirable of economic reasons. As mentioned in Section 2.5, corporate customers are often charged for the maximum power consumption per month. Consequently, these customers should focus on levelling their consumption. This is, however, also an advantage for the network companies with regard to grid stability and security of supply. By levelling out the power consumption, the strain on the grid reduces, thus resulting in less losses and extended lifetime of the network components.[33] There are a number of strategies for peak load shaving, two of which are demand side management (DSM) and integration of an energy storage system.[53]

2.6.1 Demand-side management

Demand-side management techniques aim at reducing the system peak loads by encouraging customers to use less energy during peak hours, or to move the time of energy use to off-peak periods. For a bus depot, this can involve using charging strategies in order to even out the consumption of a day. DSM is categorised into two main parts: energy efficiency and demand response (DR).[51]

Increasing energy efficiency involves maintaining the same level of services but lowering the overall energy consumption. Using more energy efficient appliances and reducing consumption will contribute to reducing the overall load. Examples of relevant technologies are heating systems with higher efficiency, ventilation with heat recovering systems and lighting systems with sensors. For an electric bus, the overall demand can be reduced by, for example, using natural ventilation for cooling or a heating system that is not dependent on electricity.[51]

Demand response does not focus on reducing consumption, but on the other hand, encourages shifting parts of the load to periods of lower demand. DR refers to the ability of the demand side to be flexible, responsive and adaptive. Load shifting is one of the techniques of DR and is preferable as the total system peak demand and the cost of energy consumption for the customers decreases, as a result of more equalised power withdrawal. The concept is illustrated in Figure 2.7. There are several methods for load shifting, such as storing electricity during low load periods for use in peak load periods. Other examples are delaying the use of dishwashers, washing machines and charging of electric vehicles to off-peak hours, such as at the night.[51]

Dynamic energy management, also called flexible load shape, is another method of DR that aims to maintain electricity supply reliability. One of the flexible load shape types is direct load control, where network companies have specific contracts with customers that allows them to regulate their load when needed, in return for a cost reduction. This arrangement is described in Section 2.5. Figure 2.8 illustrates the arrangement, where the filled area represents the flexible consumption available for regulation.[51]

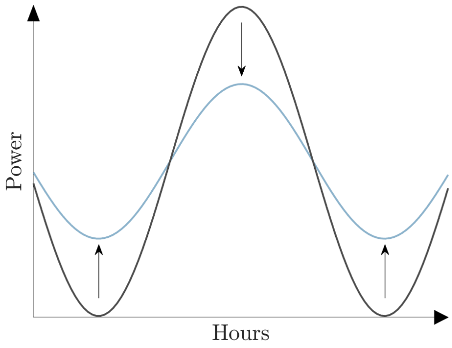

Figure 2.7: *Load shifting.[51] Note: The figure is recreated based on the original and edited to improve readability.[25]*

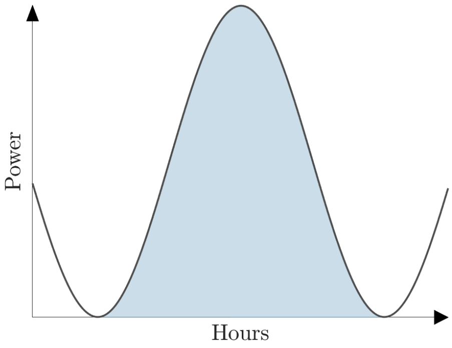

Figure 2.8: *Direct load control.[51] Note: The figure is recreated based on the original and edited to improve readability.[25]*

2.6.2 Energy storage systems

An energy storage system (ESS) is a favourable strategy of peak shaving as it provides fast response and emission-free operation.[54] The purpose of ESS is to even the power consumption of a day, by delivering power to the load during peak demand periods and restoring energy during off-peak periods.[55] The use of ESS is a technique of load shifting, illustrated in Figure 2.7. Instead of moving the time of the activities to off-peak hours, ESS has the advantage that it allows the customers to carry out their daily activities as usual, at the same time as their peak demand charge is being reduced. For a bus depot, this can be beneficial, as fixed departures make it difficult to move the consumption. Among the different storage technologies, battery energy storage systems (BESS) is most common as it allows the system to be easily sized or modified for most applications. However, an important aspect when deploying BESS is proper power and energy sizing. If the battery is not optimally dimensioned, it can generate negative results from an economic perspective.[56]

3 Battery Technology

The development of the price and the battery technology has been important factors in making electric vehicles and battery energy storage systems increasingly relevant. By mass-production and more cost-effective solutions, the battery price has fallen significantly. From 2010 to 2018, the price of the battery technology decreased from approximate 1,160 $/kWh to 176 $/kWh, corresponding to a reduction of 85 %. In addition to cheaper technology, the performance has generally increased significantly.[57, 58]

This section gives an overview of the current status of battery technologies relevant for electric vehicles and stationary energy storage. Based on the current status, this section specifies which battery technology this thesis further focuses on. In addition, relevant parameters and factors that affect the lifetime and capacity losses are presented.

3.1 Current technologies

When considering the use of a battery as an energy storage system, it is important to be aware of the properties that are relevant. In order to compare the performance of various energy storage systems, a Ragone plot is used where specific power is plotted against specific energy.[59] This is graphically illustrates in Figure 3.1, where the characteristics of five current battery technologies is presented. As illustrated, the specific energy decreases as specific power increases for all of the technologies.

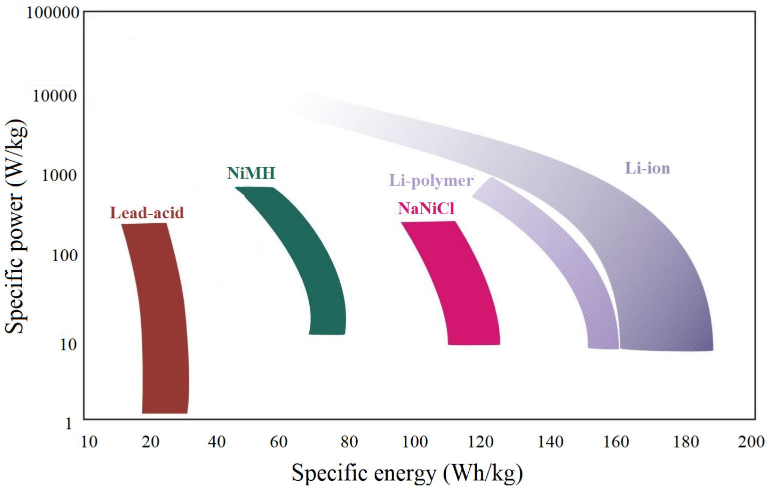

Figure 3.1: *A Ragone plot of five different battery technologies suitable for stationary energy storage systems and automotive applications.[59] Note: The figure is edited based on the original to improve the readability.*

Among the available energy storage technologies, lithium-ion (Li-ion) batteries have the best combination between specific energy and specific power. This, in addition to high efficiency, long lifetime and fast response time makes Li-ion batteries attractive for short- and medium-time stationary energy storage applications. Drawbacks with the technology are high material cost and temperature sensitivity.[60]

Lead-acid batteries, on the other hand, have a relatively low material cost and high availability of materials. Because of these factors, lead-acid batteries account for the biggest share of the marked today. The technology was first introduced in 1860 and has been significant improved over the years. It is used in several applications, both mobile and stationary, but the combination of low specific energy and a limited depth of discharge causes a higher weight of the applications.[61]

Nickel metal hybrid (NiMh) batteries are considered as a relatively mature technology and offer a higher specific energy and more cycles compared to lead-acid batteries. At the same time, NiMh has several disadvantages that make the battery less preferable than Li-ion. In addition to high self-discharge and low voltage, NiMh suffers from ”memory effect”. The consequence of memory effect is reduced available energy over time.[62]

Sodium-sulphur (NaS) and sodium-nickel-chloride (NaNiCl/ZEBRA) batteries are both types of molten-salt batteries, where the operation temperature is typically between 300-400 °C. The difference between NaS and ZEBRA is the material of the cathode, where both have an anode that consists of molten sodium. The NaS battery has a molten sulphur cathode, while the ZEBRA battery has a nickel or nickel chloride cathode depending on the discharge or charge state. Both of the battery types have a specific energy comparable with Li-ion batteries. Furthermore, they have a fast response time, low material cost and long lifetime. Because of the high operation temperature, the use of the batteries is limited. NaS batteries are primarily suitable for stationary energy storage applications and not for battery electric vehicles because of fundamental safety issues. ZEBRA will generally be used in applications where the use is frequently, for example public transport.[63]

To summarise, the various battery technologies are listed in Table 3.1. They are presented with relevant parameters and associated values. Within each battery technology it exist various types, and values can therefore vary from those given in the table.

Table 3.1: *Comparison of the most common battery technologies used in stationary energy storage systems and automotive applications.[62]a][64]b] The cost for Li-ion is based on updated, guided information.[65]c]*

Battery parameters	**Lead-acid**	**NiMh**	**NaS**	**ZEBRA**	**Li-ion**
Specific energy [Wh/kg]	30-40[a]	30-80[a]	90-110[a]	100-120[a]	100-250[b]
Specific power [W/kg]	60-180[a]	140-300[a]	345[a]	160-190[a]	100-500[b]
Cycles	300-800[a]	1,000-2,000[a]	500-1,500[a]	1,000[a]	1,000-20,000[b]
Energy efficiency [%]	60-90[b]	80[b]	90[b]	90[b]	90-98[b]
Nominal voltage [V/cell]	2.0[a]	1.2[a]	2.0[a]	2.6[a]	3-4[b]
Self-discharge [%/month]	3-5[a]	30[a]	0[a]	0[a]	1-5[a]
Operating temperature [°C]	-20 to +60[a]	-20 to +60[a]	300 to 400[a]	300 to 400[a]	-20 to +50[b]
Cost [$/kWh]	150-200[a]	200-300[a]	350[a]	100-300[a]	150-350[c]

This thesis will further focus on Li-ion technology, as most of the available technology related to stationary energy storage and electric vehicles are based on Li-ion batteries. It exists several types of Li-ion chemistries that employ various combinations of anode and cathode materials. The most common Li-ion chemistries that are used today are nickel manganese cobalt (NMC), nickel cobalt aluminium (NCA), lithium iron phosphate (LFP), lithium titanate (LTO), lithium manganese oxide (LMO) and lithium cobalt oxide (LCO).[66] In Figure 3.2, the different combinations are compared according to safety, performance, life span, specific energy, specific power and cost. The further the shapes extend outward the axis, the better are the properties.

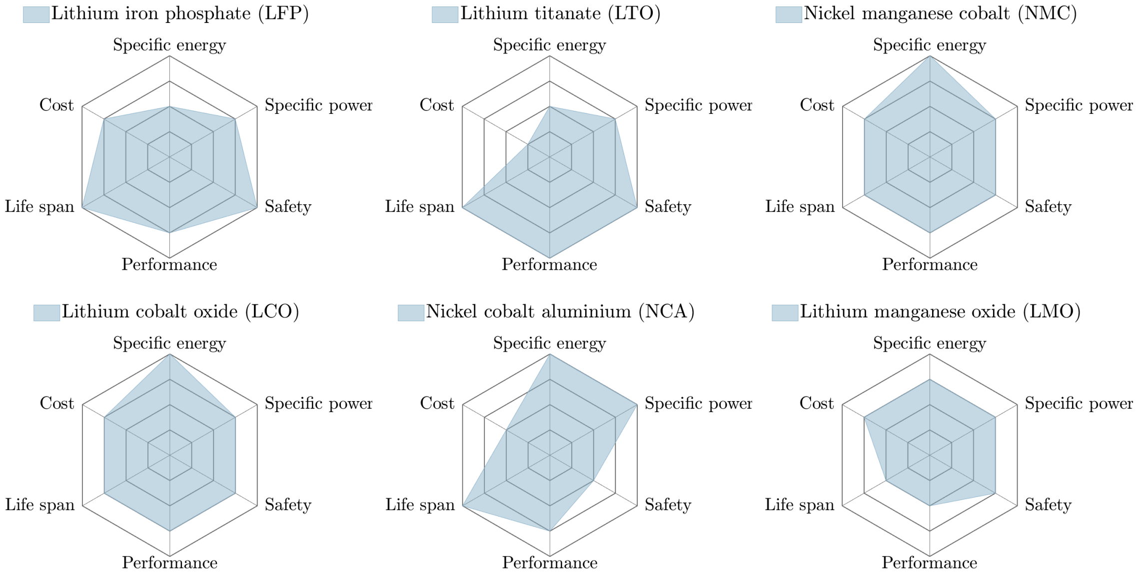

Figure 3.2: *The six most prominent lithium-ion technologies for automotive applications compared in relation to specific power, specific energy, cost, life span performance and safety.[66] Note: The figures are recreated based on the original and edited to improve the readability.*

3.2 Battery terminology

In order to get a proper understanding of the battery technology, it is important to understand the common terminology. The terminology describes properties such as the battery capacity and the rate of charge/discharge. These are key parameters in order to operate the batteries safely and sustainable.

The battery capacity expresses how much energy a battery can store and is measured either in watt-hours (Wh) or ampere-hours (Ah), where the most common unit for battery capacity is Ah. Two parameters describing the state of the battery are state of charge (SoC) and depth of discharge (DoD). State of charge describes the percentage of the maximum capacity that is still available to be supplied. Depth of discharge describes the opposite and indicates how far the battery is from being fully discharged. Both terms are referred to as ”operation window”.[61]

The charge/discharge characteristic is often expressed by a C-rate and is defined as the current through the battery, I, divided by the capacity of the battery, Q, given by Equation 3.1. If both the capacity and charge/discharge current is multiplied by the battery voltage, the C-rate becomes a ratio between the charge/discharge power, P, and the energy capacity of the battery, E. A C-rate of 1C would deliver the rated capacity of the battery in one hour. If the C-rate is doubled to 2C, it would charge or discharge twice as fast. The maximum charge or discharge rate at a given temperature is specified by the cell manufacturer.[61]

$$C - rate = \frac{I}{Q} = \frac{P}{E} \tag{3.1}$$

3.3 Lifetime and capacity losses

The energy and power of a battery fades due to multiple degradation mechanisms; some related to cycles and others related to time. Rate of degradation is controlled by factors such as temperature, C-rate and operation window. It is common to define the end of life for a battery when the storage capacity has faded to 70-80 % of its original capacity.[67]

Lithium-ion batteries can operate over a wide temperature range, but for best results it is recommended to charge/discharge between 10-30 °C. Exposing a battery for elevated temperatures for a longer period reduces the lifetime. On the other hand, lower temperatures increase the internal resistance and lower the capacity. The extremes of the temperatures in the Nordic region are large and can cause challenges in relations to the battery performance. A cooling or heating system can be implemented to reduce the impact, but the consequence is a lower efficiency as both systems requires an energy consumption. The resistance loss increases proportionally to the square of the current through the battery. As the C-rate describes the amount of current transmitted to or from the battery, a lower C-rate is recommended in the winter as the internal resistance is higher.[68]

Depth of discharge and state of charge range are known to have a strong impact on the cycle ageing as these causes more stress inside of the cell. The voltage over the terminal of the battery increases or decreases depending on the charging level. For a Li-ion battery the voltage is kept approximately stable between a SoC of 20-90 %. The voltage increases if the battery is charged to over 90 % SoC and decreases if it is discharged below 20 %. A high or low voltage over a significant period will degrade a battery faster.[60]

During the first charge-discharge cycle, a solid electrolyte interface (SEI) is formed on the negative electrode. Solid electrolyte interface layer protects the anode from a direct electrolyte exposure as it is electronically not conductive. However, as the SEI is not an ideal insulator it may grow slowly during further operation, resulting in a loss of active lithium. Capacity loss and increased resistance is a consequence of this growth. High temperature and high state of charge accelerate the formation of SEI.[60]

4 Electric Buses

Electrification of buses is an effective way of reducing emissions and climate impact from the bus traffic. This section gives an overview of the different types of electric buses and charging technologies existing on the marked. It also considers the factors effecting the energy consumption of an electric bus, as the range of an electric bus is significantly lower than a conventional diesel bus. Finally, emission and cost related to electric buses are presented.

4.1 Powertrain options

There are mainly two types of electric buses; overnight and opportunity buses. The main difference is the duration of charging, thus the battery size. The usage of these types forms the operation strategy and must be adapted to the complex needs of the current operation area. Both overnight and opportunity buses have been tested in Norway and are expected to be partly commercially available in 2020.[69]

4.1.1 Overnight buses

Overnight buses mainly charge during night with no or limited charging during the day. The electric buses are equipped with a large battery pack, with an average capacity of about 300 kWh, corresponding to a driving range around 240 km. The consequence of a large battery pack is the negative effect on passenger capacity. For an overnight bus the passenger capacity is 85 % of an equivalent biodiesel bus. The extra weight, caused by larger battery pack, will also affect the energy consumption.[69]

Recharging of the buses is mainly done at a depot with a low charging power of 22-80 kW. The advantage with charging on bus depots is the absence of infrastructure in the city. Overnight buses normally use lithium iron phosphate batteries (LFP), due to the high safety degree. Nickel manganese cobalt (NMC) batteries are a good competitor to LFP batteries because of their higher charging rates and energy density. However, the danger of overheating or damaging the battery is higher compared to LFP.[69, 66]

4.1.2 Opportunity buses

Opportunity buses charge along the route, either on bus stops and/or at end stations. As the buses frequently charges, the battery capacity is significantly lower compared to overnight buses. The capacity is normally 100 kWh, corresponding to a range of 50-100 km depending on the energy consumption. The passenger capacity is 95 % of an equivalent biodiesel bus.[69]

Disadvantages with opportunity buses are low route flexibility and high investments due to city infrastructure. The opportunity buses are usually fast charged at end stops during the day and slow charged at a depot during the night. The power level of the fast charger can be from 150-600 kW. A battery type suitable for opportunity buses is lithium titanate (LTO) battery. LTO batteries can be charged fast and have more lifetime charging cycles than other lithium-ion batteries.[69, 70]

4.2 Charging methods

This section addresses the different charging methods of a bus battery. Different charging technologies require different properties of the electric buses. Electric buses can be charged either conductively or inductively.

4.2.1 Conduction

Conductive charging requires a physical connection between the power supply and the battery of the electronic device. There are both manual and automatic charging possibilities with conductive charging, such as plug-in and pantograph. Conductive charging is currently the most common charging method for electric buses.[71]

As it exists several suppliers within the charging technology, it is important with a common standard for the infrastructure. This means that the connection point of both the charger and the bus is standardised and that the electrical parameters must be the same. Currently, it is not a standard solution for either plug-in or pantograph, but this section gives an overview of what the market converges towards.[72]

Plug-in
Plug-in is a manual charging system used for depot charging and is suitable for both opportunity and overnight buses. The charging technology is the most common way to charge electric vehicles and has a typical charger output range of 10-200 kW. Even though it exists several types of plug-in chargers, the market seems to converge towards a CCS-2 connector charger for overnight charging (depot). The CCS chargers include a commutation protocol for signals between the charger and the bus.[73, 74]

Pantograph
A pantograph is an automatic charging system mainly used for opportunity charging. This technology is delivered with two solutions. The movable part (pantograph) can either be installed on the charging station or on the bus. Several companies have agreed to use pantographs installed on the charging station, referred to as inverted pantographs. The cooperation is called OppCharge.[70]

Inverted pantograph allows high charging power and has an output power of 150-600 kW. Because of the high values, the battery can be charged within few minutes while the bus is standing at the bus stop.[73] The benefits with this method are reduced weight on the bus and number of pantographs installed.[70] Figure 4.1 illustrates the charging of an electric bus using inverted pantograph. Due to greater construction and complexity of a pantograph charger compared to a plug-in charger, the cost of the hardware with the same charging power is around twice as high.[75]

Figure 4.1: *An electric bus using an inverted pantograph for charging.[76]*

4.2.2 Induction

Induction charging is a contactless charging system where the current is transmitted in an electromagnetic field. The magnetic field is activated between the bus and the induction coils, which are installed under the road surface. Figure 4.2 illustrates the charging of an electric bus using a contactless system. Induction charging is suitable for opportunity buses as the technology has no moving parts and can easily be used to charge buses standing on the bus stops. In addition, the technology has minimum visibility. Even though there are several benefits with this charging system, there are still many challenges to overcome. Among other things, induction charging is not as efficient as conduction charging and the charging power is restricted to 200 kW.[69]

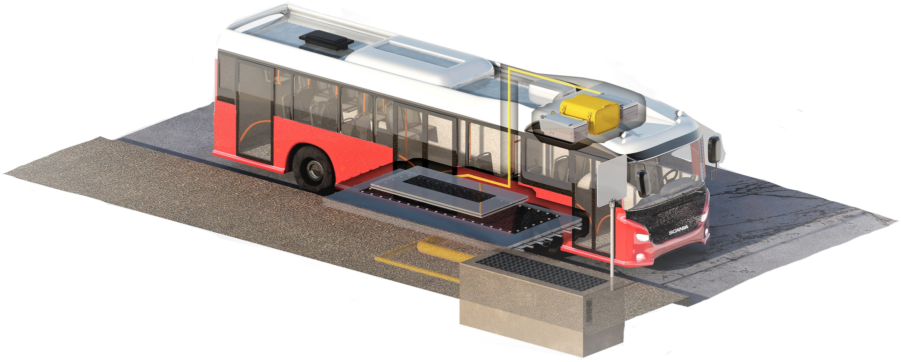

Figure 4.2: *An electric bus charging with a contactless charging system. The yellow block on the top of the bus represents the battery cells and the two blocks in the middle represent the coils, one installed under the road surface and one mounted on the bus.[77]*

4.3 Energy consumption

The energy consumption per kilometre of an electric bus depends on several parameters, such as driving style, topography, temperature, speed profile and weight.[78] However, electric buses have a significantly lower consumption compared to conventional diesel buses. This is mainly because diesel engines have lower efficiency and lack energy regeneration capabilities. Table 4.1 compares electric and diesel buses in relation to specific energy, energy density, consumption, engine efficiency and range. The range of an electric bus depends on whether it is an opportunity or overnight bus and is calculated based on the energy consumption given in the table. Diesel buses have an average tank capacity of 300 L and fuel consumption of approximately 40-50 L/100 km.[79]

Table 4.1: *Specific energy, energy density, consumption, engine efficiency and range for electric and diesel buses.[80]a][81]b][79]c]*

Bus type	Specific energy	Energy density	Consumption	Engine efficiency	Range
	kWh/kg	kWh/L	kWh/km	%	km
Electric	0.35[a]	0.25[a]	1.5[b]	91[c]	70-200
Diesel	13.8[a]	10.9[a]	4-5[c]	45[c]	600-750

The bus driver has a relatively big impact on the energy consumption, as the driving style affects both the amount of energy used and regenerated. Based on a test performed by the transport company Movia in Denmark, an inefficient driving style can have an impact of 15 % on the energy consumption.[82] An important measure for reducing the energy consumption is to exploit the regenerative capability. The bus regenerates energy by e.g. breaking or rolling downhill. However, the bus is in most cases not able to regenerative the same amount of energy required of a demanding topography. According to Ruter, demanding topography can increase the average energy consumption by 15 %.[83]

If a bus is to be defined as an electric bus, both propulsion and other technical system (lighting, heating, cooling, etc.) on the bus must be powered by electricity. The technical system can require up to 50 % of the total energy demand. To prevent the heating to preserve the driving range, several electric bus manufacturers use diesel or biofuel for auxiliary heating. The downside of this solution is the emissions related to the fuel.[84] As the tender rounds focus on buses being completely emission-free, the manufacturers must develop new solutions for heating. A solution can be to replace the auxiliary diesel heater with a heat pump efficient for lower temperatures. Electric preheating is also an solution, where the bus is heated when it is still connected to the charger.[83]

The energy consumption is usually highest below 2 °C and above 18 °C, if an auxiliary diesel heater is used. Increasing consumption at high temperatures is due to increased use of air condition, while increasing consumption at low temperatures can cause higher demand due to ice and snow.[82] A low temperature will also affect the driving range due to the higher internal resistance in the battery.[68]

The duration of the route also influences the energy consumption, as the auxiliary power is constantly being drawn. The most energy-consuming auxiliaries are air-conditioning, heating and ventilation. Bus trips during rush hours will therefore have considerably higher energy consumption than bus trips at other times, as the average speed is lower.[79]

4.4 Emissions

Electric buses have basically the same vehicle body as diesel buses. The main difference is that electric buses are equipped with an electric engine and converter instead of a conventional diesel engine. In addition, they are equipped with a battery and a charging equipment instead of a fuel tank.[69] As the body is approximately the same, there are especially two factors which determines how environmentally friendly electric buses are compared to diesel buses; the energy sources of the electricity and the emission related to production of lithium-ion batteries. This section will give an overview of these factors and, in addition, argument for the choice of electricity mix used in this thesis.

4.4.1 Guarantees of origin and Nordic mix

Guarantees of origin (GOs) are an electronic warranty that ensure the customer that an amount of energy is produced from a specific energy source. Several public transport authorities require that the public transport operator must buy a guarantee of origin for the electricity used through the contract period. The power supplier buys the GOs from the power producer and it is optionally for the customer to include this in their subscription.[85] The price of GOs depend on supply and demand, in addition to the type of GOs. The price of the Norwegian GOs was in 2018 around 1.65 EUR/MWh, which is an increase of 600 % compared the average price in the period from October 2016 to October 2017. The increase is partly due to reduced supply (small amounts of precipitation) and a general increased demand.[86]

Power suppliers selling power without GOs must refer to the national electricity disclosure of NVE. The disclosure is calculated based on the power production in Norway, adjusted for the European trade of GOs and supplemented with a composition equivalent to the European attribute mix. The composition of energy sources of the disclosure is therefore different than the Norwegian power production. This results in a CO_2 factor of 531 g/kWh, compared to 16.4 g/kWh from the Norwegian power production estimated in 2017.[87]

The emissions related to electric buses depend on the electricity mix used. The CO_2 factor for both the national disclosure and the Norwegian power production is not a representative value in relation to the actual carbon intensity of the electricity in Norway. This is because the Norwegian power production does not consider import and export of power and the national disclosure includes a high share of European attribute mix. A Nordic mix will therefore be used in this thesis when evaluating the emissions from electricity. The mix includes import and export of electricity between the Nordic countries and has a CO_2 factor estimated to 107 g/kWh.[88]

4.4.2 Battery production

The production of lithium-ion batteries is associated with large amount of greenhouse gas emissions (GHG). According to a report that IVL Swedish Environmental Research Institute has carried out, the GHG emissions for production of larger batteries are 150-250 kg CO_2eq/kWh. Most of the energy used for production is electricity, meaning that the electricity mix for the location of the production greatly impacts the total result. The study uses an electricity mix with a fossil share of 50-70 %.[89]

Due to the high emissions related to the production of the battery, the excepted lifetime is an important parameter in relation to the evaluation of the environmental impact of electric buses. Expected lifetime for a battery is six years, meaning a new battery has to be replaced after this period of time.[90] It is possible to give the battery a second life in applications where the weight or volume is not critical, such as stationary energy storage. However, the second life marked of today is small or not existing.[89]

As electric buses have zero local emissions, emissions related to electric buses largely depend on the energy sources used to produce the electricity. Table 4.2 gives well-to-tank (WTT), tank-to-wheel (TTW) and well-to-wheel (WTW) emissions for an electric and a diesel bus, in addition to the percentage reduction in emissions of an electric bus. The Nordic mix and the energy consumption from Table 4.1 has been used to calculate WTT for an electric bus. The energy and fuel consumption vary according to the bus type, thus also the emissions. In addition, the WTW assesses only the energy consumption and the emissions of road transport fuels, and emissions related to the whole cycle are therefore not accounted for.

Table 4.2: *A comparison of an electric and a diesel bus in relation to WTT, TTW and WTW emissions.[91]*

Bus type	**WTT**	**TTW**	**WTW**	**Reduction**
	g CO_2eq/km	g CO_2eq/km	g CO_2eq/km	%
Electric	160	0	160	87
Diesel	218	1,004	1,222	0

4.5 Economy

In 2017, the procurement of an electric bus was about twice the price of a conventional diesel bus with similar capacity. However, it is important to evaluate the cost for the life cycle when comparing the two buses due to different cost profile. Higher investment cost for electric buses and charging infrastructure can be compensated by a lower operating cost and profit related to climate impacts.[92] Figure 4.4 gives an overview of cost given in NOK per kilometre for procurement, fuel, infrastructure, maintenance and personal for opportunity, overnight, hydrotreated vegetable oil (HVO) and diesel buses.

The total cost of a bus fleet depends on the associated route characteristics, such as departure frequency and charging strategy. On lines where it is few or none regulation time for charging at end stations, more buses must be inserted to maintain the same offer (normal operation). The same applies for overnight buses where the range is not sufficient. Ruter assumes 10 % extra buses when opportunity charging and 12 % when depot charging.[93] Additional buses reduces the utilisation rate per bus, resulting in a larger difference in total costs of electric buses compared to diesel buses.[92]

Ruter expects that electric buses will be financially competitive in the future. Figure 4.3 illustrates how the cost per kilometre decreases over the years, where overnight buses are expected to be competitive from 2025. Both figures include the additional cost related to the electrification of the buses.[93]

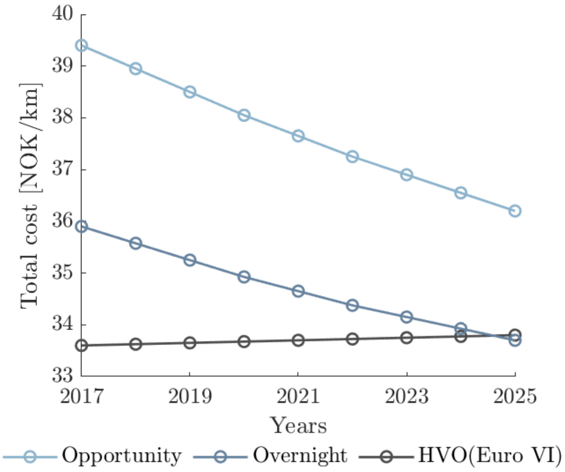

Figure 4.3: *How total cost for a 12 m city bus develops over a time interval of 9 years. The additional cost related to the electrification is included.[93] Note: The figure is recreated based on the original and edited to improve the readability.*

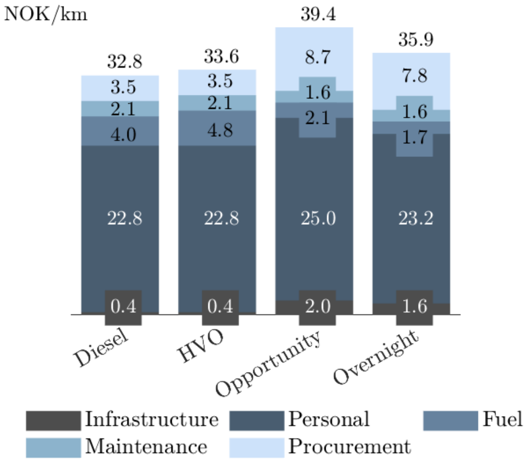

Figure 4.4: *Total cost given in NOK per kilometre for 12 m city bus in 2017 divided into categories. The additional cost related to the electrification is included[93] Note: The figure is recreated based on the original and edited to improve the readability.*

5 Case Study

A case study is presented in order to apply the generalised theory to a specific depot where an electrification is planned. Furubakken depot was chosen as a case study as this depot was the next on the list to be electrified in Oslo and Akershus. A system is simulated by using bus lines associated to the depot and available information. The focus is to design and optimise the operation of Furubakken depot to adapt to charging requirements and available network capacity. The study is limited to only evaluating overnight buses. This section includes a description of Furubakken depot, as well as methodology and results of the case study simulation.

5.1 Description

This section includes a description of Furubakken depot, with information about key parameters essential for the operation. It contains relevant information about Ruter's tender round and facility specifications. This involves a planned expansion of the depot and associated grid specifications. Finally, information about each line is presented.

Tender round
Ruter's tender round concerning bus services for route area 1 - "Vestre Aker" and "Østre Bærum" includes the use and rent of Furubakken depot. The duration of the contract is eight years and the operation start-up is 28th of July 2020. The contract is allocated to the public transport operator (PTO) that presents the best relation between price and quality, based on the criteria shown in Table A.1 in Appendix B. The winning PTO buys and operates the buses, as well as the charging infrastructure. Ruter demands zero emission for city buses with a maximum road speed of 70 km/h. In the evaluation it is given points for quality in relation to bus materials and the environmental properties of the fuel. For example, electric and hydrogen buses receive the highest score (10 out of 10 points). Points for other engine technologies and fuels can be found in Table A.2. The type of bus and fuel is emphasised corresponding to the proportion of the total fleet.[94]

Facility specifications
Furubakken depot has around 90 parking spaces. It is further planned to expand the facility to accommodate for articulated and electric buses. The planned renovation is illustrated in Figure 5.1. In order to charge the electric buses, a cable with a capacity of 4 MW is planned to be installed from the substation to the facility. Every parking space will be installed with slow chargers, while articulated buses will fast charge close to the substation. For all the electricity used throughout the contract period, it is required that the PTO purchases a guarantee of origin for electricity from renewable energy sources.[95]

The grid Furubakken is connected to is considered as stiff and the impact of connecting large loads is therefore small. Haslum substation is placed right next to Furubakken depot, and consists of three transformers with tap changers, transforming the voltage from 47 kV to 11 kV. Hafslund AS is the owner of the substation, in addition to the distribution network around Furubakken. The degree of redundancy at Furubakken depot is high, as the substation manages to supply the depot even if one of the transformers is unavailable.[96]

Figure 5.1: *A sketch of the planned renovation of Furubakken depot.[97]*

Information about the lines

Route area 1 - "Vestre Aker" and "Østre Bærum" has 15 associated bus lines, which are listed in Table 5.1. The table contains information about route driving distance, daily driving distance and altitude between the two end stops for each respective bus line. As route 225 is a new line, the timetable, bus stops, route driving distance and topography is not available. Route 130N and 140N only operate in the weekends.

Table 5.1: *Route driving distance, daily driving distance and altitude between the two end stops for each bus line associated to route area 1.*

Route	Route driving distance	Daily driving distance	Altitude difference	Route	Route driving distance	Daily driving distance	Altitude difference
	km	km	m		km	km	m
40	11.6	805.4	162	140E	14.1	289.8	146
41	10.6	503.4	44	140N	20.8	299.9	71
45	7.5	1,002.4	271	145	6.5	453.1	66
46	7.6	1,235.8	130	220	7.1	579.2	62
48	6.1	168.0	0	225	-	468.4	-
130	14	2,390.3	7	230	14.5	2,680.0	146
130N	18.7	243.4	47	235	2.8	41.7	10
140	16	2,741.6	69				

The route schedule for the respective bus lines is extracted from Ruter's website.[98, 99] Line 40, 41, 45, 46 and 48 was applicable from 03.03.2019, while the remaining lines uses route schedules valid from 07.10.2018. Figure 5.2 illustrates the end stops of the lines associated to Furubakken depot. The frequency of the departures varies with the rush hours. The rush hours refer to periods where the traffic is increased. In this thesis the rush period is defined from Monday to Friday between 7:00-9:00 a.m. and 3:00-6:00 p.m.

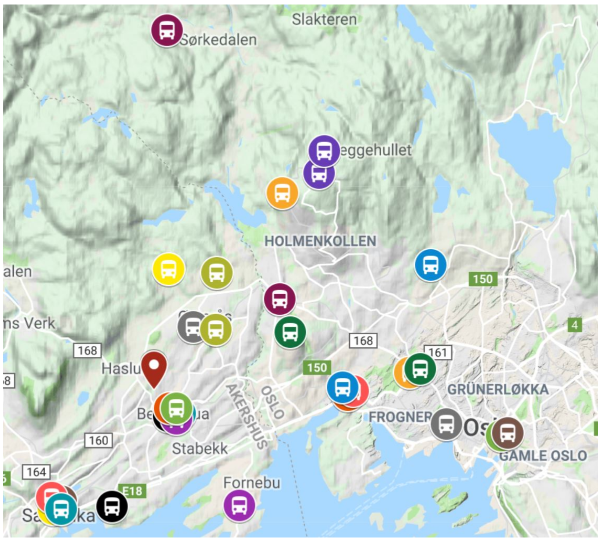

Figure 5.2: *A map of the end stops of the lines associated to Furubakken depot.*

5.2 Methodology

This section explains how the load profile for the depot is simulated using available software and how important system parameters are determined. Further, a description of the optimisation strategies and the approach for dimensioning the stationary battery is given. Finally, the approach for an economic assessment is described.

The simulation is done using a self-produced script in *MATLAB*, a programming-based mathematical program for numerical calculations, simulations and visualisations. All parameter data from the bus lines is extracted from Excel and loaded to MATLAB using an import function. MATLAB is also used to create self-made curves. These are based on existing figures extracted from other sources.

5.2.1 Load profile simulation

In order to determine the total load, and thus the power output needed from the grid, it is necessary to simulate the bus operation for each line associated with Furubakken depot. The load profile simulation will also produce information such as when the buses arrives and departures the depot, level of energy on each bus and the driving schedule for each bus. This section will cover the parameters and the load profile simulation structure with the two integrated parts; bus route and depot simulation.

Simulation parameters

The Excel sheet used for parameter data contains departure frequency, travel time and kilometre distance per route for each line. The kilometre distance is extracted from Google Maps by listing each stop in the travel route. For both travel time of the route and between the end stops and the depot, the time usage is considered when there is no queue. This is because it is difficult to determine the impact of rush traffic on the public transport, as it can vary from day to day and some roads have public-transport lanes. All data is collected for a regular weekday, and deviations regarding weekends and holiday periods are therefore not accounted for.

The simulation has been based on two types of buses. A 12 metre electric bus, from the bus manufacturer BYD, and an 18 metre VDL SLF-180 electric bus is used. The solo buses use slow charging with 80 kW, while the articulated buses fast charges with 450 kW. These buses were chosen based on testing of different bus types, where a combination of slow and fast chargers resulted in the fewest buses in operation.

Of the associated bus lines, three uses articulated buses, while the remaining uses solo buses. The classification of the bus type for each specific line is given in Table B.1 in Appendix B. In the simulation, each bus does not belong to a particular line, however, a bus will only choose a route matching its classification. This entails that an articulated bus can dive any route associated with the three bus lines using this classification. The simulation uses this system as it is expected to optimise the model. Weekend lines 130N and 140N, as well as the new line 225, is not included in the simulation. The parameters for the two bus types are given in Table 5.2.

Table 5.2: *Parameters and consumption values for the two bus types used in this thesis. The buses are supplied from BYD and VDL.[100, 101, 102] Consumption values for the best-case scenario are calculated based on given range and battery capacity, while values for the worst-case scenario for 18 metre buses are provided by Ruter.[103]*

Bus type	**Range**	**Weight**	**Battery capacity**	**Charging power**	**Charging time**	**Consumption best-case**	**Consumption worst-case**
	km	kg	kWh	kW	min	kWh/km	kWh/km
BYD	250	19,000	320	80	240	1.28	2.03
VDL SLF-180	90	29,000	170	450	20	1.89	3.00

Two scenarios, a best-case and a worst-case, are simulated using different values for energy consumption. The design of the depot in this thesis is based on the worst-case scenario, as this gives a greater degree of security in the event of deviations. The purpose of the best-case scenario is to compare the difference in power demand from the depot for the extremes of consumption. The consumption value used in the simulation of the best-case scenario is based on the energy consumption provided by the manufacturer, and calculated by dividing the battery capacity by the range for each bus type. These buses use biodiesel for heating, thus the value does not include energy used to heating.

The consumption value for the worst-case scenario is based on information given by Ruter.[103] The values are based on testing done of class 1 buses, corresponding to city buses. For an 18 metre electric bus, a worst-case value of 3.0 kWh/km is used, where factors such as inefficient driving style, rush and demanding topography and temperature are included. In addition, the value includes use of electricity for heating. The worst-case consumption value for the 12 metre bus is calculated using the ratio between the best- and worst-case scenario consumption values for the 18 metre bus. The consumption value for each bus type and scenario is given in Table 5.2. For the bus battery, it is decided to use a SoC between 20-100 %. This decision is based on information given a public transport operator (PTO).[104]

Simulation structure

The simulation operates with one matrix for each line, as well as a matrix for the depot. Each matrix addresses values for buses in operation at the various positions at a given time. The columns in the matrix give information about remaining capacity, position status, remaining travel time to next destination, arrival time at the current position, charging power when charging, waiting time for the next departure and information about whether the bus is a solo or an articulated bus. The structure of the matrices is given in Table 5.3.

Table 5.3: *Structure of the matrices used in the load profile simulation.*

Bus ID	**Capacity**	**Position status**	**Remaining travel time**	**Arrival time at current position**	**Charging power**	**Waiting time**	**Solo or articulated bus**

The position status gives information about where a bus is driving to, or where it is parked. Some of the different statuses are given in Table 5.4, where the rest are given in Appendix C. In the script, additional statuses indicating interactions with a third end stop and the depot is accounted for, however this is not included here for simplicity. The column for charging power will only have a value if the bus charges and can either have a value of 80 kW or 450 kW depending on whether it uses slow or fast charging.

Table 5.4: *Explanation of some of the status codes used in the simulation.*

Status	1	2	3	4
Explanation	At ES1	On the way to ES2	At ES2	On the way to ES1

Description of the bus route simulation

The bus route simulation is an integrated part of the load profile simulation that includes the buses in operation on designated lines and their interaction with the depot. A simplified flow chart of the simulation can be studied in Figure 5.3. It describes the different events when a bus is driving on a line. These events are valid for all the lines associated with the depot and includes two end stops, *ES1* and *ES2*.

The simulation uses time iteration with one-minute intervals from 1 minute to a set time limit t_{max}, which can be set to for example 1440 minutes to simulate 24 hours. One-minute intervals are chosen because the departure times from the timetables and the travel time is given in minutes. In addition, there are too many variables and uncertainties to have the different times given in seconds.

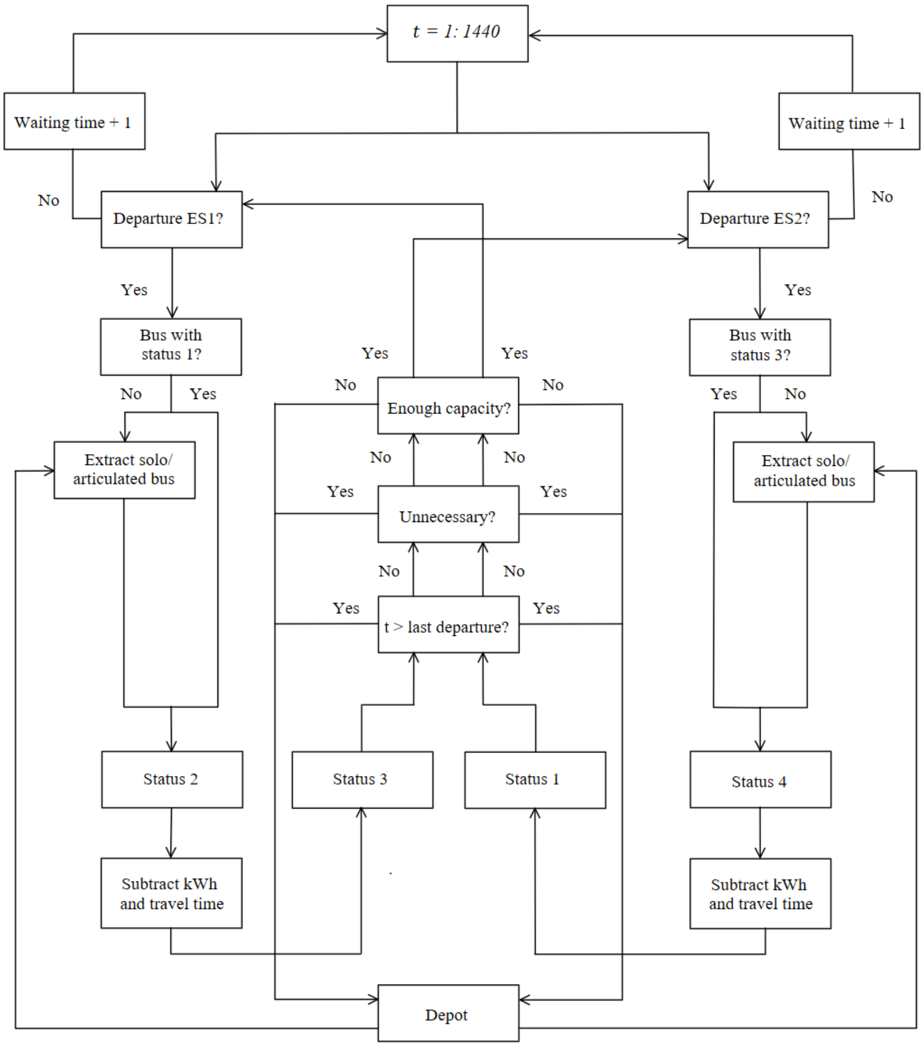

Figure 5.3: *Simplified flow chart illustrating the bus route simulation for each bus line associated to the depot.*

For each line matrix and minute simulated, the simulation checks the timetables for any departures from the end stops. If an end stop has a departure, two scenarios can occur. In the first scenario, a bus is ready on the respective end stop and takes the next trip. In the second scenario, there are no available buses on the end stop to take the next trip. For this case, a bus is implemented from the depot matrix to the respective line matrix. The simulation includes the extra time and energy the bus requires from the depot to the end stops.

When a bus is driving, the simulation deducts the energy capacity from the bus battery depending on the energy consumption and driving length. In addition, it uses the expected time associated with the current route to determine the time length of its driving status. When the driving status changes, the bus has reached its designated destination.

When a bus arrives an end stop, the simulation checks certain parameters to make it more effective and reliable. If the remaining energy capacity of the bus battery is less than the energy needed to drive to the other end stop and back to the depot, the bus drives directly to the depot. The bus is also sent back to the depot if there is another bus on the way to the end stop and that reaches the next departure. This usually happens when the frequency of the departures decreases, meaning fewer departures per hour, hence fewer buses needed per line. At the end of the day, or during long periods of time when it is no departures, all the buses on the specific line drives back to the depot.

Description of the depot simulation

The depot simulation is an integrated part of the load profile simulation that simulates the bus activity on the depot with associated chargers. A flow chart of the simulation can be studied in Figure 5.4. The slow charging power (80kW) is referred to as *P1* and the fast charging power (450kW) is referred to as *P2*.

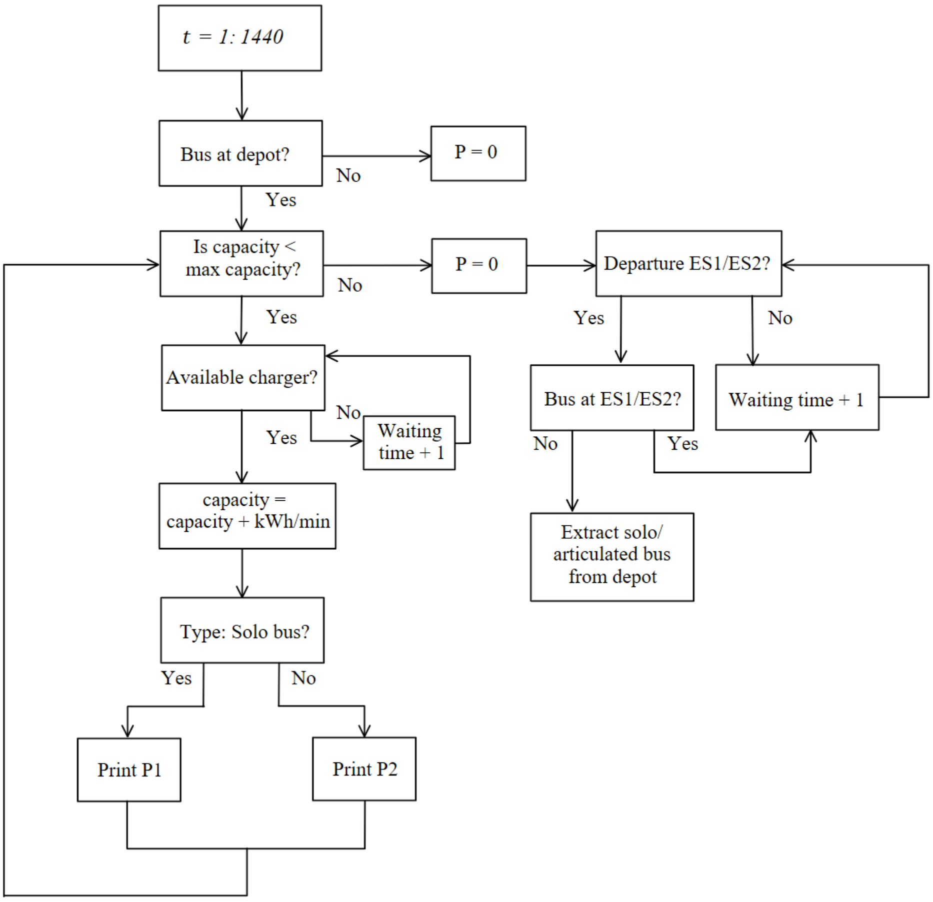

Figure 5.4: *Simplified flow chart of the model used for the depot simulation.*

The depot matrix represents all the buses at the depot at any given time in the simulation. At the start of the simulation, all buses are stationed on the depot. One after another, the buses depart the depot as they are needed on respective lines. When buses are being sent back to the depot, they start to charge. The solo buses use slow chargers and the articulated buses use fast chargers. The sum of the active charging power is equivalent to the total load power at the depot.

The number of simultaneously active slow and fast chargers can be limited. If all respective chargers are is use at a given time, a queue of buses with low energy capacity will form. The simulation can arrange this queue with regard to two parameters; waiting time at the depot or remaining capacity.

5.2.2 Peak shaving

In order to reduce the power consumption peaks at Furubakken depot, two strategies are being evaluated; demand-side management and integration of an energy storage system. This thesis limits the number of simultaneously active chargers with specific queue priority as a demand-side management technique, referred to as *smart charging* in this thesis. In addition, a stationary battery is used to further reduce the peaks. These two strategies are based on the worst-case scenario. The purpose of reducing the power peaks is to lower the costs related to the network tariff and reducing power grid strains.

Smart charging strategy

The bus simulation can limit the number of chargers that are simultaneously active. If the number of available chargers is infinite, the buses will charge on arrival. By setting an upper limit for active chargers, the amount of energy consumed is distributed throughout the 24 hours. It is important that the number of buses do not increase when reducing number of chargers, as an increase of buses result in a more expensive bus fleet. It is also important that the number of buses does not increase if the charging time should extend to the next day.

The optimisation is executed by reducing the number of active charges until the number of buses increases or affects the operation for the next day. The adjustment is done for both slow and fast chargers individually as they are not dependent on each other. This is because the two types of chargers have their own pool of buses (solo and articulated buses). In this thesis the method is referred to as smart charging, as it is a system controlling which buses charge at what time. Any available charger will get occupied by the next arriving bus. If the maximum number of active chargers is reached, all incoming buses have to wait for an available charging point and a queue will form.

In this thesis, two methods are used for how the queuing system for charging is prioritised; based on the longest waiting time or based on the highest capacity. When there are more buses ready to charge than the available chargers, it is the buses that have waited the longest or the buses that have the highest capacity that will be prioritised. The purpose is to see how these methods affect the operation of the depot and the possibility of reducing the power peaks. The time prioritisation queue is chosen to prevent long waiting periods for buses on depot. The capacity prioritisation in done to prevent that buses with relatively short charging period have to wait on buses with low capacity to finish recharging. By prioritising the buses with high capacity, they will get ready earlier to take on a new route. Based on the worst-case scenario and the different queuing systems, three scenarios are simulated: 1) Charging on arrival, 2) Smart charging with time-based queuing system, and 3) Smart charging with capacity-based queuing system.

Dimensioning of the stationary battery

Implementing a stationary battery can be advantageous for reducing high power peaks. In some cases, this application can be a cheaper alternative than upgrading the grid infrastructure. In addition, it can result in a lower network tariff cost due to peak shaving. In this case study, a roughly estimate of the profitability of a stationary battery is investigated.

The simulation is done with the basis of scenario 3: smart charging with capacity based queuing system. This scenario was chosen as it was the most optimal with regard to power peaks and number of chargers, as given in Section 5.3.1. In addition, it is desirable to dimension the battery based on the worst-case scenario to increase reliability.

Some limiting specifications for the battery performance are decided with the intention of preventing battery degradation. The lower and upper SoC for the battery is 20 % and 80 %. The charging and discharging power, $P_{B,charging}$ and $P_{B,discharging}$ are calculated from this battery size using Equation 5.1 and 5.2. This equation is based on Equation 3.1. The rate the battery is charged, $C_{charging}$, and discharged, $C_{discharging}$, is set to 3C (20 minutes) and 1,33C (45 minutes) based on guiding information.[105]

$$P_{B,charging} = 3C \cdot E_{B,max} \tag{5.1}$$

$$P_{B,discharging} = 1.33C \cdot E_{B,max} \tag{5.2}$$

The simulation consists of three cores. The inner core is where the battery is peak shaving the original load from the results. The second core is where different battery sizes is decided. The outer core is where the max peak limit is set for the simulation.

A simplified flow chart of the inner core simulation is given in Figure 5.5. At first, the simulation calculates the difference between the maximum power limit and the load profile of the buses, P_{diff}, for each minute. Depending on whether the difference is positive or negative, the battery charges or discharges. The battery charges or discharges with this difference, unless the value exceeds the possible charging or discharging power. For this case, $P_{B,charging}$ or $P_{B,discharging}$ is used. For each minute, the simulation adjusts the amount of energy in the battery, E_B, by accounting for the amount of power supplied or deducted from the battery. The total power consumption with battery peak shaving, P_{tot}, is also calculated by adding the bus load, P_{load} and the power output or input to the stationary battery, P_B. This is given by Equation 5.3. P_B can either be equal to P_{diff}, $P_{B,charging}$ or $P_{B,discharging}$. The time iterations of the inner core simulation run until $t = t_{max}$, where $t_{max} = 1440$ minutes. For this case, P_{tot} for each t is saved in the scope.

$$P_{tot}(t) = P_{load}(t) + P_B(t) \tag{5.3}$$

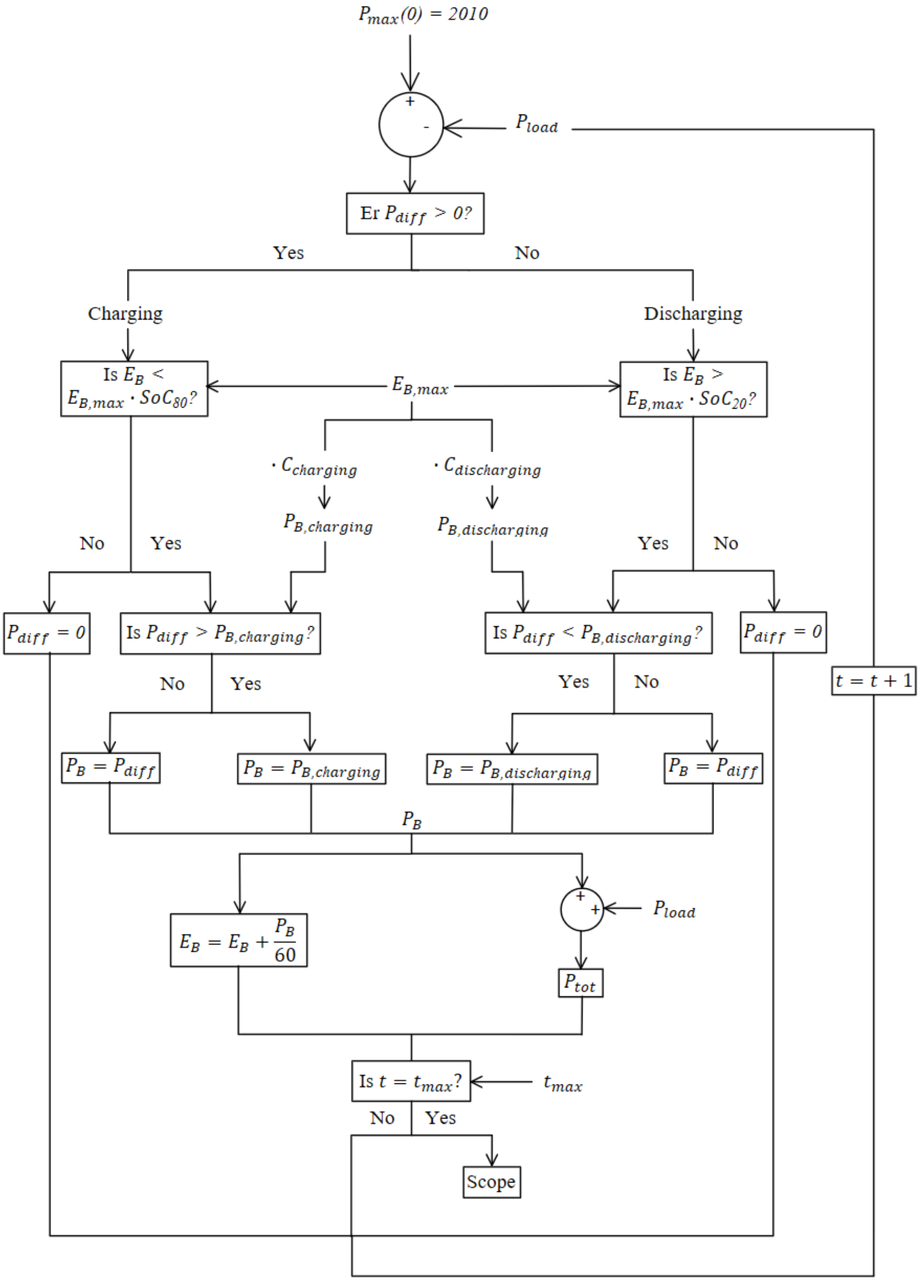

Figure 5.5: *Simplified flow chart of the model used for the inner core simulation of the stationary battery.*

The second and outer core simulation is based on the maximum value of P_{tot} from the inner core simulation. A simplified flow chart of the second and outer core simulation is presented in Figure 5.6. First, the simulation checks if the maximum value of P_{tot} is greater than P_{max}. This means that the maximum power load for the depot exceeds the desired maximum power peak. If this is not the case, the maximum value of P_{tot} is used to calculate the profitability of this scenario. This procedure is described in the paragraph below. Thereafter, the second core simulation calculates all valid values of $E_{B,max}$ for the specific P_{max} value. If however, P_{tot} is greater than P_{max}, the scenario is not valid. For this value of P_{max}, the profitability is the same as in the previous scenario. Further, P_{max} is subtracted by one, and the time iteration is repeated with the new value. When presenting the result for the entire simulation it is used the lowest value for $E_{B,max}$ for each P_{max}, as this corresponds to the minimum battery size possible.

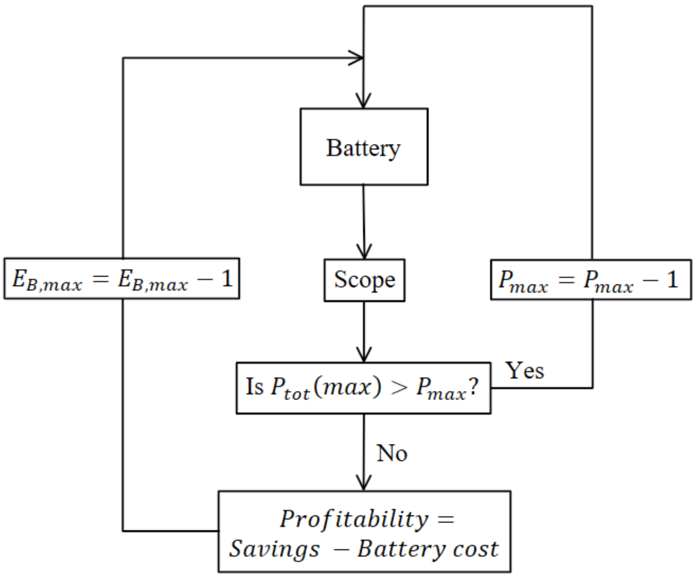

Figure 5.6: *Simplified flow chart of the model used for the second and outer core simulation of the stationary battery. The profitability of the different combinations of P_{max} and $E_{B,max}$ is calculated in this model. The scope in the chart is equal to the scope in Figure 5.5*

For each power shaved and the corresponding minimum possible battery capacity, the profitability is calculated. The calculation is based on the cost of the battery and savings from the power segment of the network tariff. The energy segment and the electricity costs are not included as the daily energy consumption is the same regardless of the use of a stationary battery. The approach is described in Section 5.2.3. The total cost is equal to the price of the stationary battery. As described in Table 3.1 in Section 4.4.2, the cost for a lithium-ion battery span between 150-350 $/kWh. Based on this and guiding information, it was determined to use a battery cost of 200 $/kWh. To include cost for the entire energy storage system, the battery cost is multiplied with a factor of 4. This is also based on guiding information, where three commercial independent battery package systems has indicated that a factor of 3-4 is representative when including the energy storage system.[65] The total battery cost is calculated by multiplying 800 \$/kWh with a conversion value from dollar to NOK of 8.559 and the battery size, $E_{B,max}$. The conversion value is extracted 23.04.2019. The total profitability is found by subtracting battery cost from savings.

5.2.3 Economic assessment

This thesis includes several economical assessments. In all calculations of the network tariff, it is used the power tariff that Hafslund Nett offers their low-voltage corporate customers. This includes a power and an energy segment, as well as a fixed amount. First, a comparison of the costs for the three scenarios of the worst-case scenario is made. The savings of using smart charging with capacity prioritisation compared to smart charging with time prioritisation and charging on arrival is calculated from the power segment of the network tariff. This is based on the difference in maximum consumption value for the three scenarios. December month is used in the analysis of the savings, as this is one of the months that is likely to operate closer to the worst-case scenario.

Secondly, the savings of using the best-case versus the worst-case scenario with capacity prioritisation for a month is analysed using electricity cost and network tariff. The month of May is in this case used, as this is one of the summer months that is likely to operate closer to the best-case scenario. This can be argued through high temperatures, but lower likelihood of using air conditioning compared to other summer months. As the simulation assumes a worst-case, the month of May gives a good representation of what is possible to save. The calculation assumes that the consumption of each day is equal to a regularly weekday.

Finally, an analysis is done for the savings of using a stationary battery for peak shaving. Only the power segment of the network tariff has an impact on this value. As the battery has a lifetime of approximately six years, the savings are calculated for this time period.

Savings based on electricity prices

The electricity cost is based on the average price for each month for Oslo in 2018, extracted from Nord Pool.[41] The values used are presented in Table D.1 in Appendix D. The cost is calculated by using Equation 5.4. Due to the requirement that all electricity used during the contract period for Furubakken depot must have a guarantee of origin, this has to be included. Given from section 4.4, the price of the Norwegian GOs in 2018 was 1.65 EUR/MWh. The price for May, 32.98 EUR/MWh, is therefore added with the GO, with a result of 34.63 EUR/MWh. It has been used a conversion value of 9.58 NOK/EUR, extracted 23.04.2019. The price is multiplied with the daily energy consumption, E_{demand}, and thereafter the days within the respective month. This results in an electricity cost per month. To determine the savings of using a lower consumption value, the difference in electricity cost for a specific month is calculated with the respective values for E_{demand} for each scenario.

$$C_{electricity} = Price\,per\,month \cdot E_{demand} \cdot Days\,in\,month \tag{5.4}$$

Savings based on the network tariff

The network tariff is based on the price Hafslund provides for their company customers. For this calculation it is assumed that the depot will be connected to low voltage. Both the values for energy and power segment are dependent on the summer and winter months. The fixed segment is not included as this does not change with the power consumption. The values used in the calculation are given in Table D.1 in Appendix D, where the number of months associated to each segment is given. The calculation of the costs from the power segments is based on Equation 5.5. The costs are determined by multiplying the maximum power consumption with price per kW for the respective month. For the comparison of the worst-case scenarios and the best-case versus worst-case, the number of months is equal to one and the price is respectively 23 NOK/kW and 150 NOK/kW, corresponding to the months of May and December. For the savings of the stationary battery, the costs are determined for an entire year, thus summing the power segments associated to the three seasons; winter 1, winter 2 and summer. The savings for both analyses are calculated from the difference in maximum power consumption.

$$C_{power,monthly} = Number\ of\ months \cdot C_{power} \cdot P_{max} \tag{5.5}$$

In order to calculate the costs from the energy segments, Equation 5.6 is used. As E_{demand} is the energy consumption for each day, the parameter is multiplied with days and price for the associated month. As this segment only applies for the analysis of the worst-case versus the best-case, the savings are calculated from the difference in daily energy consumption. The energy segment price for the month of May is 0.039 NOK/kWh. The total savings when using the best versus worst-case scenario are calculated by summing the savings from the network tariff and the electricity cost for May.

$$C_{energy,monthly} = E_{demand} \cdot Days\ in\ month \cdot C_{energy} \tag{5.6}$$

5.3 Results

This section covers the results produced in the case study, where the purpose has been to optimise the operation of the depot. Three different scenarios are first presented, where the productivity of the bus fleet is calculated for the most optimal scenario. The best-case scenario is presented where the overall energy consumption of the buses is considerably lower. For the stationary battery, capacity and profitability for different amount of power shaved, is illustrated. Finally, a simplified calculation of the carbon footprint of the buses is presented.

The battery capacities for solo and articulated buses are 320 kWh and 170 kWh, respectively. The SoC limits are 20 % and 100 %, meaning only 80 % of the battery capacity is utilised. The solo buses are slow charged with a power of 80 kW and the articulated buses are fast charged with a power of 450 kW.

5.3.1 Simulation of the worst-case scenario

The simulation of the worst-case scenario is based on a relatively high energy consumption of the buses. For the solo and articulated buses, the consumption values are 2.03 kWh/km and 3 kWh/km. The simulation is executed with two charging methods; charging on arrival and smart charging. For charging on arrival, the buses charge immediately when arriving the depot, meaning unlimited active chargers available. With smart charging, a queuing system is required, as the number of simultaneously charging buses is limited. Two prioritisation systems for the queue are evaluated, in order to determine the most optimal solution. This involves a capacity-based and a time-based queuing system. Based on the charging methods and the prioritisation systems, three scenarios are evaluated.

In this section, a load profile for the depot during 24 hours for the three different scenarios is presented. The key numbers for each scenario are further summarised. Finally, the number of available buses at the depot is illustrated, in order to evaluate the sensitivity of the depot.

Scenario 1: charging on arrival
Figure 5.7 illustrates the load profile for the depot, where the buses begin the charging procedure as soon as they arrive at the depot. This simulation results in a bus fleet of 73 buses, distributed as 48 solo buses and 25 articulated buses. Maximum number of chargers in use simultaneously is 5 fast chargers and 22 slow chargers. The profile of the load consists of high and narrow power peaks, where the highest peak is at 3.32 MW.

The tendency of the load profile is closely related to the departure frequency and the capacity of the buses. As departure frequency decreases after the morning and afternoon rush hours, some buses drive back to the depot as it is no use for them at the lines. This is illustrated by the increased load between 8:00 a.m. and 9:00 a.m. and around 6:00 p.m. The increase of slow charging power around 2:00 p.m. indicates that several solo buses are sent back to the depot for charging due to low battery capacity. As the articulated buses have a shorter range than the solo buses, they have to charge more often. This is illustrated by the frequent peaks during the day. In addition, articulated buses use a charging power of 450 kW instead of 80 kW, resulting in power peaks that are more sensitive to their charging patterns.

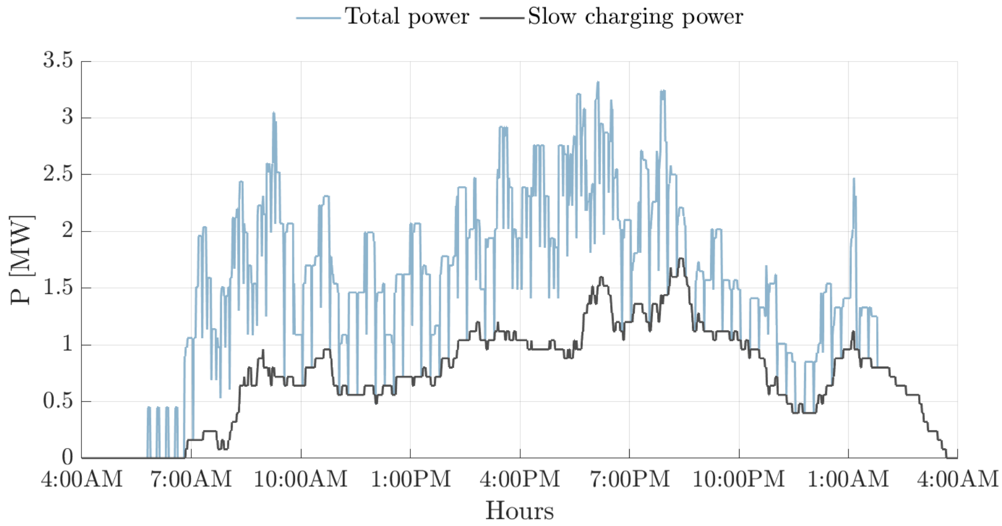

Figure 5.7: *Load profile for the depot of the worst-case scenario with charging on arrival. The total power is equivalent with the sum of slow and fast chargers.*

The first four minor peaks are due to the extra departures implemented on one of the lines in the morning hours. The extra departures require four buses, which drives back to the depot after completing their route. The charging time for the buses is short as a result of relatively high SoC on the respective bus batteries. The last increase of total power around 12:00 p.m. is due to the returning buses after the last departures of the day.

Scenario 2: smart charging with time-based queuing system

Figure 5.8 illustrates the load profile for the depot with time-based smart charging. The order of the queue is based on which bus has been waiting the longest at the depot. The highest power peak is 2.31 MW, which is a reduction of 1.01 MW compared to when the buses charged immediately when arriving the depot. Further, the number of active slow and fast chargers has been reduced from 22 to 12 and 5 to 3.

In case of malfunctioning chargers, it is important to evaluate the consequences on the depot operation, later referred to as risk assessment. This is done by evaluating how many additional solo and articulated buses are necessary if the number of active slow and fast chargers is reduced with one unit, from 12 to 11 and 3 to 2. Due to the reduction, several buses will wait for a longer period before charging. This results in a need for additional 1 solo bus and 14 articulated buses in order to maintain the same departure demand.

The load profile is characterised by wide peaks for both the slow and fast charging power. In the interval between 2:30 p.m. and 2:30 a.m., all the active slow chargers are in use. This corresponds to a load of 960 kW. All the fast chargers are frequently in use from approximately 7:00 a.m. to 8:30 p.m. All buses are fully charged at 4:33 a.m.

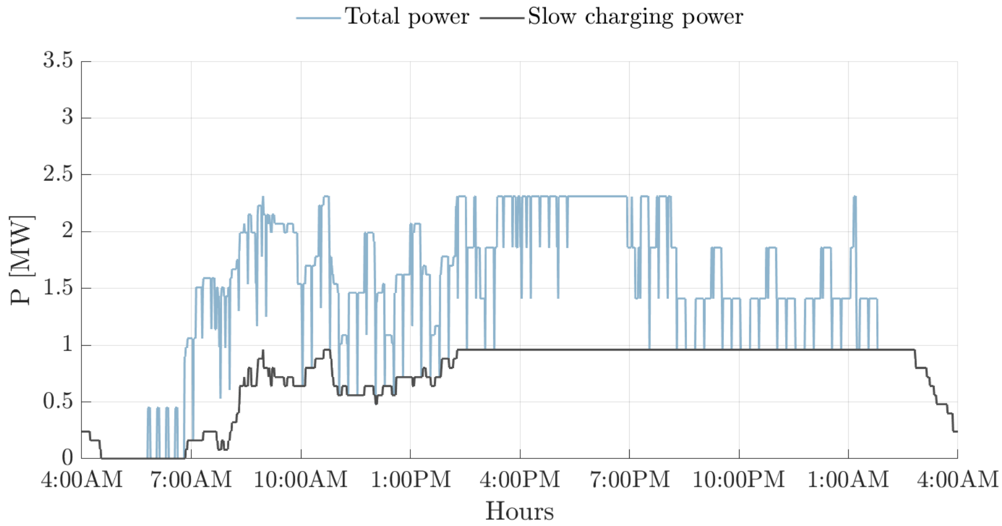

Figure 5.8: *Load profile for the depot with smart charging and a queue system based on time prioritisation. The total power is equivalent with the sum of slow and fast chargers.*

Scenario 3: smart charging with capacity-based queuing system

Figure 5.9 illustrates the load profile for the depot with capacity-based smart charging. The order of the queue is based on which bus has the highest SoC in the battery. This results in a maximum power peak of 2.15 MW, which is a reduction of 160 kW compared to the time-based queuing system. Further, the number of active slow charger has been reduced from 12 to 10, while the the number of active fast chargers remains at 3. The risk assessment of this scenario, results in an increase of 3 solo buses and 14 articulated buses.

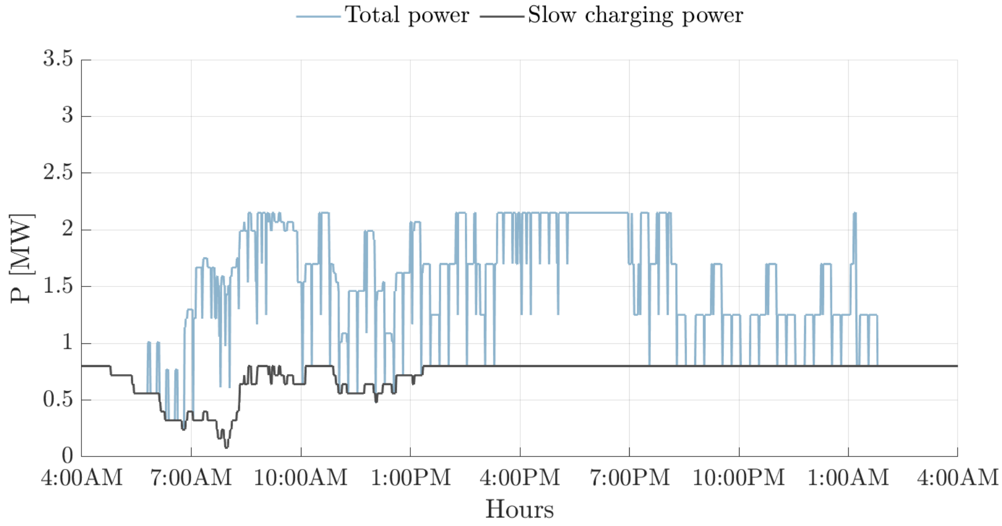

Figure 5.9: *Load profile for the depot with smart charging and a queue system based on capacity prioritisation. The total power is equivalent with the sum of slow and fast chargers.*

For this scenario, an additional active slow charger is made unavailable compared to the scenario with time-based queuing system, resulting in an extended charging time into the next day. Consequently, this scenario will never have periods with zero active chargers. At 4.33 a.m., scenario 2 has zero active chargers in contrast with the 10 slow chargers for scenario 3. Except for this, the charging sequence is approximately equal, both for solo and articulated buses.

Summarise of the scenarios

Table 5.5 summarises key numbers for the three scenarios from the worst-case simulation. It also includes the savings of using smart charging per month in relation to scenario 1. The calculation of the savings is based on the power segment for December, resulting in savings of 151.5 kNOK for scenario 2 and 175.5 kNOK for scenario 3. The approach for these calculations is given in Section 5.2.3. The number of buses in operation is the same for all scenarios. The number of active chargers and the maximum peak value is different for the three scenarios. However, the total amount of energy consumed throughout the day is the same. Scenario 3 has the lowest peak of the three scenarios, with a reduction of 37 % compared to scenario 1. Further results are therefore based on this scenario.

Table 5.5: *Key numbers for the three scenarios from the worst-case simulation. Savings per month in relation to scenario 1 is also included.*

Scenario	Buses in operation	Solo buses	Articulated buses	Active slow chargers	Active fast chargers	Maximum peak	Savings per month
Scenario 1	73	48	25	22	5	3.32 MW	-
Scenario 2	73	48	25	12	3	2.31 MW	151.5 kNOK
Scenario 3	73	48	25	10	3	2.15 MW	175.5 kNOK

Available buses at the depot

Figure 5.10 illustrates the number of fully charged buses in function of time. The demand is higher during rush hours, resulting in fewer buses at the depot. During the rush hours in the afternoon, a critical point occurs where only one fully charged solo bus is available.

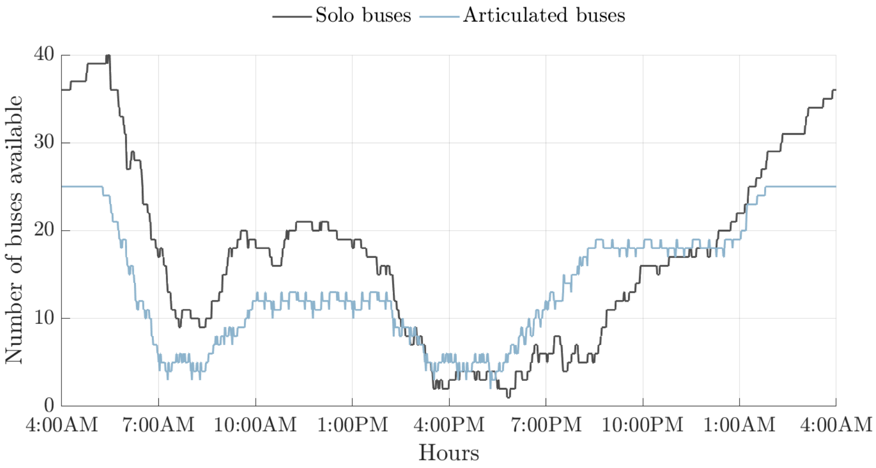

Figure 5.10: *Number of buses available at the depot during 24 hours.*

5.3.2 Evaluation of the productivity of the bus fleet

The productivity is defined as the number of hours the bus is in operation during 24 hours. To evaluate the productivity of the bus fleet, the daily variation of the SoC for the least and most productive solo and articulated buses are presented. A decrease of the SoC indicates driving, while an increase indicates charging. The rate of the decrease depends on the average speed of the line. The figures are developed based on the load profile simulation, where the SoC is limited to 20 and 100 %. This results in a reduced available capacity from 320 kWh to 256 kWh for solo buses and 170 kWh to 136 kWh for articulated buses.

Figure 5.11 illustrates the SoC of the battery in function of time for the most and least productive solo bus. These buses have IDs 28 and 4. The graphs are presented with numbers associated to the respective line the buses are driving.

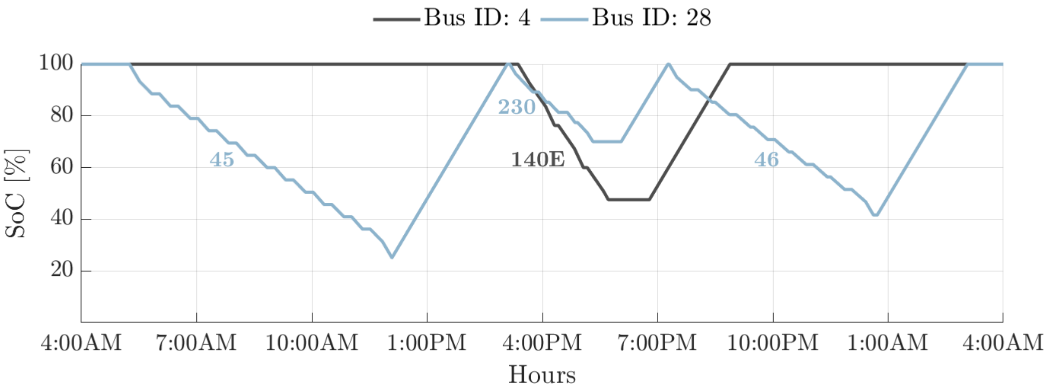

Figure 5.11: *SoC for the most and least productive solo bus. The graphs are presented with numbers associated to the respective line the buses are driving.*

The bus with ID 28 drives three different lines during a day, where the bus is sent back to the depot once due to low capacity. This applies when operating line 45. In this case, a replacement bus must be inserted to maintain the operation, as the charging time from 20-100 % SoC is 3.2 hours. In general, the bus is in operation for maximum seven hours and the minimum waiting time at the depot is three minutes. When the bus operates line 230 and 46, the bus is sent back to the depot due to no or fewer departures. This applies also for the bus with ID 4, operating line 140E.

Figure 5.12 illustrates the SoC for the most and least productive articulated buses during a day. The bus with ID 102 is the most productive articulated bus and the bus with ID 110 is the least productive bus. The capacity of the articulated buses are 170 kWh, 150 kWh less than for the solo buses.

As the battery capacity is smaller compared to solo buses, they are charged more frequently. The most productive bus drives 10 times back and forth to the depot during a day, corresponding to an energy amount of 133 kWh. It takes approximately 20 minutes to charge the bus from 20-100 % SoC. Due to frequent departures, an additional bus must still be inserted to maintain the operation. After being fully charged, the bus waits at a minimum of one minute to a maximum of 23 minutes before it departures.

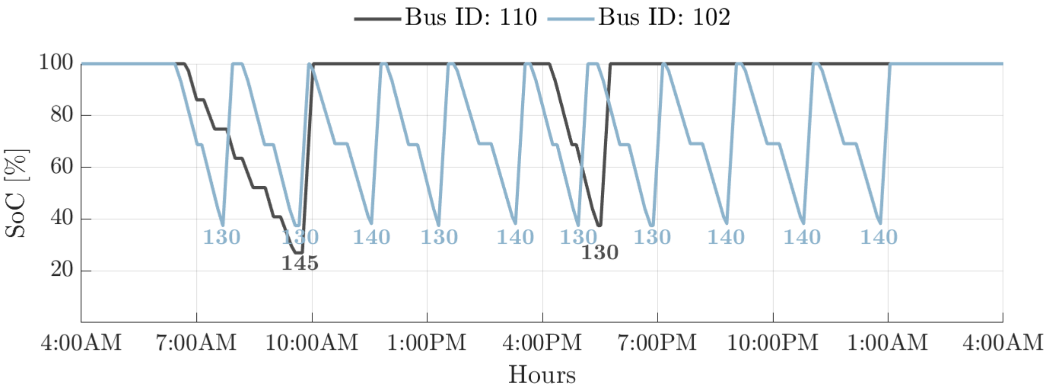

Figure 5.12: *SoC for the most and least productive articulated bus. The graphs are presented with numbers associated to the respective line the buses are driving.*

Line 130 and 140 have both long routes and the buses operating these lines have to be recharged after driving only one round trip, corresponding to an operation time of 60-70 minutes. Line 145 has a shorter route, resulting in a longer operation time for each bus without recharging. The bus with ID 110 is in operation on this line for 156 minutes.

The average, minimum and maximum productivity, in addition to percentage average waiting time, is given in Table 5.6. The productivity and percentage waiting time are calculated over a time interval of 24 hours. The difference between the minimum and maximum productivity for both bus types is high, resulting in an average productivity of 35 % for solo buses and 37 % for articulated buses. This corresponds to an operation time of 8.4 and 8.9 hours.

Table 5.6: *An overview of how productive the buses associated to Furubakken are through 24 hours. The productivity of the most and least productive bus is given, in addition to the average productivity and percentage waiting time of the whole bus fleet.*

Bus type	Average productivity	Average waiting time	Minimum productivity	Maximum productivity
	%	%	%	%
Solo	35	46	8.5	57
Articulated	37	57	16	57

Conventional diesel bus fleet

In order to assess the number of diesel buses needed to operate the line associated Furubakken, the load profile simulation is executed with a range, fuel consumption and a refuelling time that corresponds to a diesel bus. The fuel consumption and range used is extracted from Table 4.1 in Section 1.3, where the consumption is 5 kWh/km and the range is 600 km. The refuelling time is fixed to 15 minutes. The simulation results in a total amount of 53 diesel buses. This means that an electric bus fleet requires an increase of 38 % buses compared to a diesel bus fleet. This calculation assumes that all diesel buses are of the same type.

5.3.3 Simulation of the best-case scenario

The simulation of the best-case scenario is based on smart charging with a capacity-based queuing system, as this resulted in the most optimal result in the worst-case simulation. For this scenario, solo and articulated buses have energy consumption values of 1.28 kWh/km and 1.89 kWh/km. The load profile for the depot throughout a day for the best-case scenario is presented in Figure 5.13. The load profiles for the worst- and best-case scenario are also given in Appendix E for better visualisation of the similarities.

A lower consumption value for the best-case scenario results in a longer driving range for each bus, thus reducing the need for bus replacements throughout the day. The consequence is illustrated in the figure by reduced need for charging earlier at the day. A comparison of Figure 5.9 and 5.13 clarifies the difference in power consumption, especially between 10:15 a.m. and 4:30 p.m. For this period, the worst-case scenario uses almost all its 10 slow chargers, while the best-case scenario only occupies 0-6 of the slow chargers. This corresponds to a power consumption difference of 320-800 kW, only with respect to the slow chargers. The total consumption for this period, including both slow and fast chargers, is roughly halved compared to the worst-case scenario.

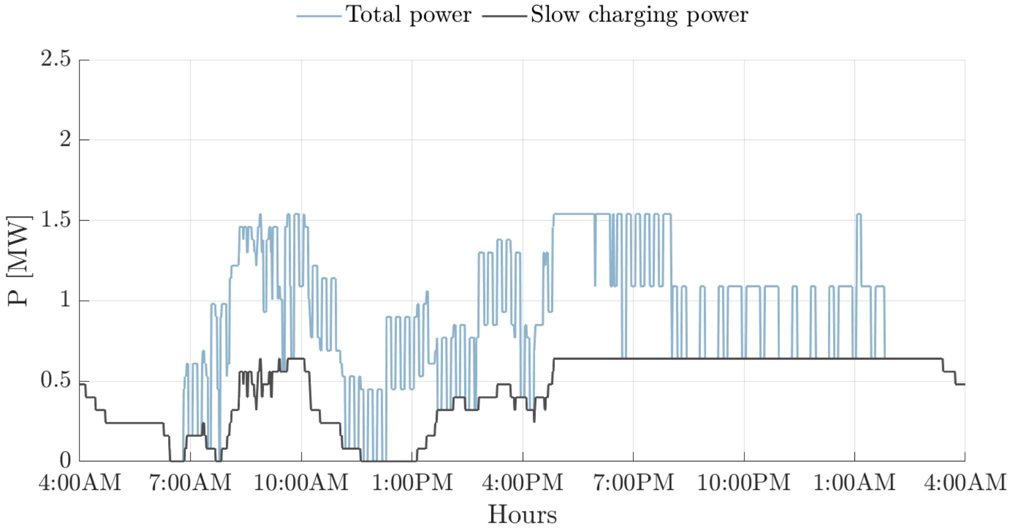

Figure 5.13: *Load profile for the depot with the best-case scenario.*

The results from the simulation of the two scenarios are listed in Table 5.7. As each bus of the best case scenario has a longer driving range, the number of buses in operation is reduced from 73 to 67, a difference of 6 buses. Further, this results in a reduction in the maximum number of slow chargers and fast chargers in operation, from 10 to 8 and 3 to 2. The risk assessment results in an increase of 1 solo bus and 9 articulated buses.

Concerning power peaks, the best-case scenario has a maximum power consumption of 1.54 MW. This corresponds to a reduction of 610 kW from the worst-case scenario, equivalent to two slow chargers and one fast charger. The daily energy consumption for the worst-case scenario is 34.6 MWh against 19.9 MWh for the best-case scenario. This corresponds to a 43 % reduction. An analysis of the savings achieved by using the best-case versus worst-case scenario for the month of May is made using electricity cost, price of the guarantee of origin and network tariff. The approach for the calculation is given in Section 5.2.3. The calculation results in a monthly saving of 182.3 kNOK, where 31.7 kNOK amount to the network tariff and 150.6 kNOK amount to the electricity cost.

Table 5.7: *A comparison of key numbers from the best-case and worst-case scenario.*

Scenario	Buses in operation	Solo buses	Articulated buses	Slow chargers	Fast chargers	Highest peak	Total energy consumption
Worst-case scenario	73	48	25	10	3	2.15 MW	34.6 MWh
Best-case scenario	67	44	23	8	2	1.54 MW	19.9 MWh

5.3.4 Simulation of the stationary battery

Figure 5.14 presents two evaluations done for the simulation of the stationary battery; the battery capacity and the profitability. The blue line illustrates how the battery capacity increases with increasing amount of power shaved from the bus load. For each amount of power shaved, the minimum battery size is used. The calculation includes an available energy of 20-80 % SoC. Similarly, the black line describes how the profitability changes with the amount of power shaved. The end points of the graphs equal an amount of 774 kW power shaved, corresponding to approximately 1.5 articulated buses or 10 solo buses. For this case, the available capacity of the battery is equal to the energy needed to be shaved, meaning the stationary battery only needs one charging cycle per day.

By studying the black curve, it is evident that the use of a stationary battery is never profitable for this depot, regardless of the amount of power shaved or the size of the battery. In the interval of 0-470 kW power shaved, both the profitability and battery capacity curve have a second order polynomial behaviour. This involves that the battery size constantly increases in line with increasing power shaved, and hence also the deficit.

When reaching an amount of power shaved of 470 kW, the slope of the curves increases significantly. This can be explained by studying the load profile in Figure 5.9. When shaving 470 kW, the maximum load power is 1.68 MW. This requires a substantially larger battery size, as the potential available energy between the peaks becomes less than the energy shaved. This means that the battery cannot charge or utilise the energy between the peaks in the same extent when increasing the amount of power shaved. This is due to the increased amount of energy needed when shaving at levels higher than 450 kW, hence the wider peaks occurring at a load level below 1.70 MW. The reason for the linear development of the profitability and battery capacity curve beyond 470 kW shaved, is that the possibility for charging between the peaks is non-existent, thus the size of the battery increases with a constant value.

For a desired shaving amount of for example 250 kW, meaning a power reduction from 2,15 MW to 1,90 MW, a battery capacity of 1,263 kWh is needed. This results in a deficit of 7.49 MNOK, with a battery cost of 8.65 MNOK. For this scenario to be profitable, a battery of this size had to cost 1.16 MNOK on the market today. The approach for the calculation is given in Section 5.2.3.

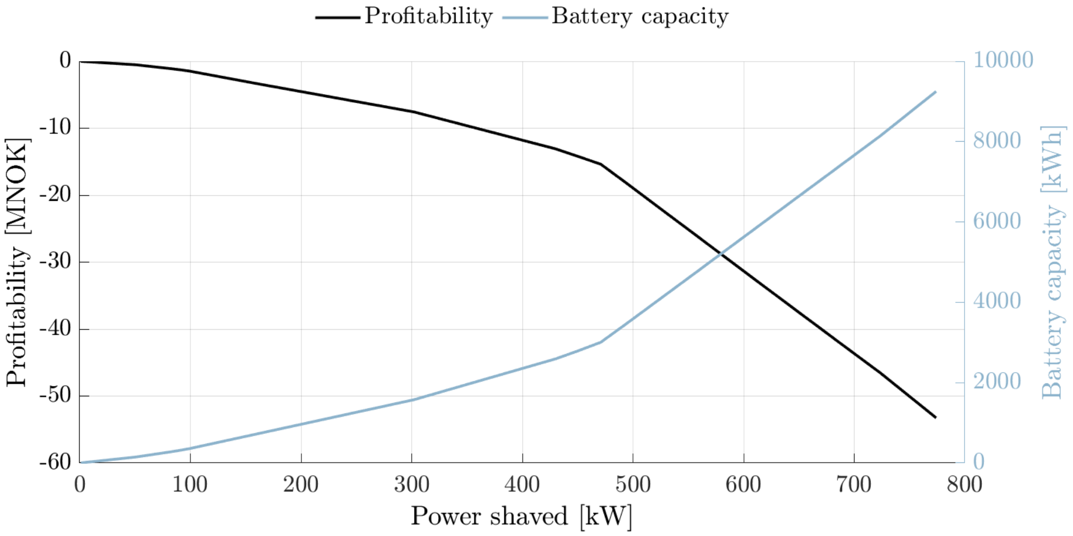

Figure 5.14: *The profitability of the battery and the minimum needed battery size in correlation to how much power is shaved.*

5.3.5 A carbon footprint analysis

Figure 5.15 illustrates the carbon footprint for electric and diesel buses. The frame of the analysis is six years, due to the lifetime of a battery. The analysis only includes emissions related to production of the battery and the well-to-wheel (WTW) process. Emissions related to vehicle production and maintenance of the buses are not included as this is assumed to be approximately the same. This assumption is based on a study of the life cycle of diesel and electric public buses written by Cooney (2013 p.691-695).[106]

The calculation uses an emission of 250 CO_2/kWh for the battery production extracted from Section 4.4.2. The energy consumption used is equal to the worst-case scenario for solo buses. The emissions related to the electricity production are based on a Nordic Mix (2017). Finally, the WTW emissions for a diesel bus is extracted from Table 4.2. As it is expected an increase of buses when electrifying the bus fleet, an increase of 38 % is included based on the result given in Section 5.3.2.

A solo bus at Furubakken depot has an average driving distance of 48,200 kilometre per year. The figure illustrates that electric and diesel buses will break even at 119,500 km, corresponding to approximately two years and three quarters. The factor between the CO_2-emissions for diesel and electric buses is 1.8 after six years.

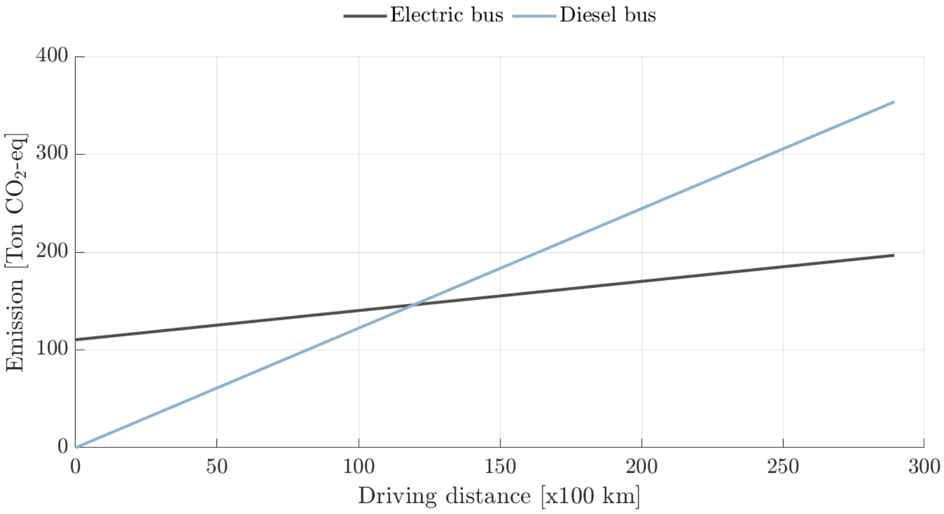

Figure 5.15: *A simplified emission analysis of electric and diesel buses. The analysis includes only emissions related to production of battery and WTW. In addition, an increase of additional buses due to electrification is included.*

6 Discussion

This section discusses the findings of the simulation results. It also investigates some of the aspects and potential regarding demand-side management. Challenges a public transport operator might face due to the electrification of the bus fleet is discussed. This includes both challenges related to the operation and regarding the business models, roles and responsibility. Further, an evaluation of the case study assumptions is given and followed by a recommendation for further work regarding overnight charging and electrification of bus fleets.

6.1 Depot operation

This section discusses the aspect of the depot operation. The use of smart charging i order to optimise the operation by making it more efficient and reducing the related costs is evaluated. Even though Furubakken depot is connected to a stiff grid, it is discussed how the charging process can be regulated for depots connected to weaker grids. The use of a stationary battery, both for Furubakken depot, but also for a general depot, is finally discussed. This assessment includes both economic and network purposes.

6.1.1 Smart charging

Smart charging is a system used to optimise the charging process for different purposes by using communication between the chargers and the buses. In this thesis, the purpose has been to reduce the power peaks of the depot by limiting the number of active chargers. This results in reduced costs due to the network tariff and decreased need for charging infrastructure. The system can be more advanced and prioritised using other areas of focus, to any PTOs desires.

Effects of reducing number of simultaneously active chargers
For Furubakken depot, smart charging contributed to reducing the power peaks from 3.32 MW to 2.15 MW. This resulted in a monthly saving of 175.5 kNOK, when only accounting the network tariff. The resulting power peaks for the three scenarios are all below 4 MW, which is the available network capacity at Furubakken depot.

The system predicts the number of chargers that must be active at once without implementing additional buses. In order to predict this, it is necessary to have real-time monitoring and a system that is constantly evaluating the driving schedule of the buses. If a bus has a substantially increase in energy consumption, it would need to drive back to the depot earlier than expected. The control system must then evaluate if it is necessary to activate an additional charger, thus increasing the highest power peak for the month. This would result in an increased cost due to the network tariff.

Queuing systems

As a part of the smart charging system, two different queuing systems were tested. From the results, it is given that a capacity prioritisation reduces the need for simultaneously active chargers, hence lowering the power peaks and increasing the savings. A disadvantage of using capacity- versus time-based prioritisation is that some buses may wait longer than others. In order to prevent that some buses become more unproductive, a combination of the two queuing systems can be utilised.

Charging infrastructure

The simulation of the worst-case scenario with capacity-based prioritisation results in a total of 13 active chargers, however it should be installed chargers beyond this number. This is due to two reasons: reliability and usability. According to the results, a 24 hours long down-time on one of the fast chargers will lead to 14 additional articulated buses in operation per day. This emphasises the reliability and the importance of having additional chargers installed at the depot. The usability is improved by having several installed chargers than active chargers, as the need for moving the buses back and forth from the charging points decreases. A PTO should consider whether it is most profitable to have drivers moving the buses or installing additional chargers. A future solution could be to have autonomous buses driving to the charging points or having movable chargers between the buses.

A key factor when choosing an optimal number of chargers installed, may be experiences. The possibility for down-time periods of the chargers may depend on area specific factors, such as weather, usage patterns and quality. It may therefore be important to monitor current depots already in operation to determine the impact of different factors.

Preserving the lifespan of the buses

It may be advantageous to regulate the charging process with the intention of better preserving the lifespan of the buses. One alternative can be to activate an additional slow charger at night, with the intention of replacing a fast charger. As there are only few or no departures at night, it is not necessary to charge the buses quickly, and slow charging can then be preferable. Likewise, the buses can be charged with reduced power during periods where the buses are not needed immediately. For instance, two buses can be charged simultaneously from one slow charger, thus doubling the charging time of each bus.

Another method for preserving the lifespan is by predicting the energy usage for a daily route. If there is a bus scheduled for a short trip, thus needing only a portion of its full battery capacity, it may not be necessary to charge the battery to 100 % SoC. By estimating the needed capacity, the bus can be charged to a sufficient SoC. This will, in addition, result in a more optimised depot, as chargers will become vacant earlier, thus reducing the length of the queue.

6.1.2 Charge regulations for depots with weaker grids

In course of the electrification of the transport sector, there will be a massive expansion of charging points, thus resulting in a higher demand on the grid. This can particularly be an issue in places where the grid is weak. Even though Furubakken depot is connected to a stiff grid, it is important to emphasise that other depots may be more vulnerable against changes in the load. It is not a matter of course that all bus depots will be located nearby a substation, and with longer distance, the voltage drop, as a result of power in- and output, will increase. For a bus depot with frequently in- and outputs of chargers, it is especially important to pay attention to the voltage variations.

For depots that are connected to grids with a voltage level of 11 kV, a maximum of 5 % stationary voltage drop is permitted. In order to remain within this variation limit, the charging process at some bus depots may need to be adjusted. Connecting several chargers at once, especially fast chargers, can cause large voltage drops in weak grids. It can therefore be necessary to regulate the connection of the chargers, so that each charger is activated with a certain time interval. Accordingly, the magnitude of the voltage drop can be kept within the 5 % limit. Another approach can also be to increase the effect gradually when activating the chargers. Consequently, an instantaneous power increase of e.g. 450 kW due to the connection of a fast charger, would be prevented. If this was applied, the time interval between activating the chargers would no longer be that significant.

Expanding the network or using a stationary battery are other solutions that can be implemented in order to remain good delivery quality for such depots. The most optimal solution depends on the depot, and a socio-economic analysis should therefore be made for each one. A stationary battery can be more profitable, as major expansions can result in an increased network tariff for related customers, as well as ripple effects for the society. Nevertheless, the purchase and installation price for the battery must be considerably lower than the price for expansion. In addition, an economic analysis must take into account that the lifetime of a new grid is considerably longer than for a battery.

6.1.3 Stationary battery

In this thesis, the stationary battery is only used for the purpose of reducing costs for the PTO, as grid sensitivity is not an issue. From the results of the simulation it is evident that a stationary battery is unsuitable for peak shaving of a load profile similar to the one Furubakken depot generates. This can be explained by studying the operation of the depot. For the respective bus type, all buses within the classification have equal capacity. In addition, many buses start their day at approximately the same time. Consequently, the need for charging for each bus often occurs in the same period as other buses, thus resulting in wider peaks. The fact that the number of chargers in addition is limited, amplifies this effect.

For a stationary battery to be profitable for peak shaving of a bus depot, narrower peaks, higher power tariff and/or cheaper engineering costs are required. As wide peaks are typical for a bus depot, a large battery is often required either way. To avoid deficits, it is therefore essential that the battery technology becomes cheaper. If the price trend for batteries continues with the same decline as in recent years, a stationary battery could be profitable for the purpose of peak shaving in the future.

A stationary battery could also have several other utilisation areas that would benefit for a depot. This can involve both economic and network purposes. These applications are not assessed in this thesis, mainly because they would require cheaper battery systems. Depots that are located on places with a weaker grid can however benefit from using a stationary battery in order to avoid network expansion.

Economic potential
In combination with peak shaving, the stationary battery could be used for purposes that would increase the overall profitability. If there were to occur unexpected events, such as delays, there may be a need for an extra active charger. To prevent a peak of additionally 450 kW due to an extra fast charger, the stationary battery could be used to cover the demand. It could thus prevent the extra cost caused by the power tariff.

Peak shaving with an on-site stationary package has its cost solely related to purchasing the system. The deficit given in Figure 5.14 could have been avoided by using the battery pack of the buses as a storage system. As given from the productivity value for the least productive buses in Table 5.6, not all buses are fully utilised anyway. This application could therefore be especially suitable for bus depots.

For days that require a lower operational window for the stationary battery, it could be profitable to use the battery for energy trading. It would then buy power when the electricity price is low and sell when the price is high in the spot market. Another application for the stationary battery could be to shift the load of the depot from periods where the electricity prices are high, to periods with low prices. The potential for these applications would improve with cheaper battery technology or an increasing proportion of non-dispatchable power in the Nordic mix due to greater variations in the electricity price.

Network potential
For depots that are connected to a weaker grid than Furubakken, a stationary battery could contribute to increased delivery quality through regulation of active and reactive power. This could, however, have a negative impact on the battery lifetime if the battery was always to be on standby. A possible approach is to only assist with reactive power during high load hours and to use the battery to other applications in the remaining time.

To maintain high delivery reliability, it is important to operate the grid according to the N-1 principle. A stationary battery could have been used as a backup component to increase the degree of redundancy. This would not have been necessary at Furubakken depot as the degree of redundancy is relatively high, however it could be applicable for other depots. A disadvantage with this application is that the battery would always have to be fully charged, resulting in significantly degradation. In addition, the batteries of today are too expensive compared to other technologies, such as diesel generators, for it to be beneficial to use for this purpose.

6.2 Productivity of the bus fleet

In this thesis, the productivity of a bus is defined as the number of hours it is in operation during 24 hours. This parameter is important to evaluate when electrifying a bus fleet. One of the greatest impacts of the electrification is the increasing proportion of buses needed in operation. This is due to the considerably shorter range of an electric bus, resulting in the need for additional buses in operation during charging. As the total driving distance for each line is the same regardless of the bus type, each electric bus will have a shorter operating time. This is because the same total kilometre distance is divided on a greater amount of number of buses. As the procurement cost for an electric bus is approximately twice as high compared to a conventional bus, it is important that the public transport operator (PTO) designs the depot with the purpose of increasing the productivity of the buses.

The average productivity for solo and articulated buses associated to Furubakken depot is calculated to 35 % and 37 %, respectively. It is important to emphasise that the calculations include charging time, as well as periods where there are no or few departures, such as night-time, meaning the productivity can never reach 100 %. Due to Ruter's tender round, information about the productivity of today's buses is not available. It is therefore difficult to discuss the quantity of the values. However, it is evident that the average productivity can be increased. This section addresses how energy consumption affects the productivity of the bus, as well as factors that can contribute to increasing the operation time for each bus.

6.2.1 The effect of varying consumption

The productivity of the bus fleet is directly related to the consequence of varying consumption. In order to clarify the effect of these variations, this thesis addresses two extremes of what the buses can consume. This is given by the best- and worst-case scenarios. The best-case scenario is based on consumption values provided by the manufacturer, while factors such as demanding topography and temperature, inefficient driving style and rush is included in the worst-case scenario. In this thesis, the depot is designed based on the worst-case scenario, however many buses are likely to operate between the extremes. It is therefore important to emphasise that neither of the scenarios are representative for every day within a year.

As given in Table 5.7, an operation equal to the best-case scenario results in a total reduction of six buses. It is therefore essential that the public transport operator (PTO) can predict the energy consumption to a certain extent when designing the depot. The PTO should, among other things, determine how the topography for each line will affect the consumption. Based on information given by Ruter, the energy consumption can vary with about 15 % depending on the type of topography. If some of the lines have undemanding topography, the associated buses will have a longer driving range then what is assumed for the worst-case scenario. The number of buses for these lines can therefore be reduced, resulting in less investment costs.

The PTO can also predict the variations in consumption from day to day and season to season, in order to reduce the number of buses in operation. A possible approach can be to monitor data for buses in operation, in order to determine the impact of the different factors. This thesis simulates the load profile on a regular weekday. The consumption on weekends will be significantly reduced as there are fewer departures and less rush for these days. Similarly, the demand in periods with mild temperatures is lower. If the PTO can predict the impact of rush hour and temperature conditions, the number of buses in operation for these periods can be reduced significantly. The PTO can then evaluate if the buses should be used for other purposes, however the profitability must be assessed against the degradation of the bus battery.

Another factor that affects the consumption value is the driving style of the driver. According to tests performed by the transport company Movia, inefficient driving style can increase the energy consumption with 15 %. For the worst-case scenario, this is included. However, with coursing of the bus drivers and guiding software, the driving style becomes more efficient. With time, the PTO can expect a general lower consumption for all the lines, thus a reduced need for buses in operation.

It is important to emphasise that all the factors presented also affects the consumption of a diesel bus, however the impacts may be more critical for an electric bus. This is directly related to the range of the bus, and thus also the need for charging. The operation of an electric bus does therefore require considerably more planning. In addition, it is essential for the lifetime of the bus battery to be able to anticipate these variations. Buses taken out of operation due to reduced demand, should be charged to a lower SoC, as it is not optimal for buses to be fully charged over longer periods. Another option is to rotate the buses between routes according to utilisation patterns. This would be beneficial as some lines may demand more charging cycles or a wider operational window than others. In this way, it is possible to obtain similar battery performance of the buses in order to increase the reliability.

6.2.2 Evaluating overnight charging

In this thesis, a battery capacity of 320 kWh and 170 kWh is used for the respective solo and articulated buses. The charging power is fixed based on these capacities, with values of 80 kW and 450 kW. The decision was based on testing of different specifications, where a combination of fast and slow charging proved to be favourable with regard to the number of buses in operation.

Based on the results given in Figure 5.11 and 5.12, it can be argued that the battery capacities used in this thesis are not the most practical for all lines associated to Furubakken depot. For the articulated buses, some only drive one round trip before they need to charge due to the low battery capacity. The buses use a considerable amount of time and energy to drive back and forth between the depot and the end stops, meaning the amount used to transport the passengers reduces. In order to reduce the amount of wasted energy, articulated buses could either have a higher battery capacity or use opportunity charging.

Lines, such as 130 and 140, are examples of where opportunity charging could be favourable in order to reduce the amount of wasted energy. These lines are characterised by frequent departures, resulting in a high daily driving distance. This is given in Table B.1 in Appendix B, with distances of 2,390 km and 2,741 km per day. Lines with short route distance and frequent departures during a day is important for opportunity charging to be applicable. This is because the pantographs require frequent charging in order to be profitable.

In some cases, the use of opportunity charging can be a difficult matter. Cost, political and local resistance are factors that must be considered when evaluating opportunity charging. In addition, the route schedule must be adjusted to account for the regulation time for charging. The high power related to opportunity charging can also cause large voltage variations as a result of in- and outputs, which can be problematic, especially for weaker grids. A public transport operator must assess the significance of these factors and evaluate if the profit of using opportunity charging compensates for the disadvantages.

6.2.3 Reduced benefits of unproductive electric buses

Low productivity for some of the buses is a consequence of electrifying an entire bus fleet. Based on the results given in Table 5.6, the least productive solo and articulated bus are in operation only 8.5 % and 16 % during 24 hours. A public transport operator (PTO) must evaluate if it is profitable and environmentally friendly to have electric buses with a productivity level similar to the results.

The simulation of a full diesel bus fleet at Furubakken depot resulted in 53 buses in total. When comparing this value with the worst-case scenario of the electric bus fleet, the electrification resulted in an increase of 38 % buses in total. This increase is significantly higher than the expected 12 % increase given from Ruter. The high increase of electric buses will result in a significantly higher procurement cost as they are approximately twice as costly compared to conventional diesel buses. As Figure 4.3 only includes an increase of 12 %, this thesis expects that overnight buses will be competitive with HVO buses later than 2025.

The environmental benefits of implementing electric buses can be reduced as a result of low productivity. This is due to fact that the number of kilometres an electric bus drives per year decides when it breaks even with a diesel bus. Based on the result given in Figure 5.15, an electric bus must drive more than 119,500 km during six years. The result includes an increase in number of buses of 38 % due to electrification. Due to low productivity and the resulting increase in number of buses, the carbon footprint of an electric bus could be higher than a diesel bus after six years.

In the tender round of route area 1 in Oslo and Akershus, electric buses, together with hydrogen buses, receive the highest score in the evaluation of environmental properties of the fuel. The price of the operation is, however, emphasised higher than the environmental properties of the fuel. It is therefore possible that the contract is allocated to the PTO offering the best price, and not necessarily the PTO offering the highest proportion of electric/hydrogen buses. As the environmental benefit of using an unproductive electric bus is reduced, in addition to that electric buses are expensive, a suggestion could be to replace these buses with biodiesel buses.

6.3 Business models, roles and responsibilities

When electrifying the transport sector, new challenges arises regarding the business models, roles and responsibility, particularly the design and ownership of the charging infrastructure. The market for electrical buses in Norway is relatively immature, and a standard for distribution is therefore not established. It is expected an increase of electrical buses in the coming years. With an absent solution for who is to own and build the charging infrastructure, unnecessary costs and sub-optimal solutions may occur.

In Oslo and Akershus, the public transport operators (PTOs) buy and operate the infrastructure. This can result in an issue where the PTOs establish systems that are beneficial for their contract period. Consequently, this can cause the infrastructure to be depreciated after seven to eight years, corresponding to a normal tender round. In order to prevent this, a possible solution would be to exclude the charging infrastructure from the tender. The PTOs would then only compete about the bus operation. This approach would, however, require a well-defined interface between the PTO, as a user, and the owner of the infrastructure. In this way, it is clear who is responsible for installing the chargers before commissioning and who is held economical accountable in the case of malfunctions.

If the infrastructure is excluded, it could be beneficial that the public transport authority (PTA) organises the distribution of opportunity and overnight buses, as well as the location of the charging infrastructure. In this way, pantographs can be placed strategically with the intention of creating junctions where several buses could fast charge. Consequently, several lines can share the same charging infrastructure, resulting in reduced number of places with pantographs and thus preventing the same extent of local resistance. This strategy would, however, require alteration and optimisation of the existing route schedule.

Ownership of the charging infrastructure is a much-debated topic. PTOs and PTAs may be unsuited due to insufficient knowledge about the charging infrastructure. In order to ensure long-term technical architecture in a greater extent, a professional operator with knowledge and core competence regarding charging infrastructure can contribute. Such operators could be subsidiaries of energy companies. These operators should cooperate closely with the PTA and PTO for designing a long-term and reliable system.

For the charging infrastructure to be used in more than one contract period, it is important that the external operator uses standardised technologies for both buses and pantographs. This includes a connector between the buses and the chargers, in addition to electrical parameters. As a result, the chargers can be used independently of the supplier.

6.4 Evaluation of the case study assumptions

In this thesis, some simplifications have been made in order to make the simulations and calculations feasible within the given time frame. Some parameters vary hourly and from day to day, such as electricity price, delays and driving time between end stops and depot, however it would be too complex to include these variations. Other parameters, such as route distance, are difficult to determine exactly as they are not publicly available, while power losses and margin on waiting time are not included. It is also used one-minute resolution in the simulation instead of shorter intervals. The consequences of these simplifications are presented in this section.

Power losses

Power losses related to the energy system at the depot, has not been considered in the calculation. The main losses are associated with components such as converters, transformers, chargers and the stationary battery. In addition, some losses will occur in the cables, where the degree depends on the length. Including these losses would have resulted in a higher demand of energy, as well as a higher maximum peak compared to the results given in the case study.

Distance parameter

Google Maps was used to find distance values for each route and between end stops and the depot. It was desirable to receive the information directly from Ruter, however, due to the tender round, this was restricted information. To get as realistic values as possible, every bus stop along the routes were plotted in Google Maps. The deviations from the actual values would most likely have non or very little impact on the simulation results.

Time parameter

The driving time between the end stops on each route was already available information that could be extracted from the timetables on Ruter's web pages. However, expected time between the depot and the end stops were extracted from Google Maps. These values can differ from the real values, due to rush and other factors. Similar with distance parameters, these deviations would most likely have none or very little impact.

Resolution of the simulation

The simulation resolution is at one-minute intervals, meaning that the data updates for each minute. When charging power is applied or removed instantaneously, the load in the one-minute interval increases or decreases linearly. Consequently, the graph less accurately indicates that the chargers are connected with varying power.

Electricity price

When calculating the savings at the depot using the best- versus worst-case scenario, the electricity cost was based on monthly values. The variations in electricity price during a day and from day to day is therefore not considered. Consequently, the calculated savings are less representative.

When calculating the savings of using smart charging and the profitability of using a stationary battery, the electricity cost was not included. This is because all the scenarios of worst-case have the same daily energy consumption. This also applies for the use of the stationary battery, as the load is only being shifted. The electricity cost will in most cases be highest for scenario 1, as the largest amount of energy is centred around the times where the electricity price usually is highest. Due to the levelled energy consumption for scenario 2 and 3, it is likely that the deviations are less significant. If electricity cost had been included in the calculation of the stationary battery, the deficit could have been reduced. The battery charges when the demand at the depot is low and discharges when the demand is high. As the demand at the depot is highest during the period where the electricity price is also high, a stationary battery would have contributed to lower electricity cost.

Margin on waiting time

It was decided to not include a margin on minimum waiting time at the depot, as optimising the route schedule for each bus has not been in focus. Buses at the depot selected for the different routes are arbitrary, regardless of the waiting time. The only criteria is that the bus has to be fully charged. A consequence is that some buses take departures only one minute after being fully charged. This applies, for example, for bus ID 102, as shown in Figure 5.12. In practice, this can be difficult to maintain due to delays and other factors. However, fully charged buses are available at the depot throughout the day and another bus can therefore take the route instead. The impact on the operation of the depot would therefore have been minimal.

A margin on how long a bus should minimum wait on the end stops before it takes a departure, is not included in the simulation. In case of delays, the bus may not make the scheduled departure. However, most of the lines have been arranged in a way where the arrival at the end stop is scheduled few minutes before the next departure. For lines that this is not accounted for, it is assumed that the route schedule is designed in a way where delays have limited impact on the operation.

Deviations due to delays
The simulation is subject to variations in consumption, however, the consequences of possible delays are not included. Due to rush or unforeseen events, delays may cause significant changes in the load profile. This can include a shifted load profile, with possible impacts on the next day. Another impact could be the need for an additional bus in operation or activation of an additional charger during the day.

6.5 Further work

To improve the results of the case study of Furubakken depot, some new and current areas of focus should be further investigated. These areas are not covered in this thesis due to lack of information or time. The operation of the depot and the buses could be optimised by considering other alternatives for bus types and charging methods. It would also be interesting to investigate the possibility of implementing a photovoltaic system, charging of the service fleet and the use of buses for grid support.

Alternative operation methods
This thesis only evaluates overnight charging, where also fast charging of the buses is done using pantographs at the depot. In a further assessment, it would have been desirable to implement opportunity charging as a part of the simulation. This could have contributed to optimising the bus operation, regarding productivity and the overall energy system.

For the method of overnight charging, it could be beneficial for the public transport operator (PTO) to consider other options for bus battery specifications and charging methods. The articulated bus chosen in this thesis has a relatively low capacity. If all buses are to be charged at the depot, a bus with higher capacity, thus longer driving range, could be beneficial to use instead. Another evaluation for the PTOs is whether to replace the pantographs with plug-in chargers. This may be practical as the plug-in technology is less expensive. However, a change in bus type or charging method could result in an increase in number of buses. An economic analysis must therefore be made to determine what is most profitable. It is also important to emphasise that these factors must be adapted to each individual depot. Other factors that must be evaluated is the safety and cooling system of high voltage plug-in chargers.

Photovoltaic system

To improve the energy system of Furubakken depot it might be worth investigating the possibility of a photovoltaic system (PV). A characteristic with the scenarios simulated at Furubakken depot is a constant demand of energy, with peak hours on daytime. As a PV system has its energy production at daytime, it could directly contribute to shave the load demand of the grid. When energy production can be used directly, it eliminates the need of an energy storage unit, thus its associated financial and energy losses.

Idle buses as grid support

Theoretically, in times of low demand on a depot, it might be a significantly amount of unused energy storage capacity of the buses. They could then be available as a grid supporting unit, thus deliver power back to the grid. This might open a market potential, with a possible income for the PTO. The potential income must compensate for the losses caused by an increase in charging cycles, affecting the total lifetime of the bus battery. A decisive factor for this application to be profitable, is high short-term price variations in the power market.

Service fleet

Depots generally have a service vehicle fleet and employees might also bring their private cars to work. These vehicles might be electric and demand additional chargers at the depot. When designing a depot, it might be beneficial to add this factor to the energy system. By having connectors and a system that supports both buses and cars, it might reduce infrastructure costs.

7 Conclusion

Based on the results, a smart charging system with capacity-based queuing system is the most effective measure for reducing the power peaks. The reduction resulted in savings of 175.5 kNOK/month, due to the network tariff. In addition, this system caused a decrease of 14 active chargers. The maximum power peak of all scenarios is well below the available network capacity.

A stationary battery used for peak shaving is not profitable at Furubakken depot. As the characteristic of the load profile for the depot includes wide peaks, the costs of a sufficient battery capacity exceed the savings due to the network tariff. A stationary battery could, however, be profitable at depots with a weaker grid in order to compensate for the costs related to upgrading the grid infrastructure. The stationary battery could also be used for economic purposes.

The results indicate that some of the electric buses on Furubakken depot is unproductive. In order to reduce the number of buses, and thus increase the productivity, the PTO should accurately predict the consumption for each line. In addition, the PTO should evaluate the economic and environmental profit of having relatively unproductive electric buses. A solution can be to have a portion of the bus fleet consisting of e.g. biodiesel buses.

On lines with frequent departures where buses need to charge at the depot often, opportunity charging should be considered in order to increase the productivity. Lines with a short route distance and high daily driving distance is especially suitable, as the pantographs are used more frequently. The use of opportunity charging must be assessed for each line, with regard to cost, political and local resistance, and local grid availability.

In order to design an optimal and long-term depot, a well-defined interface between the ownership and operation of the charging infrastructure is essential. A possible owner can be a subsidiary of an energy company with knowledge and core competence within this field. In addition, a standardised charging technology would be beneficial, as the infrastructure could be used in more than one contract period.

Conclusively, an electrification of a bus fleet causes significant economic challenges for the PTO related to the planning of the operation. For Furubakken depot, a fully electrification requires a 38 % increase of buses compared to the diesel bus option, resulting in a significant increase in procurement costs. Other challenges are related to decreased productivity of the buses, as well as an indistinct interface between ownership and operation. By addressing these challenges and implementing smart solutions, electric buses can in a greater extent replace conventional buses.

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A Round tender of route area 1

Table A.1: *Shows how the different allocation criteria are emphasised.[94]*

Allocation criteria	Route area 1
Price	40 %
Environmental properties	10 %
Quality of the realisation of the assignment	10 %
Quality and functionality of the bus materials	10 %
Quality of the route order for a bus	15 %
Quality of operation on - and facilities at - the facility	5 %
Quality of the hydrogen option	10 %

Table A.2: *Shows point given in the evaluation of bus material and fuel.[94]*

Engine technology	Fuel	Points in the evaluation
El-/hydrogen bus	Electricity/Hydrogen	10 p
Euro VI Gas engine	Biomethane from biogas	3.5 p
Euro VI Diesel engine	Advanced biofuel	3 p
Euro VI Diesel engine	Conventional biofuel	1 p
Euro VI Gas engine	Mixture between natural gas and biomethane from biogas	0 p

[*] The client does not allow the use of fossil fuels

B Route information

Table B.1: *Route information of the lines associated to Furubakken depot.*

Route	Bus stations	Route driving distance [km]	Daily driving distance [km]	Yearly driving distance [km]	Number of stops	Altitude* [m]	Type**
40	Skøyen - Øvre Sogn	11.6	805.4	242,672.4	20	215/53	NL Class 1
41	Skansenbakken - Røa	10.6	503.4	174,619.8	22	33/77	NL Class 1
45	Voksen skog - Majorstua	7.5	1,002.4	330,003.0	19	12/283	NL Class 1
46	Ullerntoppen - Majorstua	7.6	1,235.8	393,195.8	20	87/217	NL Class 1
48	Voksenkollen - Tryvann	6.1	168.0	18,356.2	6	145/145	NL Class 1
130	Sandvika - Skøyen	14	2,390.3	788,514.5	26	110/117	LE Class 2
130N	Sandvika - Oslo bussterminal	18.7	243.4	27,505.6	30	121/131	LE Class 2
140	Bekkestua - Skøyen	16	2,741.6	901,346.5	31	145/214	LE Class 2
140E	Hosle ekspress	14.1	289.8	64,974.7	18	69/215	NE Class 2
140N	Bekkestua - Oslo bussterminal	20.8	299.9	33,893.0	35	172/243	LE Class 2
145	Bekkestua - Fornebu	6.5	453.1	104,447.3	14	29/95	LE Class 2
220	Sandvika - Bekkestua	7.1	579.2	214,087.3	16	130/68	NE Class 2
225	Veritasparken - Bekkestua	-	468.4	163,288.0	-	-	NE Class 2
230	Sandvika - Bekkestua - Østerås T - Ila	14.5	2,680.0	886,468.0	38	287/141	NE Class 2
235	Østerås T - Grini naringspark - Listuveien	2.8	41.7	10,053.5	5	29/47	NE Class 2

* The first value represents the located altitude of the start station and the second value represents the end station.

** NL: Normal bus low floor; NE: Normal bus low entrance; LE: Articulated bus low entrance

Class 1: City buses. More than 45 % of the total number of passengers is registered for standing places.

Class 2: Up to 45 % of the total number of passengers registered for standing places. Legal requirement for seat belts.

C Explanation of the status codes

Table C.1: *Explanation of all the status code used in the simulation.*

Status	Explanation
1	At ES1
2	On the way to ES2
3	At ES2
4	On the way to ES1
5	At depot
6	On the way to ES3
7	At ES3
11	Slow charging
12	Fast charging
13	Fully charged

D Electricity prices and network tariff

Table D.1: *Average electricity price for each month in Oslo in 2018. The third column includes the days within each month of the year. This is used to calculate the energy consumption for each month.*

Month	Price (EUR/MWh)	Days in month
January	32.41	31
February	38.30	28
March	44.36	31
April	38.84	30
May	32.98	31
June	44.60	30
July	52.49	31
August	51.47	31
September	46.41	30
October	41.78	31
November	48.02	30
December	51.79	31

Table D.2: *Price for the power and energy segment for the power tariff provided by Hafslund.*

Tariff segment	Symbol	Price
Power segment - winter 1 (Jan, Feb and Dec)	C_{power}	150 NOK/kW/month
Power segment - winter 2 (Mar and Nov)	C_{power}	80 NOK/kW/month
Power segment - summer (Apr - Oct)	C_{power}	23 NOK/kW/month
Energy segment - winter (Jan-Mar and Nov-Dec)	C_{energy}	0.07 NOK/kWh
Energy segment - summer (Apr - Oct)	C_{energy}	0.039 NOK/kWh

E Comparison of the worst-case versus the best-case scenario

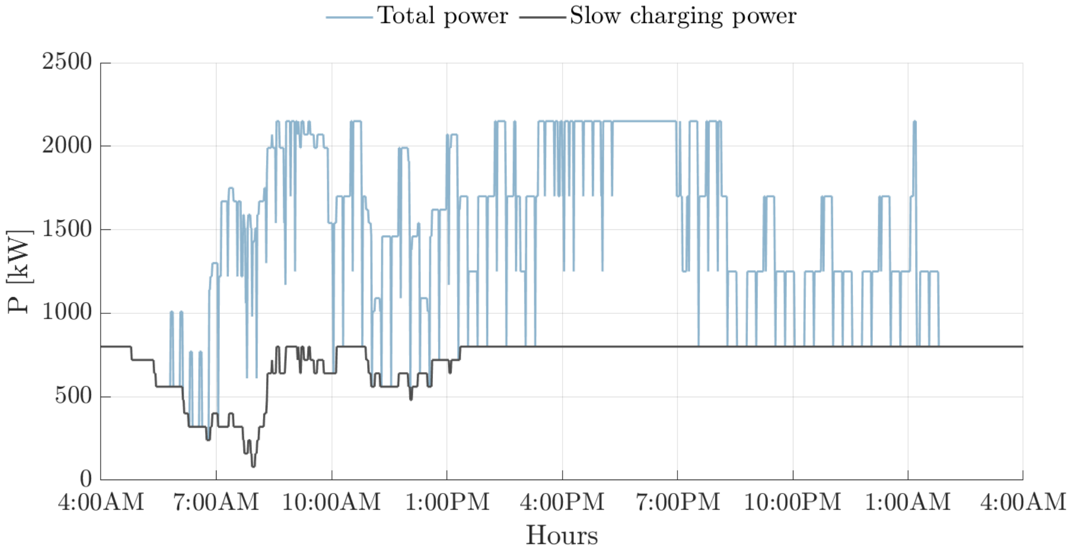

Figure E.1: *Load profile for the depot with the worst-case scenario using smart charging with a capacity-based prioritisation. The total power is equivalent with the sum of slow and fast chargers.*

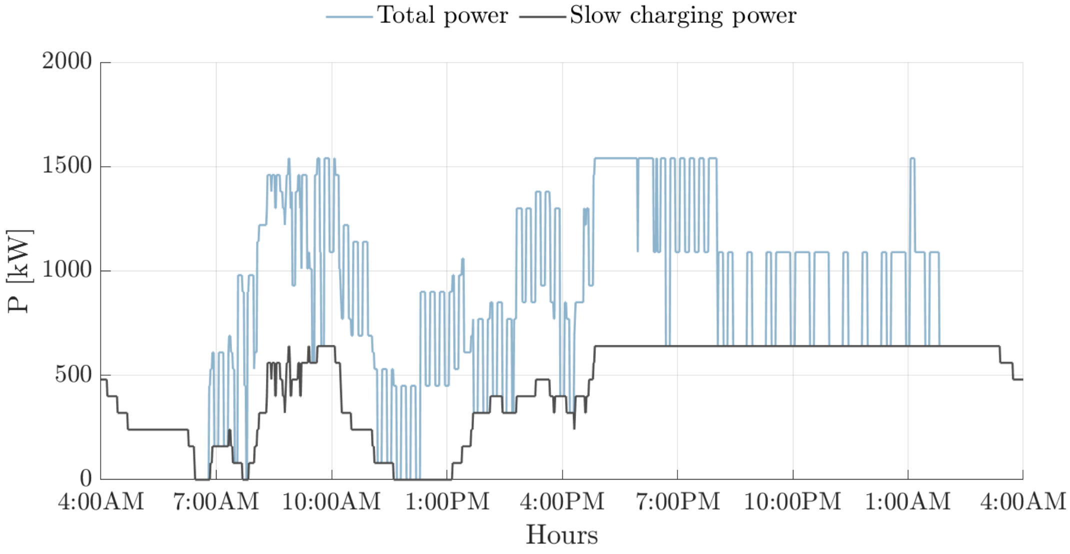

Figure E.2: *Load profile for the depot with the best-case scenario using smart charging with a capacity-based prioritisation. The total power is equivalent with the sum of slow and fast chargers.*