Bachelor's project

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Optimising fast charging of electric vehicles by smart charging technologies in areas with limited grid capacity

Designing the operation of charging systems at Smestad, Oslo, and Sekkelsten, Indre Østfold

Bachelor's project in Fornybar energi
Supervisor: Håvard Karoliussen, Federico Zenith
May 2020

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Kunnskap for en bedre verden

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Preface

This bachelor thesis is written by three students at the Norwegian University of Science and Technology in Trondheim in cooperation with Tor Didrik Krog from Siemens AG and Lars Ketil Bjørnå from Circle K Norge AS. All students attend the Renewable Energy Engineering programme at the Department of Energy and Process Engineering. The Bachelor thesis is the final part of the Bachelor programme and counts 20 credits of the courses TFNE3001.

This bachelor thesis analyses the improvement of fast charging electric vehicles in areas with limited network infrastructures by smart charging technologies in Smestad, Oslo and Sekkelsten, Indre Østfold.

First of all, we want to thank our internal supervisors at NTNU, Associate Professor Håvard Karoliussen, at the Department of Energy and Process Engineering, for counselling, proofreading and informative discussions. Accordingly, we want to thank Senior Research Scientist, Federico Zenith, from Sintef substituting as our internal supervisor and assisting us in the final weeks.

Our gratitude reaches out to our external supervisor, Tor Didrik Krog, and Sindre Solberg for counselling and technical guidance. Additionally, we want to thank Tor Hennum for technical advice regarding coding. Finally we want to thank Ragnar Ulsund from Elvia AS and Jonathan Fagerstrøm from IFE for interesting discussions and enlightening information.

Trondheim, 22.05.2020

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Abstract

Adaption of fast charging technologies contributes to reach Norway's goal of zero emission vehicles by 2025 and will be crucial in order to encourage the electrification of the transport sector. Today, Circle K owns a substantial amount of fast charging stations nationwide and intends to quadruple the amount by 2021, consequently challenging the grid infrastructure. The purpose of this thesis is to evaluate the optimisation of alternative smart charging systems at potential energy stations to sustain a positive charging experience and avoid costs related to grid extension and power tariffs.

This thesis examines three different charging structures, Grid Charging (GC), Simple Smart Charging (SSC) and Microgrid Enabled Smart Charging (MESC), at two Circle K stations: Smestad, Oslo, and Sekkelsten, Indre Østfold. GC supplies the station through grid extension. The presented SSC system focuses only on load management, while MESC includes a stationary battery charged by photovoltaic panels and supplemented power supply from the central grid. Both smart energy systems aim to lower the cost of demand charge tariffs. The scenarios are analysed considering technical and economic parameters, and compared to the standard GC simulation in order to determine the ideal number of chargers in the interest of identifying the optimal business model at each Circle K station.

A common thread throughout the project demonstrates a debate between the profitability of Grid Charging and Microgrid Enabled Smart Charging. The remaining scenario, Simple Smart Charging, generally results as the least favourable option. All alternatives were considerably affected by the daily traffic flow, while an additional influence derived from the battery capacity in the MESC simulation. A lower car intensity appears to be less lucrative but more customer friendly, and higher battery capacities dominate the annual costs. Eventually, an optimal solution considering an ideal charging service and excellent financial stability appears controversial.

Moreover, both locations support different charging strategies. The solution for Smestad would be a GC scenario with six chargers and an optional regulation of SSC to avoid high power tariffs. This solution offers an excellent customer experience and reliability by minimising financial costs. On the other hand, an installation of MESC with two chargers is favourable at Sekkelsten due to its exceptional combination between good customer service, reduction of the electricity bill and fast implementation. These two options will support Circle K's futuristic plan to be part of the smart energy system movement. Additionally, the combination of higher power tariffs and lower battery costs will gradually improve the profitability of installing microgrids for charging operators, such as Circle K.

Ultimately, additional investigations of other distributed energy resources and energy storage systems supporting a microgrid solution can be interesting. Further piloting of new technologies and solutions can improve knowledge about smart EV charging systems and lead to beneficial fast charging stations. An improvement of lithium-ion battery technology and decrease of investments might lead to more sustainable microgrids and conform to EU's goals regarding smart energy system.

Sammendrag

Tilrettelegging av hurtigladeteknologi bidrar til Norges mål om at alle biler skal være utslippsfrie innen 2025 og vil være avgjørende for elektrifiseringen av transportsektoren. I dag eier Circle K et betydelig antall hurtigladere på landsbasis, og planlegger en firedobling av dette antallet innen 2021. Av den grunn vil dette utfordre kapasiteten til kraftnettet. Hensikten med oppgaven er å evaluere alternative smarte ladesystemer på Circkle K stasjoner i henhold til å unngå kostnader relatert til utvidelse av nettet og effektariffer.

Denne oppgaven tar for seg tre ulike ladesystemer, nettlading, smart effektfordeling og mikrogrid, på to Circle K stasjoner: Smestad, Oslo og Sekkelsten, Indre Østfold. Nettlading forsyner stasjonen gjennom utvidelse av nettet. Smart effektfordeling baseres kun på distribusjon av effekt på ladere, mens mikrogrid inkluderer et stasjonært batteri oppladet av solceller og ledig effekt fra nettet. Begge smart systemene har til hensikt å senke effektariffene og blitt analysert i henhold til tekniske og økonomiske parametre, videre sammenlignet med konvensjonell nettlading. Dessuten har det ideelle antall hurtigladere blitt definert for å identifisere den optimale bedriftsmodellen for Circle K.

En rød tråd gjennom prosjektet demonstrerer en debatt mellom lønnsomheten av nettlading kontra mikrogrid. Smart effektfordeling resulterte i hovedsak som den minst gunstige løsningen. En felles påvirkningsfaktor er bilintensiteten, i tillegg varierer resultatene i mikrogrid stort med batterikapasiteten. En lav bilintensitet sørger for en mindre lønnsom ladestasjon men et bra ladetilbud, mens høyere batterikapasitet er en dominerende kostnadsfaktor. En optimal løsning basert på kundeservice og finansiell gjennomførbarhet er diskutert på bakgrunn av simuleringenes resultater.

Begge lokasjoner er imidlertid best egnet til ulike løsninger. For Smestad ble løsningen nettlading med seks ladere, inkludert en opsjonell smart effektfordeling for å unngå høye effekt tariffer. Denne løsningen har et eksepsjonellt ladetilbud og pålitelighet, i tillegg minimale finansielle kostnader. I det andre tilfellet, ble løsningen installering av mikrogrid med to ladere foretrukket på Sekkelsten i henhold til kombinasjonen av en god ladeopplevelse, redusert strømregning og rask installering. Disse to løsningene vil fremme Circle K sine fremtidsplaner om å være en del av utviklingen til smarte energisystemer. Dessuten, kombinasjonen av høyere effektariffer og lavere kostnader relatert til stasjonære batterier forbedrer lønnsomheten av mikrogrid installering for ladeoperatører, som Circle K.

Avslutningsvis kan andre distribuerte energiressurser og energilagringssystemer som støtter en mikrogrid-løsning være interessante å undersøke nærmere. Videre pilotering av nye teknologier og løsninger kan forbedre kunnskap rundt smarte elbil ladesystemer og bidra til gunstige ladestasjoner. En forbedring av litium-ion batterier og reduksjon av investeringer kan lede til mer bærekraftige mikrogrid og samtidig ta del i EUs mål om integrering av smarte energystemer.

Contents

List of terms

Term	Definition
Behind-The-Meter	Energy management behind the electric meter.
Bulk management	Management of large quantities effectively.
Bus line	Depot connecting all elements in the microgrid.
Charging anxiety	The fear of insufficient or defect charging stations.
Charging performance	Refers to the electric vehicles achieving desired State of Charge.
Congestion management	Operating tool for efficient use of available power in the grid.
Connection charge	A one-time cost related to initiating an expansion of the grid.
Converter	Element converting electrical energy.
Deliver reliability	The power grid's ability to deliver electrical energy to the end user.
Depth of Discharge	Degree to which the battery is discharged.
Distributed energy resources	Main power resources in the microgrid.
Distributed energy storage systems	Energy storing devices delivering electricity in the microgrid.
Drop-out rate	Refers to the EVs leaving before charging at the station.
European Attribute Mix	A common power composition from different energy sources in Europe
Electrification	The process of substituting conventional power systems with electricity.
Fast charging	Charging above 50 kW.
Flickers	Fluctuation in the voltage of the power supply.
Front-of-the-Meter	Energy management in front of the electric meter.
Grid cost	Monthly payment to the grid company.
Grid extension	Expansion of the utility grid in order to increase the local power capacity.
Intraday markets	Financial aspect referring to selling stocks within the same day.
Inverter	Element converting DC to AC.
Island mode	Mode when the microgrid is disconnected from the utility grid.
Load management	The process of balancing the supply of electricity with the electrical load.
Microgrid	Local group of electrical components operating with or without the utility grid.
N-1 criterion	Central grid operating on the basis of this criterion to ensure grid stability.
Off-grid	Equal to island mode.
Off-peak	Periods with no power peaks.
Pay back time	The time it takes to recover the costs of an investment.
Photovoltaic systems	Power system delivering power through solar energy.

Term	**Definition**
Power tariff	Charge for highest power consumption.
Power performance	Refers to the electric vehicles being able to charge at 50 kW and 150 kW.
Range anxiety	The fear that an electric vehicle has insufficient range.
Rectifier	Element converting AC to DC.
Redundancy	A back-up system that supports an event of a component failure.
Self discharge	Automatic process decreasing the batteries capacity over a longer period.
Self-sustainability	Personal or collective sustainable autonomy.
Shelf life	Life time of a battery without being used.
Smart charging	Intelligent functionalities to optimise charging infrastructure.
State of Charge	Degree to which the battery is charged.
State of Health	Condition of the battery compared to its ideal condition.
Stiff and weak grid	High and low short circuit performance, respectively
Tap changer	A mechanism in transformers which allows for variable turn ratios to be selected in discrete steps.
Voltage dip	Short duration of reduced RMS voltage.

List of abbreviations

Term	Definition
AC	Alternating Current
AMS	Advanced Measurement System
AP	Annual Profit
BESS	Battery Energy Storage System
BNEF	Bloomberg New Energy Finance
BTM	Behind The Meter
CAPEX	Capital Expenditures
CCS	Combined Charging System
CHAdeMO	CHArge de MOve
CHP	Combined Heat and Power
DC	Direct Current
DER	Distributed Energy Resources
DESS	Distributed Energy Storage Systems
DG	Distributed Generation
DoD	Depth of Discharge
DSM	Demand Side Management
DR	Demand Response
DSO	Distribution System Operator
ESS	Energy Storage Systems
EoL	End-of-Life
EV	Electric Vehicle
FTM	Front of The Meter
GC	Grid Charging
IT	Insulated Terra
LAB	Lead Acid Battery
LCoE	Levelised Cost of Energy
LCO	Lithium Cobalt Oxide battery
LFP	Lithium Iron Phosphate battery
LIB	Lithium-Ion Battery
LV	Low Voltage
MESC	Microgrid Enabled Smart Charging
MGC	MicroGrid Controller
NMC	Lithium Nickel Manganese Cobalt battery
NVE	Norwegian Water Resources and Energy Directorate

Term	Definition
OPEX	Operational Expenditures
O&M	Operation and Maintenance
PCS	Power Conversion System
PPC	Point of Common Coupling
PV	PhotoVoltaic
RES	Renewable Energy Sources
RTE	Round Trip Efficiency
SSC	Simple Smart Charging
SoC	State of Charge
SoH	State of Health
SSB	Statistics Norway
TN	Terra Neutral
TT	Terra-Terra
TSO	Transmission System Operator
VAT	Value Added Taxes
VOC	Open Circuit Voltage

List of symbols

Symbol	Unit	Definition
a	-	Annuity factor
$AOTC$	NOK/year	Normalised annual one-time BESS cost
AP_{GC}	NOK/year	Annual profit in Grid Charging
AP_{MESC}	NOK/year	Annual profit in Microgrid Enabled Smart Charging
AP_{SSC}	NOK/year	Annual profit in Simple Smart Charging
$C_{connection}$	NOK	Investment cost of connection charge
C_e	NOK/kWh	Cost of energy section
C_{ep}	NOK/MWh	Monthly elspot prices
C_f	NOK/mo	Cost of fixed section
C_{FC}	NOK	Investment cost of fast chargers
C_{life}	-	Number of cycles before end-of-life
C_p	NOK/kW/mo	Cost of power section
C_t	NOK	Annual investment cost
C_0	NOK	Investment expenditure
D	%	Discount
DoD_s	%	Depth of Discharge of the BESS
EB	NOK	Electricity bill
E_c	NOK	Electricity cost
E_{cha}	kWh	Charge energy
E_{demand}	kWh	Electricity demand
E_{dis}	kWh	Discharge energy
EP	NOK/mo	Electricity price
$E_{s,max}$	%	Actual available battery capacity SoC window
E_t	kWh	Electricity delivered from the PV system and BESS
E_0	kWh	Initial energy capacity
$E_{0,min}$	kWh	Minimum ideal energy capacity energy
E_1	kWh	Energy consumption of all the EVs charging at maximum 50 kW
E_2	kWh	Energy consumption of all the EVs charging at maximum 150 kW
F_t	NOK	Annual fuel expenditures
GR	NOK/mo	Grid Rent
I	A	Current

Symbol	**Unit**	**Definition**
IN	NOK	Income
I_L	A	Line Current
l	years	Life time
L	-	Number of chargers
M_t	NOK	Annual maintenance expenditures
N	-	Total amount of cars currently charging
N_1	-	Total amount of cars currently charging at maximum 50 kW
N_2	-	Total amount of cars currently charging at maximum 150 kW
OM	NOK/yr	Operation and maintenance cost
OM_{BESS}	NOK/kWh/yr	Operation and maintenance cost for BESS
P	W	Active Power
P_{access}	kW	Accessible power from the utility grid
P_{BN}	kW	Power at 1 C-rate
P_{batt}	kW	Power charging or discharging the BESS
$P_{CK,1}$	NOK/kWh	Price for 50 kW fast charging
$P_{CK,2}$	NOK/kWh	Price for 150 kW fast charging
P_{fast}	kW	Total charging power
$P_{fast,1}$	kW	Charging power at one 50 kW fast charging stations
$P_{fast,2}$	kW	Charging power at one 150 kW fast charging stations
P_{grid}	kW	Power sold to the utility grid
P_{load}	kW	Demanded power by fast chargers
P_{max}	kW	Power at 1.5 C-rate
P_{needed}	kW	Maximal used power from the utility grid
P_{over}	kW	Excessive power from the grid
$P_{reserve}$	kW	Power needed from the reserve to charge all EVs at full power
P_{rest}	kW	Available power for 150 kW fast charging
P_1	%	Ratio of how often 50 kW was delivered
P_2	%	Ratio of how often 150 kW was delivered
Q	Ah	Battery capacity
r	%	Interest rate
S	VA	Apparent Power

Symbol	Unit	Definition
SoC_a	%	State of Charge of battery A
SoC_b	%	State of Charge of battery B
SoC_s	%	State of Charge of the BESS
S_p	kW	Solar power
$S_{p,over}$	kW	Excessive solar power
t	sec, min or yr	time
TC_{BESS}	NOK/yr	Total annual cost of the BESS
TCC	NOK/kWh	Total capital cost
TC_{PV}	NOK/yr	Total annual cost of the PV system
U_L	V	Line Voltage
η_{cha}	%	Charge efficiency
η_{dis}	%	Discharge efficiency
μ	%	Inverter efficiency
ϕ	$^\circ$	Power factor

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1 Introduction

The global consumption of energy is increasing drastically due to the growing population and electrification. This demand has to be answered by exploiting renewable energy sources (RES) and improving technology related to effective power consumption. In order to promote this international improvement, the Paris agreement was arranged as the first climatic contract truly binding for all countries associated. The main goal of the agreement is to keep the global temperature rise under 2°C. Consequently, one of Norway's contributions has become to reduce 40% of its CO_2 emissions of 1990 by 2030 and to be defined as a "low emission society" by 2050. [1, 2]

The road transport sector causes 17% of all CO_2 emissions nationwide, and passenger cars are responsible 52% (Figure 1.1). Since a substantial amount of Norway's energy production is renewable, replacing traditional cars with electric vehicles (EV) is one of the main priorities. The Norwegian EV Association aspires that all cars become zero emission vehicles by 2025. Electric vehicles contribute to 7% of all road transport in Norway with an annual increasing market share of approximately 40%, henceforth the national electricity demand will consequently affect the grid. [3, 4]

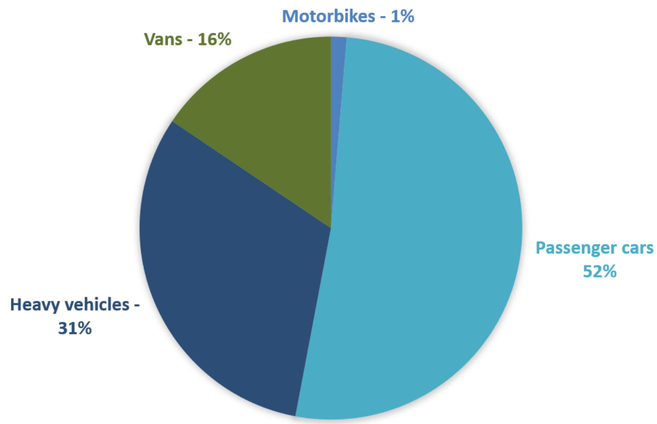

Figure 1.1: *Emissions of greenhouse gases deriving from the road transport sector in 2018 [3].*

The Norwegian Water Resources and Energy Directorate (NVE) has estimated an increase of 1.5 million electric passenger vehicles by 2030. This transition can consequently increase the power demand up to 4 TWh, which corresponds to a growth of 3% of Norway's electricity consumption. The largest contribution in electrification of the transport sector emerges from home charging and fast charging of EVs (Figure 1.2). Hence, the average load of EVs is relatively low, implying the grid can withstand a relatively fast transition. However, the highest power output will determine the strength of the grid. Depending on the maximal power output, some regional and distribution networks will require an upgrade in the grid infrastructure to tolerate the load. Fast charging of multiple vehicles simultaneously, especially in regions with weak network infrastructure, can be challenging. Subsequently, generating an overload affecting the grid's stability. [5, 6]

A consultancy report from THEMA in 2016 states that the Norwegian distribution and regional grid will be improved by 2026 in order to manage congestion and high peak demands. This investment plan can amount up to 80 billion NOK. [8] An economically attractive alternative to handle bottlenecks can be the benefit of local flexible

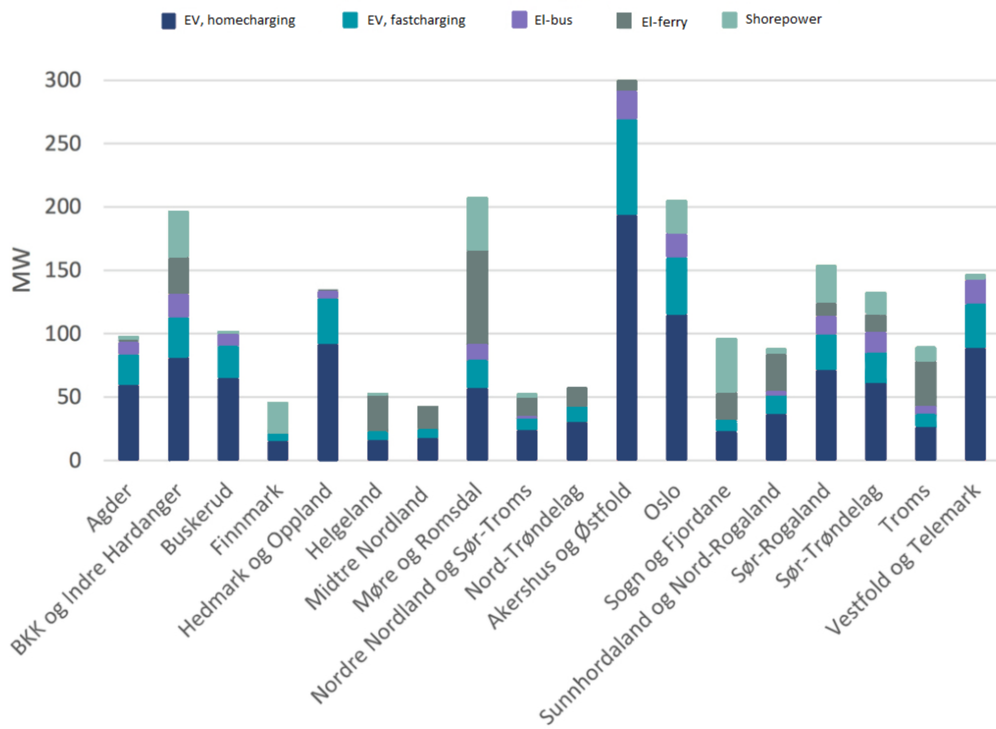

Figure 1.2: *Total increase in power due to electrification of the transport sector by 2030 [7].*

resources. Norway's Ministry of Petroleum and Energy stated in 2016 that energy flexibility of electricity producers and consumers can benefit the security of the supply. Eventually, new technologies will gradually administer the consumption of energy. NVE evaluates several options to manage capacity constraints and price mechanisms in the power grid. With an effective price mechanism, local residential and commercial owners will take a more active part in the energy system, collectively with grid companies. Although, this mechanism is not introduced hitherto, therefore both economic and technical aspects are restricting charging operators to expand. [5, 9]

An electrification could be beneficial for a country based on renewable energy. However, despite the amount of renewable energy sources, whether the Norwegian electricity is green or dirty has been a well discussed theme. The Norwegian power grid is connected to a Nordic power flow system, and will periodically import power. Importing periods occur when foreign fossil energy plants experience lower demand and the power price drops. In addition, Norway sells most of its renewable guarantee of origins and cannot assure green electricity. Most of the actual power composition is defined as European Attribute Mix. These arguments can slow down the enthusiasm and progress of smart electric energy systems in the community. [10, 11]

Recently the European Union has reformed regulations for grid operation and development to meet the growing electricity demand. Moreover, the European Commission intends on turning towards smarter energy system communities. The main purpose of this strategy is to transform the European electrification structure into a more cost-effective energy system. By adjusting to more decentralised and flexible methods, energy will be delivered in a smarter, hence more self-sustainable and secure, manner. [8, 12]

In this thesis, smart charging options are analysed to resolve the problem of restricted capacity network infrastructure and possibly avoid grid extension. Initially, the Norwegian power grid properties are explained and its economic structure. Furthermore, the growth of the EV market is introduced, establishing the installation of direct current fast charging technologies. Moreover, the state-of-the-art EV charging systems is described, such as Microgrid Enabled Smart Charging (MESC), by deploying distributed generation and energy storage systems. To achieve an optimal solution, Siemens AS and Circle K AS have provided necessary information. Two areas are contemplated in this thesis, whereas Smestad, Oslo, and Sekkelsten, Indre Østfold, have implemented zero and four fast chargers, respectively. However, the existing four fast chargers at Sekkelsten are not accounted for in this thesis.

1.1 Problem of the thesis

The problem addressed in this thesis is:

Can smart local energy systems contribute to strengthen the business model of electric vehicle charging operators to provide fast charging service with limited network capacity?

This optimisation will analyse the smart charging systems in the perspective of the charging operator, Circle K, including a satisfying customer service followed by a positive annual profit. Hence this thesis will focus on requirements of various energy system regarding their longevity, accessibility and flexibility with increasing number of chargers. The potential revenue will also be analysed by evaluating capital and operational expenditures of components in smart energy systems. Eventually, a balance between the customer's perspective and the profitability will be examined to find the optimal outcome for the charging operator.

1.2 Delimitations

As a result of time restriction and limited resources, delimitations will evidently be a part of this thesis. Moreover, estimations are conducted for simplicity due to restrained access of data. Several assumptions are formed in communication with experts.

The distribution networks related to the stations are assumed to be stiff in order to exclude heavy loads, such as fast charging of EVs, affecting the voltage quality. However, the regular daily power performance of both Circle K stations are included, in order to analyse the load profile presented for the EVs independently. The impact on the central grid is assumed to be relatively small. Moreover, while analysing the elements in the microgrid, the assumed power losses of the components are theoretical. Power loss in cables and transformers are estimated by Circle K and other losses are found in reviewed literature. Retrieving information about charging patterns and EV statistics was challenging. Furthermore, a thorough estimation of the traffic patterns were assessed. However, the estimation is imperfect. The annual simulation is based on the same daily car intensity. Further, the battery energy storage system (BESS) will only assist the Circle K stations and does not account for the grid company's objective. Hence, the function of the BESS is to control the demand peaks and charging stations rather than voltage regulations in the distribution network. Finally, this thesis is first and foremost a technical report, thus the economic aspects are minimised. Regarding the economic assessment, all values are presented in million Norwegian Kroners (MNOK) and standard deviations smaller than 10 000 NOK are not presented in the results.

1.3 Contributors

The list below represents all the contributors answering questions and sharing valuable information concerning this bachelor thesis.

Name	Position	Company
Lars Ketil Bjørnå	Manager E-Mobility - Deployment and Tech	Circle K AS
Ragnar Ulsund	Senior Engineering Grid Development	Elvia AS
Tor Didrik Krog	Head of Business Development and Strategy	Siemens AS
Sindre Solberg	Senior Engineering	Siemens AS
Hemund Vebenstad	Senior Principal Engineer	Norwegian Public Roads

Circle K Norge AS

Circle K owns 473 fuel outlets nationwide. More than half of these are full service gas stations offering gas, car wash, coffee and food. Circle K is also a fuel wholesaler, owning several terminals and depots supplying customers in all of Norway. Circle K Norway is a part of Alimentation Couche-Tard Incorporation, the world leading fuel and retail operator.

Siemens AG

Siemens is a global company centralising on the areas of electrification, automation and digitisation. Being one of the largest providers for energy-efficient and resource-saving technologies, Siemens is a leading company in systems for power generation and transmission as well as medical diagnosis. The company plays a pioneering role in solutions for infrastructure and industry.

2 Power grid structure in Norway

A power grid is a nationwide network connecting electricity production to the end user. The Norwegian power grid is geographically dependent with a structure divided into two levels: the transmission and distribution network. The transmission network is responsible for a secure supply of electricity, efficient operation of the power system and maintaining the high voltage grid. Statnett monopolises the central grid in Norway. The main function includes maintaining the instantaneous balance between consumption, production and power exchange, furthermore connecting the nationwide system to major manufacturers and consumers. These interconnected power lines are transmitting high voltage fixed at 420 kV/ 300 kV, however, 132 kV transmission lines are used in some areas. [13, 14]

Networks operating below the transmission voltage are considered regional (132 kV/ 33 kV) and local distribution networks (22 kV/ 0.23 kV). Figure 2.1 illustrates the downstream process from power producers to end users. The regional network connects the transmission grid further to smaller energy consuming facilities, using transformers to step down the voltage. Moreover, local networks provide electricity to associated households, service and small-scale industries. Transmission system operators (TSO) regulate the high transmission voltage, while distribution system operators (DSO) regulate the high and low voltage levels of the local distribution networks. Power grid companies operate the majority of the voltage level below 132 kV. [13]

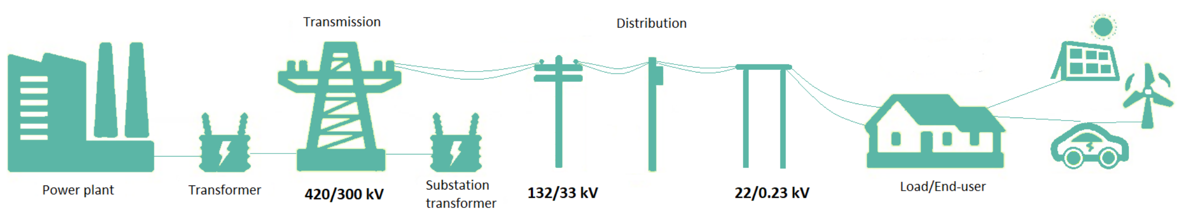

Figure 2.1: *The Norwegian grid infrastructure from power plants to end users. This figure is recreated based on the original [15].*

The electricity is transmitted through the grid as three phase AC. A three phase voltage consist of three separate cables with a 120 ° phase shift between each phase. Given the line current and type of network, the corresponding power can be defined in equation 2.1. There are three types of distribution networks, IT, TN and TT. Firstly, IT-networks transmit electricity by three phase conductors, with a 230 V potential between two phases. Furthermore, the TN-network consists of three phase leaders including a protective earth and neutral conductor. TN can extract 230 V from one phase and 400 V from all three phases and the neutral. TT networks are similar to IT, however the transformer zero is grounded. Today, IT is the dominating network in Norway, while TN is the most typical worldwide... P describes the active power, while U_L and I_L symbolise line voltage and line current, respectively. By multiplying with $cos\phi$, the reactive part of the power is accounted for. Active power describes the amount of the total power than can be directly used. Reactive power is unused power created by appliances that establishes phase shift between current and voltage. [16, 17]

$$P = \sqrt{3} \cdot U_L \cdot I_L \cdot cos\phi \tag{2.1}$$

To keep the power flow on a balanced level, consumers get restrictions from grid companies of how much power cables and transformers can withstand. To estimate power losses in cables and transformers can be challenging due to the distance from the substation and the length of the cables. Additionally, old transformers and cables can have greater losses than new ones. For cables, maximum current is often the limiting factor. In order to enhance the transmission capacity, substations can be connected in a ring structure. However, most of the cables have thermal protection in order to decrease the probability of failure. [13, 18]

2.1 Balanced power grid

A unified Nordic network is developed in order to maintain a balanced power grid. Considering Norway being almost solely dependent on hydro power plants, periods of little rainfall can create inconsistent electricity supply. However, Norway has the ability to import cheap electricity from interconnected countries in periods of higher demand. On the other hand, Norway can export electricity when there is an excess. Hence, the connection between borders increases stability, flexibility and security of supply, contributing to a balanced power grid. [19]

Power system stability is imperative to resist physical disturbance and to maintain an intact network. This is directly related to voltage stability. Incidents accompanying voltage instability can cause blackouts or low voltages in parts of the grid. Integration of renewable energy generation can contribute to fluctuating power output. Additionally, some electrical appliances have a bigger impact on the distribution grid than others. According to Skagerak Energy, appliances, such as EV chargers and PV systems, connected to the distribution network can create disturbance. It is important to examine how charging electric vehicles in a greater extent can affect the capacity and stability in the distribution network. As a result, it can lead to overload and failure of main electrical components. [5, 20]

Another important grid characteristic providing grid stability is the frequency. The frequency can give an indication of whether there is higher energy consumption than energy production or vice versa. If this instantaneous balance between consumption and production is not sustained, frequency variation can occur. A higher consumption and export than production and import gives a decreased frequency, while an opposite situation causes an increased frequency. Imbalanced frequency can consequently affect the grid stability. In Norway, the frequency is required to maintain stable at 50 Hz $\pm 2\%$. [21]

2.2 Supply quality

According to NVE, deliver quality and reliability is important to obtain an acceptable performance of all electric appliances connected to the grid. The term deliver quality includes voltage quality and characterise the applicability of the electric energy. The deliver reliability is related to the frequency and duration of supply interruptions. In order for the grid to be reliable, NVE has implemented measures to reduce the extent or consequences of short- and long-term interruptions. Statnett has to operate on the basis of the N-1 criterion to maintain electricity supply at all times, albeit a main component experience failure, due to blackouts, voltage jumps or dips. Hence, the remaining components in the grid must not be overloaded. [21, 22]

The network redundancy varies throughout the annual seasons. In Norway, periods of higher loads can challenge the deliver reliability. The power grid is designed to supply for the highest demand periods. Eventually, the relation between power generation and demand regulation will be controlled by more effective power systems. This contributes to costumers being a more integrated part of the power regulation system. In order to maintain the instantaneous balance, demand peaks are transferred to periods when the strain on the grid is lower. Nonetheless, the load profile will remain higher during the coldest months of the year (November - March), illustrated in figure 2.2. [13]

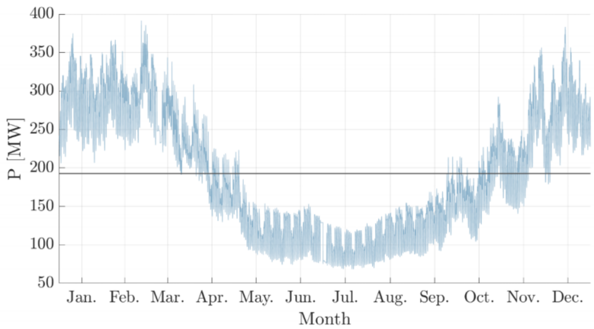

Figure 2.2: *Monthly based power consumption of a typical Norwegian municipality in 2018. The dark line represents the annual average consumption [23].*

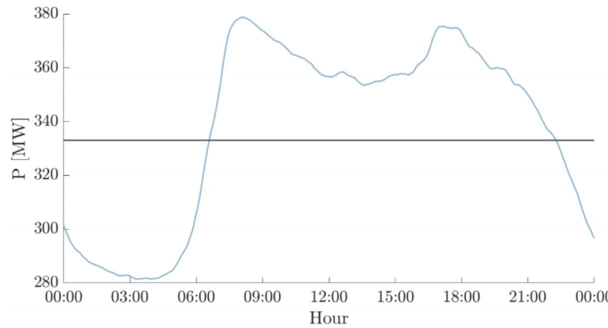

Figure 2.3: *Hourly based power consumption of typical Norwegian municipality at the 30th of January in 2018. The dark line represents the daily average [23].*

Hourly power consumption varies throughout the day. Figure 2.3 presents a typically higher demand in the morning and late afternoon compared to evenings and working hours, corresponding to most households. The highest peaks are around 8 am and 5 pm whereas a large proportion of the power demand emerges from heating households. [13]

A power grid can be classified as either stiff or weak depending on the short circuit performance. A short circuit occurs when a part of the grid is exposed to either ground, external components or another phase. A short circuit current is usually stronger than the standard current. Accordingly, the grid has adapted protection mechanisms to cut the circuit when such high currents occur. A higher short circuit can ensure a stabilised grid, hence resist voltage variations. One method of improving the short circuit current can be to increase the wires' cross section in pursuance of enhance the capacity. Otherwise, increasing the capacity of the transformer or decreasing the distance between transformer and load is another approach. All these measures will lower the impedance and make the grid more stiff. [24, 25]

In weaker grids, the short circuit performance is low, resulting in more voltage variation than stiff grids. Typically, a grid with a higher load will experience more voltage variation and losses. On the other hand, stiff grids are more robust, having a high short circuit performance. Depending on the distance from the distribution transformer, voltage quality can vary. If the connected point is further away from the transformer, the supply is more prone to voltage variation. [21, 26]

2.2.1 Voltage quality

Voltage quality describes the utility of the voltage delivered to end users. Good voltage quality defines the power system's ability to withstand operational interruptions without transfer limits and voltage limits being exceeded. The strength of the low voltage (LV) grid is strongly dependant on the voltage quality. The rate of the voltage quality can give a measure of how safely and correctly the voltage can be utilised. Further, LV quality in the distribution networks develops complications for electrical appliances such as over harmonic voltages and flickers. Most electric appliances are connected to the grid and are designed to function within a range of $\pm 10\%$ of the nominal voltage, implying that the variation will be defined from 207–253 V or 360–440 V. [22, 27]

2.2.2 Voltage regulation

In general, the consequences of increased power consumption and generation are greatest in the distribution network. Approximately, 70% of the distribution grid consist of 230 V, thus more exposed to larger power outputs than higher voltage networks [5]. Although voltage variations are primarily accompanying distribution networks, the voltage can be influenced by active and reactive power. The need for voltage regulation can arise from large voltage variations over a period, or over short intervals such as voltage jumps or dips during load switching off and on. The increase of renewable power generation and electrification in distribution networks can consequently require more voltage regulation, as a result of larger load switching off and on. Larger voltage variations occur when power generation is directly connected to voltage levels below 132 kV. [12, 28]

Transformers are a central component of the grid infrastructure and the main function is to regulate the output voltage. Instead of upgrading the network, an economic alternative can be an installation of components regulating voltage such as automatic tap-changer transformers. Grid companies typically utilise transformers with automatic tap-changers to reinforce network connectivity. The reactive contribution of the electrical power is crucial for the voltage balance. Consumers, transformers, and cables are typically inductive and consume reactive power. On the other hand, capacitor batteries are capacitive and produces reactive power [22]. Upon entering or switching off large loads, reactive power can be supplied or recovered to quickly regulate voltage. Grid companies utilise capacitors to either absorb or generate reactive power, result in a decrease or increase of the voltage, respectively. [12, 29]

3 The Norwegian power market

Today, the power market is a liberalised market where the power price is characterised by competition between different suppliers. The power market is composed of producers connected to a common power stock. Grid companies function as DSO, while power suppliers offer consumers electricity purchase agreements. Grid companies have monopoly on its services within its geographical area, while power suppliers can deliver electricity independently. The foundation of this market took place in 1990, where Norwegian authorities adopted the so-called "energy law". This law opened a free power market. The purpose of the law was mainly to increasing the number of power plants. Accordingly, local power plants are required to deliver energy to everyone who wants to be part of the grid. [30]

3.1 Price mechanism

This section describes several price mechanisms related to the electricity supply. Nord Pool ASA is the operator of the European power market, and can offer day-ahead and intraday markets. Further, power suppliers purchase the electricity based on spot prices. Finally, different costs contributing to the consumers electricity bills are presented.

3.1.1 Spot prices

The common Nordic market known as Nord Pool was established in 1996, when countries merged their individual markets. This is a power stock market where power can be transferred across borders. These interconnections include Sweden, Denmark and Finland, which in turn are integrated into the European power market via transmission lines to Germany, Netherlands, Estonia, Poland and Russia. Nord Pool analyses the amount of supply and demand and sets the power price in each country. Power trading facilitates the management of electricity demand in countries. The purpose with this exchange is to ensure that the power flows from low priced to high priced areas. [31]

The electricity prices from Nord Pool are divided into geographical locations, representing the elspot areas (Figure 3.1). Events of high consumption direct the power flow from areas with a large amount of production to areas with larger cities and consumption. In Norway, this will in general be from western to eastern and southern regions. Typically, the power flows in the direction of NO1 [33]. The spot price is the real hourly power price throughout a day and is based on the ratio between the needed and available power. Based on a comparison of production and consumption each hour, spot prices for each delivery hour are set for the next day. Since electricity is poorly suited to be stored, the market price attempts to maintain a balance between demand and supply. The transmission capacity has a great influence on the variation in the power price. Additionally, weather diversity like variations in temperature and rainfall through the seasons are factors that also may be encountered in the price setting. [31, 34]

Figure 3.1: *Norwegian elspot areas [32].*

3.1.2 Consumer's electricity costs

The customers must pay an electricity bill that includes power consumption, electricity tariffs and value added tax (VAT). The first part, the energy consumption, is measured in kWh and is registered by a home installed Advanced Measurement System (AMS). The AMS samples the hourly consumption each month. The energy price is based on Nord Pool's spot price, but the term adapts between the customers and the supply company. [35, 36]

A second part of the electricity bill is governmental payments, representing approximately 39% of the total electricity bill and includes several elements like electric taxes, Enova costs, electric certificates and VAT. For 2020, the rate of electrical power tax is 0.1613 NOK/kWh. These expenditures are reduced for specified businesses, for example energy shipping or mining industries. [37, 38]

The third part, grid rent, of the electricity bill is required by the grid company. This part covers costs by power transport and costs of operation and maintenance. The total grid rent is separated in three segments: fixed section, power section, and energy section. The power section price is set in NOK/kW and depends on the maximal amount of kilowatt used per month, while the energy section measured in NOK/kWh depends on the total amount of kilowatt hours used per month [38]. In addition, grid investment initiated by a costumer in the distribution networks will result in a *connection charge*, also required by the grid company. This charge is a one-time investment. The purpose of this establishment is to highlight the costs of a new affiliation or reinforcement. Another purpose of this is to distribute the costs between the initiator and the customers of the grid company. [37, 39, 40]

3.2 Peak shaving

Peak shaving is the process of mitigating high demand peaks. Operators can face economic challenges due to peak demand charges. The overall cost of the electricity bill can be reduced by peak shaving or load levelling. To even out the peak loads, effective methods such as demand side management (DSM) or energy storage system (ESS) are used. [41]

3.2.1 Demand side management

Demand side management aims to balance customers electricity consumption and optimise their energy use. This management can be categorised by the energy efficiency or demand response (DR). By improving the energy efficiency, the same service can be accomplished with less energy drawn from the grid [42]. DR is the part of peak shaving that affects the customers normal consumption patterns. There are different types of demand responses. Incentive based DR are programmes meant to reduce customer's loads over a given period. The loads can be reduced by offering consumers incentives in exchange for a reduction in the electricity consumption. Another strategy is price-based DR. In this case, tariffs can promote customers to shift their electricity demand to off-peak hours. [43]

The price-based DR strategy is about to be a more important part of Norway's power structure. New methods to impose tariffs on customers has been established in order to handle the strain on the central grid. In the future, more powerful appliances and self-producing customers will be the standard. Accordingly, NVE has investigated some new suggestions for a tariff system, with a purpose to exploit the power grid in a more effective manner. [44]

As of today, the energy segment has a predominate part of the total grid rent. Eventually, the energy based tariff will gradually become less influential, while power based tariffs becomes more dominating. According to NVE, the impact of the intensity of the consumption measured in kW contributes to costumers being more aware of their power consumption. Changing the tariff structure will make it more expensive for customers to draw electricity from the grid simultaneously. This will clarify the importance of smarter electricity utilisation according to avoid unnecessary high peak tariffs. In the perspective of a charging service operator, the opportunity to adapt to a more effective power consumption can promote the need for smart energy systems. NVE wants to offer incentives to customers using smart technology and energy storage to distribute consumption more evenly over time. [44]

3.2.2 Energy storage systems

ESS can offer peak shaving, thus reduce the high demand periods. The operation of shifting loads from peak hours to off-peak hours characterise a storage system. Storing excessive energy provides a better utility of the energy in the system. The demand is levelled out over time in order to ensure stable and even consumption. The curves in figure 3.2 illustrate power consumption with and without ESS. Accordingly, the green line represents the new load on the grid. The ESS can be charge or discharge in periods of low and high demand, respectively. This is advantageous for the consumers and operators, as they avoid high demand charges. [42, 45]

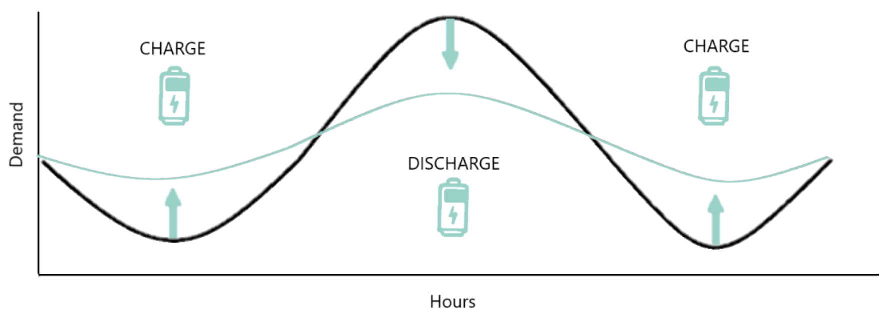

Figure 3.2: *Peak shaving with an energy storage system [28].*

4 Electric vehicles

An increase of EVs will quickly advance and contribute to electrify the transport sector. Norway is in the forefront of the roll out adaption of fast charging stations in order to rapidly accommodate to a more sustainable road traffic. Accordingly, Norway has one of the highest shares of EVs per capita worldwide. As of September 2019, the most popular EV was the Nissan Leaf, followed by Volkswagen e-Golf, BMW i3 and Tesla Model S (Figure 4.1). EV technology is rapidly developing to withstand extreme conditions. Norway is an elongated country with a cold distinctive climate. Improvement associated with Norway's circumstances is expected in the near future, respectively higher battery capacities and new technology according to battery heating. [46, 47]

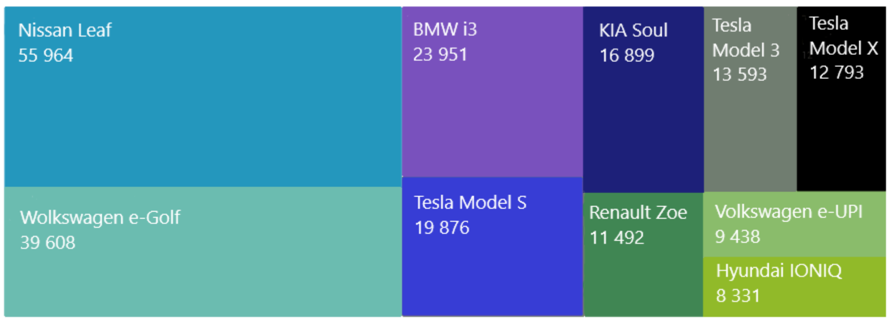

Figure 4.1: *Top ten brands of electric cars in Norway by September 2019. This figure is recreated based on the original [47].*

4.1 Battery technology in electric vehicles

All models of electric vehicles have different battery capacities, affecting the ability to charge with greater power. The battery capacity of an electric car nowadays is between 14.4 kWh and 100 kWh. By 2030 Norway expects EV manufacturers to increase the battery capacity to a range of 80 kWh and 100 kWh. An average battery discharges 0.18 kWh to 0.20 kWh per kilometre. During the winter, more electricity is used per kilometre for heating. [8]

Lithium-ion batteries installed in electric vehicles do only tolerate a certain amount of charging power. If this limit is exceeded, the function of the battery can be severely impaired. Several studies state an increased ageing rate at long charging periods at temperatures above 40°C. Moreover, the high charging current in fast charging increases the risk of individual cells being damaged by overpotential. [48]

However, some researchers have found techniques to prevent this problem by using an internal battery-heater of nickel foil. By heating the battery quickly and briefly to around 60°C during charging and cooling down right after, it is possible to avoid degradation of the battery. Hence, this increases the possibility to charge at greater speed. Although, if this heating lasts for too long, the structure of the electrolyte changes, which in turn also affects the functionality of the battery. Due to this heater, the battery itself can withstand 400 kW without forming lithium deposits. The studies state that even an electric car battery with 209 Wh/kg maintains approximately 92% of its capacity after 2 500 extreme fast charging cycles. [48]

4.2 Future electric vehicle market

Since 2012, the Norwegian EV market has expanded to around 252 000 electric vehicles in 2019 (Figure 4.2). NVE estimates the amount of EVs in Norway to reach 1.5 million by 2030, meaning that the amount of EVs will escalate immensely in 10 years, although the "Elbilbarometer 2018" from the Norwegian EV Association states that 19% of the population feel that the charging infrastructure for EVs is to weak. [4, 5]

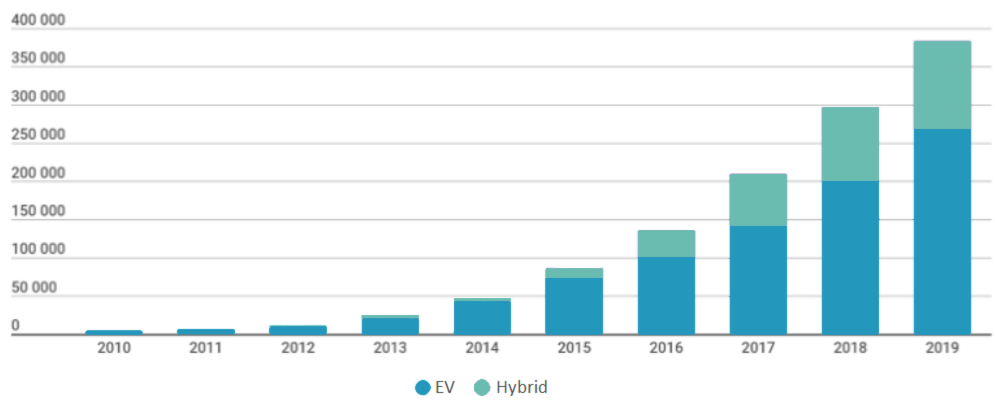

Figure 4.2: *Amount of electric vehicles in Norway over the years. This figure is edited based on the original [49].*

Another barrier for the EV industry is the speed of charge. Many Norwegians prefer traditional cars because the refill time is much shorter than for alternative cars. As of today, relatively few cars can charge with a fast charger above 50 kW. Car companies have therefore announced upgrades for the current models. BMW will launch the BMW iX3 in 2020 having a 70 kWh battery. Volkswagen is developing the new ID.3 model, replacing the e-Golf and having three separate battery capacities: 48, 55 and 62 kWh. With increasing battery capacities, the speed of charge increases as well. However, the new Nissan Leaf with 62 kWh is unable to charge at 150 kW due to its limiting charger being able to only deliver 100 kW. The 150 kW fast charger will hence become the standard eventually. Thus, the EV market grows rapidly and the position as the most popular EV in Norway changes constantly. For instance, Audi e-tron was recently launched and has proven to become an important competitor. The amount of fast chargers delivering 150 kW or more has gone from 25 to 226, an increase of 804% from 2019 to 2020. [50, 51]

4.3 Demand side patterns

For the majority of EV owners, the easiest and cheapest option has been charging at home. However, the increasing EVs in the transport sector forces the adaption of fast chargers to keep up with the pace. Since a higher share of EVs are able to charge at faster speed and having a better battery capacity, more people can travel longer distances. Hence, a substantial amount of fast chargers will need to be installed nationwide. Today, electric vehicle owners can experience the insufficient amount of fast charging stations leading to "range anxiety" and "charging anxiety". Recently, the charging anxiety has grown as a result of multiple EVs arriving at the stations causing queue problems. According to the Norwegian EV association, 64% of electric vehicle owners experience queue frequently. Furthermore, analysing the fast charging pattern, a similar number of 75% is measured in Oslo. [52, 53]

A great worry is the driving distance between the charging stations. In order for the Norwegian community to replace conventional with electric cars, a sufficient amount of charging opportunities have to be ensured. Since the installation of fast chargers depend on local demography and infrastructure, demand side patterns must be considered. The necessity of regular customers is significant. [54]

A research by Sintef examined the charging habits of fast charging throughout the day. The majority of the owners charge their car from 12 pm to 7 pm with a peak around 4 pm in a normal workday. Regular charging occurs during evening and night. The daily charging demand is primarily covered by home charging, or chargers installed at work. However, fast charging can become the new standard and will consequently affect the charging patterns. [8]

5 DC fast charging

In order for the society to adapt to EVs, charging stations have to be expanded rapidly. However, the desire to charge the EV at the same speed as the conventional fossil fuel vehicles is challenging. Expanding the fast charging market will increase the roll-out pace of electric vehicles in Norway.

Fast charging technologies usually draw current faster than regular charging methods. They need access to a three phase 400 V source. If the charging station is connected to an IT network, a local transformer adjusting the voltage is necessary. Fast chargers are divided in three main components: rectifier, computer controller and a communication module. A rectifier transforms the current from AC to DC, the controller regulates the voltage and current through the charger, and the module communicates between suppliers and grid companies. A regular EV battery charged with 50 kW will proceed from 0% to 80% in 30 minutes. This method is called mode 4 [55]. A rough interval between 43 kW and 150 kW is defined as fast charging. As of today, the two standard fast chargers are at 50 kW and 150 kW. [56]

The speed of fast charging depends mainly on two factors: State of Charge (SoC) and the temperature. SoC defines how full the battery is. As of today, the regular EV is usually charged with a speed between 40 kW and 50 kW until 70% SoC at 50 kW fast charging (Figure 5.1). Therefore, it only takes around 30-60 minutes to charge the battery from 0% to 80%, but it will take longer to charge the remaining 20%. [56]

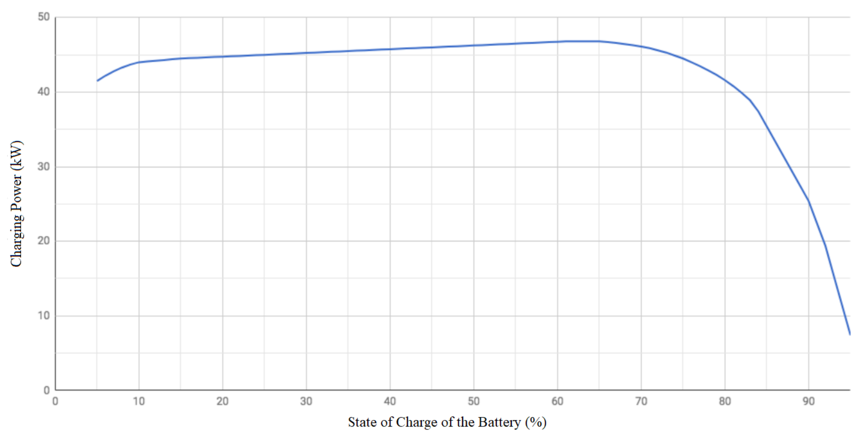

Figure 5.1: *Speed of 50 kW fast charging compared to SOC [56].*

Another factor is the temperature. Electrochemical processes are known for being sensitive in temperature fluctuations. Ideally, a battery charges at a temperature between 20°C-30°C. If charging a cold battery with a high charging power, the battery can be destroyed. Therefore, a lower charging power is required to protect the battery and the charging system, for instance at -90°Ca regular EV can take up to 90 minutes to charge from 0% to 80%. Often batteries are equipped with a thermal control, cooling or warming, to support the battery. [56]

5.1 Type of chargers

In Norway, there are three types of chargers. CHArge de MOve (CHAdeMO) is the most popular charger, while the Combined Charging System (CCS) and Tesla Supercharger are competing chargers (Table 5.1). All of these are DC chargers. Most of the manufacturers offer multi-chargers, enabling cars with CHAdeMO and CCS to charge at the same charger. Infineon, a semiconductor manufacturer, states that the energy efficiency of all DC fast chargers is equal to 95% with an expect growth to 98% in the future. [56, 57]

AC Type 2 is the least popular fast charger. Since this charger excludes the rectifier, the car needs an extra adaptor to convert from AC to DC, additionally offering a lower charging power. AC fast chargers can only charge up to 43 kW, which is the lowest boundary for fast chargers. By 2017, the greatest charging station providers in Norway are Fortum Charge & Drive, Grønn Kontakt and Tesla with respectively 130, 75 and 31 fast chargers nationwide. [8, 58]

Table 5.1: *Amount of multiple type of chargers in Norway in 2017 [8].*

Charger	Amount in Norway
CHAdeMO	602
CCS	555
Tesla SC	246
AC Type 2	63
Total	1466

5.1.1 CHArge de MOve (CHAdeMO)

CHAdeMO was the first EV charger launched in Europe. This model uses type 1 and can supply the EV battery with up to 100 kW DC with 500 V and 125 A. The standard charging time is around 30 minutes from 0% to 80%. CHAdeMO is the most widespread charging type in Norway. Cars adjusted to CHAdeMO need two different charging sockets, one for AC normal charging and one for DC fast charging. [56, 59]

5.1.2 Combined Charging System (CCS)

Combined Charging System is a combination of the type 2 connector and two additional DC contacts, allowing high power DC and AC fast charging. The type 2 contact in fast charging communicates between the charging station and the EV. CCS is meant to be an alternative to CHAdeMO. Thanks to the combined system, an EV only needs one charging socket. This is one of the reason why CCS most probably will surpass CHAdeMO in the market. Today CCS can deliver up to 350 kW with corresponding voltage and current. [56]

5.1.3 Tesla Supercharger

Tesla has designed its own charger, called the Supercharger, which is a modified version of the type 2 contact, used for AC and DC. It can supply up to 150 kW DC with 500 V and 250 A. Currently only Tesla cars can charge with the Supercharger, although Tesla is working on a version, where CCS adjusted cars are able to charge. [56, 60]

6 Smart charging technologies

Smart charging is defined as accustoming charging patterns of electric vehicles compared to market price signals. Operators and EVs are connected with the charging station in order to share data. Hence, it is profitable to sell and buy electricity when the demand is respectively high and low at the charging stations. In regions with limited grid capacity, smart charging is a practical, cost-effective, self-sustainable and a reliable charging service. [8]

The main intention of smart charging is to reduce high demand peaks. The system can prefer to charge during periods of high production of green energy. Smart charging empowers the independence of the local owner and promotes local renewable energy sources (RES), grid stability, as well as energy efficiency. As a result, the load profile is more smoothed. [8]

There are several types of charging control methods. The first one is uncontrolled. Passive control, such as DSM, is defined as power consumption regulated to when the power tariffs are low. Active control, equivalent to smart charging, can be unidirectional, where only the charging power can be modulated, or bidirectional where power flows back to the grid. The active control adjusts the power flow direction, power capacity, starting time, duration and location of the electric vehicle. Control methods can either be controlled by a centralised party or by the owner which responds to signals of a decentralised third party. To ensure optimal results, specific algorithms are built for these charging strategies. The European Union's aim is to redirect society towards smarter energy systems, assuring independence for energy service companies and consumers. Hence, self-production will lead to more flexibility and a more flattened charging profile. With active control, new economically attractive alternatives to grid extension are emerging. [8]

6.1 Simple Smart Charging

In Simple Smart Charging (SSC), the controller considers the maximal capacity of the network, the charging duration, the State of Charge and the amount of cars. The smart controller will automatically charge with the maximal amount of power available. Load management can result in a reduced electricity bill compared to grid extensions. Using smart charging will also lead to safer charging solutions. The device compares the connection between the vehicle and the charger to secure carefree charging. [8]

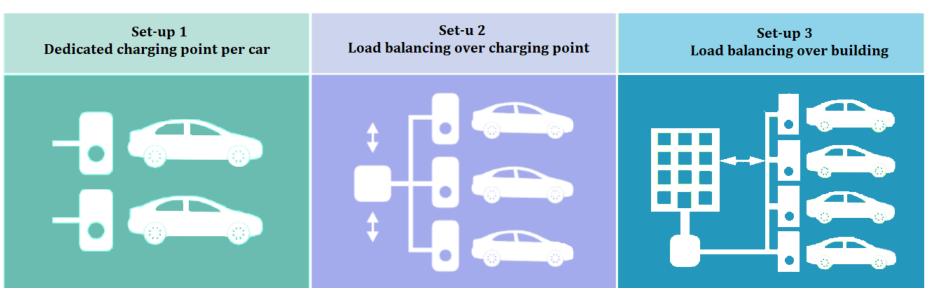

Figure 6.1: *Three different scenarios for load management. This figure is edited based on the original [8].*

Load management reduces power peaks in the grid by distributing the load and increasing the charging time. With static load management the charging power is distributed equally across all electric vehicles (Figure 6.1, Set-up 2). Thus, peak loads and high costs are avoided. In contrast, by using dynamic load management, the charging power capacity is adjusted to the power consumption of the associated building. That way, the power capacity for the charging station increases if the power capacity for the building decreases (Figure 6.1, Set-up 3). Although load management is cost-effective and grid friendly, it results in longer charging periods, because of a lack in power capacity. Accordingly, power generation in a microgrid can be a reasonable solution. [8]

6.2 Microgrid Enabled Smart Charging

A microgrid is a locally delimited power grid consisting of one or more electricity plants. It supplies a geographically narrow area and can have a synchronous connection to the utility grid. A microgrid can be set to island-mode (off-grid) and thus disconnected from the central grid. Microgrids contain several key parts. The local energy generation produces the electricity for the microgrid. Typically, these components, identified as distributed energy resources (DER), are photovoltaic panels or wind turbines. This electricity is possibly further stored in ESS, such as batteries or flywheels. Other elements consume this generated energy, for instance buildings or electric vehicles. In events of overproduction, a smart meter calculates hourly electricity sales and investments. Accordingly, the point of common coupling (PCC) connects the microgrid with the utility grid to enable the smart meter to sell surplus electricity. The low inertia of microgrids can cause problems when connecting with large utility grids and bulk power systems having a relatively large inertia. This difference can promote frequency deviations off-grid. Further, controlling energy storage systems can be a solution to balance the frequency. [61]

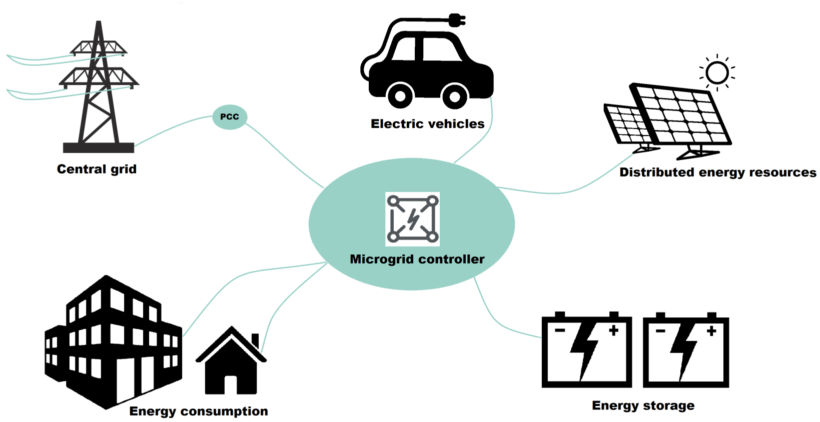

Figure 6.2: *Elements in a microgrid.*

However, the main part of the microgrid is the microgrid controller (MGC), which is either centralised or decentralised. It analyses the data of all components to ensure the optimal outcome. This controller manages the microgrid's resources, in order to achieve the operator's interests (Figure 6.2). To ensure optimal performance of the microgrid, a MGC is defined by a three-levelled hierarchy control: primary, secondary and tertiary. The primary controller regulates the power sharing between distributed generation (DG) units and maintains the stability of the microgrid operation. The secondary control compensates for the voltage and frequency deviations caused by the operation of the primary control. Eventually, the tertiary control is the highest level of the power management, regulating the power flow between the microgrid and the central grid. Hence, it is responsible for economic optimisation based on energy and electricity prices. To counterbalance the microgrid, all power flow is converted to the either AC or DC, regarding the microgrid bus, limiting imbalances following the irregular demand and power generation. [61, 62]

6.2.1 AC and DC microgrids

A microgrid can be classified as either DC, AC or hybrid. Since AC power network has been the standard, AC loads are dominating most electrical appliances. However, DC distribution is becoming more popular due to more application connected to DC native elements, such as EVs, PV systems and batteries. By supplying electrical appliances with DC, the use of inverters will eventually be decreased. Beneficially all electricity generating units (e.g. DG units) with AC power output are directly connected to an AC bus line and vice versa for DC power output. This configuration is advantageous because it reduces the use of converters. Hence reducing losses associated with the AC–DC energy conversion. [63]

Power flow in a microgrid

To transfer the power flow between different components such as solar modules, stationary batteries, connected EV chargers and the public grid, some power electronic devices is required. Converting electricity from one form to another. For example, a shift between AC and DC regulating is important for the power supply. All power flows are administered by the microgrid controller, illustrated in figure 6.3. These operations will occur through a power conversion system in order to obtain high efficiency and performance. [64]

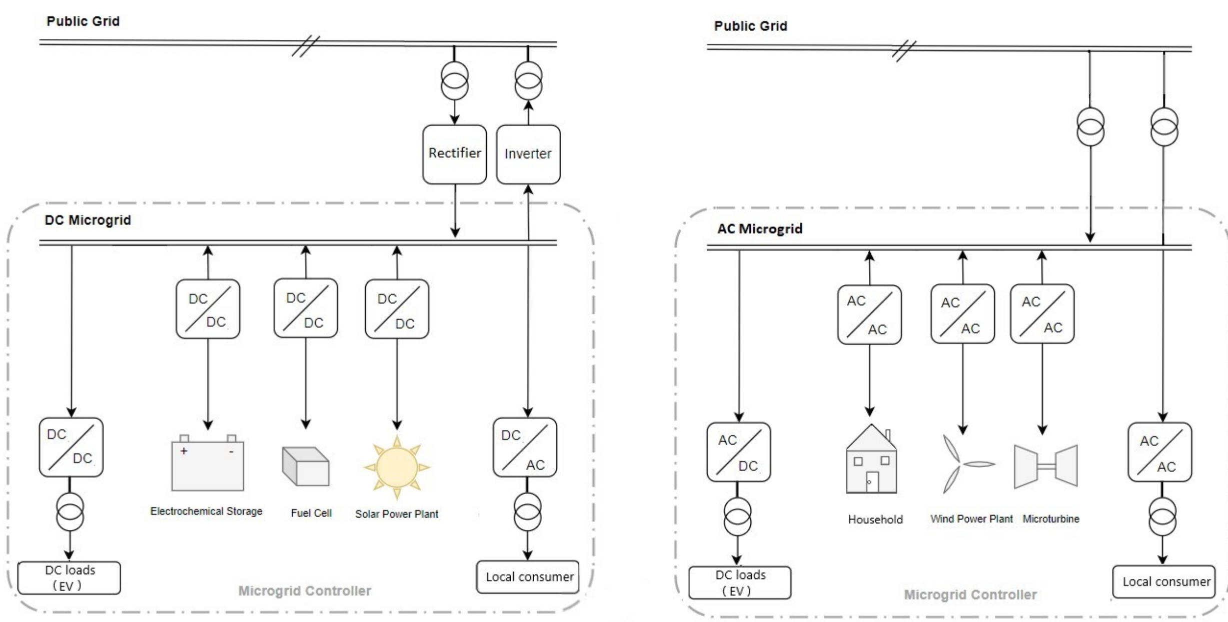

Figure 6.3: *Simplified power flow in a microgrid between converters, inverters and rectifiers. This figure is edited based on the original [65].*

Three power conversion components are especially important: converters, inverters and rectifiers. Adversely, a power conversion system (PCS) account for a significant part of the total capital cost of a typical microgrid system and are often the least reliable part of the system. Additionally, every PCS has an efficiency, affecting the operation of the microgrid. Accordingly, the converter system between the power supply and the load has to be designed for greater capacities. The bidirectional power flow can present challenges in microgrids. A reversed power flow may lead to problems in unwanted power flow sequences, voltage variation and deficient current circulation. In decentralised systems, the communication between control systems of the elements may generate local oscillations, demanding stability analysis from the secondary control. Instability may furthermore be created in transition of the grid connection to island mode. Not to mention, the economic and reliable operation of microgrids is uncertain. Load profile and the weather lead to a more challenging coordination in the microgrid. Nevertheless, DC microgrids can simplify the control structure and lead to a more energy-effective distribution and higher current capacity. [61, 64, 66]

Converter

Converters are installed to convert electrical energy. It may be converting AC to or from DC, or the voltage or frequency, or a combination. A DC/DC converter can be used in battery appliances to regulate the voltage. Converters can either increase or decrease the voltage, called DC/DC boost converter and DC/DC buck converter respectively. This appliance allows high conversion efficiencies. The efficiency for a DC/DC converter is able to be over 95% under ideal conditions. [67]

Inverter

An inverter transforms DC to AC in order for a DC microgrid to deliver power to the utility grid. The efficiency of the inverter represents the loss of converted power from DC to AC. A typical efficiency for a high-quality inverter is 90%-95% when the power output is higher than 20% of its maximum. For a power output lower than 20%, the efficiency is remarkably lower. This power flow is an important communication link between the microgrid and the utility grid. [68]

Rectifier

Aforementioned in section 5, a rectifier is used to convert AC to DC. There are several types of rectifiers, but the bridge rectifier is typical in DC power supplies with an efficiency of 81% [69]. Rectifiers in fast chargers can create disruptions, for instance electric noise. These phenomena occurs when voltage and current deviate from the standard fluctuation, causing harmonic disruptions. The ideal voltage and current curve are sinus formed. The voltage phase should be preserved adequately to maintain the voltage quality. Figure 6.4 illustrates the change of voltage signals during disruptions. [70]

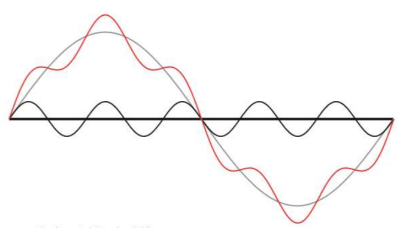

Figure 6.4: *Illustration of change of voltage signals during disruption. The grey graph is the ideal signal, the black one represents the harmonic disruption, while the red one shows the actual signal [70].*

Over harmonic disruptions occur when the grey signal surpasses the red signal. A consequence of over harmonic waves is the overheating of elements, for instance cables and transformers, leading to flickering and short circuits. Additionally, the rectifier has a significant effect on the voltage quality. A high short circuit performance is required to regulate the voltage. Appliances with rectifiers connected to the grid decrease the short circuit performance. Therefore, it is challenging to avert variations and disruptions. [70]

7 Distributed energy resources and distributed energy storage systems

Distributed energy resources (DER) provide energy to the microgrid. Generally, energy sources are renewable, such as small hydro, geothermal, solar and wind power. Other DER systems can be devices storing energy and delivering electricity to the utility grid. These devices are generally defined as distributed energy storage systems (DESS). Both systems are characteristics in a smart grid. The following table 7.1 illustrates different types of DER and DESS. [71]

Table 7.1: *Different types of DER and DESS.*

DER	DESS
Microturbines	Pumped hydro
Photovoltaic systems	PV batteries
Small wind power systems	Compressed air
Combined heat and power (CHP)	Thermal energy storage
Fuel cells	Battery
Heat engine	Flywheel

7.1 Photovoltaic system

Photovoltaic (PV) systems have become the most typical small-scale energy generating unit. A PV system produces energy during daylight, however during the evening and night hardly anything is generated. Unfortunately, the charging demand is highest in the evening around 5 pm. In addition, the energy production of PV modules is significantly lower during the winter season when the load is typically higher, compared to the summer season. Although the electricity production is intermittent, it can still provide electricity in periods with generally higher demand. Photovoltaic panels should be oriented south on the buildings if the main power demand is around midday. The optimal inclination for solar panels is the difference between 90° and the latitude. In Oslo, the optimal inclination is approximately 30°. [8, 72]

Photovoltaic panels portray as a local energy generation in a microgrid. Although, PV systems are becoming more prevalent, figure 7.1 illustrates the forecast of the cost decreasing even more significantly in the following years. Installing solar panels can help reduce the overall operational cost of a microgrid, hence it is favourable to consume self-generated green electricity. In 2014, over 93% of the worlds solar panel were based on silicon, where poly-crystalline silicon is the most common type. The energy efficiency of a regular poly-crystalline solar panel is defined between 15%-16%, while older are below 12%. [72, 74]

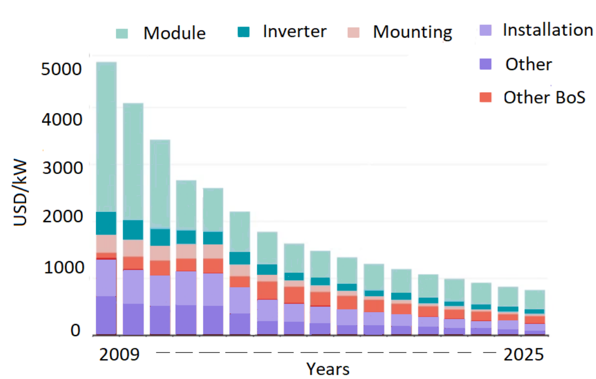

Figure 7.1: *Annual installed PV cost. This figure is recreated based on the original [73].*

7.2 Other distributed energy resources

Other DER are gas based microturbines containing a compressor, combustor, turbine and a generator. Using the pressure difference and enthalpy of the gas to generate electricity and heat, this type of energy resource is mainly used for houses. Likewise, CHP is most common in houses, combining heat engine or a power station to generate electricity and useful heat simultaneously. [75]

Fuel cells offer a reliable energy generation because of its continuous electricity generation considering constant fuel supply. Fuel cells convert chemical energy from gas, such as hydrogen, into electrical energy. Unfortunately, fuel cells require advanced storage technologies and specific operation temperatures. [76]

Power generation from small wind power systems can be an unpredictable power resource. Electricity generation varies depending on the weather and can create fluctuating and intermittent power output. Wind turbines extract kinetic energy from the wind and convert the energy to AC electricity. Principles of aerodynamics are considered to optimise the absorption of wind and extract the most energy. [77]

When DERs produce surplus power, maximally 100 kW can be sold to the utility grid. Exceeding this limit, the former plus costumer is then characterised as a power plant. Hence, the costumer has to pay expensive tariffs. However, suggestions for new regulations of solar power feeding more than 100 kW are discussed. These approaches introduce a price of 1.3 øre/kWh for costumer surpassing the limit. [78, 79]

7.3 Battery energy storage system

BESS has the ability of being an integrated part of the microgrid as a load with high flexibility and is the most effective way to reduce demand peaks. Energy storage can become a key for solving capacity and voltage problems in the distribution network. Storing and delivering active power is advantageous during low and high power demand periods, respectively. [80]

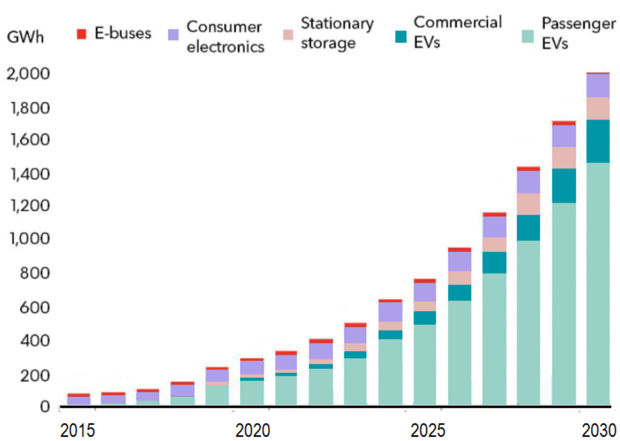

Figure 7.2: *Annual lithium-ion battery demand. This is recreated based on the original [81].*

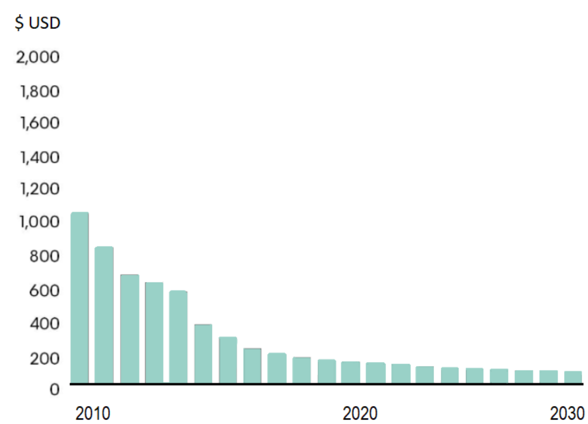

Figure 7.3: *Annual BESS cost. This figure is edited based on the original [82].*

The increasing global demand of batteries forces development in technology (Figure 7.2). Moreover, the growth of battery appliances is particularly expected to be linked to electric vehicles and PV systems. According to Bloomberg

New Energy Finance (BNEF), the year 2050 expects to have over 1 200 GW of additional lithium-ion battery (LIB) capacity. Although LIB is considered the most mature battery storage technology, calendar life, energy density, and number of cycles can still be significantly improved. Hence, figure 7.3 illustrates the forecast of improved battery technology consequently decreasing the battery cost. [82, 83]

The battery storage can function as a Behind-The-Meter (BTM) application of the microgrid. This can include levelling the grid demand in order to reduce electricity costs and store excess solar power. Consequently, improving delivery quality and reliability. BESS offers solutions for load management, peak shaving, voltage dip mitigation and emergency backups. Instead of investing in new cables and substations, better utilisation of existing capacity and balanced loads will be beneficial. Accordingly, BESS becomes increasingly important for the technical interaction between renewable energy generation and power consumption of EVs. [84, 85]

7.3.1 Battery fundamentals

Battery capacity (Q) is measured in ampere-hours (Ah) and defines the amount of energy a battery is able to store. The value of Q is not constant and decrease. The capacity of a battery depends on temperature, age of the cells, energy density, SoC, the rate of discharge and the current drawn by the load. [86]

The power density of a battery defines the power delivered per unit volume at a specific SoC, usually at 20%. The specific power is measured in watts per kilogram (W/kg). Energy density describes the ratio between the energy of the cell and its volume. The specific energy of a cell describes its energy divided by its weight (Wh/kg). Moreover, the energy efficiency is commonly greater in modern batteries. This appears because of the increased energy density and decreased current density, operating closer to the open cell voltage than to the voltage of the maximum power. Generally the nominal voltage of a LIB is 3.6 V, however the battery is charged with a relatively higher voltage of approximately 5 V. In order to increase the voltage of the total battery system, the battery cells are typically configured in stacks. In these battery stacks, battery modules are put together in series to reach the required DC voltage which is compatible with the PCS. [87, 88]

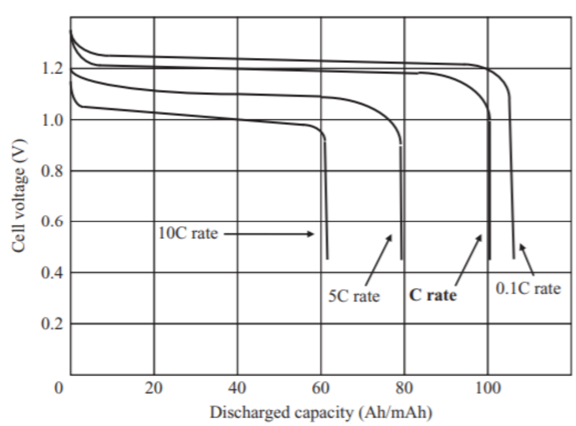

Figure 7.4: *The capacity in function to the cell voltage with different C-rates [86].*

The charge or discharge rate of a battery is defined as the C-rate. This parameter is linked to the battery's capacity. At low C-rates, the actual capacity of a battery is greater than at high C-rates (Figure 7.4). If the battery's capacity is 5 Ah, a discharge rate at 0.1 provides 5 A for 10 hours. [89]

The C-rate is defined as the current drawn from the battery, I, divided by the capacity of the battery, Q. This relationship does also equal to the power, P, fed from or to the battery divided by the initial energy capacity, E. This is illustrated in equation 7.1 [90]. The C-rate can also be described as the ratio between the actual current drawn from the battery and the theoretical current drawn at nominal capacity in one hour. [89, 91]

$$C_{rate} = \frac{P}{E} = \frac{I}{Q} \tag{7.1}$$

Life cycles describe the amount of discharge and charge cycles the battery can undergo before it irreversibly loses too much capacity. If cycles occur frequently, the battery's life can decrease. The optimal amount of life cycles depends on the application. Cheaper and older technologies will often have shorter lifetime, hence fewer life cycles. [88]

The Depth of Discharge (DoD) is the degree to which the battery is empty. It directly affects the life cycles of a battery. The higher the DoD, the lower the life cycle. Hence, the life cycle for conventional batteries is a function of its DoD. [92]

In contrary, State of Charge (SoC), introduced in section 5, describes the degree to which the battery is full. SoC affects the discharge current of the cell. An SoC is to be maintained around 50% for optimal battery life. In applications, where the focus is set on energy transfer between battery and load, the integral of the instantaneous power fed from the battery into the load, $P(t)$, is important. Equation 7.2 describes the SoC estimated based on the initial energy capacity, E_0, where t_0 is the initial time. The discharge and charge efficiency, $\eta_{dis/cha}$, are involved when the battery is discharging and charging, respectively. [86]

$$SoC(t) = SoC(t_0) \pm \frac{1}{E_0} \cdot \eta_{dis/cha} \int_0^t P(t)dt \tag{7.2}$$

When calculating the difference between the two terms, the battery is discharging. Conversely, the battery is charging when the terms are added.

Higher C-rates can lead to higher inefficiencies, due to heat loss. In addition, with higher cell temperatures, side reactions and accelerated capacity fade can occur. A factor affected by the C-rate is the State of Health (SoH). This term refers to the available charge in coulomb at a given C-rate compared to the new battery. The SoH is more likely to be lower at a higher C-rate. By definition, for electronic systems a battery with a SoH under 80% has reached its End-of-Life (EoL). The State of Health is defined similarly to the SoC (Equation 7.3), where L_{cycle} is the total amount of cycles before EoL. L_{cycle} depends on other conditions, for instance DoD and C-rate. [86, 88]

$$SoH(t) = SoH(t_0) - \frac{1}{2L_{cycle} \cdot E_0} \cdot \eta_{dis/cha} \int_0^t P(t)dt \tag{7.3}$$

In general, batteries that have been used over time have a lower measurable. This is due to li-ions immobilising when ageing. The self discharge rate is a major factor affecting the SoH. This rate describes how long a battery can be stored before it can not provide minimum capacity and recharge at its rated capacity. Irreversible side reactions consume charge carriers preventing current generation. Eventually, the battery is unable to produce power. The batteries lifetime will also experience degradation due to temperature. [86]

The round-trip efficiency (RTE) describes the net energy lost in one cycle. It is defined by the ratio of the discharge energy, E_{dis}, and the charge energy, E_{cha}. This equation does not take into account self discharge. RTE is also known as energy efficiency or cycle efficiency of the battery. [83]

$$RTE = \frac{E_{dis}}{E_{cha}} = \eta_{dis} \cdot \eta_{cha} \tag{7.4}$$

The RTE is equal to the square root of the charge and discharge efficiency of the battery, η_{cha} and η_{dis}, being the energy lost in the battery while discharging and charging, respectively. Energy losses can occur by high operating temperatures, internal resistance related losses or by auxiliary loads, for instance air-conditioning, (PCS) or ventilation. Response time or ramp time is the time the battery system needs to react and go from rest to rated power. Response time depends often on the chosen inverter for the battery. [83]

7.3.2 Lithium-ion battery characteristics

LIB has proven to be the most promising alternative when evaluating energy and power density. Therefore, LIB is frequently used in EV technology and ESS. Another commercial battery technology is Lead Acid batteries (LAB). The characteristic of these two state-of-the-art technologies are presented in figure 7.6. LIB have higher efficiency, reliability and an optimal specific energy to specific power ratio. [93]

Table 7.2: *Properties of LIB and LAB [88].*

Capacity factor	LIB	LAB	Unit
Sp. Energy	150 - 250	20 - 40	Wh/kg
Sp. Power	100 - 500	5 - 200	W/kg
Cycles	1 - 20	1 - 5	1000
Energy Efficiency	90 - 98	60 - 90	%
Temperature range	-20 - 50	-10 - 50	°C
VOC	3 - 4	2.05	V
SoC window	20 - 90	0 - 100	%

Both LIB and LAB batteries are suitable for large capacity storage application. Nonetheless, LIB is superior regarding this performance in limited areas because of the high energy density and output power density. Both LIB and LAB have a low self discharge. In frequent life cycling applications this loss is of little consequence [94]. The temperature range of LIB is greater, as well as the energy efficiency. Moreover, demonstrates exceptional performance in high power output applications, resulting in a better adaption for microgrids (Table 7.2). [95]

A disadvantage with LIB is the high internal impedance. Less than 80% of the rated capacity is available for LIB at a discharge rate of 2C compared to other batteries still having 95% of the rated capacity. However, LIB surpasses LAB battery in terms of performance. This is due to their lower internal resistance. During fast charging less heat is developed, which in turn decreases side reactions but increases efficiency. To help reduce the impact of discharge currents reducing the capacity, LIBs are sold in battery stack configurations. The SoC window for LIB is supposed to be between 20% and 90% because of the ageing rate, although only exploiting 70% of available energy reduces the actual battery capacity. [86, 88, 93]

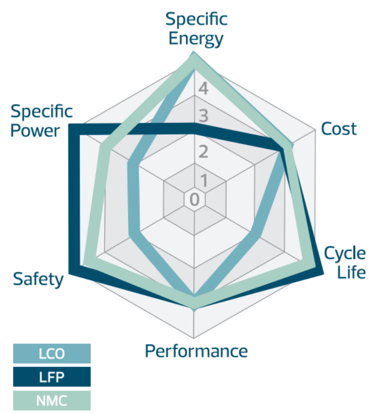

Figure 7.5: *Relative performance of LCO, LFP and NMC batteries [96].*

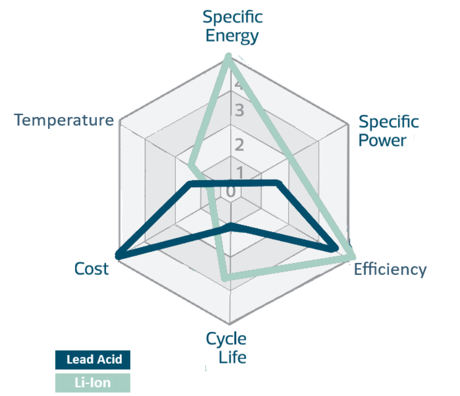

Figure 7.6: *Relative performance of LIB and LAB. This figure is recreated based on the original [93].*

Carbon-Graphite anode is the most prevailing anode material for LIB. The combination of graphite and hard carbon provides stability, low cost and high specific capacity. The most developed and commercial LIB is the Nickel Manganese Cobalt (NMC) battery. Other state-of-the-art chemistries include Lithium Iron Phosphate (LFP) and Lithium Cobalt Oxide (LCO) (Figure 7.5). LFP has high safety and long lifespan, however limited specific energy. LCO has a high specific energy but specific power is moderate. The NMC cell has a wider temperature range than LCO. Due to NMC's ideal combination of both high energy and power density, it is the most typical battery technology in grid-scale ESS. NMC usually has life cycles of 1 000–2 000, but can reach up to 5 000. This chemistry offers the highest efficiency and lowest cost. In terms of safety and lifespan, NMC shows an overall good performance compared to other LIB chemistry's. [93, 97, 98]

7.4 Other energy storage systems

ESS can work as a buffer to compensate for the effects of intermittent power output of RES and boost the efficiency of a microgrid. There are various storage system technologies such as, electrical, electrochemical, thermal, mechanical and hydrogen-related, illustrated in figure 7.7. Although the Norwegian power grid mostly rely on pumped hydro storage systems, BESS can offer to manage congestion in distribution networks. Whereas pumped hydro storage systems provide bulk power management, BESS have the ability to to solve the local grid problems and has no restrictions on geographical locations. [99]

Flow batteries are an electrochemical storage system. The energy is stored in electrolyte solutions in external tanks. The capacity of the system is related to the size of the external tanks, while power is determined by the size of the cell stacks. This storage technology is highly flexible in terms of energy, however the energy density is significantly lower than LIB systems. Additionally, this technology has a relative long discharge time, less suitable for supporting fast charging of EVs. [100, 101]

Storage technology such as supercapacitors are more suitable for response service. The energy is stored between two electrodes. Supercapacitors have higher capacitance than standard capacitors and are typically used for frequent life cycles at high current and short operation period. However, this technology has an excessively low energy density and high costs compared to LIBs. [100, 101]

Flywheels have the ability of storing the electricity as kinetic energy. When the energy is discharged, the kinetic energy is retreated. Conversely to batteries, flywheels do not degrade and are immune to the number of cycles. However this technology has some deficiencies, due to low energy density, high cost and poor discharge characteristics. [100, 101]

The heat in thermal energy storage can be converted to electricity by heat engines, typically applied to reduce power peaks in heating and cooling demands. Conversely, air is released and converted to electricity in gas turbines. Some disadvantageous are comparatively slow response time and low efficiency. [100, 101]

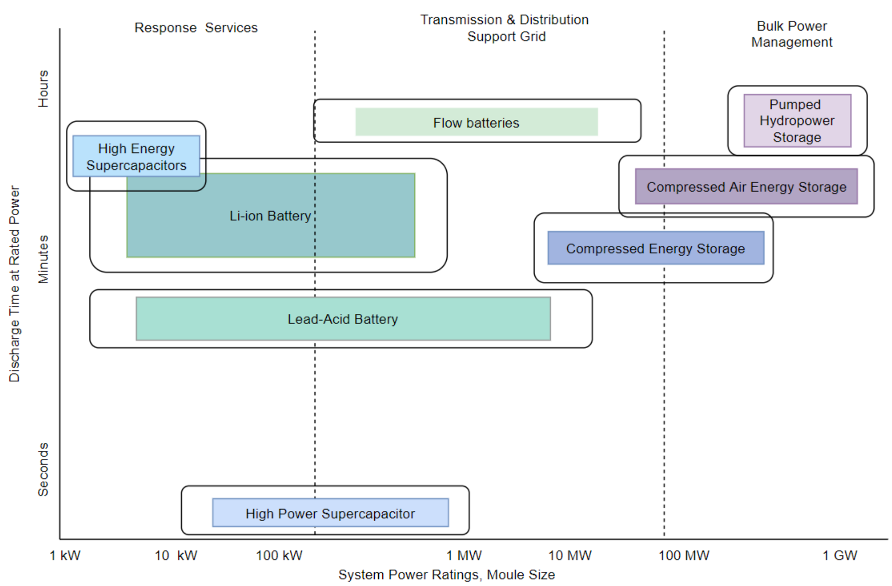

Figure 7.7: *Alternatives to energy storage systems. This figure is recreated based on the original [102].*

8 Case description

This case study implements the theory into two specific Circle K stations intending an installation and optimisation of fast chargers. Smestad, Oslo, and Sekkelsten, Indre Østfold, were selected by Circle K as case studies. The main focus is to design the stations adapted to charging requirements and available network capacity. For each *location* there are *three scenarios* with respect to three charging options: Grid Charging (GC), Simple Smart Charging (SSC) and Microgrid Enabled Smart Charging (MESC). Each scenario has *three cases* with two, six and twelve fast chargers. In total, two locations with three scenarios containing three cases of fast chargers will be presented. This study does only consider fast charging and specific technologies, principally photovoltaic system and battery energy storage system. 50 kW and 150 kW fast charging alternatives are analysed because of the increasing demand in faster charging technologies. However, all fast charging stations installed are assumed to be able to deliver 150 kW in order to consider future growth in the EV market. The two Circle K charging stations are described below.

To determine the required power capacity for an extension of the charging park, the difference between maximal capacity and the current power demand must be defined for each minute. Maximal available capacity at each Circle K station is calculated from equation 2.1 with further information explained in appendix A. Circle K Sekkelsten offers a higher transmission capacity with a TN-network at 400 V compared to Smestad with an IT-network at 230 V. The maximal capacity limit for each station is presented in table 8.1.

Table 8.1: *Maximal capacity limit for each station*

	Smestad	Sekkelsten
Capacity	193.21 kW	470.42 kW

8.1 Smestad, Oslo

In general, the Oslo region is in deficit of electricity. An overall increase of electricity consumption by 0.5% - 1% per year is expected, while the substations and cables around Smestad are reaching the end of their lifespan. Hence upgrading these components will become increasingly important. However, Statnett is currently developing a plan to improve the grid infrastructure in the centre of Oslo. This plan is designed to meet the electricity demand along with the electrification of the EV sector in the years to come. [103]

The Smestad intersection on the western side of Oslo is one of the capital's busiest regions (Figure 8.1). The intersection connects Oslo city with outer residential regions, like Bærum and Holmenkollen. As of today, the Smestad Circle K station, Viggo Hansteens vei 1, has zero fast charging stations. The closest competing fast charging stations are at Majorstuen (32 chargers) and Rikshospitalet (7 chargers) which are both approximately 2.7 km away. Oslo Kommune Skøyen (20 chargers) and Circle K at Skøyen (2 chargers) are both 2 km away. Figure 8.2 presents the daily average power demand for Circle K Smestad throughout a year.

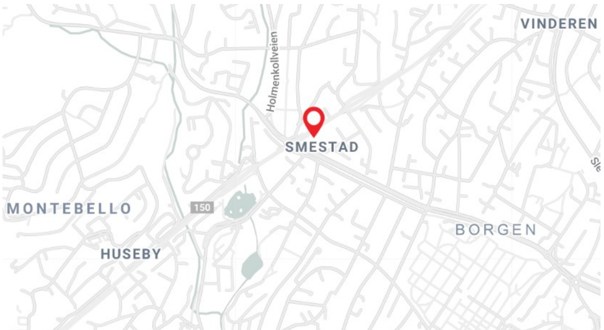

Figure 8.1: *Location of Circle K Smestad.*

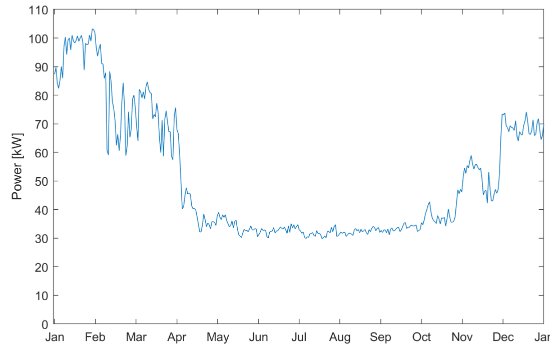

Figure 8.2: *Daily average power consumption at Smestad.*

8.2 Sekkelsten, Indre Østfold

Østfold is the area with the greatest electrical production in Oslo, Akershus and Østfold region. In total, Østfold produces approximately 4 500 GWh in a regular year. The largest power producers are Hafslund Production owning FKF, Vamma in Askim and Sarpefossen. Statkraft has power plants in Sarpefoss in Askim as well. The maximal power consumption in 2016 was 1 200 MW. Prognosis state that the power consumption will stagnate in Østfold in the following years. [104]

Sekkelsten is located in Askim, Indre Østfold (Figure 8.3). The 6.5 km motorway Momarken - Sekkelsten (E18) road has become a four-lane highway and is the main road for commuters and travellers from Sweden, for example Karlstad. Circle K Sekkelsten, Rakkestadveien 50, has already installed four 50 kW fast chargers. Other fast charging stations nearby are located 3.2 km away in the centre of Askim (6 stations) and 7.9 km away in Momarken (6 stations). Figure 8.4 presents the daily average power demand for Circle K Sekkelsten.

Figure 8.3: *Location of Circle K Sekkelsten.*

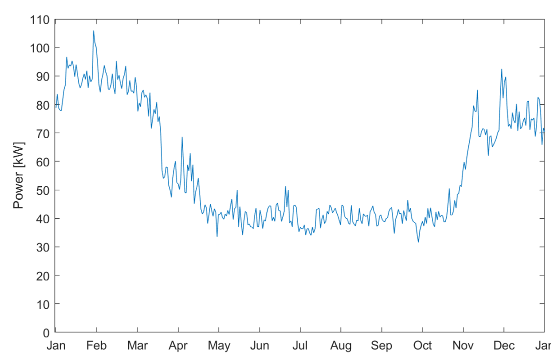

Figure 8.4: *Daily average power consumption at Sekkelsten.*

9 Methodology

This section explains the method and software used to achieve the results. A self-produced MATLAB script performed calculations and simulations of the presented scenarios. MATLAB is a software programme enabling the programmer to analyse data, develop algorithms and perform iterative analysis. Another software, called PVsyst 6.8.6, was used to calculate the annual solar power production. This software uses weather data from a database, named Meteonorm. Furthermore, MS Excel was applied for simpler calculations. All flowcharts represented in this section were designed through a programme called Drawio. Data input was gathered from reviewed literature and personal communication with Circle K, Siemens and Elvia.

Description of the programmed traffic patterns

The simulation of each case and scenario, is based on the local car intensity assumptions for Smestad and Sekkelsten. In order to estimate the cars and its respective power profile for the two Circle K stations, data from Norwegian Public roads was analysed in appendix B. These traffic patterns are based on two main assumptions: the amount of vehicles passing the station and the fraction of cars being electric vehicles. The daily intensity of EVs is estimated to be somewhat similar throughout the whole year. A distribution by percentage of cars per hour, was calculated considering the ratio between total cars per hour and cars per day. This percentage represents the probability of passing cars each hour. The more cars registered through an hour, gives a higher probability for a passing car. An algorithm generates random numbers from 1 to 1440 minutes a day, with a different probability for each minute.

When simulating the time arrival for each car, a random number between 1 and 1440 with a given probability is extracted. Importing a new randomised traffic intensity every day required a high run time for the code. Therefore, the simulation is simplified with same daily car intensity. Moreover, in order to calculate the minutely power demand from the EVs at the Circle K station, the examination of the car intensity is important. Generally, the amount of cars is relatively low in the night between 8 pm and 5 am and has a peak around 3 pm.

Further, data of the Circle K Kiellands Plass station provided by Circle K was examined to ensure the precision of the car intensity estimation at Smestad. The maximal amount of EVs is assumed to be 13 at 4 pm (Figure B.1), while a smaller peak of ten EVs is at 9 pm. Circle K Smestad has a total amount of 143 EVs estimated to charge in one day. On the other hand, no statistics were available to ensure precision of the assumption at Circle K Sekkelsten. However, a maximal amount of EVs is estimated to be four at 3 pm (Figure B.2). Circle K Sekkelsten has a total amount of 43 EVs estimated to charge in one day.

Description of the electric vehicle simulation

A matrix was created to simulate the daily amount of EVs arriving and departing at the Circle K stations. Each row in the matrix represents one EV. The matrix consists of six columns (A-F), which represent specifications for each car. Table 9.1 shows different conditions for each column. In every column of the matrix, a randomiser with conditions and probabilities was implemented.

Table 9.1: *Structure of the matrix used in the electric vehicle simulation*

A	B	C	D	E	F
Time of arrival	Time of departure	SoC	Desired SoC	Battery Capacity	Numerator

The time difference between column A and B is always between 20 and 50 minutes. The initial SoC of an EV arriving at the station is set to be between 20% and 50%. As for column D, the desired SoC is always defined between 70% and 90%. The time interval of the EV and its desired SoC are correlated by an estimation trough reviewed literature. However, literature shows relative ideal charging times, therefore the correlation is adjusted by adding 10 minutes to the ideal charging time. For instance, an EV with a small battery capacity requires longer time intervals at the station to reach its desired SoC. The battery capacity of the EVs can have six separate values. These values are influenced by the most sold EVs in Norway, described in section 4 and future cars being released in 2020 [50]. The probability of each type of EV arriving at the station is illustrated in table 9.2. The probability of the cars being able to charge at 150 kW is at 25% to get a more futuristic perspective.

To simplify calculations in the code, the last column was set as a numerator being equal to one, two, three or four in every row. State 1 defines that the EV has not charged at the station. State 2 means that the EV is charging, while state 3 represents a car having charged and left the station without considering the possibility to charge fully. State 4 defines the cars having arrived at the station, but having left after 5 minutes due to a long charging queue.

Table 9.2: *Probability of separate electric vehicles arriving at the charging station.*

EV Model	Capacity [kWh]	Probability [%]	Charging power [kW]
Nissan Leaf	40	40	50
VW e-Golf	38	29	50
Tesla Model S	85	14	150
BMW i3	42	12	50
VW ID.3	62	6	150
BMW iX3	70	5	150

Description of the charging simulation

Additionally, a code was implemented to compare the amount of cars with available chargers. While all chargers are occupied, the maximal charging time will be set to 30 minutes and the maximal state of charge will be set to 80%. When an EV has reached one of its maximal values, the charger will stop charging and the EV will have to leave. A flowchart representing the queue code, is illustrated in figure C.1 in appendix C. The corresponding queue-code to this flowchart starts before the main code. The queue code will also display the fraction of the cars being able to charge at 150 kW.

In order to charge the cars, the SoC at a certain time, t, is calculated by equation 7.2 in the charging code. The SoC will replace column C of the present cars every minute until other conditions obligate the charging simulation to stop. The EVs have different energy capacities and will therefore have different charging curves. Hence, the EVs will not always be able to charge at maximal power. Therefore, specific charging equation are implemented in the code for each car brand. The equations derive from the charging curves in appendix D. All four figures in appendix D represent the SOC of different battery capacities onto the speed of charge, charging with 50 kW or 150 kW. All cars being able to charge at 150 kW will follow the charging curve from figure D.4.

9.1 Simulation structure of Grid Charging

Grid Charging represents the scenario where all power is extracted directly from the grid resulting in increasing the capacity with grid expansion. Thus, GC can be seen as the exemplary scenario regarding technical results, due to its infinite capacity. This scenario will charge the cars only with power supplied by the utility grid to the station, illustrated previously in Set-up 1 in figure 6.1. The main focus is to design a new maximal capacity for each station. This will further contribute to supply the demand at the station without any smart charging. In other words, GC is defined as an uncontrolled control system. Losses through the cables and fast chargers are respectively 10% and 5%, (Appendix E).

9.2 Simulation structure of Simple Smart Charging

SSC, scenario two, is defined as unidirectional active control system. The electric vehicle, the controller and the chargers are the three elements in this system. The installed controller consists of an algorithm using available data in the current situation to organise charging and handle capacity problems based on regulations.

The simulation structure of SSC will mainly be based on load management explained in Set-up 2 in figure 6.1. In this scenario, the station will only consume electricity from the grid, however a balancing of load over the charging points is established to improve the grids stability and prevent power tariffs. Additionally, the total load will not exceed the station's capacity limit. The flowchart below is presented to portray the simulation structure (Figure 9.1).

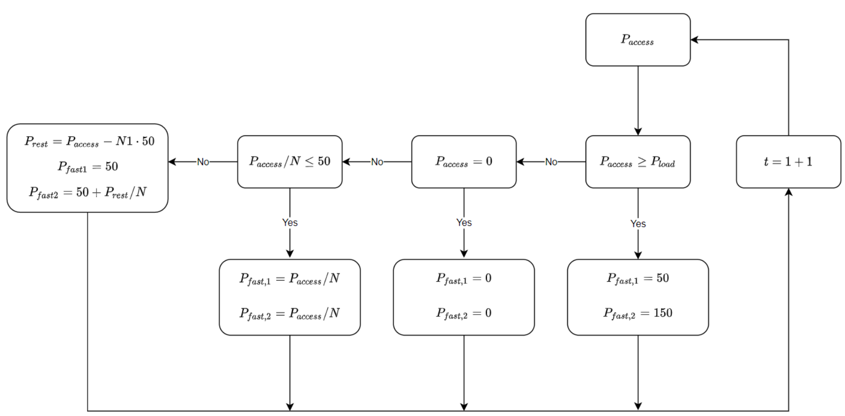

Figure 9.1: *Flowchart of the SSC simulation.*

Load Management Simulation

When the capacity is close to its limit, load management will force the system to divide the total available charging power by the amount of charging EVs. The individual charging power at each charger will occasionally be lower than the maximal charging power. The simulation, illustrated in figure 9.1, is programmed to prioritise charging all EVs at 50 kW. If more power is desired for singular cars, the simulation will thereafter divide the total available power and add the remaining power to the car wanting to charge at 150 kW. Losses are similar to the previous scenario, however it is not illustrated in the flowchart.

9.3 Simulation structure of Microgrid Enabled Smart Charging

In this thesis, scenario three describes a DC microgrid including solar panels and battery energy storage as the main DER and DESS units. Moreover, regarding the power output of PV systems, BESS and charging stations, a DC grid is more beneficial than an AC grid. Hence, the use of converters and losses associated with the AC–DC energy conversion is reduced. MESC is therefore defined as a DC bidirectional active control system.

The simulation of MESC is structured in several layers. The main layer will represent the microgrid controller (MGC), combining and evaluating all information from the sublayers. The following flowchart portrays the MATLAB code of the MGC, describing the main layer (Figure 9.2). The green and red boxes define the beginning and the end of the code respectively. The main code starts running after gathering all information from grid, BESS, PV system and amount of EVs. At the end of the code, the MGC will decide if the present EVs will be charged by fast charging or load management. If the battery system is not able to support the station with sufficient power, fast charging at full speed is not possible. The MGC will also define the elements of the MESC contributing to the charging process. The yellow boxes illustrate the sale of excessive electricity to the utility grid. After this main code has run, the charging station code, describe previously, will run.

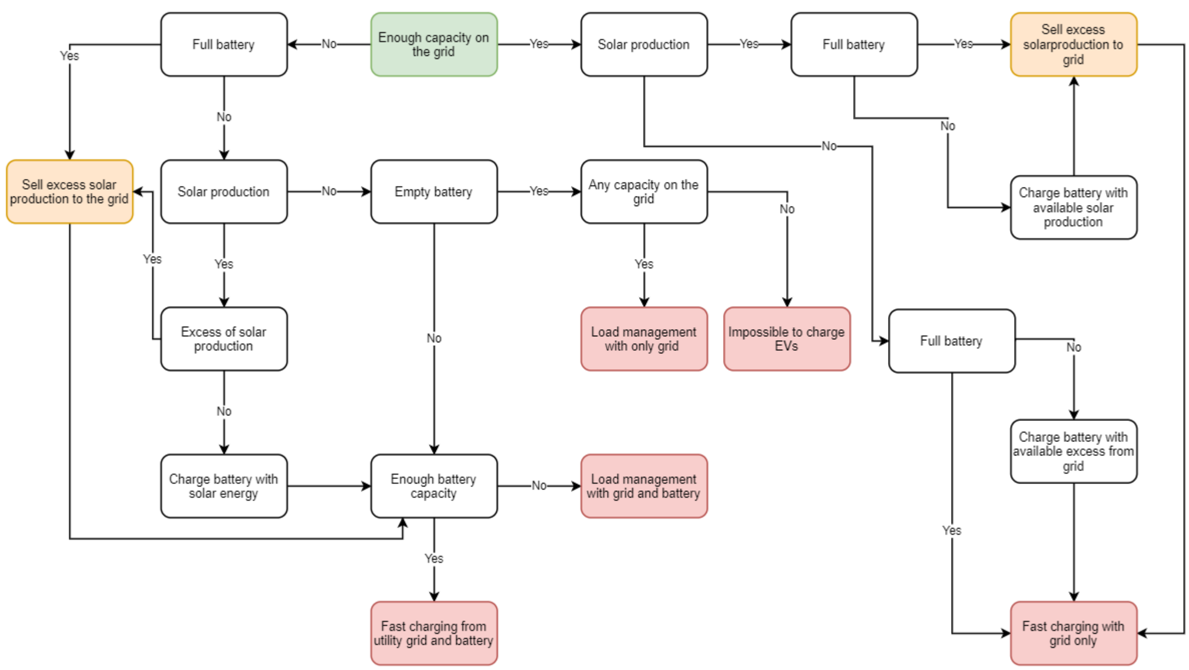

Figure 9.2: *Flowchart of the main layer of the MESC simulation.*

In the flowchart, an *excess of solar production* signifies too much solar energy compared to the available DoD of the stationary battery. Excessive sun power will continuously be sold to the grid, since the PV system will not be able to charge the EVs directly. The battery in the microgrid will work as a energy reserve when the utility grid is not able to cover the demanded energy from the station.

Flowchart 9.2 is a simplified version of the following flowchart and presented to display the main purposes of the MGC. The flowchart in figure F.1 in appendix F illustrates the complex code implemented in MATLAB. The red boxes in the code represent the end of the main code and thereafter the current EVs will be charged in the charging simulation. Figure F.1 does only illustrate the MGC's function at the presence of EVs at the charging station. Furthermore, the flowchart presented in figure G.1 in appendix G describes the functions of the MGC at the absence of electric vehicles.

Although losses are not mentioned in the flowchart, they are included in the code. Losses in fast chargers and cables are similar to the previous scenarios. Other losses from the efficiency of the inverter in the sale of solar energy, are also included. The efficiency of the inverter between the microgrid and the public grid is equal to 94%. The efficiency of the converter between the PV system and BESS is equal to 96.5%. Moreover, the efficiency of the rectifier from the utility grid to the DC grid is at 81%. All losses of electrical components are presented in appendix E.

Simulation of the battery energy storage system

The stationary storage system in the microgrid is equipped with two separate NMC batteries to ensure longevity of each individual battery. For instance, battery A will discharge to feed the electric vehicles, while battery B is charged by the solar energy. At the beginning of the simulation, the batteries will have an SoC equal to 90%. None of the batteries will be discharged under a SoC of 20%. The charge and discharge simulation of the stationary batteries is illustrated in the following figure 9.3.

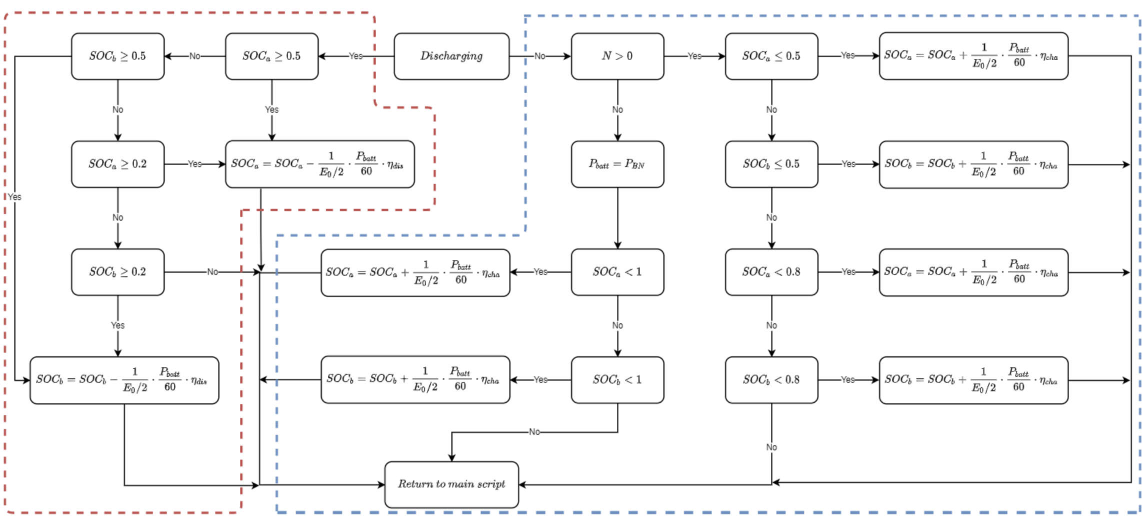

Figure 9.3: *Flowchart representing the charge simulation of the stationary batteries.*

The flowchart illustrates three separate codes called *charge*, *discharge* and *constant*. The charge code is consistently the first one to run at each minute. The discharge will follow with the condition of insufficient available power, otherwise the constant code will proceed, keeping the SoC of the BESS, SOC_s, constant. The charge code is displayed in blue on the right-hand-side of the flowchart, while the discharge code is in red on the left-hand side. The charge code has a variable defined as $check$. This variable preserves the rule that a battery cannot charge in the same time period as it discharges.

The State of Health is also considered during the charging and discharging of the batteries to calculated the decrease of SoH of the BESS after a regular year. Equation 7.3 is implemented in the charge, discharge and constant code to get reasonable results.

9.3.1 Dimension of the photovoltaic system

The dimension of the photovoltaic system in the microgrid is assumed out of the present rooftop space available at the stations. The rooftop surface was estimated using Google Maps and Solcellekraft.no. Both PV systems at Smestad and Sekkelsten are facing south with an inclination of 30°. The solar panels are assumed to be perfectly cleaned and free of snow throughout the year, thus the annual power production might be enhanced. Table 9.3 presents the designed PV system of both Smestad and Sekkelsten, including the amount of panels, installed power and annual production.

Table 9.3: *Dimensions of the photovoltaic system for both sites.*

	Smestad	Sekkelsten
Rooftop surface	$300m^2$	$100m^2$
Amount of panels	188	60
Installed power	60 kW	19 kW
Theoretical production	56 000 kWh/yr	17 800 kWh/yr
Empirical production	24 000 kWh/yr	9 000 kWh/yr

The technical methods and output values do not correspond with the economic solar data presented in appendix H, hence the simulation is simplified. The technical approach of calculating the solar power production utilises PVsyst. Each panel consisting of 60 cells can deliver 275 W. Smestad and Sekkelsten include 120 and 60 solar panels respectively. The annual solar production of the simulation presents half of the theoretical production, however the efficiency used in PVsyst, 14.7%, is considerably lower than the theoretical, 19%. [105]

The power produced by the PV system is hourly measured values, these values must be replicated 60 times to complete all input values in the minute simulation in MATLAB. Furthermore, all minute values is equal in the same hour, variations during one hour are not accounted for. Eventually, in order for the PV system to charge the battery, the voltage output has to be corresponding or higher. A converter is required to perform this voltage scaling.

9.3.2 Dimension of the stationary battery system

The stationary battery system has to be designed in order to give an optimal electricity supply to the microgrid in periods with low capacity. The batteries are estimated to have a RTE of 86%. The discharge and charge efficiency is calculated to be 93% by equation 7.4. Typically, the stationary battery has a certain response time, going from rest to rated power. However, since the response time usually is lower than one second, it will be neglected in the simulations. The data used to define the batteries technical data is in presented in table I.1 in appendix I.

The load should be satisfied for every hour; i.e. the power available from the main grid and the BESS should be sufficient to charge the amount of electric vehicles. Therefore, the capacity of a battery energy storage is sized for different amount of chargers. The size of the stationary battery is optimised considering technical and economic aspects. At first, the technical aspect is analysed. The minimum ideal required capacity of the battery, is calculated by equation 9.1 if no efficiencies and losses are considered. Here, P_{load} is the power needed to charge the EVs currently at the charging station, while P_{access} and S_p respectively describe the accessible power from the utility grid and the power generated by the solar modules. Hence, the available power is the sum of these two components. Losses from converters are considered in the calculations. [106]

$$E_{0,min} = \int_0^t P_{load} - (P_{access} + S_p)\, dt, \;\; P_{load} > (P_{access} + S_p) \tag{9.1}$$

This equation is applied only when power of the load is higher than the available power. By integrating these periods with respect to the time t, the minimal required amount of energy the battery is defined. Dividing the energy by the discharge efficiency, the required capacity will be defined for each day. Moreover the EoL of the battery and the SoC-window has to be considered. The battery has reached its EoL when SoH is equal to 80% and the estimated State of Charge window will be between 20% and 100% and therefore have a 80% range. These two factors will also divide the energy of the battery (equation 9.2). [88]

$$E_0 = \frac{E_{0,min}}{\eta_{dis} * 0.8 * 0.8} \tag{9.2}$$

Since the car intensity in the electric vehicle simulation is random to a certain degree, the required battery capacity varies for every new car matrix. Therefore, ten values of battery capacity for each scenario are sampled and the average of the data is implemented. All averages are rounded up to the nearest 500 kW. In cases with significantly lower battery capacities, for instance below 100 kW, the capacities were rounded up to the nearest fifty. At two chargers at Sekkelsten, the demand is so insignificant that a battery is not necessary. Hence, a 50 kW is designed in order to simulate MESC. Usually batteries should not be able to perfectly cover the worst day in a microgrid. Therefore, the dimension of the battery is designed to have the ability to supply the station ideally 95% of the year. All final technical dimensions are presented in the following table 9.4. The economic data is presented in section 11.6.2.

Table 9.4: *Dimensions of the stationary battery for both sites.*

	Smestad			Sekkelsten		
Charging stations	2	6	12	2	6	12
E_0 [MWh]	2 000	7 500	8 500	50	500	500

The C-rate will in general vary with the energy capacity of the battery and power demand. To calculate the required discharge C-rate, equation 7.1 is applied, where E is the available energy capacity of the stationary battery and P is the total maximal power needed in that moment. Nonetheless, the discharge C-rate is decided to never be higher than 1.5 C. The charge C-rate will vary considering if it charges from the utility grid or the photovoltaic system. When the battery charges from the utility grid, the C-rate will be the optimal C-rate equal to 1. Otherwise, the charge C-rate will be calculated the same way as the discharge C-rate except that P will represent the power delivered from the photovoltaic system.

9.4 Sensitivity analyses of technical parameters

A sensitivity analysis is a methodology applied to assess how sensitive key results react to minor changes in input parameters. A sensitivity analysis is conducted in this thesis to analyse the preciseness of estimations and gathered information in this project. Three input parameters are inspected: the estimation of traffic patterns, the life cycles of the BESS and the capacity of the BESS.

9.4.1 Traffic patterns

The traffic pattern is one of the most influential factors for all scenario simulations throughout this project. Hence, imperfection and imprecision in the estimation of traffic pattern must be evaluated by a sensitivity analysis to understand the extent of its impact. The definite estimation for the following results explained in appendix B is therefore shaped in a more optimistic and a rather pessimistic perspective by including other factors.

In this sensitivity analysis, Sekkelsten and Smestad will both be analysed in order to evaluate the impact of the traffic flow in the microgrid system. In appendix B, the estimations have some uncertainties and therefore, the purpose of this sensitivity analysis is to define if a change in traffic patterns would lead to a better user experience in scenario three. Since the competition is pretty low around Sekkelsten, it might be possible that the car intensity shows a higher number in reality, while for Smestad, the competition is relatively high, maybe resulting in lower traffic flow.

Accordingly, all stations will have new battery capacities since the daily load increases with greater car intensities. Therefore, new battery capacities are calculated with the same method from section 9.3.2. All dimensions with unit of kWh are presented in the following table 9.5.

Table 9.5: *Dimensions of the stationary battery for the sensitivity analysis of traffic flow.*

	Smestad			Sekkelsten		
Charging stations	2	6	12	2	6	12
43 EVs	1 000	2 000	2 000	50	500	500
93 EVs	2 000	4 500	5 000	100	1 500	2 000
143 EVs	2 000	7 500	8 500	100	3 000	4 500

9.4.2 Battery energy storage system

The BESS is one of the most important components in the microgrid. Moreover, the stationary battery itself has multiple properties affecting the battery's performance. Determining factors influencing the specific battery capacity are traffic patterns, number of chargers and capacity limit. Therefore, two factors in the BESS are evaluated by a sensitivity analysis: the life cycles and the battery energy capacity.

Life cycles

The life time of a battery depends especially on the battery's life cycles, calendar life and shelf life of a battery are difficult to estimate regarding fast charging. However, there are few reviewed literature stating a specific number of life cycles. Therefore a sensitivity analysis was conducted considering four different life cycles at 1 500, 2 000, 3 500 and 4 000, in order to evaluate how the microgrid affects the life time of the battery. During the simulation of the microgrid a variable, SoH, is implemented to analyse the batteries state at the end of one year with an operating SoC-range of 20% to 100%. In order to implement this analysis all cases at Circle K Smestad are evaluated. The reason for selecting Smestad is due to the battery capacity varying more for each number of chargers compared to Sekkelsten.

Battery capacity

In order to analyse the battery capacity, Smestad with six chargers is evaluated for an incremental with 10% of the maximal capacity. The size of the battery capacity may consequently affect the customer experience. To understand this influence and the reason more specifically a sensitivity analysis is conducted by examining how the charging performance, power performance and *drop-out* rate is affected with a decreasing battery capacity. Furthermore, this analysis can provide a better indication of the influence on the technical parameters by adjusting the battery capacity.

9.5 Delimitations

Throughout the composition of all three scenarios, simplifications and assumptions have led to delimitations impacting the outcome of all simulations. The main delimitations considers the grid capacity, traffic patterns, load profile and the microgrid components.

In events of high demand, a short period of approximately 30 minutes can overload the electrical components. This is considered when determining the connection charge with respect to the "free limit". This implies that exceeding the capacity limit can occur a few times without damaging the main components. However, while simulating, these overload periods are not considered. Consequently, the results are affected negatively.

The group and the contributors were challenged to gather specific information, such as the statistics of charging patterns. Electric vehicles analysed in this report will be average passenger cars, shorter than 5.6 m. Other vehicles like trucks are not considered. In addition, some passing cars are categorised as invalid registrations leading to lower amount of registered vehicles. The annual simulation is based on the same daily car intensity, although multiple samples reduce the standard deviation of the results. All arrival and departure times are estimated as integers, impacting the accuracy of the traffic patterns. The correlation of the desired time interval and state of charge of the customers is somewhat imperfect, implying that the final State of Charge might not be perfectly realistic. The charging EVs need only to reach one of the desired properties, SoC or departure time. Moreover, the outside temperature affecting the battery and the degradation of the EVs battery will not be considered, enhancing the SoC again. Finally, every charging customer is treated equally. Hence, advantages for privileged customers are not taken into account.

The daily power demand of both Circle K stations was taken into account and substituted from the overall load profile to isolate the EV load profile. Hence, all results concerning the electricity bill and the available maximal capacity do only account the power demand from the EVs. For Sekkelsten, it is unclear if the previously four installed fast chargers are included in the provided daily power demand. Therefore, it is assumed that all four chargers are included and not taken into account in the calculations of the EV load profile.

Since a monthly table for electricity prices has been implemented, daily variations are not accounted for. The monthly prices are extracted directly from the Nord Pool group and are therefore not directly related to power suppliers own prices. Variations in electricity prices may affect the electricity bill.

While analysing the elements in the microgrid, the assumed power losses of the components are theoretical. Power loss in cables and transformers are estimated by Circle K, other losses are retrieved from reviewed literature. However, the impact of the losses may not have a great influence on the final conclusion. Secondly, the high penetration of distributed generation units in the microgrid can degrade the power quality due to intermittent power output, is not considered. Finally, some of the microgrid components are seen as improved, thus overall results might be enhanced. Since there are no costs related to the investment of a microgrid controller and the costs considering the overall installation of the microgrid, the expenditures related to scenario three may be lower. However, this is assumed to be a minor investment, compared to the installation of fast chargers and batteries. Moreover, the microgrid controller involves no voltage and frequency regulation of the whole microgrid system.

The battery storage system will only assist the Circle K stations and does not account for the grid company's objective. Hence, the function of the BESS is to control the demand peaks and the charging station rather than voltage regulations in the distribution network. Hence, the BESS is considered a BTM application, only providing services related to the station. However, the BESS may support the microgrid controller by regulating voltage and frequency in the DC microgrid itself. This aspect was not examined while designing the battery and may hence impact the quality of the microgrid. Nonetheless, if accounting for this in the control structure of a DC microgrid, the grid may be less susceptible to problems in voltage control.

In the charging process, without additional energy supply, the microgrid will prioritise charging the electric vehicle rather than the stationary battery. Solar generation will only charge the stationary battery, not the EVs. In addition, the PV system only presents hour-based power values, all minute values within the same hour will be equal for the MATLAB code. Variations during one hour are not accounted for and can cause inaccuracy. This simplified model can therefore exclude diversity of minutely sun production, thus the solar power aspect is minimised in this thesis.

The battery can also be charged by the utility grid. However, there is no simultaneous charging combination between solar and grid energy. For this case study, the battery storage system is considered charged with clean electricity. Nonetheless, the battery itself will exclusively charge the EVs, thus no battery energy is sold to the utility grid. Some parameters, such as the efficiency, the available capacity, and the lifetime, depend on the operating temperature range of the BESS, which is not considered. Moreover, the equation applied to calculate the minutely SoC of the BESS is simplified, leading to faster charging and discharging times.

As mentioned in section 5, fast chargers require access of 400 V AC. Circle K, Smestad is located in an IT network with 230 V, hence a transformer need to be installed in order to step up the voltage to 400 V. This is not accounted for in this thesis, due to limitations. However, the grid infrastructure might be upgrade eventually. Therefore, it is estimated that the IT becomes a TN network in the near future.

10 Technical results

This section presents all technical results deriving from the simulations described in the previous section. For each scenario, different parameters are studied in order to examine the performance of the stations. In addition, the GC performance is considered the "ideal" scenario, hence SSC and MESC scenarios are compared with the technical performance of GC. In all three scenarios three parameters are consistently put forward: $SoC_{\%}$, $SoC_{80\%}$ and *drop-out*. All parameters have their corresponding standard deviation resulting from ten samples. Detailed results according to the three scenarios can be found in appendix O.

The first element, $SoC_{\%}$, describes the fraction of the customers having reached their desired SoC, while $SoC_{80\%}$ represents the fraction of the customers having reached 80% of their desired SoC. Thus $SoC_{\%}$ will always be less than $SoC_{80\%}$. These two variables will be described as *charging performance*. Since the correlation of the EVs time interval and their desired SoC is imperfect, $SoC_{\%}$ might not give a realistic result. Therefore, $SoC_{80\%}$ is introduced to observe the EVs achieving a satisfactory SoC. The third parameter, *drop-out*, represents the amount of cars having left the station due to a long waiting time. These cars represent state 4 in the EV simulation. The percentile of $SoC_{\%}$ and $SoC_{80\%}$ does not take into account the *drop-out* cars. Further, the *drop-out* rate can be described as the effectiveness of the management of the car intensity. Eventually, for the two last scenarios, another parameter is introduced, *power performance*, to analyse the cars being able to charge at 50 kW and 150 kW. All following presented results derive from an average of ten different samples, including the corresponding standard deviation. Eventually, *drop-out* rate, charging and power performance will describe the customer experience, whereas an optimal user service includes short waiting and charging time.

10.1 Scenario 1: Grid Charging

Figure 10.1 and 10.2 present the maximal power load of two, six and twelve fast chargers in comparison to the maximal available capacity. Moreover, the black line in each graph represents the maximal capacity at each station. Both maximal capacities are calculated from equation 2.1 and presented in appendix A.

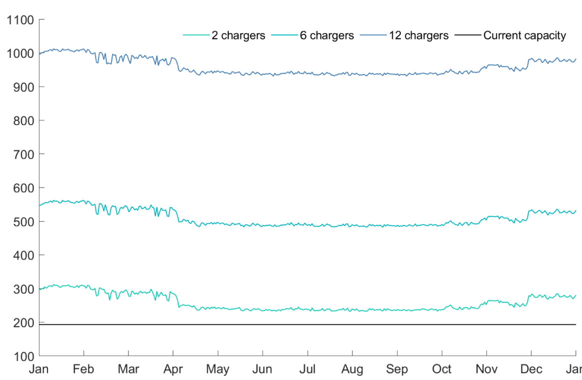

Figure 10.1: *Daily power peaks compared to current capacity. Every number of chargers exceed the black line due to higher car intensity at Smestad.*

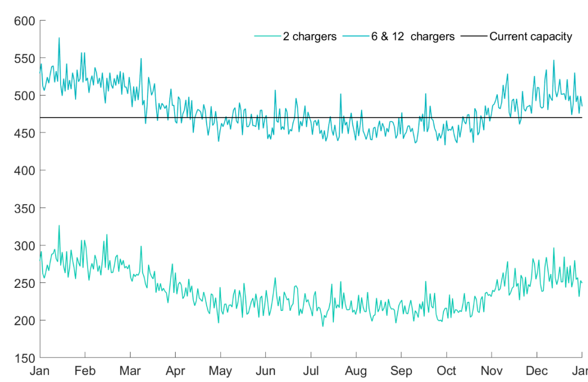

Figure 10.2: *Daily power peaks compared to current capacity. Six and twelve chargers will have the same daily power peaks due to lower car intensity at Sekkelsten.*

The presented load profiles are constant throughout all scenarios and give a realistic representation of the supplementary capacity needed to install fast chargers without any smart charging. Figure 10.1 gives an overview of the EVs power demand from Smestad fast charging station compared to the cables and substation's capacity limit. This required power demand is calculated in order to meet the demand of two, six and twelve chargers. Every situation exceeds the capacity limit at 193.21 kW for Smestad. On the other hand, figure 10.2 presents the EV load for Sekkelsten. Although, the demand of two chargers does not exceed the capacity limit of 470.42 kW throughout the whole year, six and twelve charger surpass the limit during winter months.

Figure 10.3 represents the technical results of the Grid Charging scenario for Smestad and Sekkelsten. This operation will not display the results of power performance since both variables will be at 100%, due to the extension of the capacity limit.

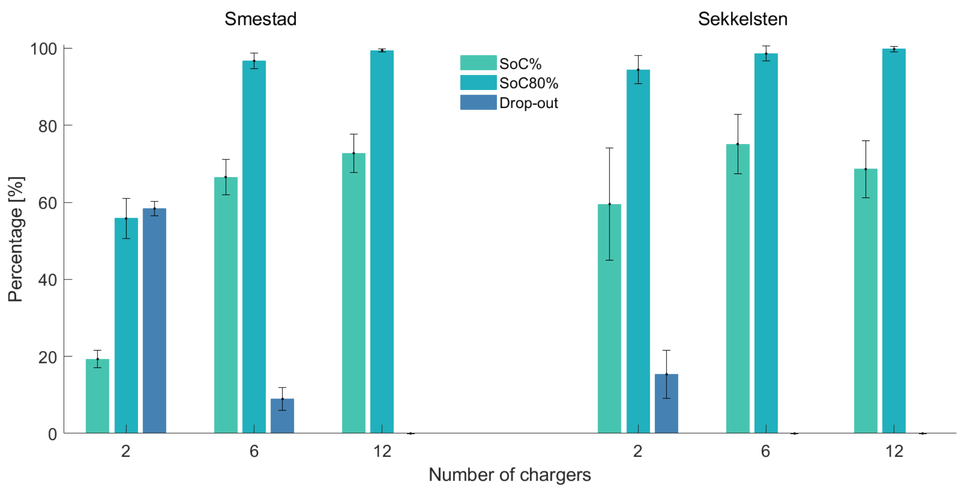

Figure 10.3: *Charging performance and drop-out rate of the GC simulation.*

In general, increasing the number of fast chargers results in a higher amount of EVs reaching their desired SoC, as well as 80% of their desired SoC. However, this increase is generally greater from two to six than from six to twelve. One outstanding value in this trend is the lowered $SoC_{\%}$ parameter for twelve chargers at Sekkelsten. Anyhow, the high standard deviation might still indicate a similar pattern as Smestad. At both stations, the standard deviation of $SoC_{80\%}$ reduces with an increase of chargers. Nevertheless, the standard deviation of $SoC_{\%}$ remains irregular. Comparing the two stations, Sekkelsten shows a higher charging performance than Smestad. Albeit, these parameters become progressively more resembling. Moreover, for two fast chargers the *drop-out* percentage at Smestad is above 50%. The rate decreases immensely for six and twelve chargers. On the other hand, the overall *drop-out* rate is better at Sekkelsten. After all, the *drop-out* rate is already relatively low at two chargers and zero thereafter.

10.2 Scenario 2: Simple Smart Charging

Figure 10.4 and L.1 in appendix L display the technical results of the Simple Smart Charging scenario for Smestad and Sekkelsten. Figure 10.4 illustrates the charging performance and *drop-out* rate, while figure L.1 represents the power performance. All parameters are expressed in percent. The power performance does not take into account the EVs having left the station without charging or the time in the absence of cars. Moreover, in this scenario the maximum capacity limit is not changed nor exceeded, and therefore no load profiles are presented.

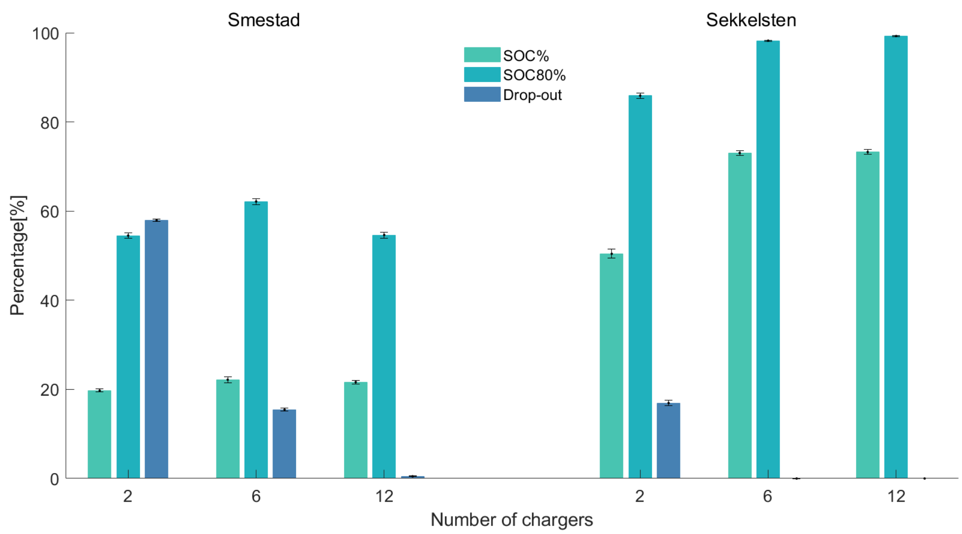

Figure 10.4: *Charging performance and drop-out rate of the SSC simulation.*

At Smestad, a higher number of fast chargers does not necessarily result in higher charging performance, similarly with P_1 and P_2. The best charging performance is at six chargers, while the power performance is highest for two chargers and decreases by adding chargers. Moreover, P_1 is always superior to P_2.

Compared to the operation at Smestad, the charging and power performance at Sekkelsten is distinctively greater. There is a significant improvement in charging performance from two to six chargers. On the other hand, from six to twelve, both variables stagnate. Regarding the performance of Sekkelsten in scenario one, the charging and power performance are relatively alike. The power performance decreases slightly, but stays relatively constant.

Anyhow, similarly to Smestad, the *drop-out* patterns of Sekkelsten are decreasing with an increase of chargers. Further, in comparison with Grid Charging, the *drop-out* rate is relatively similar.

10.3 Scenario 3: Microgrid Enabled Smart Charging

Figure 10.5 and L.2 in appendix L illustrate the results from the microgrid simulation with a BESS and a PV system. Figure 10.5 displays the charging performance and *drop-out* rate, while figure L.2 shows the power performance of both locations. All cases have a battery capacity covering 95% of the exceeding power demand throughout the year.

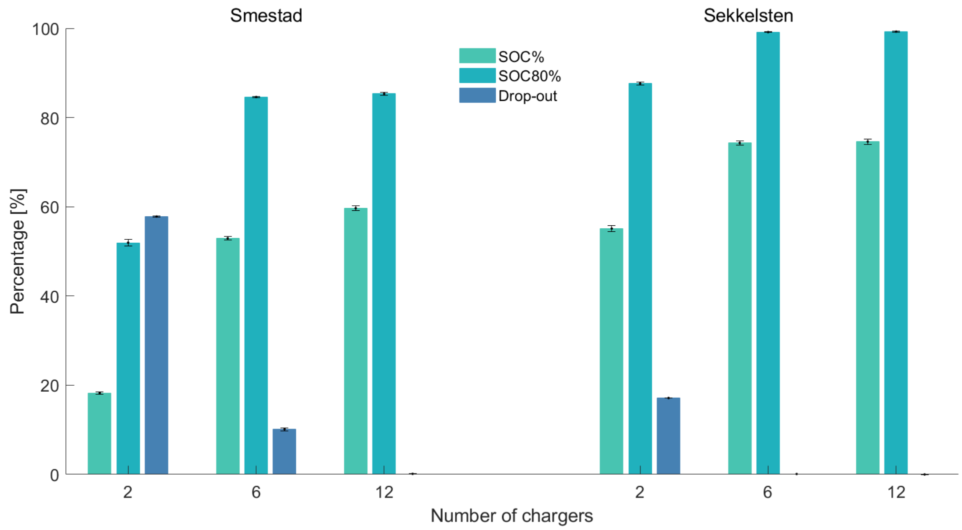

Figure 10.5: *Charging performance and drop-out rate of the MESC simulation.*

At both locations, the charging performance increases with a higher number of chargers. Similar to Grid Charging, the values slightly stagnate after six chargers. The maximal charging performance is already reached with six chargers at Sekkelsten which demonstrates the same trend as scenario one.

The power performance is overall better at Sekkelsten and is nearly at 100% in every case. Furthermore, Smestad has a higher power performance at two chargers. These parameters decrease nevertheless at six and twelve to around 80%. Moreover, the *drop-out* rate shows similar patterns compared to Simple Smart Charging and Grid Charging.

10.4 Results of the sensitivity analyses of the technical parameters

The results from all three sensitivity analysis are presented subsequently. These results will clarify the importance and effects of certain input values for the main results. Furthermore, the outcome of the sensitivity analysis might question the original assumptions and methodology.

10.4.1 Traffic patterns

A traffic pattern sensitivity analysis in scenario three is presented to illustrate how well the chargers handle different number of customers. Figure 10.6 represents the impact of the daily traffic flow regarding the charging performance at the stations. Three different car intensities are evaluated: 43, 93 and 143. These include the original traffic flow for both Smestad at 143 and Sekkelsten at 43. These initial car intensities are highlighted with a dark blue frame. Smestad seems to show the same pattern for each case and the $SoC_{\%}$ rate increases with increasing number of chargers but decreases with more intense traffic flow.

Furthermore, Sekkelsten has the same trend as Smestad at two and six chargers. Although, at twelve chargers, the $SoC_{\%}$ value is alike for 43 and 143 daily EVs at the station. In general, both locations present a similar overall performance. However, one parameter stands out in particular, regarding twelve chargers at Sekkelsten. For an intensity of 93 vehicles, the SoC drops to around 60%, this is considerably lower than for 43 and 143 vehicles.

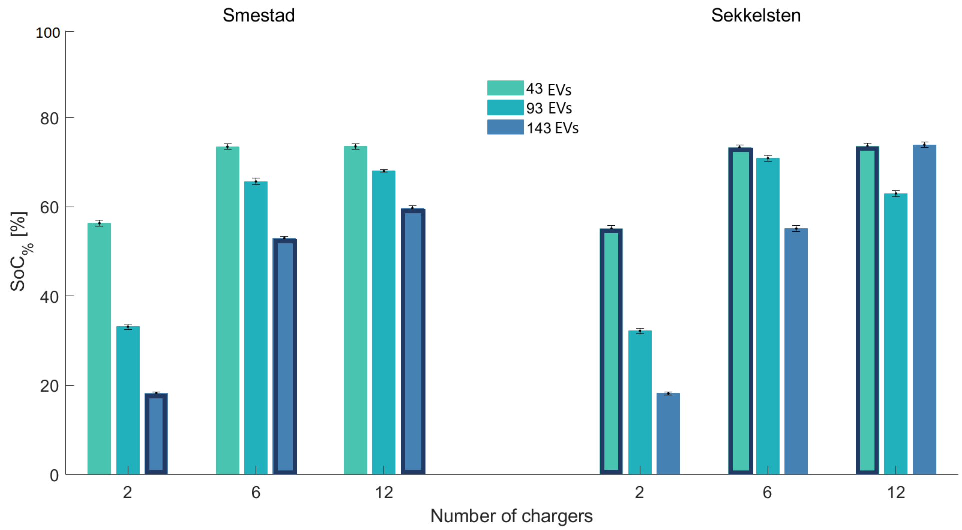

Figure 10.6: *Sensitivity analysis of the MESC simulation with varying traffic patterns related to charging performance. The bars with dark edges illustrate the original car intensities with their respective cases.*

10.4.2 Life cycles

The BESS is tested with relevant number of cycles to illustrate how different operations of the battery, affects the lifetime after one year. According to figure 10.7, an increase of designed number of cycles will improve the SoH. The lowest SoH occurs for the battery designed for two chargers. Hence, the case with two chargers will faster reach its EoL at lower life cycles. However, at 4 000 life cycles, all chargers have approximately the same SoH rate. The sensitivity analysis is performed for Smestad, because this location includes more variation of the load profile and hence the battery capacity.

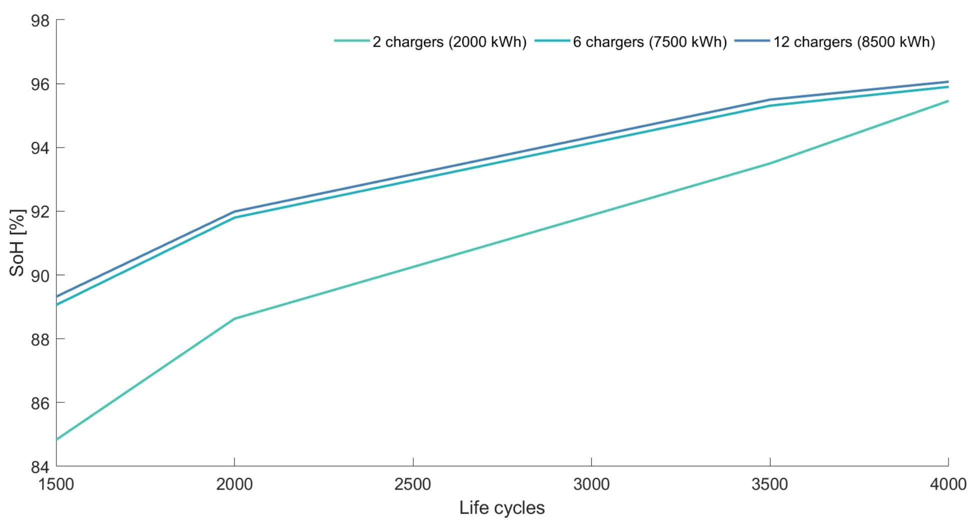

Figure 10.7: *Impact of life cycles and chargers on State of the Health of the BESS at Smestad with six chargers.*

The SoH and SoC are correlated, therefore a typical daily SoC curve for one day at Smestad with six chargers is presented in appendix M in figure M.1 in order to understand better the behaviour of the SoH of the battery. Figure M.1 illustrates that the SoC typically is around 23% in this simulation and increases in the morning while it decreases after 8 am during the day. Between 6 pm and 9 pm hardly no energy is fed to the battery and at nighttime the battery is charged from the central grid.

10.4.3 Battery capacity

Figure 10.8 illustrates a sensitivity analyses of the battery capacity's influence on technical performance. Increasing the battery capacity will directly influence all technical parameters, analysed for the case of six chargers at Smestad. The reason for presenting this case is to establish a basis of comparison with the technical and economic aspect. Another factor is the development of the technical curves in respect to the battery capacity being more interesting for six chargers. Additionally, Smestad has more exceeding power load compared to the capacity, resulting in a higher battery capacity.

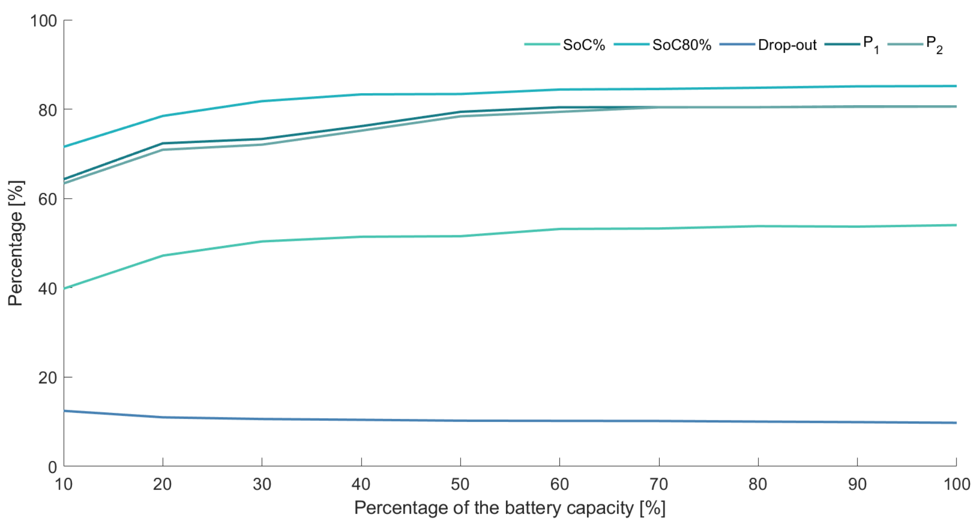

Figure 10.8: *Sensitivity analysis of the increasing battery capacity at Smestad with six chargers, regarding the technical aspect.*

Every parameter, except for the *drop-out* rate, presents a stable behaviour after reaching 60%. Both SoC parameters present a similar curve, however SoC_{80} has an overall higher charging performance than $SoC_{\%}$. Furthermore, the power performance shows a similar curve for both P_1 and P_2. An increase in performance can be observed until reaching 60%, hence a stagnation can be noticed. The least influenced parameter is the *drop-out* rate, which decreases slowly, but only with a magnitude of 2%. Although it remains relatively constant, it presents an interesting result in comparison with the other technical parameters.

11 Economic assessment

Although forecasts show that Norwegian electricity prices, including spot prices and grid rent, will increase substantially, the customer's electricity bill will be reduced by the development of smarter energy systems. Furthermore, the relation between advanced technology and the rate of electrification can contribute to decreased costs of DER and DESS, especially for technology related to solar panels and battery storage. To decide Circle K's economic limit before the installation of fast chargers becomes unprofitable, the annual revenue of all scenarios are compared. Each scenario has an economic assessment, regarding capital and operational expenditures, as well as the income from the fast charging stations. In the economic assessment the car intensity is halved during public holidays, such as Easter or Christmas. This corresponds to fifty days in a year of 360 days with a reduce amount of electric vehicles.

Circle K's economic base is mainly established on the car intensity and, for scenario three, the battery capacity. Both parameters affect the income and electricity bill. For scenario one and two, the difference between the income from fast chargers and the electricity bill will mainly describe the annual profit. While the profit of the third scenario will be defined as the difference between the income, the electricity bill and the total expenses of the distributed generation units. These variable parameters depend on the number of installed fast chargers.

This thesis is first and foremost a technical report, thus the economic aspects are minimised. Information regarding several aspects were estimated by Circle K, such as investment and operational costs of fast chargers, discount rates and salary. Every result represents an average of ten annual simulations, in order to reduce the standard deviation deriving from the electric vehicle simulation. Along the economic assessment, a conversion course of 10.51 NOK per USD, from the 16th of April 2020 is applied. The financial life time of the project, l, is equal to 8 years. The interest rate, r, is set to 4%. Operational cost, OM, includes maintenance of fast chargers, salary and auxiliary costs.

11.1 Economic analysis of fast chargers

The charging prices of fast charging at Circle K in 2020 are displayed in table 11.1. The prices depend on the amount of energy customers have consumed to charge their EVs. Hence, the price is defined in NOK per kWh. Besides, the 50 kW and 150 kW fast charging customers are charged differently. Moreover, Circle K offers two separate prices for registered customers and drop-in customers. In this assessment, 90% of the customers are drop-in while 10% are registered members. This part will account for the income of the scenarios, IN.

Table 11.1: *Prices for fast charging at Circle K [107].*

Power	Members	Drop in
50 kW	4.39 NOK/kWh	5.49 NOK/kWh
150 kW	4.99 NOK/kWh	5.99 NOK/kWh

To calculate the income from the fast chargers equation 11.1 is adopted. $P_{CK,1}$ defines the price for 50 kW fast charging, while $P_{CK,2}$ is the price for 150 kW fast charging. Accordingly, the two parameters, E_1 and E_2, represent the energy consumption in kWh of the all EVs charging at maximum 50 kW and 150 kW respectively. In other words, a customer charging at 30 kW will still be charged the $P_{CK.1}$ price.

$$IN = P_{CK,1} \cdot E_1 + P_{CK,2} \cdot E_2 \tag{11.1}$$

Regarding that all installed fast chargers have the ability to charge at 150 kW, the price per charger is 650 000 NOK and its further equipment costs is 650 000 NOK as well. The total capital cost of fast charging stations, C_{FC}, is therefore equal to 1 300 000 NOK. Costs related to technical operation, employment and maintenance are also considered. The cost related to the maintenance is estimated to be 3% of C_{FC}, while the annual salary is equal to 100 000 NOK per charger. These investments are identical for both Circle K stations. [108]

11.2 Cost based on the electricity bill

The electricity bill, EB, contains both the grid rent and the electricity cost, which are regulated by Elvia AS. These cost will vary depending on the number of fast charging stations and each scenario. Regarding a power based gird rent, the predominant factor will evidently be power segment. The power tariff is displayed in table J.1, appendix J and provided by Elvia. To calculate the total Grid Rent (GR) of a month, equation 11.2 is implemented. In equation 11.2, C_p and C_e represent the prices of the power and energy section in the corresponding month, respectively. C_f is the cost of the fixed section. P_{needed} in kW is the maximal amount of power used at a certain time. E_{demand} in kWh is the energy used throughout one month. In addition, MVA of 25% and electrical power tax are added to the equation.

$$GR = C_p \cdot P_{needed} + C_f + C_e \cdot E_{demand} \tag{11.2}$$

To calculate the electricity cost, the elspot prices provided from Nord Pool are monthly average prices from 2019. The data is presented in table J.2 in appendix J. The part of the electricity bill charged by the power supplier, EP, depends on the total amount of kWh. Equation 11.3 calculates the monthly electricity prices. C_{ep} represents the average monthly elspot prices and E_{demand} is the energy used throughout the month. [109]

$$EP = C_{ep} \cdot E_{demand} \tag{11.3}$$

11.3 Annuity factor

In the economic assessment, all analyses of the scenarios will calculate an annual profit. To normalise the investment cost into an annual cost, an annuity factor will be introduced. An annuity factor is a parameter in finance indicating the sum of interest and depreciation per year, in other words, the annual performance to reimburse investment cost regarding interest rate and annuity loans. Hence, all investment cost must be multiplied with an annuity factor in order to give a good overview of the annual profit. Equation 11.4 represents the annuity factor, a, whereas the interest rate, r, and lifetime of the project, l, are defined as previously. [110]

$$a = \frac{r \cdot (1+r)^l}{(1+r)^l - 1} \tag{11.4}$$

11.4 Economic analysis of Grid Charging

In order to enable fast charging services of electric vehicles only through grid support, both Smestad and Sekkelsten need to invest in a local grid expansion. Grid investments initiated by Circle K will result in a connection charge. Capital investments for GC include both a one-time connection charge, $C_{connection}$ and installation of fast charging stations, C_{FC}. Equation 11.5 is based on the income, electricity bill (EB), capital and operational expenditures, OM, to calculate the annual profit, AP_{GC}. To normalise the capital investment in a annualised one-time cost the interest rate and the life time are considered in this equation.

$$AP_{GC} = IN - a \cdot (C_{connection} - C_{FC}) - OM - EB \tag{11.5}$$

In order to determine how much the grid needs to be expanded, the difference between the highest fast charging demand and maximal capacity is calculated. The grid companies can impose a connection charge on the charging service station initiating the grid investment. This is determined by the amount of power exceeding the capacity limit at each Circle K station. In communication with Elvia and Circle K, each station with the respective load profile of two, six and twelve fast chargers have an estimated connection charge displayed in table 11.2. The exceeding power is based on a day with high car intensity and a high frequency of 150 kW cars. However, the connection charge does not vary depending on the amount of chargers installed, unless the exceeding power is under the *free limit*.

The term *free limit* describes the limit where the exceeding power provoked by the EV charging load, does not require an upgrade of the grid. If the overload on the cables and transformers occur infrequent, the components can endure the overload in short periods (Appendix A). Another explanation can be that the exceeding limit, does require an upgrade, but the connection charge is very low, hence referred to as free.

Table 11.2: *Connection charge at Smestad and Sekkelsten, respectively [108].*

	Smestad		Sekkelsten	
	Exceeding power	Connection charge	Exceeding power	Connection charge
2	100 kW	Free	0 kW	Free
6	350 kW	3 MNOK	110kW	Free
12	800kW	3 MNOK	110 kW	Free

The connection charge depends on the requirement of digging additional cables to supply the station. Since Smestad has a more densely populated area, it is more likely that the new cables have to be dug under the roads. Consequently increase the connection charge. In addition, the new cables drawn from the substation at Smestad contemplate other connected units. The estimation made for Smestad is dependent on the other units not increasing the consumption, thus the free limit is uncertain. On the other hand, Sekkelsten is supplied alone from the substation, thus slightly more flexible. Given the station has enough capacity and the digging is not included, the assumed charge is less expensive.

11.5 Economic analysis of Simple Smart Charging

For the economic analysis of SSC, the costumer has to pay the price of 50 kW, regardless of the charging power. Hence, the EVs are occasionally charged with a considerably lower power. In this scenario, investment includes only the installation of fast charging stations. Equation 11.6 calculates the annual profit of SSC, AP_{SSC}.

$$AP_{SSC} = IN - a \cdot C_{FC} - OM - EB \tag{11.6}$$

11.6 Economic analysis of Microgrid Enable Smart Charging

The economic analysis of MESC examines whether it is financially beneficial to install solar panels and battery storage in the microgrid system to reduce investment cost. The focus is directed on the savings based on the electricity bill compared to the total cost of the PV system, T_{PV}, and the BESS, T_{BESS}. Investment in this scenario includes PV systems, BESS and installation of fast chargers. The annual profit, AP_{MESC}, is calculated in equation 11.7. In this case the income, IN, represent the earnings from the fast chargers but also the income from the sold solar energy to the utility grid.

$$AP_{MESC} = IN - a \cdot C_{FC} - TC_{BESS} - TC_{PV} - OM - EB \tag{11.7}$$

11.6.1 Cost of the photovoltaic system

Installing a PV system is beneficial to subsidy the grid in periods of high demand periods. Due to the decrease in silicon price and global growth in the solar cell market, module costs are expected to be reduced by 40-50% by 2030. Usually photovoltaic panel costs between 9 NOK/W and 17 NOK/W depending on the efficiency and type of solar panel. The Payback Time in Norway has also decreased and is 12-13 years today. Additionally, it is expected to be 7 years within 2030. The photovoltaic system has a lifespan of 25 to 30 years, if the replacing of the inverter is taken in to account. [111]

The economic assessment is described in appendix H and summarised in table 9.3, H.1 and H.2. The price for the installation of the solar panels at Smestad and Sekkelsten are 850 112 NOK and 274 775 NOK, respectively. Operational costs over 8 years is assumed to be relatively low due to its long lifespan and is therefore neglected. The converter system will be the only component with maintenance costs and has to be replaced once in the solar panels lifetime. Thus, the maintenance cost of the converter is neglected as well. Moreover, the solar panels are assumed to be perfectly clean throughout the year. Hence, the normalised annual total cost of the PV system, TC_{PV}, includes only the capital expenditures.

11.6.2 Cost of the battery energy storage system

The economic motivation of installing a BESS can be to integrate more renewable energy power sources and storing energy in off-peak hours, hence reducing the tariff charge in high peaks periods. Although, the battery cost increases with a higher battery capacity (NOK/kWh), the operational and maintenance cost of BESS can contribute decreases the overall cost of the microgrid. Hence profitability may come from reduced electricity bills, with an increased consumption of self-produced power. [80, 112]

In order to calculate the expenditures of the stationary battery system, several aspects have to be calculated. Depending on applications, capital expenditures most often considered the cost of rated power in kW and the cost of rated capacity kWh, while operation and maintenance (OM_{BESS}) expenditures vary because of BESS individual OM_{BESS} requirements. A clear trend in literature is difficult to obtain.

The capital costs of the system include the price of the energy capacity, the power conversion system, the balance of the plant and the construction and commissioning costs. The total capital cost of the rated capacity, TCC, is equal to 438 $\$/kWh$ defined in table I.1 in appendix I. To simplify the economic aspect of the battery system, the TCC will be normalised in the annualised one-time BESS cost, $AOTC$, in $\$/yr$. Equation 11.8 describes how the BESS's life time is l years, the interest rate for financing the BESS, r_{BESS}, and TCC, defines the one-time BESS cost. The interest rate is set at 6% in this paper, while the life time is equal to 8 years (Table I.1). [106]

$$AOTC = \frac{r(1+r)^l}{(1+r)^l - 1} \cdot TCC \cdot E_0 \tag{11.8}$$

In addition to the capital cost, operation and maintenance cost, OM_{BESS}, are added to include the economic life of the operating battery system and its annual discharge energy. OM_{BESS} costs are defined to be equal to 9 $\$/kW/yr$. To find the total cost TC_{BESS} of the battery system per year, equation 11.9 is implemented. The OM_{BESS} are multiplied by a factor of four to respect the units.

$$TC_{BESS} = AOTC + E_0 \cdot OM_{BESS} \cdot 4 \tag{11.9}$$

Hence, the cost for the stationary battery will depend on the size of the capacity. Therefore, each scenario will have different capital and operational expenditures. All different battery costs are presented in table 11.3. All costs are expressed in million NOK per year.

Table 11.3: *Cost of the stationary battery for both sites.*

	Smestad			Sekkelsten		
Charging stations	2	6	12	2	6	12
E_0 $[MWh]$	2 000	7 500	8 500	50	500	500
$AOTC$	1.31	4.90	5.56	0.03	0.33	0.33
OM	0.73	2.74	3.11	0.02	0.20	0.20
TC	2.24	7.97	9.03	0.05	0.53	0.53

11.7 Sensitivity analyses of economic parameters

A sensitivity analysis is likewise conducted regarding the economic parameters to understand the impact of input values on the economic outcome. First, the impact of the battery capacity is analysed in order to understand the impact of the battery cost on the annual profit of the microgrid. Further traffic patterns are evaluated in interest of its affect on the total costs compared to energy produced and the annual profit.

11.7.1 Traffic patterns

Additionally, LCoE is an interesting factor to evaluate in a sensitivity analysis. Levelized Cost of Energy (LCoE) presents a measure of lifetime (NOK) cost divided by the energy production (kWh). LCoE defines the costs required of energy conversion of another form of energy into electric current. The electricity costs are derived from the capital costs, the fixed and variable operating costs, as well as the strained capital delay over the operating period represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle. In equation 11.10, C_t represents the investment and M_t maintenance expenditures in a year. F_t represents the fuel expenditures in a year, while E_t represents the electricity delivered from the PV system and the BESS. Further, t, defines the operating period of 8 years, r, stands for the discount rate at 4%. [113]

$$LCoE = \frac{Total\ life\ cycle\ cost}{Total\ lifetime\ energy\ production} \implies \frac{\sum_{n=1}^{t} \frac{C_t+M_t+F_t}{(1+r)^t}}{\sum_{n=1}^{t} \frac{E_t}{(1+r)^t}} \tag{11.10}$$

Corresponding with the sensitivity analyses of the traffic patterns regarding the technical parameters, the economic parameters may also be an interesting outcome. Therefore, the annual profit will be analysed with a total daily electric vehicles of 43, 93 and 143. This analysis is conducted in order to evaluate how the change of traffic patterns can lead to a more profitable microgrid.

11.7.2 Battery capacity

Furthermore, a sensitivity analysis of economic parameters may be interesting in scenario three in order to evaluate the impact of the battery cost and performance, including the adjustment of the electricity bill. As an example, a case of six chargers in scenario three at Smestad was adapted. Two main purposes are observed along this sensitivity analysis. One focuses on the battery cost affecting the annual profit, while the second one is based on the behaviour of the electricity bill with increasing battery capacity. These two analyses may contribute to find an optimal battery size compared to the economic outcome. The battery capacity will be increasing with an increment of 10% of the maximal required capacity.

12 Economic Results

The economic results were calculated by the equations in the previous section, based on the technical results. An economic analysis is preferable for the investors, providing information about the profitability of the investment. Annual profit, income and electricity costs are key elements, providing information about the business model. The annual profit is calculated in order to provide information about the normalised cost of both investment, income and cost. Income and electricity costs are derived from the MATLAB code. The income is calculated from equation 11.1, from table 11.1. The electricity bill is calculated by adding equation 11.3 and 11.2. All investments related to the fast charging stations are further explained in appendix K. All costs and income are presented in million Norwegian Kroners throughout this section. Appendix O contains all detailed results associated with the diagrams according the three scenarios.

12.1 Scenario 1: Grid charging

The annual profit presented in figure 12.1 is calculated through equation 11.5 and affected by the connection charge. This connection charge depends on the number of fast chargers installed and the aforementioned "free limit".

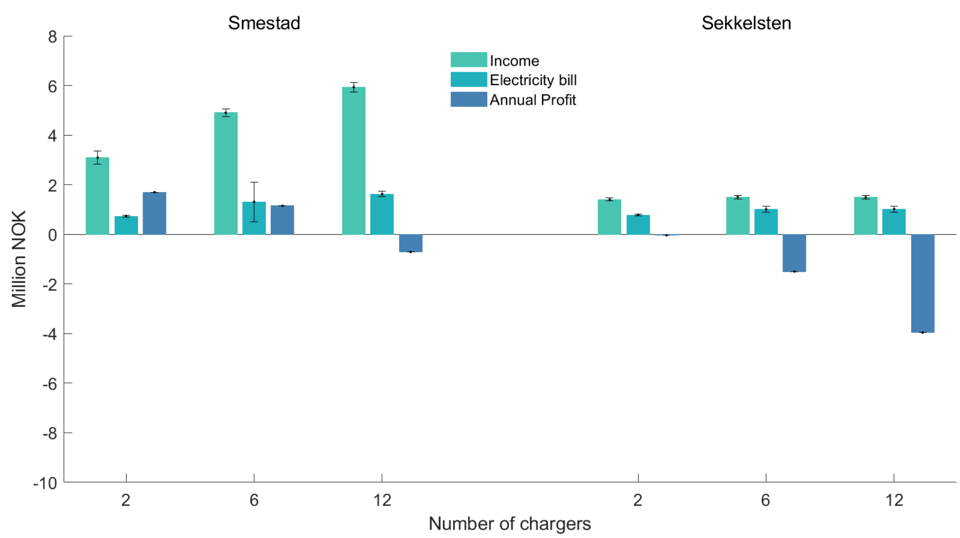

Figure 12.1: *Economic results of the GC simulation.*

In general, Smestad shows a higher overall economic performance. However, the income increases with higher numbers of chargers in both locations. Although Smestad shows a greater difference of income, at Sekkelsten the income is relatively constant. The same pattern can be observed for the electricity bill. A number of two chargers has proven to have the highest annual profit at Smestad, similar to Sekkelsten. Twelve fast chargers are the least economic alternative in both locations. However, this case at Sekkelsten demonstrates the effect of low income and an increase of investment costs. In general, a higher number of chargers lead to a less profitable station. Overall, the error bars seem to be relatively small except for the standard deviation representing the electricity bill at Smestad for six chargers.

12.2 Scenario 2: Simple Smart Charging

The annual profit presented in figure 12.2 is calculated by equation 11.6. When load managing, the income and electricity bill behaves in a relative constant fashion as the number of fast chargers increase in both locations. However, the annual profit decreases with increasing chargers. The optimal number of chargers is two, with respect to the annual profit at both stations.

Figure 12.2: *Economic results of the SSC simulation.*

In general, the economic performance is significantly higher for Smestad compared to Sekkelsten, indicating a similar trend as the grid charging scenario. However, the annual profit of each case is higher for SCC compared to GC except for Smestad at twelve chargers. This scenario does not include a connection charge, resulting in a lower initial investment. Overall, there is less variation in the results, thus the error bars are rather small for all parameters.

12.3 Scenario 3: Microgrid Enabled Smart Charging

Figure 12.3 illustrates the economic results of the microgrid simulation. In general, the economic performance shows the same trend for both locations. Nevertheless, at Smestad, the income increases significantly with a higher number of chargers, while the income stagnates after six chargers at Sekkelsten. Moreover, the electricity bill is observed to be relatively constant for all cases. However, the annual profit decreases with higher number of chargers in both locations, although Smestad has a considerably lower annual profit. Throughout all three scenarios Sekkelsten follows the same trend, while Smestad becomes less profitable with an increase of the complexity of charging systems.

Moreover, figure N.1 in appendix N demonstrates that the solar panels do contribute to the income in scenario three. However, the maximal sold electricity is relatively low compared to the income deriving from fast chargers. Eventually solar production will be the most decisive in summer months.

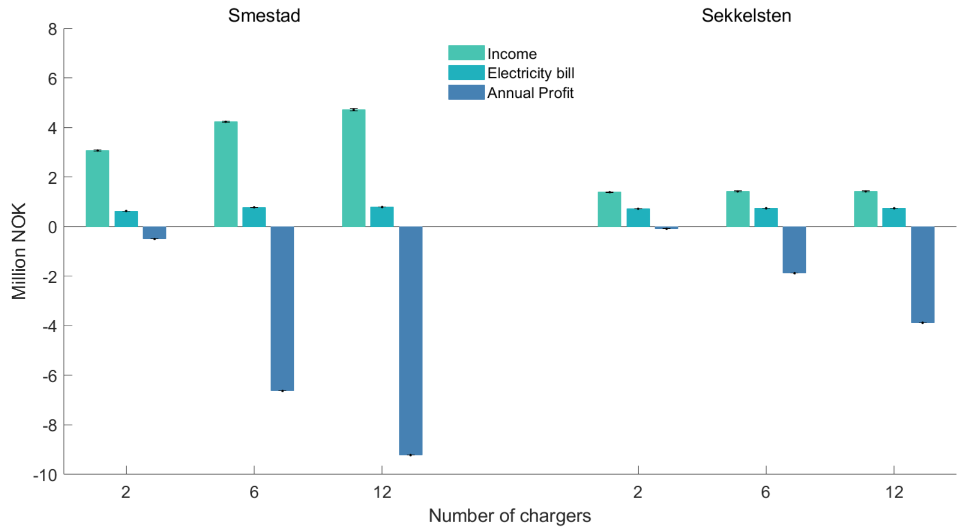

Figure 12.3: *Economic results of the MESC simulation.*

12.4 Results of the sensitivity analyses of economic parameters

The sensitivity analyses are conducted in order to present the sensitivity of the key economic results. Two approaches are evaluated: the economic aspect of different battery capacities and the profitability of different traffic patterns. These approaches can give a more detailed analysis of the initial results.

12.4.1 Traffic patterns

The sensitivity analysis for traffic patterns is done to observe how much customer Circle K needs to offer profitable charging service. A sensitivity analysis is represented in figure 12.4 evaluating the impact of traffic patterns on the economic parameter LCoE, while figure 12.5 represents the change of annual profit in respect to the varying traffic pattern. This variable gives a basis for measuring how expensive different energy systems are compared to the energy consumption. In general, the average revenue required to recover from all costs is lower at Smestad than Sekkelsten. Moreover, a similar trend can be found in all cases: the LCoE is always highest at the lowest EV intensity. Overall six chargers have the lowest LCoE in all car intensities compared to the other cases.

A Levelised Cost of Energy (LCoE) presents a measure of lifetime cost (NOK) divided by the energy production (kWh). LCoE defines the costs required of energy conversion of another form of energy into electric current. The electricity costs are derived from the capital costs, the fixed and variable operating costs, as well as the strained capital delay over the operating period. [114]

This analysis presents the same variation of traffic flow as the sensitivity analysis representing the technical performance. Both 143 at Smestad and 43 at Sekkelsten are the original car intensities, hence these are highlighted with a dark blue frame. The results at Smestad are relatively similar for all number of chargers, where 43 daily EVs always has the highest LCoE. Moreover, a car intensity with 143 EVs has a relatively similar LCoE to the one with 93 EVs. On the other hand, the results for Sekkelsten are clearly more decisive and more sensitive for changes in number of chargers. At two chargers, all values are above 30 NOK/kWh, while at six chargers all values are below

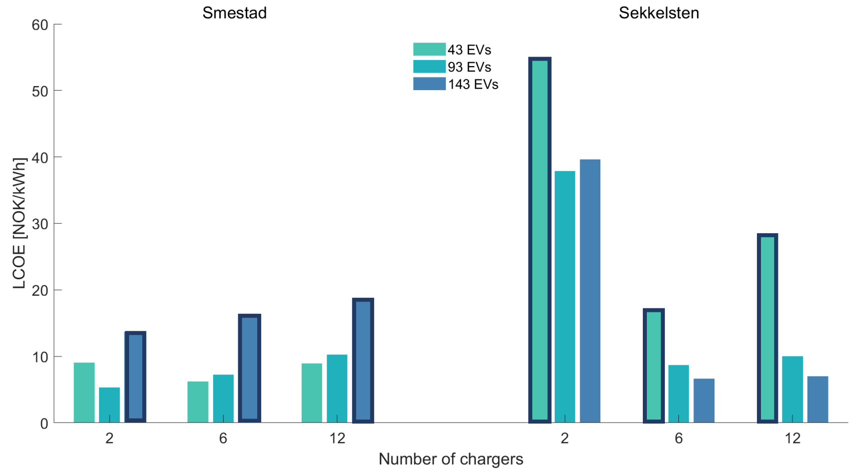

Figure 12.4: *LCoE of the MESC simulation with varying traffic patterns. The bars with dark edges illustrate the original car intensities with their respective cases.*

20 NOK/kWh. Additionally, two chargers at Sekkelsten shows an irregular trend compared to all other cases presented. Another outstanding result for Sekkelsten is the increase of LCoE from six to twelve chargers. The same trend can also be observed at Smestad only with a lower magnitude.

Another interesting parameter affected by the change of traffic patterns is the annual profit in figure 12.5. In general Smestad shows a relative regular trend, with 43 EVs being the most profitable and 143 EVs being the less profitable for every number of chargers. However, at two chargers, 143 EVs become the most beneficial outcome. On the other hand, Sekkelsten has noticeably irregular results, only the case at twelve chargers follows the same trend as at Smestad. Sekkelsten presents particularly high annual profits for two and six chargers at a 143 EVs. Overall Sekkelsten has more favourable results than Smestad.

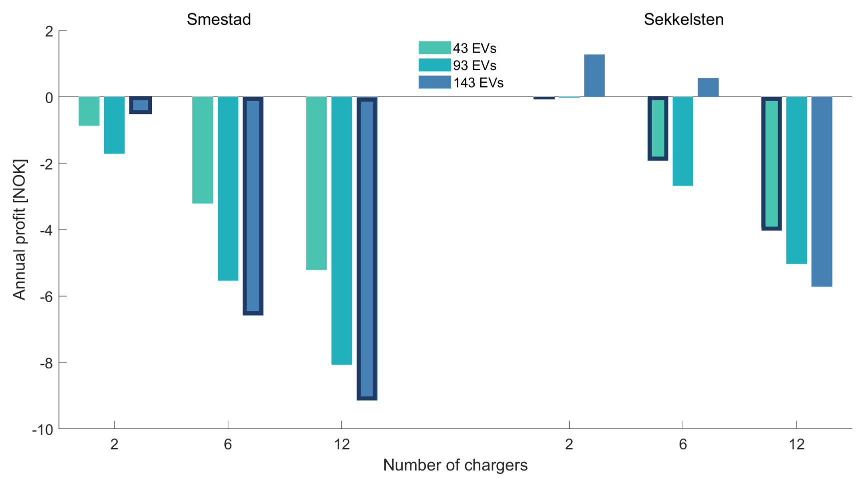

Figure 12.5: *Annual profit of the MESC simulation with varying traffic patterns. The bars with dark edges illustrate the original car intensities with their respective cases.*

12.4.2 Battery capacity

A sensitivity analysis of the BESS capacity regarding the annual profit is presented in figure 12.6. The maximum battery capacity is 7.33 MWh, equivalent to a battery cost of 7.74 MNOK. This capacity refers to exploiting 100%, covering the highest demand peak at the station and being the most expensive alternative.

Although reducing the capacity consequently affects the peak shaving performance, a poor peak shaving performance decreases the battery cost. In order to analyse the economic operation of the stationary battery, four parameters are analysed: Income, Electricity bill, Annual Profit and Annual Battery Cost. The annual battery cost is calculated by equation 11.8, while the annual profit is calculated by equation 11.7, containing every cost aspect presented in the previous sections. Both, income and electricity bill, derive from equation 11.1 and a sum of equations 11.3 and 11.2, respectively.

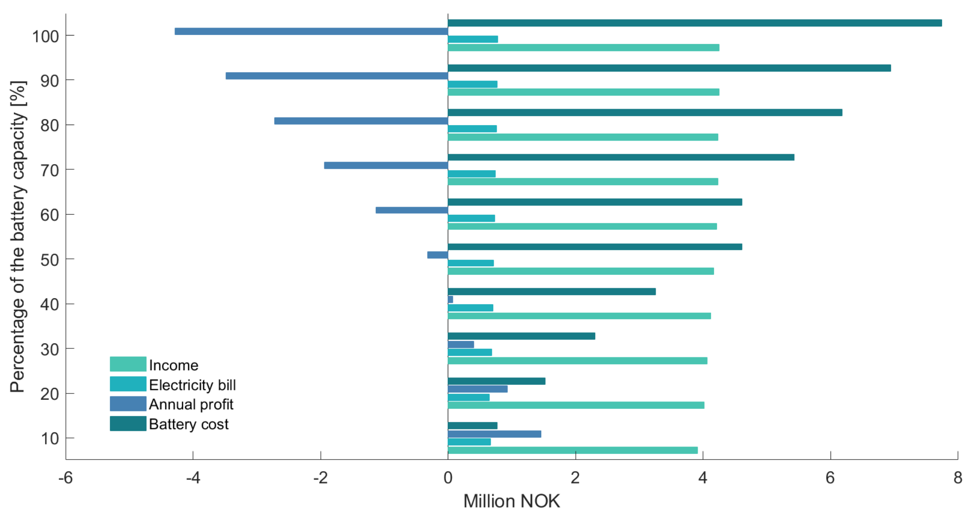

Figure 12.6: *Sensitivity analysis of the changing battery capacity for the MESC simulation at Smestad with six chargers, regarding the economic aspect.*

Figure 12.6 illustrates the relation between the increased battery capacity and the annual profit. The income increases with higher capacity percentage but stagnates around 50% to 60%. Moreover, the electricity cost has a minor increasing relation to the battery capacity, but is remains relatively constant compared to the other parameters. However, the battery cost is the one parameter increasing with the highest magnitude and surpasses the income at 50%. Accordingly, the annual profit decreases with higher battery capacity and becomes negative when the battery cost has surpassed the income.

13 Discussion

This section will discuss the technical results with respect to the economy. First, the case study assumptions are examined in order to analyse the integrity of the decisions. Secondly, the number of chargers in each scenario at each station are compared to evaluate the optimal case. Thereafter, the scenarios with their optimal case at each location will be contrasted. Lastly both stations, Smestad and Sekkelsten, will be analysed with their optimal scenario to discuss the impact of infrastructure and demography for installing fast chargers. This arrangement contributes to present the most attractive charging alternative for Circle K. When evaluating the charging alternatives, several factors must be considered.

To guarantee a sustainable charging system, favourable customer experience and profitability must be attained. The charging system should also be capable to support the future growth of the EV market and the evolution of DC fast chargers. Accordingly, the improvement of EV battery capacity and advancing ability to deliver greater power, implying faster charging speed, have to be accounted for in this analysis.

A pleasant customer service is expected to preserve the Circle K's customer base. The optimal scenario must be able to maintain a constant charging power and speed to ensure a satisfying experience for the customers, along with a confidence to leave with the desired SoC on desired time. Likewise, a highly beneficial solution may promote the reduction of the costumer's charging cost, hence attracting more costumers. However, the most attractive factor for the customers is the availability of the chargers during rush hours. By decreasing the temporal length of queues the charging stations may become more appealing to customers.

Furthermore, the systems profitability will be a fundamental aspect to ensure the longevity of the project. Each scenario evaluates different economic elements. The annual profit in each scenario will be an important factor throughout the discussion. The annual profitability of the systems is expected to increase due to economic improvement of smart technologies. Additionally, the statements in section 11.6.1 and 11.6.2 estimate a promising cost-effective future for individual elements in smart energy systems, including battery storage, PV systems and converters. Moreover, Levelized Cost of Energy in scenario three will be contrasted in order to evaluate expenses related to energy generation of DER.

Overall, the customer experience will be the most important factor to decide the most favourable option for Circle K by still writing black figures. Hence, charging performance and *drop-out* rate will be the most crucial factors throughout the evaluation of scenarios followed by annual profit.

13.1 Evaluation of the case study assumptions

Throughout this thesis, several assumptions and simplifications are established in order to complete all calculations within the given time frame. Moreover, projected approaches were implemented to get modernised results. An overall evaluation of some particular influential parameters is presented.

Firstly, power losses and connection charge are evaluated. Thereafter, the estimated traffic patterns are discussed to understand the impact on the presented results. Additionally, the structure of the queuing system and the charging simulation of the MATLAB code are analysed to evaluate their affect on the charging and power performance. Thenceforth, the elements of the microgrid will be debated. Accordingly, the PV system and battery design assumptions are studied, related to inconsistent reviewed literature. Finally, the applied economic approach is discussed. Throughout the evaluation, all conducted sensitivity analysis in this report will be examined and its results will function as arguments to put assumptions in perspective.

Resolution of the simulation

The simulation measures all parameters for every minute of the year. Although, this simplification may cover up small irregularities between the minutes, the impact will be minuscule so the outcome is neglected in this report. Moreover, the complete simulation reacts with an instant response time, hence in this aspect all elements are considered ideal to simplify the operation of each system. However, all simulations include constant and theoretical losses and efficiencies. Consequently, the results may be enhanced. Further, the average of ten samples might not be precise enough, however the standard deviation is relatively low, ergo the results are considered credible. Since the simulation accounts for a year of 360 days, the results might be slightly imprecise. However, the five subtracted days from the simulations are between the 26th to the 31st of December, a period with a reduced traffic flow.

Power losses

The overall performance of the simulation is defined by power losses in electrical components of the scenarios. All electrical appliances supplied by the utility grid involve power losses, due to transmission cables generating heat. Since an estimation of the total transmission losses are 10%, the specific appliances require a higher amount of power drawn from the grid, thus increasing the electricity bill. Assuming power losses in cables and transformers is challenging due to the unidentified distance from the substation and the length of the cables. Additionally, old transformers and cables can have greater losses than new ones, however this is not examined in this thesis and leads to imprecise losses.

Power losses related to the rectifier have a significant impact on the operation of the charging stations. These losses are substantial, resulting in a generally higher power drawn from the grid. The rectifier has the lowest efficiency and therefore highest power losses, affecting all components connected to the DC-bus and delivered electricity from the utility grid. Additionally, in order to charge the EVs, the rectified power flows through another rectifier inside the charger. Although rectifiers account for substantial amount of losses, the overall operation of a DC microgrid is favourable since reduced losses of power conversion systems regarding the DER and DESS are beneficial. Moreover, inverters and converters connecting the PV system to the utility grid and BESS account for insignificant losses. Hence, an AC microgrid would induce more power conversion losses.

Connection charge

At first, grid expansion was considered to be noticeably expensive and unfavourable. However, through communication with the contributors and by analysing the results, the connection charge presents a minor investment compared to the high income of fast chargers. Although, these estimations can be particularly uncertain. These preliminary estimations from Circle K and Elvia may be sensitive to subjective assumption. In order to estimate the connection charge precisely, preconditions of digging new cables and other related obligation must be clarified. Further investigation requires more communication with the respective grid company.

Estimation of traffic patterns

All presented results are influenced by the car intensity. An uncertainty related to car intensity in this thesis might manipulate the outcome. As mentioned in the description of traffic patterns in section 9, the daily car intensity is similar throughout the year. On the other hand, since the same scenarios are simulated ten times, the average results with respective standard deviation should be representative. Although public holidays and high seasons probably lead to altered traffic patterns, these are only considered in the economic results in order to simplify the technical simulation. This might enhance the charging performance and operation of the station. A better estimation would have required empirical data of arriving customers, since stochastic EV loads lead to unpredictable power demands.

The approach of evaluating registered passing cars may contain some uncertainties, since there are only two registration points. Some cars will not pass the registration points at all, leading to underestimated patterns. Conversely, one road might be more busy than the other, leading to more cars shifting to the other road and double the registrations. This imbalance might eliminate irregular flows between the roads. Hence, the final traffic patterns might be appropriate. However, the method to estimate the amount of passing EVs may be imprecise. The reason is threefold. First, the registration points are not able to register all passing cars categorised as invalid registrations. Second, the percentage of EVs comes from the Norwegian EV association, and is based on total passenger cars in both municipalities. Third, when estimating the ratio of electric cars and the total traffic volume at Circle K, cars above 5.6 m are not included. As a consequence, total volume of passenger cars may be too small. Although the amount of hybrid vehicles was not accounted for in the percentage from the Norwegian EV association, the car intensity is relatively high, slightly balancing out the previous statement.

At Sekkelsten, the estimated fraction of EVs passing by the station was set to 8%. This derives from a ratio only regarding Indre Østfold. However, most of the cars driving by the station originate from surrounding cities due to the highway. Therefore, the EV percentage of passing cars might be higher than assumed. Nevertheless, a fraction of 50% of the EVs passing are assumed to fast charge, being a relatively high number. These two percentages might balance out their imperfections. Moreover, it may be that people on longer journeys prefer to drive fossil-fuelled cars. However, a more futuristic assumption might invalidate the previous statement, since Norway plans to become a zero emission society by 2025. While estimating the amount of EVs on a daily basis, the competing charging stations are taken into account to a certain degree by evaluating Circle K's charging prices. However, this aspect could have been analysed in a more detailed manner by examining the distance between the charging stations and the surrounding demography. This might have led to an enhanced car intensity.

Eventually, such a time consuming estimation was necessary since EV patterns differ noticeably from conventional passenger cars. The fossil cars must fill their tank at a gas station, while EVs have a home charging option.

Furthermore, the estimation only considers some of the most popular EV models in Norway by September 2019. However, these models may not be relevant in 2020, because of the fast growing EV market. For instance, the new model Audi e-tron launched in 2020 is now the most sold EV in Norway. Further, more cars with improved battery capacity were released along the realisation of this project. This might defend the fact that 25% of the arriving EVs are charging at a maximal power of 150 kW, representing a rapid development due to progress of new innovative EV technology. This will further encourage smart technologies to reinforce the electrification of the transport sector. A sensitivity analysis could have evaluated the affect of the increasing rate of 150 kW EVs on the charging stations in order to get a more prospective view.

Eventually, the sensitivity analysis in figure 10.6 may give a better overview of the traffic flow's impact, not to mention the credibility of the operation at the station. Obviously the quality of the charging performance decreases fast with an accumulation of electric vehicles. If less than half of the customers reach their desired SOC, the station might not be able to attract the same amount of EVs in the future. For all car intensities, the results present the lowest technical performance at two chargers. Consequently, two chargers might be insufficient in order to achieve satisfactory results. By reducing the car intensity lower than 43, even better results could have been provided. The trend, demonstrating that higher numbers of chargers provide a better charging performance for all traffic patterns, becomes highly recognisable in this sensitivity analysis. Further, this analysis displays that a limited grid capacity at the station will be restricting for a high traffic flow, when comparing Smestad with Sekkelsten. This accentuates the importance of grid extension at Smestad in order to achieve similar results in scenario three.

At both locations, two chargers are inadequate due to the reduced charging performance with a higher car intensity of 43 EVs. A remarkable result is the charging performance at Sekkelsten for twelve chargers since the outcome deviates from the expected trend. The value at 93 EVs should have stagnated rather than decreased at twelve chargers, while the parameter at 143 EVs should have been lower than 93. The noticeable value at 143 EVs might have occurred due to a combination of Circle K Sekkelsten's high capacity limit being able to saturate the battery in contrast to Smestad and an exaggerated design of battery capacity. Hence, Smestad might be more prone to larger power consumption. Moreover, the deviation could occur from a miscalculation in the simulation.

LCoE only counts cost of the energy production, implying that a high LCoE can only be profitable if the income is sufficient. Different behaviours compared to number of EVs can be observed at both stations. 143 daily cars represent the most expensive energy costs at Smestad, while it occurs to be the favourable option at Sekkelsten except at two chargers. This might be due to the high car intensity at Smestad leading to a dominant battery capacity and a higher production of solar energy. For Sekkelsten, 43 cars occur to have the highest energy cost because the energy production will be relatively small compared to the actual costs. This might be due to the available grid energy most of the time being able to supply 43 cars. Hence, the effect of installing PVs and battery is therefore minimal.

According to the results, the car intensity has a great impact on the income and electricity cost further affecting the annual profit. The sensitivity analysis for annual profit accentuates the general unprofitably of a microgrid system for fast chargers at Smestad. The highest possible amount of cars appears to be the most profitable at two chargers, because 143 cars ensures a more regular and crowded station, leading to higher income. In this case, the PV system can generate an acceptable amount of energy, enough for the battery to be saturated. However, the effect of an abundance of cars will promote the opposite consequence with more chargers. Then, the available grid and PV electricity will not be able to charge the required battery energy in order to function as a profitable reserve. Hence, the non-saturated battery will not be able to generate the maximal income. In general, the same fashion can be observed at Sekkelsten, although the overall annual profit is more favourable due to the high capacity limit leading to smaller battery capacities and therefore being able to saturate the battery. Based on the analysis, Sekkelsten has the highest potential for a profitable microgrid, however, this requires a higher car intensity than estimated.

Finally, if the original estimations lead to an exaggerated car intensity, the techno-economic results might be enhanced. Per contra, an underestimated car intensity could cause a lower optimal number of chargers. Consequently, this might result in a misrepresentation of installing fast chargers.

Queuing system

The five minute waiting time due to the queue will decrease the actual daily car intensity at each station at lower numbers of chargers. This time frame may be flawed, however further information about statistics is difficult to obtain. The assumption of the one minute break, between the previous and next car at the charger is disputable. A one minute switch may be considered as a quite quick shift, however this is implemented to simplify the simulation. In some cases, the switching time might take longer due to the payment, arrival and departure, and other time delaying factors. This might consequently increase the amount of charging vehicles.

Because all electric vehicles have a charging interval of maximal 30 minutes and SoC limit of 80%, given the conditions of all chargers being occupied, the charging performance will be affected negatively. However, increasing this charging interval can in turn create more queue. Correspondingly, increasing the *drop-out* rate may result in a less popular charging station.

Eventually, Circle K can also decide to only focus on a time-based prioritisation or only a SoC-based prioritisation. A time-based queue system will potentially reduce the queue and hence, have a lower *drop-out* rate. Although, the SoC-based system will result in a higher charging performance. Both factors affect the customer experience. Consequently, a further sensitivity analysis can be done to find the optimal ratio between charging performance and *drop-out* rate when the EVs encounter queue.

Another issue of importance, is considering whether charging patterns change with an increasing number of fast chargers. If an electric vehicle drives by a station, available chargers are more likely to attract customers. Information regarding this correlation is not directly presented in this thesis, although it is somewhat accounted for in the queue simulation.

Charging simulation

Since the charging simulation only implements simplified equations of SoC curves from appendix D, the charging speed in function to the current SoC might not be ideal. This might result in more enhanced charging performance. Especially for electric vehicles charging at 150 kW, the ID.3 and BMW iX3, are assumed to have the same SoC curve as Tesla Model S and do not have an individual empirical SoC curve. Hence, these cars will be more imprecise than the other EV models.

Despite the fact that charging time is customised to each EV model, estimated charging time and desired SoC are not perfectly synchronised. Since this correlation is theoretical and simplified, uncertainties will occur regarding the charging performance of the scenarios. The charging performance may have a more negative outcome due to this simplification.

Photovoltaic System

Regarding the scope of this thesis, the PV system is considered to have a minor impact on the results. Hence, a comprehensive analysis of the effect of installing a PV system, supporting fast charging, may not be presented. The solar generation can not directly supply electricity to the EVs in order to simplify and avoid more variable parameters. Since the power output is intermittent, the battery contributes to stabilise the microgrid controller and reduces losses in converters. An improved solution for smart charging can allow the PV to perform both operations.

The power generated from the solar panels have a moderate influence on the the microgrid system. Although, the electricity production is relatively low during demand peak seasons, the overall annual production has proven to provide a substantial amount of energy. The optimal situation would have the power generation occur simultaneously as at peak periods: mornings and afternoons.

The annual solar generation presents a relatively low amount of electricity being sold back to the grid, since practically all energy is directly charging the batteries due to their high capacity. Especially for Smestad, the income from selling solar energy is insignificant compared to the income from the fast chargers, demonstrated in figure N.1 in appendix N. Another reason for this is the PVsyst software operating with lower power and efficiency per module and fewer panels in contrary with the theoretical modernised solar panels provided from Solcellekraft.no. Consequently, the performance will be poorer than the estimated sun production in table 9.3. Note that the theoretical generation is approximately double of the empirical production. Furthermore, the installation cost might be unrealistic compared to the PVsyst power output. Therefore, it contributes to increase the cost in the economic calculations. This miscalculation can make the PV system look more unfavourable, hence an adjustment of the system would be more realistic.

Designing the stationary battery

During the design of the stationary battery, several factors had to be considered and other were rejected to simplify the simulation. Throughout this thesis the self discharge of the battery, as well as its annual efficiency degradation rate, are not considered. This might lead to an enhanced state of health.

The battery capacity contains several uncertainties worth to discuss. An important aspect to consider is, when designing a battery for a higher number of chargers and EVs, a greater battery capacity is required. This can in turn generate more uncertainty in the simulation. Hence, further iterations and samples would might have eliminated some of the errors. According to the battery design at Smestad, the capacity is rounded up to the nearest 500, in contrast to the nearest 100 for the smaller batteries at Sekkelsten. Moreover, a deviation in the battery design could also arise from equation 9.1 since E_0 is calculated from an average of ten samples. These samples are more varying than desired, due to the fact that P_{load} is dependent on the car matrix. As a consequence, the average E_0 may not cover 95% of the highest load peaks, therefore the battery might not perform ideally. However, the sensitivity analysis in figure 10.8 demonstrates that these uncertainties will only have minor impacts on the final result.

According to the battery's purpose in a microgrid, the sensitivity analysis in figure 10.8 demonstrates a power performance converging to values equal to scenario one with increasing battery capacity. Already at 60% of the maximal capacity, the power performance stagnates and has reached the 80% at scenario three. This might indicate two separate causes. First, the available grid capacity and solar energy might not be sufficient to saturate the battery. Second, the need for the remaining 40% might not occur on a daily basis and may only be necessary in colder periods. Therefore, the average annual power performance is not affected. However it may be assumed that the 100% battery has an improved operation in high demand periods than, for instance, a 70% battery. Accordingly, the charging performance also converges to values equal to GC, although, the charging performance does not stagnate entirely but increases slightly until it has reached 100% of the battery capacity. Nonetheless, the increase is minor: for instance by doubling the capacity the charging performance increases with only 3%. This observation might underline the previous assumption that a 100% battery capacity performs better even though the power performance has reached its maximum. Considering the *drop-out* rate it seems that the percentage of the battery capacity has nearly no impact on the queue. This might occur from the high car intensity at Smestad and that six chargers are not enough to support the entire traffic flow.

Since the battery capacity should be able to support the charging station 95% of the time, events of insufficient battery capacity may occur during the winter season. In contrast, the battery might be practically unused during summer seasons.

In contrary to the technical performance, the sensitivity analysis in figure 12.6 demonstrates a poorer economic performance with increasing battery capacity. Here, the 50% mark might indicate a specific turning point. Moreover, the annual profit decreases and becomes negative at the same percentage. This occurs due to the increase of expensive battery costs and the small impact of the electricity bill, seen as rather constant compared to other parameters, while the income stagnates after 50%. This trend is due to the technical performance stagnating after the 60% mark. Overall, this sensitivity analysis might indicate that if the battery design would have evaluated the technical and economic aspects, the battery capacity should have been around 50% of its maximal capacity with a decrease in annual profit of 93% by halving the capacity. Most importantly, the microgrid would have become more profitable and may have been able to compete with scenario one on a higher level.

Eventually, more samples should have been taken to confirm the credibility of this assumption. Since the sensitivity analysis only contains one sample per percentage, a deviation might have occurred due to the random car matrix. Additionally, further evaluation of different numbers of chargers could have provided a better perspective of the battery capacity's ability to operate.

State of Charge

Equation 7.2 calculating the SoC of the stationary battery is a simplified equation not able to consider the maximal charging power at all times. A relatively high SoC can not receive maximal charging power at 1.5 C. This might lead to fast discharge and charging rates, furthermore an enhanced battery system. Since the charge/discharge is kept withing a range of 20%-100%, the battery is somewhat limited. However, this is established in order to avoid negative effects on the SoH. Typically, the battery is kept within a SoC range of 20%-90%. With a range up to 100%, more capacity is exploited, but results in a more harmful operation of the battery. Ultimately, this becomes a matter of value judgement, since a battery with 90% will be more costly as a larger battery needs to be adapted. Conversely, a battery with 100% may contribute to a quicker replacement. Furthermore, it depends on the operators interest of investing in batteries, and how quickly a new battery needs to be installed. In order to minimise the effect of degradation in the 90%-100% range, the charge rate is inferior or equal to 1C. By including two separate batteries, the influence of discharging the batteries completely down to lower SoC values can be diminished. In this manner, each battery is kept at a preferable 50% mark. Hence, the SoH will be less affected, due smaller SoC intervals.

Life cycles

By studying the sensitivity analysis for life cycles, both the battery size and the designed number of cycles have an influence on the SoH. Figure 10.7 shows lower SoH for smaller batteries, observed for two chargers. Furthermore, self discharge might also affect the battery's life time, which is not included in these calculations. Therefore, the SoH might decrease faster for each year.

The annual SoH at 1 500 cycles is considerably low, hence the lifetime becomes less than two years considering the EoL has reached 20% capacity loss. Thus, higher life cycles should be designed for a battery to achieve longer longevity. The technical data for the battery in appendix I states that a life cycle of 3 500 is a typical number for NMC batteries and will have a lifetime of around nine years. However, in that study the C-rate was at 0.25, whereas the C-rate for this microgrid is higher in order to be able to fast charge all EVs. Eventually this observation implies that fast charging reduces the lifetime of the batteries. Nonetheless, most battery manufacturers sell batteries with a warranty, favourable for the buyer if the battery's EoL is reached too soon. Although, a mishandling of the battery, for instance a high C-rate, might void the warranty.

Initially, while designing the battery, the SoH should not decrease below 80% to prevent it from reaching its EoL too fast. However, even a battery with 4 000 life cycles would reach its EoL after five years in this microgrid simulation, reducing the batteries profitability. The structure of the simulation of the battery energy storage system might be the cause. The specific charge and discharge requirements of the BESS might not have been programmed in the most advantageous manner. From reviewed literature, it is known that a battery's state of health is ideal if the state of charge remains around 50%. However, in this simulation the battery has an average SoC of 23%, implying a general unhealthy state for the battery (Figure M.1). This might be caused by the fact that Smestad does not have enough solar energy and available capacity to charge the battery. With this knowledge, a better simulation structure could have led to the BESS staying around 50% and maintaining a higher SoH. However, this would also have affected the power and charging performance negatively at the station. A further sensitivity analysis about this hypothesis might lead to more insightful results.

Economic assessment

During scenario two and three, customers will in some cases experience a charging power below the maximal, 50 kW or 150 kW. The model calculates, however, with the corresponding maximal charging power price despite the lower power. Hence, the quality of the charging service is worse. Therefore, the fairness of the price may be disputable. Moreover, this could also have affected the income negatively if the price is correspondingly adjusted to the power at all times. This event occurs especially when load managing.

Circle K charges their 150 kW customers with the maximal price even though, charging power might be below 50 kW. Although, in this simulation a 150 kW EV will pay the 50 kW price if load managing leads to charging power below 50 kW. This might impact the income negatively in this thesis.

LCoE's simplicity may be seen as a strength since a simple cost-effective result of energy generating units gives a relatively good insight on the energy sources in the microgrid. Conversely, the simplicity can also be considered as a weakness, hence lead to an imperfect conclusion. Other weaknesses include the estimated discount rate. Since it will be affected by inflation, the discount rate may be inaccurate. Moreover a comparison with LCoE may be biased towards some renewable energies, for instance wind, and against other energies, like solar. PV systems are more likely to generate electricity during the day when the market price is higher than the LCoE while wind generates more during nighttime, when the market price is low.

Using annual profit leads to an understandable measure of the profitability, because of its simplicity. However, the annual profit does only represent income and costs in an average year and the interest rate applied in order to normalise the investment costs might deviate.

13.2 Comparison of each case in each scenario

First, technical and economic results have been evaluated individually due to the difference in performance for each case. In order to present an optimal case and scenario, a techno-economic analogy has been established. This analogy is applied to choose realistic solutions for Circle K. Throughout the comparison of different charging systems, an important factor is to discuss how these results will interact. At first, the optimal numbers of chargers per scenario are chosen to exploit the local traffic patterns. Moreover, the capacity limit for both locations will impact the technical and economic aspects of the cases.

Scenario 1: Grid Charging

In this thesis, the Grid Charging scenario can be seen as the exemplary scenario since the capacity is defined as unlimited regarding the power demand. Firstly, it is important to be aware of the high standard deviation occurring in GC. This is due to the car matrix, which is the only factor deviating the results. In scenario two, the deviation remains low because of its constant capacity limit, while for scenario three, the design of the battery already included the deviation of the car matrix. Therefore, SSC and MESC will have lower standard deviation than GC. Since a higher number of chargers results in a more customer friendly option, this might indicate that six and twelve are the most favourable cases. This is related to the fact that there are more available chargers than EVs at the station. At Sekkelsten, the stagnation of $SOC_{\%}$ may be explained by the fact that the maximal simultaneous amount of EVs arriving is four and does not occupy all the fast chargers when increasing the amount. On the other hand, at Smestad the charging performance increases constantly, however, a lower increase is observed with higher number of chargers, since the maximal simultaneous amount of EVs arriving at the Smestad is twelve and only occurs once at 4 pm (Appendix B).

Considering the *drop-out* rate being zero for twelve chargers at both stations, the charging availability can be seen as ideal because none of the customers need to leave the queue. However, this parameter presents a slightly higher overall performance at Sekkelsten, because of the considerably lower traffic flow. Thus, six chargers can offer ideal charging availability for every customer. In other words, adding six supplemental chargers will not be necessary with the estimated car intensity.

Although twelve fast chargers are consistently put forward as the best technical performance for both Smestad and Sekkelsten, this case is the least economic option for Circle K. At Smestad one important characteristic is the connection charge of 3 MNOK, while at Sekkelsten the investment cost of fast chargers is dominant. Moreover, the economic outcome at Sekkelsten results in a lower profit than Smestad, despite the assumed free connection charge. A lower car intensity at Sekkelsten leads to a more dominant installation cost, as a consequence all cases at Sekkelsten have a negative annual profit. Another outstanding parameter is the increasing income at Smestad and stagnating income at Sekkelsten. The controversy income between both locations arises from the significant difference in traffic patterns. Regarding the standard deviation, the technical performance is relatively similar for all three cases at Sekkelsten. Therefore two chargers at Sekkelsten is believed to be the preferred case. Most probably, an overall technical assessment would have led to the case with twelve chargers as the favourable option in order to achieve the best charging experience. However, the higher income for twelve chargers turns out to not finance the costs related to extension and new chargers. The combination of positive annual profit, low *drop-out* rate and valuable charging performance leads to a fair assumption that installing more than six chargers will be unnecessary.

Scenario 2: Simple Smart Charging

It may be expected that Simple Smart Charging will provide poorer results than Grid Charging regarding technical results. Accordingly, the charging performance has a peak at six chargers at Smestad. This illustrate the effect of load managing when the demand increases in respect to more chargers installed. Since load management balances all power over the loads as a result of the limited capacity, customers will experience longer charging time, implying less vehicles achieving the desired SoC. The charging performance at two chargers has an inferior outcome in comparison to six. In this case, the queue time limit could be a reason. Restricted charging time of 30 minutes for the customer leads to more forced disconnections of the chargers before having reach desired SoC. Moreover, with fewer chargers, since the maximal charging time accounts, load management concurrently charges with lower power leading to more accumulated EVs at the station and more EVs leaving the station before having charged. Thus, the station loses customers.

However, charging performance at Sekkelsten might not resemble the trend of the charging performance at Smestad. Although, due to the lower car intensity and higher capacity limit, $SoC_{\%}$ and $SoC_{80\%}$ have reached the optimal results before six chargers. The reason for this might be because all arriving electric vehicles have the opportunity to charge as long as they prefer at already six chargers.

Considering the power performance, there is a significant distinction between Smestad and Sekkelsten. The power performance can be seen as ideal throughout every case at Sekkelsten, conceivably due to its low car intensity and relatively high capacity limit. However, at Smestad another fashion is observed. For the case of two chargers, P_2 is already down at 65%, signifying an inadequate capacity for 150 kW charging. The power performance decreases rapidly at first with higher numbers of chargers and might converge eventually, causing the parabolic charging performance. The reason is twofold. First, the traffic flow at Smestad may impose the chargers to be occupied simultaneously at least once a day. Additionally, the available power distributed over more chargers leads to a decrease of power per charger. Second, the eventual trend may be a consequence from the number of chargers being to high compared to the average daily EV pattern. Moreover, the *drop-out* rate seems to have the same coherent pattern as Grid Charging at both locations.

In general, this simulation arranges a more consistent power consumption, hence there are no high peak demand charges dominating the electricity bill. Ultimately, accounting for the economic perspective, six chargers are most realistic for Smestad due to the favourable combination between the low *drop-out* rate and positive annual profit. However, Sekkelsten can provide a positive annual profit for none of the cases. This is related to the low traffic flow resulting in considerably lower income, hence the investment of fast chargers becomes prevailing. Thus, achieving acceptable technical results with profitable economy seems quite unrealistic.

Scenario 3: Microgrid Enabled Smart Charging

Before comparing all cases, it is important to remember that every case has its specific battery capacity designed to cover 95% of the annual required energy in order to give a better basis of comparison. Since Grid Charging can be described as the exemplary scenario regarding the technical parameters, a comparison between the MESC and GC may therefore be described as a reliable quality check. Hence, the battery is designed to aspire the technical performance of scenario one.

For the technical results at Smestad, a deviation from the exemplary scenario can be observed, especially for six and twelve chargers. Moreover, a lower traffic flow introduces a better charging performance with an increase of 25% from 143 to 93 EVs (Figure 10.8). These two observations indicate that technical results from the original car intensity are more affected by the low capacity limit. Hence this combination lead to the solar generation is insufficient to charge the battery fully, at Smestad. Hence, the battery capacity is not exploited at its fullest. In case six of scenario three at Smestad, this can be proven by analysing the typical SoC curve in figure M.1 in appendix M. However, the technical performance at Sekkelsten is observed to behave approximately identical to scenario one. Hence, the difference in battery capacities and available power at each station results in a significant difference in the operation of the microgrid.

In contrast to the charging performance, the power performance decreases simultaneously with the *drop-out* rate at both locations. Furthermore, an analogy can be established: A good power performance and high *drop-out* rate imply that the customer can be given a successfully charging, as long as it occurs outside rush periods. At the opposite case with low power performance and low *drop-out* rate, the customer can charge whenever it is preferable, but the charging process goes slowly. Empirically the power performance is slightly below 100% at Sekkelsten and even lower for Smestad. A reason for this may be that the PV power and available power from the grid is not high enough to charge the BEES, this makes the BEES not capable to cover the demand from the high car intensity related to Smestad. In terms of providing a satisfying customer service, the *drop-out* rate at both stations turns out to be quite similar to Grid Charging. This may be directly associated with the grid scenario's possibility to preserve the customer flow at an satisfactory level, hence the microgrid can provide a similar outcome.

Furthermore, the economic results will be examined in the same fashion. Comparing the income with the GC scenario, almost identical results at Sekkelsten can be observed, while Smestad has a slightly lower income. Especially concerning the stagnating of income in figure 12.6, the battery cost becomes more prevailing in this scenario compared to the influence of the connection charge from scenario one. Here, the income can not cover the rising of battery costs with increasing chargers. However, one of the essential benefits with installing a battery will evidently be to reduce the electricity bill. This attribute could be observed for every case presented in this scenario. This implies that the battery can in a great extent eliminate the high peak consumption from the central grid due to solar energy, hence reduce the electricity bill. This increases the self-consumption and utilises this in a more cost-effective manner. This applies specifically to Smestad, since there is a greater reduction of the electricity bill than for Sekkelsten. Hence, a higher car intensity will further contribute to higher peak periods, thus the impact of utilising DERs is more distinct.

However, a large proportion of the investment cost related to the microgrid derives from the battery cost, illustrated in figure 12.6. Although Smestad has the highest daily car intensity, the limiting grid capacity can consequently force the battery prices up, especially if considering a 95% peak shaving performance. Hence, a smaller battery capacity around 50% might have been integrated in the microgrid instead of the original 95% at Smestad. Moreover, since the numbers of chargers will increase the battery capacity, the battery cost will ultimately become extremely expensive. This is the main reason for the annual profit to become negative at higher loads. In regards to the most outstanding economic results, the case with twelve chargers at Smestad has a very negative annual profit. This implies that a high car intensity combined with a limited grid capacity results in large battery investment cost. This may not be an optimal solution to support fast chargers as of today, since the battery cost are still noticeably expensive. Considering smaller batteries, these might contribute to a more profitable alternative, as long as the charging performance does not get significantly reduced.

At Smestad the case with two chargers seems to be the best option, considering the least negative annual profit. On the other side, it is quite conceivable that for two chargers, the technical results will not maintain the same customer flow. Therefore, six chargers might be a safer option in order for Circle K to keep the customers satisfied. However, the charging performance might increase if the estimated traffic patterns at Smestad can be defined as exaggerated (Figure 10.6). All three cases have a negative annual profit at Smestad, implying that no alternative is optimal for scenario three. Even the supposition, that a change in traffic patterns might lead to a more profitable microgrid, is rejected. This is due to the sensitivity analysis demonstrating the constant unprofitable cases of the microgrid at Smestad (Figure 12.5). In addition, the LCoE highlights this outcome since a greater battery size only results in a poorer investment to energy production ratio.

On the other hand, the quick stagnation of income between six and twelve chargers at Sekkelsten indicates that six chargers already completely cover the demand. Hence, an installation of only two chargers is conceivably more realistic. The sensitivity analysis in figure 10.6 proves that the most optimal amount of daily EVs is the originally estimated one, regarding the technical aspect. Thus, the charging performance might decrease if the traffic estimation was underrated. The annual profit will almost break even in this case, further the $SoC_{80\%}$ is at a satisfying level, implying a substantial amount of customers encountering an acceptable charging experience. However, with increasing traffic intensity Sekkelsten might be able to install a profitable microgrid for two and even six chargers (Figure 12.5). Ultimately, the BESS investment will evidently be the restricting factor, although income increases remarkably with more chargers. Finally, the summarised results present an optimal case for Sekkelsten by installing two fast chargers.

13.3 Comparison of each scenario

Presenting the optimal case in each scenario can establish a good basis of comparison to determine the best option for Circle K. In general, the GC scenario prevails as the most optimal options from both technical and economic aspects, whereas SSC provides the worst technical results and MESC the worst economical results.

Regarding Smestad, the most unprofitable solution is the microgrid alternative. The sensitivity analyses demonstrates that due to the low capacity limit every case with every traffic intensity is unlucrative. Nevertheless, a lower traffic flow will be more beneficial considering an annual profit increase at 16% from 143 to 93 EVs (Figure 12.5). However, an eventual transport sector dominated by EVs is probable, therefore a reduction of traffic flow is unlikely. Thus, a GC solution would be considered preferable, although the central grid is expected to be upgraded anyway. At first, the connection charge was presumed to be exceedingly expensive and hence unfavourable for Circle K, although, results have proven that this charge may not be as prevailing as other investments related to fast chargers. However, in order to avoid high power tariffs, load management is critical. The EV demand is still considered high, therefore a combination between GC and SSC might be the optimal solution considering a futuristic growth of the EV market. In order to reduce the electricity bill a critical power limit can be introduced. Eventually, a microgrid alternative can become more relevant in the future.

Considering Sekkelsten, a general overview of the technical performance shows no significant change between all three scenarios. This might imply that the combination of a low traffic flow and flexible capacity limit does not depend on the charging system. Moreover, a substantiate argument is the insignificant difference in the annual profit between GC and MESC. Nevertheless, Sekkelsten can optimise the annual profit with a higher traffic flow, from 43 to 143 daily EVs an increasing by 15% (Figure 12.5). Thus, in the future with more EVs dominating the transport sector, the grid capacity will become more challenged. Therefore, the best solution for Sekkelsten is to adapt to a microgrid alternative in order to ensure an energy-effective system. Given that the power tariff structure is in development, the battery can become more relevant at peak shaving to reduce high grid rent costs. In addition there has been some concerns regarding the distance of digging new cables to the station, hence a grid expansion can become very expensive. Moreover, MESC is more cost-effective than GC in the long term. After having covered all investment cost, the annual profit will be favourable at MESC due to its superior income-to-electricity bill ratio. This may derive from the fact that the solar production covers for the irregular power demand. Thus, the combination of battery and sun can in general keep the power required from the grid under the maximal capacity limit.

Another point of view can be Circle K's focus on either a better technical operation of fast chargers or an economically preferable approach. However, seen from the perspective of Circle K as a charging service operator, the intention of adapting a quick roll out pace for fast chargers is important to consider. If the installation time frame restricts the station from expanding the local grid infrastructure, a microgrid solution might be the most suitable alternative. Therefore, a smart charging alternative will be preferable, not only considering the time frame but also as a future investment.

14 Future Research

The presented fast charging cases could be optimised by considering other alternative scenarios. Thus, further DER and DESS can provide a more comprehensive evaluation of smart charging options. Furthermore, the interest and progression of new technology could solve problems related to grid infrastructure and energy-effective systems.

Since ideal technical and optimal economic results do hardly correlate in MESC, further investigations regarding specific numbers of chargers related to traffic patterns could be engaging in order to obtain a cost-effective and customer friendly charging service. Further, since regions with a relatively high charging frequency and low grid capacity become unprofitable in a microgrid solution, other locations with lower charging frequencies and more compliant circumstances, similar to Sekkelsten, might be worth investigating. Eventually, a microgrid alternative supporting fast charging can achieve improved profitability.

Since the battery can offer voltage and frequency regulation in the distribution network, a FTM application can be considered. Supporting the grid companies by improving deliver quality and reliability might avoid grid blackouts, low voltages and forced disengagement from the central grid. In addition, other than supporting fast chargers, the battery can execute DSM in order to prevent high tariffs since price-based DR is gradually dominating Norway's power structure. This model can moreover lead to a more cost-effective microgrid by evaluating daily change of electricity cost. Especially Sekkelsten has the perfect ability to implement such a prototype, since traffic patterns indicate an absence of EVs at nighttime. Ultimately, the affect of the BESS on the peak shaving performance associated with a reduced electricity bill suggests a thorough evaluation of savings by introducing a critical limit. This limit can be defined by the operator to offset variations in consumption above this boundary and obtain a decent electricity bill, hence avoid expensive power tariffs.

Due to Norway's intention of a quick roll-out adaption of electric vehicles, Enova has created a system in order to support charging operators installing fast chargers. Accordingly, the support system will lower investment cost of fast chargers and expand the EV market. However, this public support is not accounted for in this thesis, since the analysed municipalities do not comply with Enova's requirements. Eventually, the support system might adjust and more regions will portray a lucrative investment. [115]

An optional business model for Circle K could offer incentives for costumers deciding to charge their EVs in periods of lower demand. This configuration can in turn contribute to lower prices of the charging system for registered costumers in these given periods. Accordingly, the economic outcome can be preferable for both parties. Another measure might be introducing an organised prioritised charging system for costumers. This can be implemented in order to attract costumers preferring to charge at one specific station. Especially at Sekkelsten, commuters between Oslo and Sweden might be interested in such an idea.

In order to increase the income Circle K's price system has to be evaluated. Several fast charging operators have time-based price systems, which can be beneficial for the operator. Due to the price system, Circle K seems to earn more compared to Fortum at first. However, by considering the figure K.1, at lower charging speed Circle K earns less. This might increase Circle K's popularity, although, the income is moderate. Hence, a further analysis regarding the charging price might be an interesting aspect.

15 Conclusion

An overall evaluation of all 18 cases demonstrates one optimal alternative for each Circle K station. According to the techno-economic results, Smestad is subjected to a higher car intensity challenging the stations capacity limit. Hence, a complex microgrid maintaining favourable customer service becomes unprofitable due to an annual loss between 0.5 MNOK and 9.22 MNOK depending on the number of chargers. However, the sensitivity analyses confirm that, due to insufficient power supply, an improvement up to 93% of the annual profit by halving the battery capacity will have an insignificant impact of 3% on the charging experience. Hence an option to invest in microgrids is not discreditable. Nonetheless Grid Charging results in a excellent charging performance up to 97% with less than 10% of EVs leaving the station, while the annual profit is at 1.15 MNOK. To conclude the optimal case presents six chargers with a combination of grid extension and optional load management in order to avoid high power tariffs.

On the contrary, Sekkelsten is advantageous by adapting smart charging alternatives, since the station has a relatively flexible capacity, whilst the traffic flow is considerably lower. Hence, introducing several fast chargers to the station has a minor influence on the technical performance. Accordingly, the optimal case includes two chargers being managed by a microgrid solution, incorporating a photovoltaic system with an installed power of 19 kW and a battery energy storage system with a capacity of 500 kWh. Lastly, this solution will increase the charging performance up to 88% with less than 18% of the customers leaving the station. Nonetheless, the annual profit is slightly negative at -0.09 MNOK. Eventually, MESC will become increasingly substantial due to the improvement of battery technology and reduction of costs. Moreover, the introduction of a reformed power tariff structure in 2020 will contribute to a profitable investment in self-sustainability.

Further, since the annual profit and customer experience do not correlate, as a consequence, a compromise must be determined. Appropriately, the profitability of fast charging stations can be improved in certain circumstances without affecting the customer experience. Circle K's charging stations require a relatively constant, yet high traffic flow with a compliant grid capacity. The comprehensive evaluation of different traffic flows at each station is a particularly interesting result, further presenting better alternatives than the original scenarios. At Smestad, a lower car intensity will be more beneficial with an annual profit increasing by 16% from 143 to 93 EVs and introduces a better charging performance with an increase of 25%. On the other hand, Sekkelsten will require higher traffic flow in order to optimise revenue, increasing by 15% from 43 to 143 daily EVs.

Ultimately, EU promoting energy-effective systems will evidently affect Norway's management and consumption of energy. By implementing a microgrid, Circle K will become a pioneer in the smart energy system movement. The roll out pace needs to be increased in a rapid manner in order for Circle K's aspiration to modernise into an energy station with an improved business model. An extensive grid upgrade will definitely benefit a charging station service in areas with limited capacity. However, the long implementation time will restrict Circle K's vision. In conclusion, the fast adaptation of smart energy system, such as microgrids, will ultimately become the preferable alternative.

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A Grid capacity

Data of the stations power demand, from Elvia AS, is presented in this appendix. This data is necessary in order to calculate the available power at each station. This information is further utilised in the MATLAB code for input values of the available power, P_{access}. Hence the available power is calculated for each station respecting the maximum limits. Regarding the maximum limit, both cables and transformers can be overloaded in short periods. Typically, cables can go beyond the maximum at 20%-30%, while transformers can exceed values of 30%-40%. This is further utilised to estimate the *connection charge* and the repective *free limit*. [18]

The Oslo region, including Oslo and Akershus, has a deficit of electrical energy. In an average year, just over 20% of the electrical energy consumed is produced, i.e. that about 80% must be delivered from the main grid [104]. Today's transmission grid can provide 5 300 MW in the Oslo region. Because of some local productions connected to the regional and distribution network, the entire power system can supply 5 700 MW in Oslo. However, the highest measured consumption was 5 470 MW during winter in 2016. Moreover, the Bærum-Smestad line has a transmission capacity to supply just over 1 000 MW at 0°C ambient temperature. [103]

Smestad, Oslo

The Circle K station located in Smestad, Oslo, provides electricity supply amongst other power consuming units from distribution transformer 3422. Since the transformer is connected to several units the capacity is near its maximum limit. The highest consumption measured is 117kW. The cable supplying 3x500A is limited compared to the existing consumption. However, the limiting factor at Smestad is the transformer station. This is the result of more units connected to the transformer and the substation is near its maximum limit. The total power capacity the cables can supply is 193 kW with a $cos\phi$ of 0.97, calculated from equation 2.1. For transformer 3422, the maximal power consumption from all connected units is 575.3kW. [116]

Sekkelsten, Indre Østfold

The Circle K station located in Sekkelsten, Indre Østfold, provides electricity supply alone from one distribution transformer Z1107. The transformer has a rated capacity of 630 kVA, 11 kV / 0.4 kV. The cable can supply 3x700 A and is the limiting factor. Maximum power consumption historically measured since the installation of AMS is 177kW. The total power capacity the transformer can supply is 470 kW with a $cos\phi$ of 0.97, calculated from equation 2.1. P_{access} is calculated by the difference between calculated power from the rated values of the transformer and the power demand from the station. [116]

B Car intensity

In order to assume the traffic pattern in two different locations, the individual demography and infrastructure has to be considered. The car intensity throughout a day and year can be unpredictable, hence the simulation needs to be simplified in order to complete the project, given the time frame and accessible data. Therefore the car intensity can contain several inaccurate assumptions. Thus a futuristic approach may enhance the final outcome.

The car intensity is estimated to analyse traffic patterns throughout the day. The car intensity is simplified, by not account for public holidays or high seasons. The traffic data used to estimate the intensity comes from Norwegian Public Roads. At each location, a traffic meter for both roads in the intersections was available and this data was implemented in to the MATLAB code. SSB states that there was an 1.1% increase of passenger cars in Norway between 2017 and 2018. The same increase is assumed to be realistic in the following years [117].

Smestad, Oslo

The gathered traffic data from Norwegian Public Roads for the Smestad intersection derive from two registration points: RV150 S2D1 m4757 on Riksvei 150 and KV168 S1D1 m2983 along Sørkedalsveien. This data represents the amount of cars passing the station every hour. Table B.1 display the number of the following explained calculations. The amount of EVs passing the station is attained by finding the percentage of EVs in Oslo. In total, 299 147 passenger cars were registered by December 2018. With an increase of 1.1%, the amount of passenger cars should be 302 438 passenger cars by the end of December 2019. [118] The Norwegian Electric Vehicle Association states that 45 658 electric cars were registered in Oslo by December 2019 [49]. The ratio between the amount of EVs and total amount of cars in Oslo by December 2019 is therefore 15%. Moreover Circle K has provided a key assumption, estimating that of out of these 15%, only 10% will always charge at fast charging stations. This is based on EV owners having a possibility to charge at home in the Smestad area. These estimations lead to 893 EVs passing Circle K Smestad with the intention to fast charge.

Table B.1: *Detailed calculations of daily EVs at Smestad.*

Cars at RV159	Cars at KV168	Total cars	Total EVs	EVs fast charge	EVs at Circle K
100%	100%	100%	15%	10%	16%
41596	17910	59479	8922	893	143

Furthermore, other competing companies close to the Smestad intersection will reduce the amount of EVs arriving at the Circle K station. Fortum Charge&Drive has stations located nearby Smestad and is therefore the most competitive charging service for Circle K Smestad. The charging station at Majorstuen (2.7 km) has a total of 32 chargers, although 20 out of these are type 2 chargers, not being able to charge above 43 kW. The charging station at Rikshospitalet, McDonalds Gauland, (2.7 km away) has a total of seven chargers. Oslo Kommune Skøyen (2 km away) has a total of 20 chargers, while Circle K itself has a station nearby with 2 chargers. All of these fast charging stations are provided by Fortum. Since this company charges the customer regarding time and energy consumed and Circle K considers only the energy consumed, the charging prices will be different between the stations. Fortum will be more expensive at a charging speed under 40 kW for 50 kW fast charging, while for 150 kW fast charging Fortum will be more expensive under a charging speed of 50 kW. [119]

Circle K's 50 kW fast chargers are priced over 5 NOK/kWh, and the Norwegian EV Association assumes that 16% of the EV owners are willing to pay over 5 NOK/kWh. Reference [120] presents the fraction of EV owners wanting to pay for fast charging. The assumption of 16% is calculated from the presented pie chart, considering that Circle K charges 5 NOK/kWh. [120]. Therefore, 16% of the EVs with intent to fast charge, will choose Circle K Smestad. Because of the highly competing region around Circle K Smestad, the total amount of EVs might be lower than 16% of those EVs needing to fast charge. Moreover, type 2 chargers will probably be more expensive considering the charging price at Fortum. [119]. Therefore, Circle K might be more popular than assumed in this case. However, it is hard to estimate a ratio of cars that definitely will chose Circle K Smestad, since the infrastructure of the city in Oslo does not allow a precise estimation of traffic flow without specific and empirical data. Eventually, this approach demonstrates that 143 EVs will charge at Circle K Smestad in one day, with a peak of 13 cars at 4 pm and a small peak at 9 pm of 10 cars (Figure B.1).

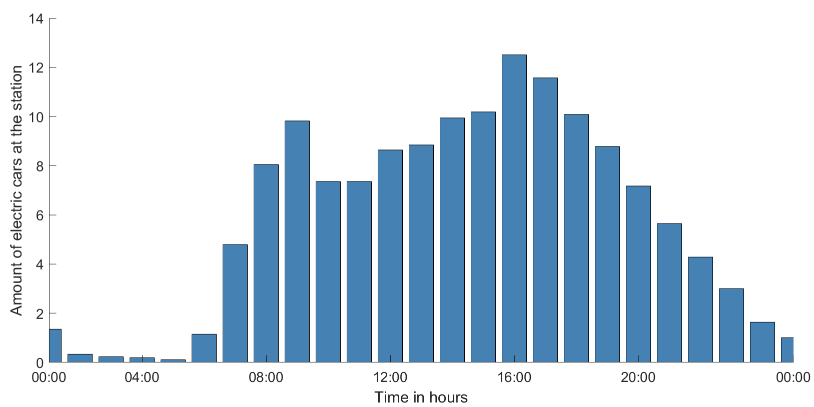

Figure B.1: *Car intensity through a regular day at Smestad.*

Sekkelsten, Indre Østfold

The gathered traffic data from Norwegian Public Roads for the Sekkelsten intersection derives from two registration points: FV124 S5D1 m7349 on Fylkesvei 124 and EV18 S64D1 m3562 along the Europavei 18. This data represents the amount of cars passing the station every hour. Table B.2 shows the number of the following explained calculations.

Table B.2: *Detailed calculations of daily EVs at Sekkelsten.*

Cars at FV124	Cars at EV18	Total cars	Total EVs	EVs fast charge	EVs at Circle K
100%	100%	100%	8%	50%	16%
1563	5179	6742	340	270	43

The amount of EVs passing the station is attained by finding the percentage of EVs in Indre Østfold. A number of 154 098 passenger cars were registered by December 2018. With an 1.1% annual increase of passenger cars, the amount is estimated to be 155 793 by December 2019. [118] The Norwegian EV Association states that 11 771 electric vehicles were registered in Østfold by December 2019. This implies that 8% of all cars in Østfold are electric [49]. Furthermore, 70% of the vehicles passing the station are driving on E-18 highway (Table B.2), being commuters from Oslo or Sweden and not locals. Therefore, the group assumes that out of these 8%, 50% will charge at fast charging stations. This fraction of passing cars wanting to charge can be higher around Sekkelsten because these cars might not have the option to charge at home, since most of them are commuters. These estimations lead to 270 EVs passing Circle K Sekkelsten with the intention to fast charge.

In addition to other competing charging stations nearby, Circle K Sekkelsten has four existing fast chargers implemented. Since this is not accounted for in this thesis, the traffic patterns may be more uncertain. Fortum Charge& Drive and Grønn Kontakt are other charging companies providing fast charging in Askim (6 stations) and Momarken (6 stations).. However, cars passing Sekkelsten are more likely to prefer charging in Sekkelsten, than leave the highway and charge in the centre of Askim, provided by Grønn Kontakt. Hence, Momarken will be the most competitive station for Circle K Sekkelsten. Momarken is operated by Fortum Charge&Drive, having a cheaper service when charging at lower speed than 40 kW, explained previously [119]. Since Circle K's 50 kW fast charging is over 5 NOK/kWh, only 16% of these EVS will charge at Circle K, regarding the price [120]. These estimations results in a daily amount of 43 EVs charging at Circle K Sekkelsten, with a peak of four cars around 4 pm (Figure B.2).

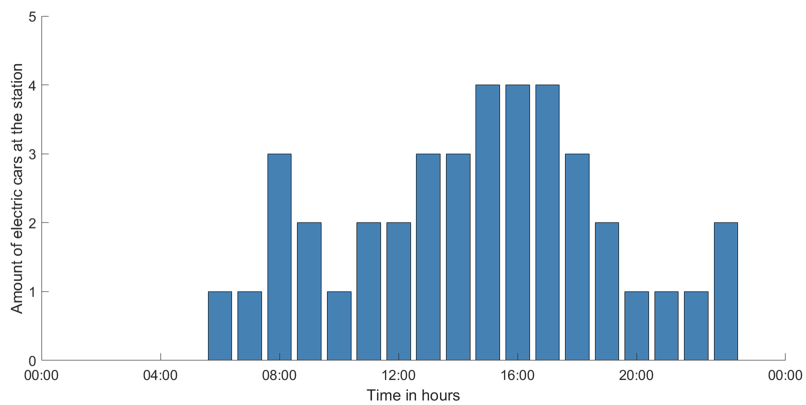

Figure B.2: *Car intensity through a regular day at Sekkelsten.*

C Queue code

Flowchart description

Figure C.1 describes the process of the queue simulation implemented after the electric vehicle simulation. B_x is the amount of cars in a certain amount of time, t, equal to the number of rows in the EV matrix, x.

The purpose of the first for-loop is to analyse how many cars are on the charging station, B, and if there are too many cars on the station compared to the amount of chargers, L. The first loop considers also the time it takes for a car to leave and a new car to start charging. The changing time is estimated to be one minute.

K is the variable defining if there is a charging queue at the station. When K is positive, there are more cars than chargers, B is greater than L. When there is a queue, other charging conditions will apply to the cars. The desired SoC will be reduced to 80% and the maximal charging time is set to 30 minutes.

The second loop starts when the first loop has gone through all rows, and counts the amount of cars charging at 50kW, N_1, and at 150 kW, N_2, while considering if there is a charging queue or not. It also decides if cars have to leave the station. As long as there are available chargers, the loop continues to run.

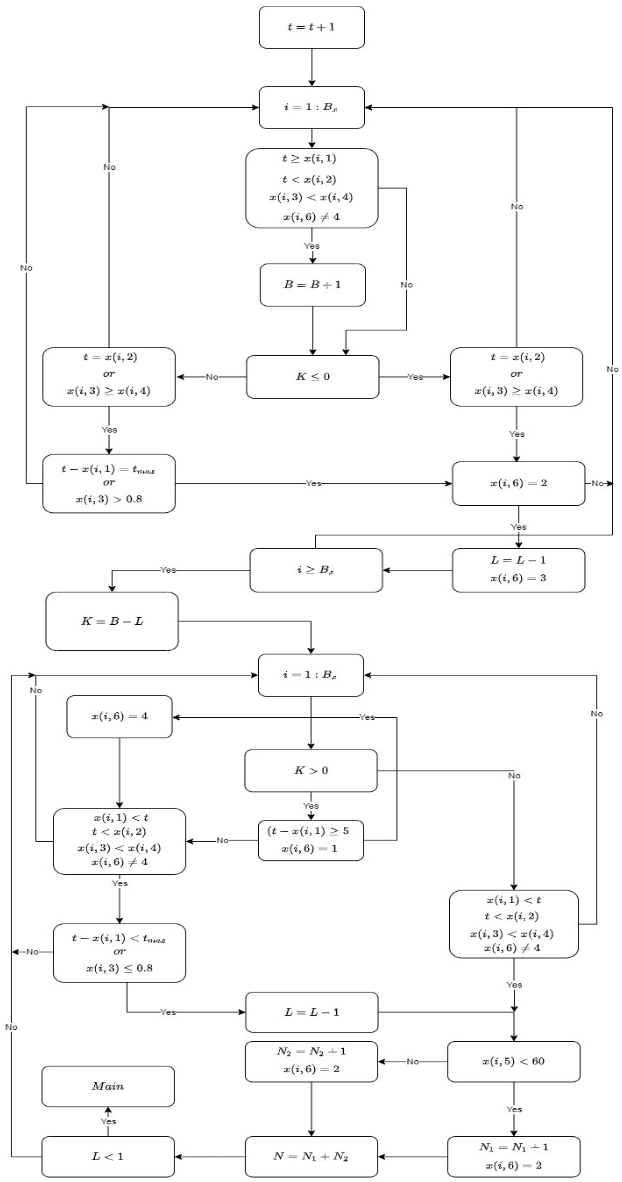

Figure C.1: *Flowchart representing the queue-code.*

D SoC of different electric vehicles

The State of Charge varies with different electric vehicles having diverse battery capacities. The SoC of all top four Norwegian electric vehicles are presented in the following figures D.1, D.2, D.3 and D.4. Since the Tesla Model S can charge at 50 kW and 150 kW, the SoC is different depending on the speed of charge. All these plots are simplifications of empirical data from Fastned. On the figures, the charge speed defines the maximal power that the battery can use while charging at a certain State of Charge. [121]

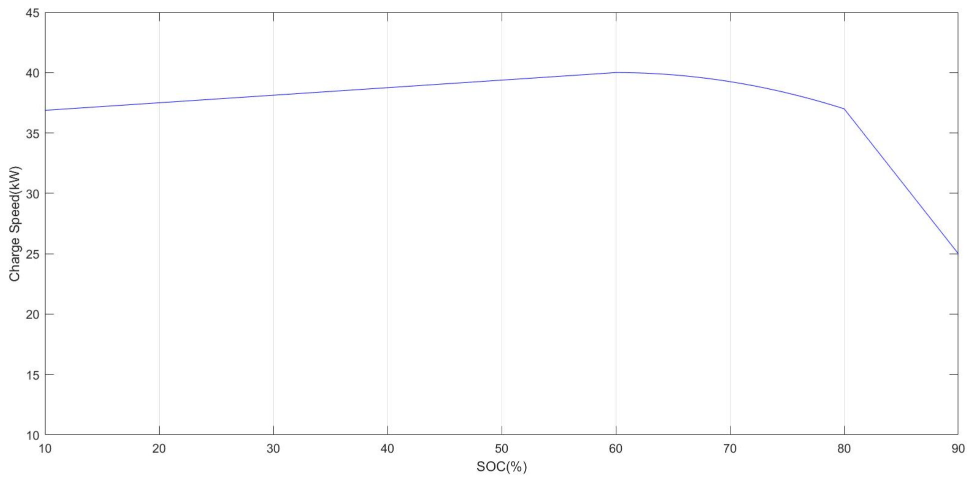

Figure D.1: *VW e-Golf, 38 kWh.*

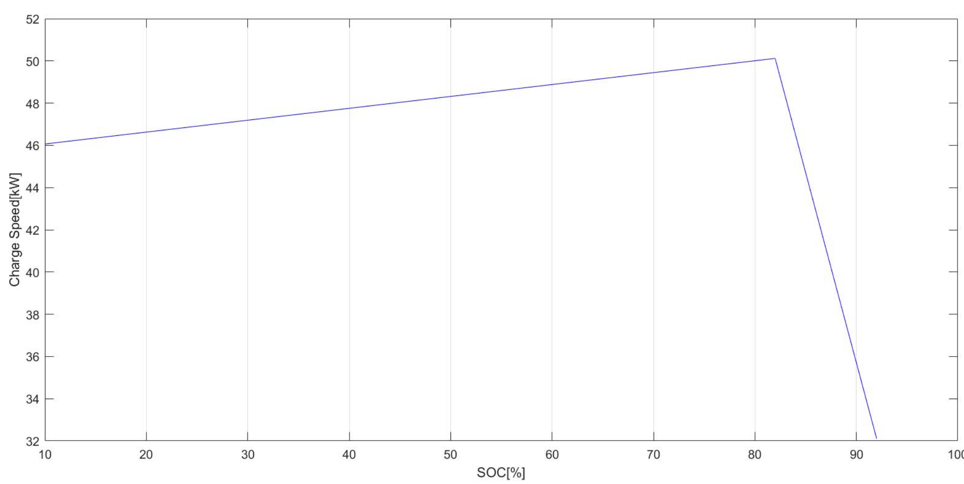

Figure D.2: *Nissan Leaf, 40 kWh.*

As illustrated in the separate figures, the battery of each electric vehicle does not have the capacity to constantly charge at maximal power. To understand when the batteries are able to charge at full speed, empirical charging curves are simplified and implemented in the code to improve the charging process. The charging curves vary with battery capacity and chemistry. Moreover, for 50 kW fast charging the curves are rather increase linearly from 20% to 80% and decrease slowly after. However for 150 kW fast charging, the charge speed remains rather constant from 20% to 45% and decrease linearly afterwards.

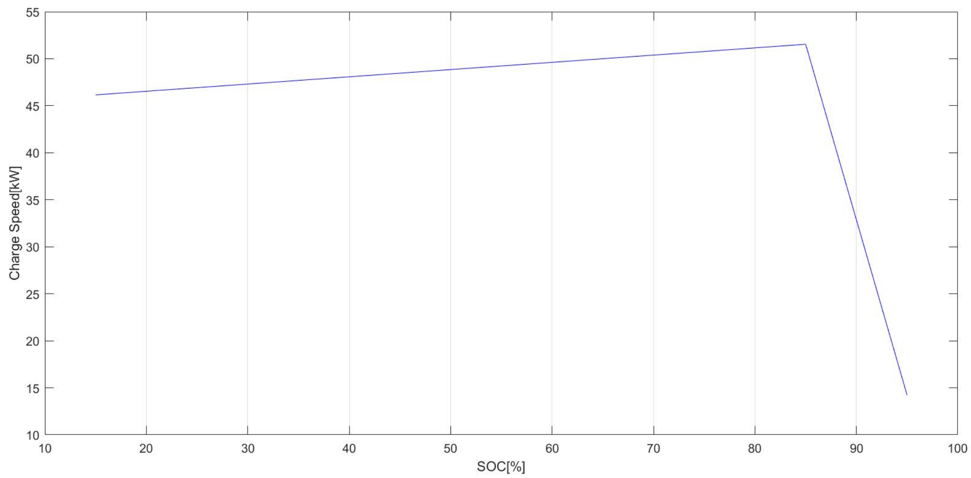

Figure D.3: *BMW i3, 42 kWh.*

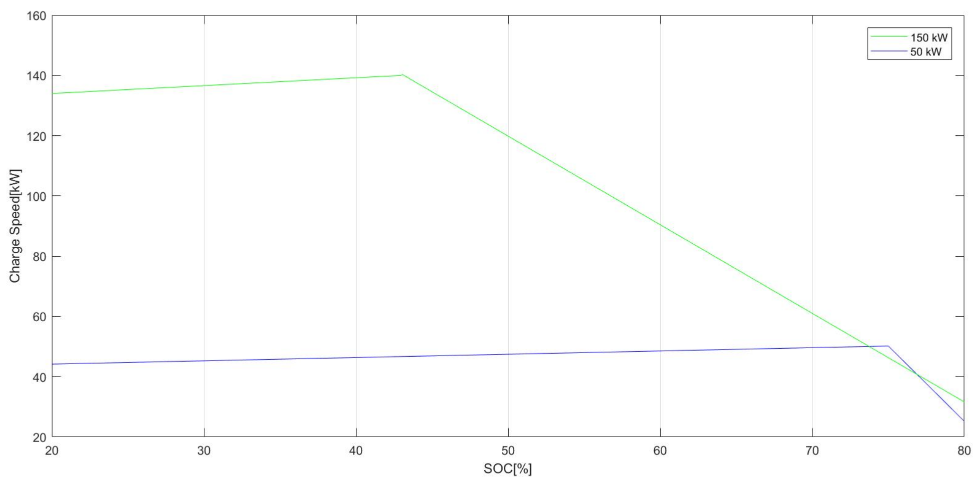

Figure D.4: *Tesla Model S, 85 kWh.*

E Efficiency of components in the simulations

To achieve the most precise results efficiency, hence losses, have to be considered in the simulations. Table E.1 presents this information for all electrical components integrated in the microgrid, except for BESS and the PV system. The voltage converter is applied between the PV system and the BESS, while the inverter is applied between the PV system and the utility grid. The rectifier is implemented between the utility grid and the DC microgrid. Cable losses are included between the utility grid and microgrid, as well as between the charging stations and the microgrid.

Table E.1: *Efficiency of different electrical components.*

Component	Efficiency
Voltage converter	0.810
Inverter	0.940
Rectifier	0.965
Fast chargers	0.950
Cables	0.900

F Flowchart of the main code at the presence of customers

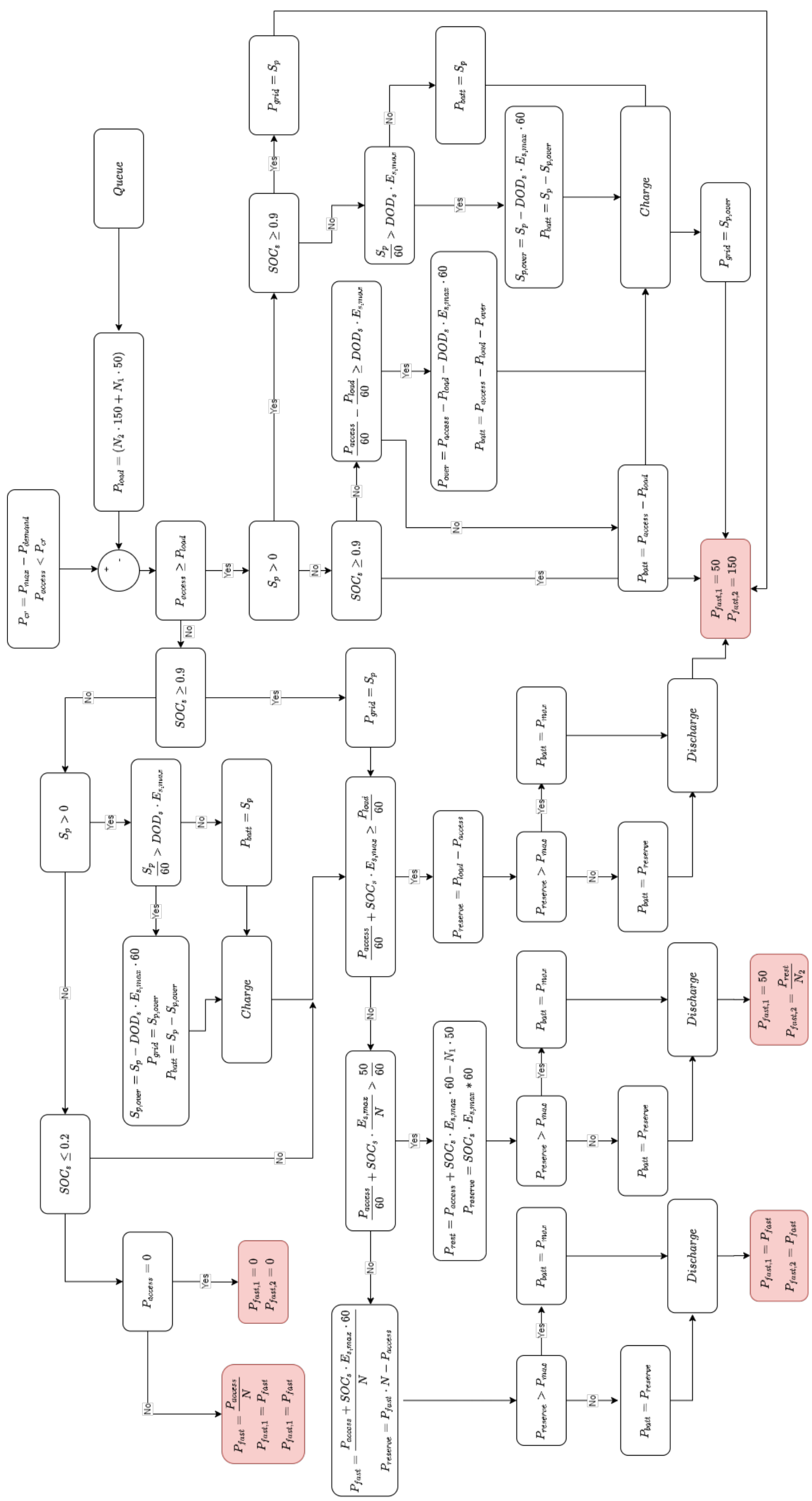

Figure F.1: *Flowchart of the main script for the MESC in the presence of EVs [122].*

G Flowchart of the main code at the absence of customers

Second part of the main code flowchart (Figure G.1) describes the functions of the microgrid controller when there are no cars at the charging station. The simulation checks the charging opportunities for the BESS in priority order. Therefore, solar energy production will be checked first. If the PV energy is not sufficient for BESS charging, accessible energy from the grid is the second choice. The charging is only possible with enough free space on BESS in that minute. If neither PV or grid energy are available, the system remains constant by going through the constant code.

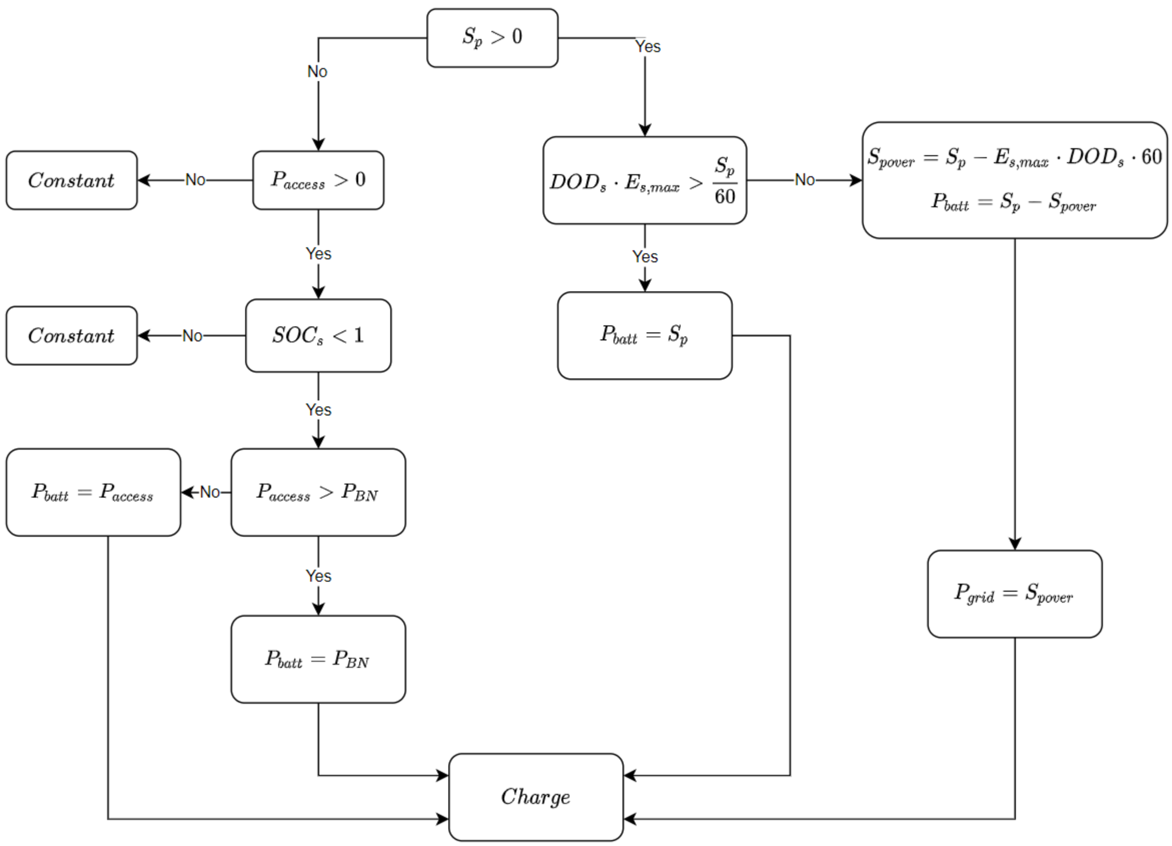

Figure G.1: *Flowchart of the main script for the MESC in the absence of EVs.*

H Economic assessment of the photovoltaic system

In order to estimate the installation cost of solar panels, Solcellekraft.no is utilised. By typing in the address, information on how many solar panels installed can be estimated. The presented data is the foundation of the cost analysis of PV. The cost of installation is determined by the capital expenditures, the operational expenditures, and the efficiency of the solar cells. Below, CAPEX and OPEX is presented for each station. Norway has a public support system named Enova, which financially contributes to sustainable initiatives supporting projects. This is the primary public support of solar panels. [123, 124]

Capital expenditures

Capital expenditures of PV systems are related to the suitability and are of the roof. The solar panels are owned by the Circle K stations. From Google Maps Distance Calculator, the area of the main roofs in Smestad and Sekkelsten are 300 m^2 and 100 m^2 respectively. However, Solcellekraft.no checks if the area is suitable for solarpanels.

Smestad, Oslo

The Circle K station at Smestad, Oslo, is limited by an area of approximately 300 m^2 and a maximum cost of 900 000 NOK. Circle K Smestad, Viggo Hansteens veien 1 can have a maximum of 188 solar panels installed on the roof according to Solcellekraft.no. Each solar panel is approximately 1.7 m^2 and the total area with 188 panels installed is 306 m^2. Roof space marked in a green, has the highest suitability, therefore more installed panels. Each solar panel can deliver 320 W and can produce annually 55 949 kWh. The total cost is 850 112 NOK, equal to 126 265 NOK as a normalised annual total cost with an interest rate of 4% and a project life of 8 years. Savings based on electricity bill is estimated to be 102 94 NOK. This is equal to savings of 823 568 NOK in 8 years. On the basis of an average price per kwh of 1.84 NOK/kWh. It is estimated 8.7 years until the installation cost is earned back again. [125]

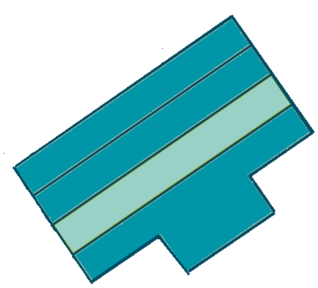

Figure H.1: *Rooftop surface of Smestad station (306 m^2)[125].*

Table H.1: *Installation cost for PV system at Smestad*

188 Solar panels	Cost
Installation cost	876 362 NOK
Enova support	26 250 NOK
Total cost	850 112 NOK
Ann. cost	126 265 NOK

Sekkelsten, Indre Østfold

The Circle K station at Sekkelsten, Indre Østfold, is limited by an area of approximately 100 m^2 and a maximum cost of 300 000 NOK.

Circle K Sekkelsten Rakkestadveien 50 can have a maximum of 60 solar panels installed on the roof according to Solcellekraft.no. Each solar panel is approximately 1.7 m^2 and the total area with 60 panels installed is 98 m^2. Each solar panel can deliver 320 W and can produce annually 17 856 kWh. The total cost is 274 775 NOK, equal to 40 811 NOK as a normalised annual total cost with an interest rate of 4% and a project life of 8 years. Savings based on electricity bill is estimated to be 32 855 NOK/yr. This is equal to savings of 262 840 NOK in 8 years. On the basis of an average price per kwh of 1.84 NONOK/kWh. It is estimated 8.9 years until the installation cost is earned back again. [125]

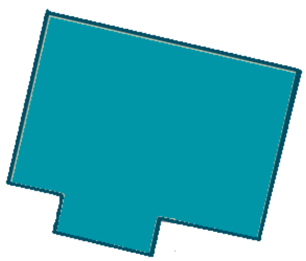

Figure H.2: *Rooftop surface of Sekkelsten station (99 m^2) [125].*

Table H.2: *Installation cost for PV systems at Sekkelsten.*

60 Solar panels	Cost
Installation cost	301 025 NOK
Enova support	26 250 NOK
Total cost	274 775 NOK
Ann. cost	40 811 NOK

Operational expenditures

Operational expenditures are related to the maintenance cost. Solar cells have almost no operating and maintenance costs. There are almost no events of unforeseen component failure. There are typically not much operational expenses related to PV systems. The lifespan is around 25-30 years. The biggest contributor to operational cost is converters and changing them. Normally, a converter or inverter is connected to a PV module, however each solar panel can be connected in series or in parallel. If the total number of solar panels per module is 20, these will have one inlet to the converter/inverter. Commonly, a converter has 2-9 inputs. [126]

I Technical and economic data for the battery energy storage system

The costs will depend on the energy capacity (kWh) and the power (kW) of the battery demanded by the microgrid. The following table I.1 will show all data about the stationary battery used in the microgrid. The data was gathered from a technical report analysing cost from 2018 and predicting costs for 2025. To find the approximate costs for 2020, an interpolation presented by equation I.1 was conducted. Regarding interpolation, uncertainties have to be kept in mind.

$$Cost_{2020} = Cost_{2018} + (Cost_{2025} - Cost_{2018}) \cdot \frac{Year_{2020} - Year_{2018}}{Year_{2025} - Year_{2018}} \tag{I.1}$$

The capital cost (CC) for electrochemical includes electrodes, electrolytes and separators. Power Conversion System (PCS) is calculated based on the costs for the inverter and packaging, as well as container and inverter controls. The Balance of Plant (BOP) consists mainly of electrical site wiring, interconnection transformers and other additional ancillary equipment (TMS, Control and Monitoring). The Construction and Commissioning (C&C) includes site design, costs related to equipment procurement and transportation, as well as the costs for labour and parts for installation. [83]

Table I.1: *Technical and economic data of the stationary battery [83].*

LIB	2018	2025	2020
Capital Cost - Energy Capacity ($\$/kWh$)	271	189	248
Power Conversion System (PCS) ($\$/kW$)	288	211	266
Balance of Plant (BOP) ($\$/kW$)	100	95	99
Construction and Commissioning ($\$/kWh$)	101	96	100
Total Project Cost ($\$/kWh$)	469	362	438
Operation & Maintenance - Fixed ($\$/kW/yr$)	10	8	9
Operation & Maintenance - variable ($\$/kW/yr$)	0.03	0.03	0.03
Round trip efficiency (RTE)	0.86	0.86	0.86
Response time	1 sec	1 sec	1 sec

The Operation and Maintenance costs (O&M) describes all important costs to operate the battery system during the time of its economic life and is normalised with respect to the annual discharge energy throughput. This cost will fluctuate based on energy usage. It does include replacement costs for fatigued materials, labour and insurance. Li-ion systems have a typical usable life of approximately nine years and require major maintenance on the battery system usually every five to eight years to remain operational. Monitoring is crucial to ensure good performances of an ESS. A battery management system (BMS) is always associated to any type of battery pack in order to protect them for over(dis)charge, short circuit, high temperature, unbalance quantity of charges between cells, etc. [83]

The total project costs are calculated based on a E/P ratio of 4 hours. This implies a general C-rate of 0.25. Although, the microgrid systems discharge C-rate of 1.5 and charge C-rate of 1 are higher. This implies that the life time of the battery will actually decrease compared to the data from table I.1.

All other properties are not supposed to change in between 2018-2025 and will remain constant. The response time is found to be 1 second. Since the simulated system calculates every minute. The response time of the battery will be neglected. The life time of the battery is estimated to be 9 years considering battery degradation, such as capacity fade and resistance increase. However, fast charging will impact the battery capacity extremely; hence it is hard to decide the calendar life of the BESS. [83]

J Norwegian electricity prices and network tariffs

An overview of Elvia's grid rent for business customers is given in table J.1. Consumption taxes are not provided for business customers. The electrical power tax is 0.1613 NOK/kWh.

Table J.1: *Network tariff from Hafslund Nett from 2020 [38].*

Tariff	Price
Fixed section	340 NOK/mo
Power section - winter 1 (Jan, Feb and Dec)	150 NOK/kW/mo
Power section - winter 2 (Mar and Nov)	80 NOK/kW/mo
Power section - summer (Apr - Oct)	23 NOK/kW/mo
Energy section - winter (Jan - Mar and Nov - Dec)	0.07 NOK/kWh
Energy section - summer (Apr - Oct)	0.039 NOK/kWh

Table J.2: *Average monthly elspot prices for Oslo in 2019 [127].*

Month	Prices in NOK/MWh
Januar	545.82
Februar	451.51
March	408.53
April	398.27
May	385.88
Juni	293.23
July	337.81
August	346.01
September	296.61
October	371.32
November	427.59
December	381.61

K Economic assessment of fast chargers

Table K.1 presents capital and operational expenditures of the fast chargers. C_{FC} symbolises the one-time investment, while ann. C_{FC} defines the normalised annual one-time investment. Maintenance cost accounts for 3% of the capital cost of the fast charging, while the salary is equal to 100 000 NOK per charger. These two costs are contained in operational and maintenance cost, OM, of the fast chargers.. [108]

Table K.1: *Installation and operational cost of fast chargers at Circle K [108].*

	C_{FC} [NOK]	Ann. C_{FC} [NOK]	Maintenance [NOK/yr]	Salary [NOK/yr]
2	2 600 000	386 172	78 000	200 000
6	7 800 000	1 158 517	234 000	600 000
12	15 600 000	2 317 034	468 000	1 200 000

Figure K.1 represents the charging service companies' different approaches on fast charging prices per kWh. Difference of charging power (kW) is also described. Since Circle K only has a charging price-based on the energy consumption of the customer, the charging price will be constant no matter the charging speed. However, other companies, like Fortum and Grønn Kontakt, have a charging price-based on energy consumption and time. This results in more expensive charging prices with lower charging speed. For example, if you charge on average with less than 40 kW of charging speed, Circle K will be cheaper than Fortum. [119]

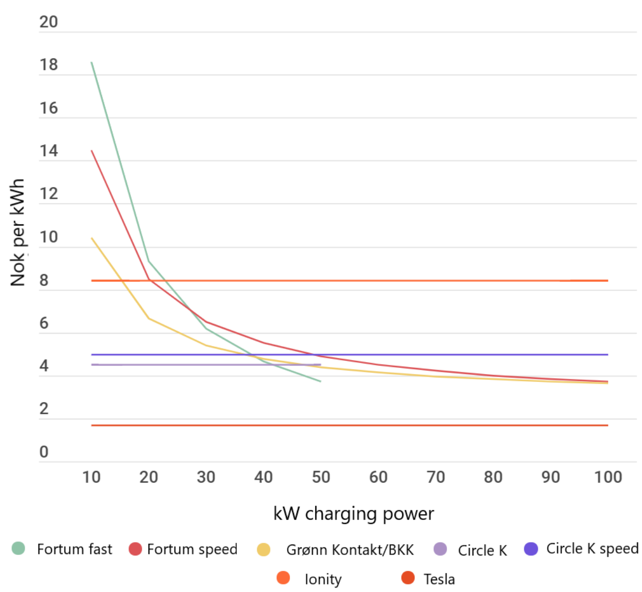

Figure K.1: *Fast charging prices per kWh, for different charging power (kW) [119].*

L Results regarding the power performance

In this appendix, the power performance for Simple Smart Charging and Microgrid Enabled Smart Charging is illustrated in order to give a better overall view. Figure L.1 shows the power performance for the SSC for Smestad and Sekkelsten.

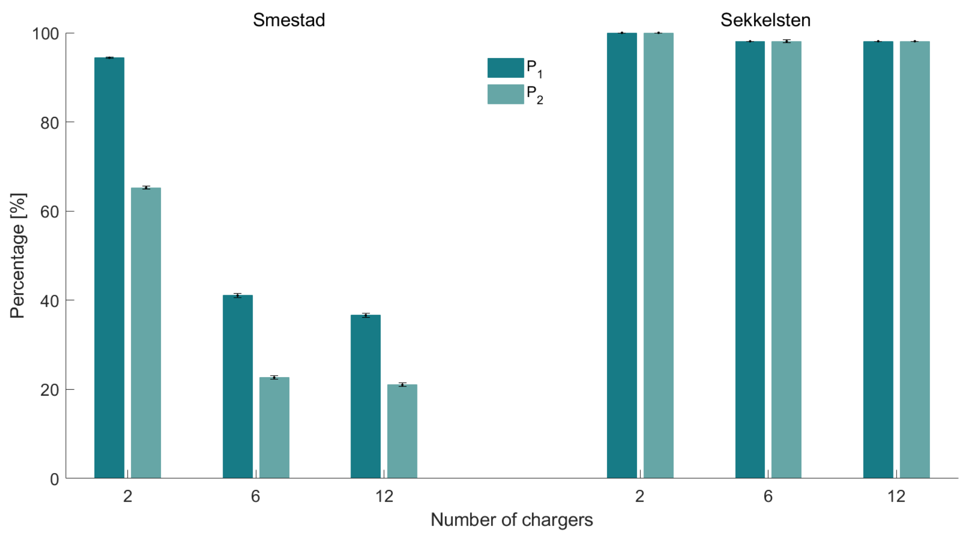

Figure L.1: *Power performance for SSC.*

Figure L.2 shows the power performance for the MESC for Smestad and Sekkelsten.

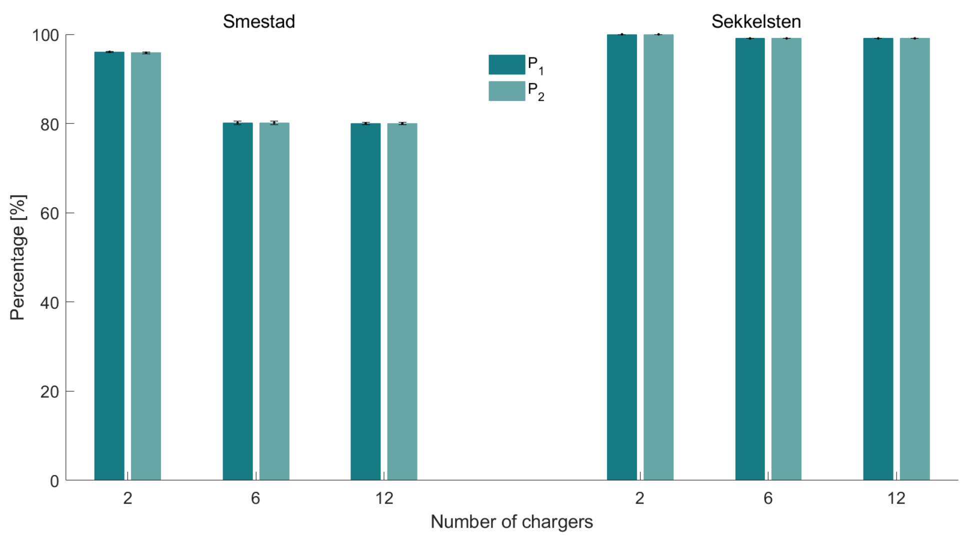

Figure L.2: *Power performance for MESC simulation.*

M Results of the average SoC at Smestad with six chargers

Figure M.1 represents a typical daily SoC curve of the BESS at Smestad with six chargers. The average SoC value is around 23%. The battery seems to charge in the morning from the grid, when the load is low and charges in small intervals from the solar production, however the total power taken from the utility grid and solar production seems to be insufficient compared to what the battery capacity and energy demand. Fo

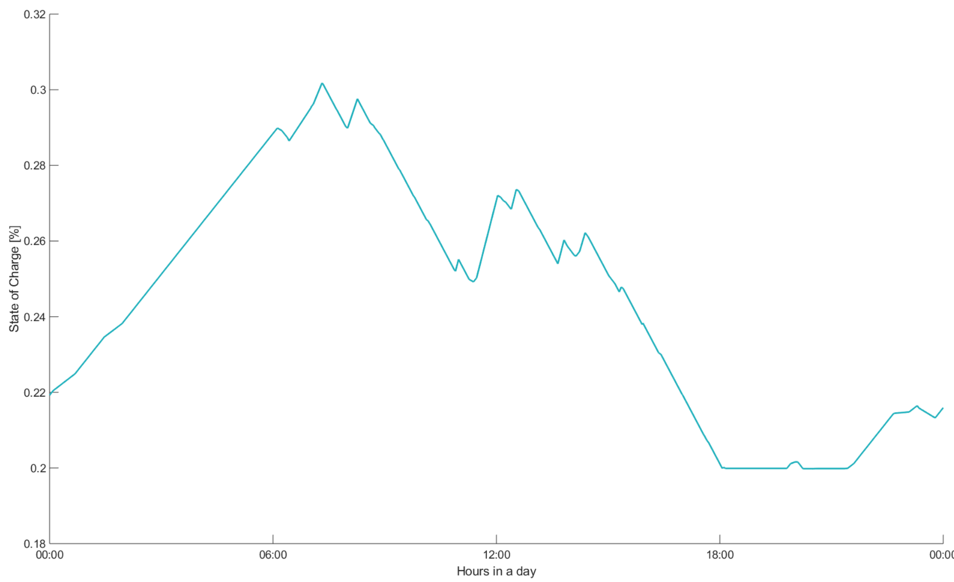

Figure M.1: *Typical SoC curve for one day at Smestad with six chargers and 143 EVs.*

N Results of the solar energy sold to the utility grid

Figure N.1 represents the sold electricity to the utility grid generated by the solar panels. The electricity is presented in NOK and depend on the monthly elspot prices. The maximal amount sold for in one day is 1 120 NOK. It can be observed that the solar panels produce more electricity in the summer season, hence more sold electricity. July seems to be the most profitable month. This figure derives from the simulation in scenario three with two chargers at Smestad and a car intensity of 143 EVs. No excessive solar energy was sold to the grid in the case of six and twelve chargers at Smestad with 143 EVs.

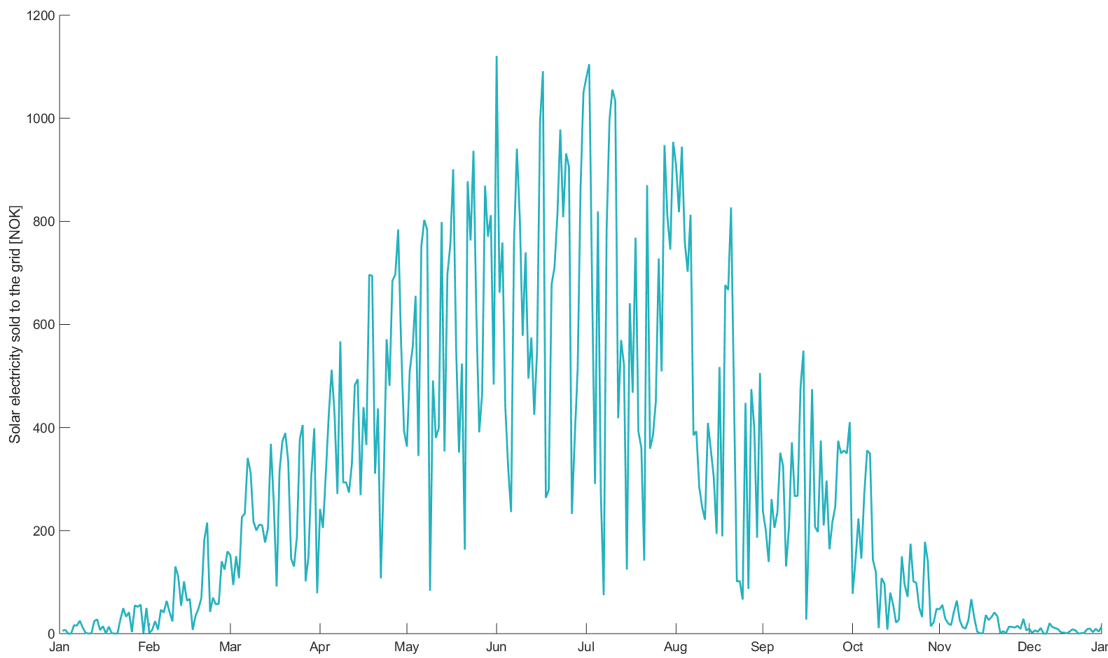

Figure N.1: *Solar energy sold to the utility grid in scenario three with two chargers at Smestad with 143 EVs.*

O Detailed technical and economic results

This following section displays more detailed results. At first the technical results are presented and the economic results thereafter in the same structure as the results were displayed in section 10 and 12. All data in the following tables were inserted in MATLAB to illustrate a more graphical presentation.

Technical

Table O.1 and table O.2 represents the technical results of scenario one, Grid Charging, for Smestad and Sekkelsten, respectively. The charging performance and *drop-out* rate were calculated in this scenario.

Table O.1: *Technical results of the GC simulation at Smestad.*

	Smestad		
L	$SoC_{\%}$	$SoC_{80\%}$	*Drop-out* [%]
2	19.30 ± 2.96	55.81 ± 5.16	58.39 ± 1.90
6	64.55 ± 4.64	96.71 ± 2.01	8.95 ± 2.93
12	72.73 ± 4.97	99.44 ± 0.44	0.00 ± 0.00

Table O.2: *Technical results of the GC simulation at Sekkelsten.*

Sekkelsten		
$SoC_{\%}$	$SoC_{80\%}$	*Drop-out* [%]
59.53 ± 14.51	94.42 ± 3.67	15.35 ± 6.22
75.12 ± 7.68	98.60 ± 1.96	0.00 ± 0.00
68.60 ± 7.37	99.77 ± 0.74	0.00 ± 0.00

Table O.3 and O.4 represents the technical results of scenario two, Simple Smart Charging for Smestad and Sekkelsten, respectively. The charging and power performance, as well as the *drop-out* rate are illustrated.

Table O.3: *Technical results of the SSC simulation at Smestad.*

	Smestad				
	$SoC_{\%}$	$SoC_{80\%}$	P_1	P_2	*Drop-out* [%]
2	19.72 ± 0.34	54.50 ± 0.62	94.41 ± 0.09	65.26 ± 0.38	57.41 ± 0.32
6	22.17 ± 0.66	62.16 ± 0.68	41.06 ± 0.52	22.65 ± 0.41	15.44 ± 0.33
12	21.62 ± 0.43	54.63 ± 0.67	36.61 ± 0.52	21.01 ± 0.41	0.49 ± 0.05

Table O.4: *Technical results of the SSC simulation at Sekkelsten.*

	Sekkelsten				
	$SoC_{\%}$	$SoC_{80\%}$	P_1	P_2	*Drop-out* [%]
2	50.42 ± 0.99	85.90 ± 0.59	100 ± 0.00	100 ± 0.00	16.93 ± 0.64
6	73.03 ± 0.55	98.23 ± 0.12	98.10 ± 0.00	98.10 ± 0.03	0.00 ± 0.01
12	73.03 ± 0.55	98.27 ± 0.08	98.10 ± 0.01	98.10 ± 0.01	0 ± 0.00

Table O.5 and O.6 represent the technical results of scenario three, Microgrid Enabled Smart Charging for Smestad and Sekkelsten, respectively. The charging and power performance, and *drop-out rate* are displayed.

Table O.5: *Technical results of the MESC simulation at Smestad.*

	Smestad				
	$SoC_{\%}$	$SoC_{80\%}$	P_1	P_2	*Drop-out* [%]
2	18.26 ± 0.30	51.95 ± 0.70	96.03 ± 0.14	95.89 ± 0.20	57.81 ± 0.11
6	52.94 ± 0.39	84.60 ± 0.19	80.18 ± 0.39	80.18 ± 0.39	10.13 ± 0.34
12	59.58 ± 0.53	85.33 ± 0.27	80.01 ± 0.24	80.01 ± 0.24	0.13 ± 0.03

Table O.6: *Technical results of the MESC simulation at Sekkelsten.*

	Sekkelsten				
	$SoC_{\%}$	$SoC_{80\%}$	P_1	P_2	*Drop-out* [%]
2	55.12 ± 0.64	87.63 ± 0.32	100.00 ± 0.00	100.00 ± 0.00	17.14 ± 0.28
6	74.24 ± 0.52	99.16 ± 0.10	99.10 ± 0.02	99.10 ± 0.02	0.10 ± 0.02
12	74.24 ± 0.61	99.27 ± 0.08	99.10 ± 0.01	99.10 ± 0.01	0.00 ± 0.00

Economic

Table O.7 and O.8 represent the economic results of the Grid Charging simulation at Smestad and Sekkelsten, respectively. The income, electricity bill and annual profit are presented.

Table O.7: *Economic results of the GC simulation at Smestad.*

	Smestad		
Chargers	2	6	12
Income	3.09 ± 0.26	4.90 ± 0.16	5.31 ± 0.19
EB	0.73 ± 0.04	1.31 ± 0.08	1.62 ± 0.11
AP_{GC}	1.70	1.15	-0.71

Table O.8: *Economic results of the GC simulation at Sekkelsten.*

Sekkelsten		
2	6	12
1.40 ± 0.06	1.50 ± 0.08	1.49 ± 0.07
0.78 ± 0.04	1.01 ± 0.11	1.02 ± 0.12
-0.04	-1.50	-3.96

Table O.9 and O.10 represent the economic results of the Simple Smart Charging simulation at Smestad and Sekkelsten, respectively.

Table O.9: *Economic results of the SSC simulation at Smestad.*

	Smestad		
Chargers	2	6	12
Income	3.06 ± 0.02	3.24 ± 0.03	3.19 ± 0.02
EB	0.70 ± 0.02	1.09 ± 0.01	1.03± 0.02
AP_{SSC}	1.69	0.16	-2.27

Table O.10: *Economic results of the SSC simulation at Sekkelsten.*

Sekkelsten		
2	6	12
1.11 ± 0.02	1.24 ± 0.03	1.24 ± 0.03
0.75± 0.00	0.78 ± 0.04	0.78 ± 0.01
-0.30	-1.53	-3.53

Table O.11 and O.12 represent the economic results of Microgrid Enabled Smart Charging simulation at Smestad and Sekkelsten, respectively. The income, electricity bill and annual profit are presented in million NOK.

Table O.11: *Economic results of the MESC simulation at Smestad.*

	Smestad		
Chargers	2	6	12
Income	3.07 ± 0.02	4.23 ± 0.02	4.71 ± 0.05
EB	0.63 ± 0.03	0.78 ± 0.01	0.79 ± 0.01
AP_{MESC}	-0.5	-6.63	-9.22

Table O.12: *Economic results of the MESC simulation at Sekkelsten.*

Sekkelsten		
2	6	12
1.39 ± 0.02	1.42 ± 0.01	1.42 ± 0.01
0.72 ± 0.01	0.74 ± 0.00	0.74 ± 0.01
-0.09	-1.88	-3.88

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