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Second-Life Electric Vehicle Batteries in the Norwegian Power System: A Feasibility Study

Karin Tråer
Environmental Physics and Renewable Energy

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Abstract

As a result of the acknowledgment of climate change and the agreements set forth to combat it, the share of renewable energies in our power systems is growing. Due to the interlinking of the European power systems, imbalances can be expected to increase in the Norwegian grid as well as in other European countries. Combined with the rising amount of distributed energy production and the electrification of the Norwegian society, it is evident that new solutions are needed.

This thesis investigates the use of used electric vehicle batteries in second-life battery systems, with the goal of determining its feasibility in the Norwegian power system. Several aspects are examined in a literature review: suitability, availability, costs, laws and regulations, and the repurposing process. In addition, an in-depth use case is conducted for the peak shaving application in south-eastern Norway.

The use case employed consumption data from one substation and its associated consumer nodes and explored peak shaving in both households and at the associated substation. Household peak shaving was achieved, but to what degree was dependent on the individual consumption patterns. The cost of the battery system was too high for it to be reasonable for households to implement these systems at current electricity prices. Substation peak shaving was most efficiently accomplished by using one large battery at the substation, although the collected peak shaving of the households also shaved the peaks at the substation. The cost of one large battery is expected to be considerably lower than the aggregated cost of the household batteries needed to achieve the same peak shaving effect as one larger battery, but it is not necessarily profitable in comparison to upgrading the substation.

The literature study revealed promising results with regards to capabilities, availability of batteries, and an increasing experience level. However, some questions remain regarding the second-life aging and lifespan. Lifespans of 4-29 years have been suggested, depending on the application. Also, guidelines and clearer regulations are needed to ensure safe handling during processing. How feasible or profitable a second-life battery system is, depends on the application, battery price, and repurposing cost. Balancing services and frequency regulation might be feasible applications today, while others could become feasible within the decade. In conclusion, second-life battery systems could have a future in the Norwegian power system, given some conditions and developments. However, it is not likely until 2025 at the earliest.

Sammendrag

Som et resultat av målsetningene til ulike klimaavtaler, er en økende andel fornybar energi på vei inn i kraftsystemene. Det europeiske kraftsystemet knyttes stadig mer sammen og resulterer i utfordringer for nettet, både i Norge og i Europa for øvrig. Dette, kombinert med en økende andel av distribuert kraftproduksjon og elektrifiseringen av det norske samfunnet, gir opphav til et behov for nye løsninger.

Denne masteroppgaven har som hovedmål å finne ut om gjenbrukte elbilbatterier har en fremtid i det norske kraftsystemet. For å avgjøre dette, er flere faktorer blitt undersøkt i en litteraturstudie: egnethet, tilgjengelighet, kostnader, lover og forskrifter og hvordan slike batterier kan gjenbrukes. I tillegg til litteraturstudiet er det uført en case-studie for såkalt "peak shaving" i Hvaler, sør-øst i Norge.

Case-studiet er basert på forbruksdata fra en nettstasjon og dens tilknyttede kunder, og undersøker peak shaving ved hjelp av simuleringer for både husholdninger og nettstasjonen de er knyttet til. Forbrukskutt ble oppnådd i varierende grad for husholdningene, avhengig av forbruksmønster. Kostanden til batterisystemet viste seg å uansett være for høy til at det vil lønne seg for husholdningskunder. Den samlede effekten av forbrukskutt hos husholdningene førte til redusert forbruk hos nettstasjonen også, men ett enkelt stort batteri gjorde jobben mer effektivt. I tillegg er kostnaden forventet å være betydelig lavere, men ikke nødvendigvis et mer lønnsomt alternativ til en eventuell oppgradering av nettstasjonen.

Litteraturstudiet ga lovende resultater når det kom til egnethet og tilgjengelighet av batterier. Kunnskapsnivået ser også ut til å være stigende. På den andre siden gjenstår en del spørsmål angående aldring og levetid for gjenbrukte batterier. En levetid på 4-29 år har blitt foreslått, avhengig av bruksområde. Det er også behov for tydeligere retningslinjer og forskrifter for håndtering av brukte elbilbatterier. Lønnsomheten til disse batterisystemene avhenger av batteripris, prosesseringskostnader og bruksområde. Systemer brukt i nettjenester, som frekvensregulering, kan være levedyktige allerede i dag. Andre bruksområder kan bli lønnsomme innen dette tiåret. Altså kan gjenbrukte elbilbatterier ha en fremtid i det norske kraftsystemet, gitt noen forutsetninger. Likevel virker det ikke sannsynlig at dette skjer før tidligst 2025.

Abbreviations

AC	Alternating Current
Ah	Ampere-hours
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
C	Carbon
Co	Cobalt
DOC	Depth of Cycle
DOD	Depth of Discharge
DSO	Distribution System Operator
EOL	End of Life
EV	Electric Vehicle
GWh	Gigawatt-hour
H	Hydrogen
Hg	Mercury
IRENA	The International Renewable Energy Agency
IRR	Internal Rate of Return
kWh	Kilowatt-hour
kWp	Kilowatt-peak
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
LFP	Lithium-iron-phosphate-cobalt
Li-ion	Lithium-ion
LMO	Lithium-manganese-oxide
LTO	Lithium-titanate
Mn	Manganese
MWh	Megawatt-hour

NaS	Sodium-sulfur
NCA	Lithium-nickel-cobalt-aluminum
Ni	Nickel
NiCd	Nickel-cadmium
NMC	Lithium-nickel-manganese-cobalt
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NTP	National Transport Plan
NVE	Norwegian Water Resources and Energy Directorate
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic (solar cell)
SEI	Solid Electrolyte Interphase
SOC	State of Charge
SOH	State of Health
TSO	Transmission System Operator
UK	United Kingdom
US	United States
V2H	Vehicle to Home
VA	Volt-Ampere
VAr	Volt-Ampere reactive
Wh	Watt-hours

Contents

1 Introduction

1.1 Motivation and Background

Climate change is upon us, leading to melting ice caps, rising sea levels, more extreme weather, and the extinction of plant- and animal species. It is evident that action is needed. In 2016, the first global and legally binding climate agreement, the Paris Agreement, was ratified. The main aim of the agreement is to keep the global temperature rise below 2 °C compared to pre-industrial temperatures [1]. The European Union's (EU) Green Deal is a strategy for transitioning to a sustainable economy. It states that by 2050, the EU will be climate neutral [2]. Decarbonization of the energy supply is key to reach these goals, and the share of renewable energy in our power systems is already on the rise. However, the increased share of renewable energies comes with some challenges, as the electricity produced by the wind or the sun is intermittent. Irregularities in production can lead to imbalances in the grid and increase the likelihood of blackouts - unless solutions are found.

One possible solution is the use of energy storages. Large-scale batteries are one of the technologies gaining interest. Tesla has introduced a battery for self-consumption [3] and built a mega-battery in southern Australia to help stabilize the grid [4]. Several studies and projects have been conducted, examining various applications and optimization of battery systems [5-10]. The general opinion seems to be that batteries are a promising technology. Nevertheless, batteries are not economically viable in all applications [11, 12]. Thus, cheaper second-life battery systems might be an option.

In general, rechargeable batteries are discarded when they reach the end of their usefulness in a specific application. This point is a matter of definition, meaning that these batteries might have something to offer in a second application after their first life is over. Therefore, second-life batteries can be defined as reused or repurposed batteries. Electric vehicle (EV) batteries are usually discarded when they reach 80 % of their initial capacity [13]. Because of the current decarbonization of the transportation sector, 10 million passenger electric vehicles are expected to be sold each year globally by 2025 [14]. This means that the storage capacity available from these batteries will be reaching the gigawatt-hour (GWh) order in the future. Combined with the possible economic and environmental effects, it makes EV batteries seem like good candidates for second-life battery storage.

Since around 50 % of the vehicles sold in Norway in the beginning of 2020 were electric [15], Norway might be especially suited to implement second-life battery storages. One could argue that the need for such energy storage is small in Norway. Electricity production is close to 100 % renewable already, and mainly consists of hydropower plants, which offer proven and reliable energy storage. However, as Norway's power system is interlinked with other European countries [16, 17], imbalances can be expected to increase due to these countries' escalating variable power supply. Furthermore, distributed energy production is on the rise, calling for smaller on-site energy storage. Distributed energy storages could also provide support in areas where the grid is operating at or above capacity or make electrification of various systems possible.

1.2 Problem Statement and Scope

Since the research on the viability of second-life battery systems seems limited, and few known studies exist for such systems in Norwegian conditions, this thesis seeks to investigate the general feasibility of second-life batteries in the Norwegian Power System. Thus, the main research question is defined as follows:

Do second-life batteries have a future in the Norwegian power system?

To answer this question, some aspects were selected for further investigation, and the following sub-questions devised:

- Is the electric vehicle battery suitable for a second life?
- Are there enough electric vehicle batteries available on the Norwegian market to sustain a second-life battery industry?
- How do Norwegian laws and regulations influence the development of a second-life battery market?
- How could a battery be repurposed into a second-life battery in Norway?
- Is the cost of second-life batteries feasible?

These questions will be answered by examining literature and performing an in-depth use case for peak shaving in Hvaler, Norway. In the use case, consumer data from the local DSO will be used for peak shaving simulations. The scope is limited to second-life batteries stemming from lithium-ion (Li-ion) electric vehicle batteries, and the thesis seeks to determine the feasibility of such systems in Norway.

1.3 Thesis Structure

The thesis is divided into five chapters, each with sub-sections. Chapter 1 introduces the thesis, explaining the motivation and background, and defining the goals of the thesis. Chapter 2 presents power system-, battery- and costs theory important to appreciate the subsequent chapters. The main part and core of the thesis are in Chapters 3 and 4. Chapter 3 contains the results of a literature study, diving into the different aspects which determine the feasibility of second-life battery systems. An in-depth use case follows in Chapter 4, examining peak shaving in Norwegian conditions. The discussion of the results and findings in Chapters 3 and 4 is found at the end of each chapter. Lastly, Chapter 5 offers conclusions and suggestions for further work. Python code, additional figures, and a second-life battery datasheet are found in the Appendices.

2 Theory

The theory chapter is divided into three main parts. Subsection 2.1 contains information about the electric power system: the structure, the three-phase system, how power is regulated and consumed, and applications for batteries in the power system. The following subsection considers batteries. It introduces the Li-ion battery and explains battery specifications and aging. Subsection 2.3 goes through the Norwegian electricity pricing system and some energy economics.

2.1 The Electric Power System

2.1.1 The Norwegian Power Grid

The Norwegian power system is divided into three parts: production, transmission/distribution, and consumption. From the production site, electricity is transported through the grid to the consumers. The grid is composed of three main parts, with different voltages, as shown in Figure 2.1. The transmission grid has the highest voltages, reaching 420 kV [18]. In Norway, Statnett is the Transmission System Operator (TSO). Before the electricity reaches the consumer, it goes through several transformers. A transformer can either step down (decrease) or step up (increase) the voltage. From the transmission grid, the voltage is stepped down before reaching the regional grid. The regional grid typically has voltages from 33 kV to 132 kV. From the regional grid, the voltage is stepped down further, to below 22 kV, before the electricity enters the distribution grid. The operators of the regional and distribution grids are called Distribution System Operators (DSOs). These operators are responsible for delivering electricity to consumers. Before it reaches the consumers, it is stepped down to 230 V. While only Statnett is responsible for the transmission grid, there are approximately 130 DSOs throughout the country [18].

Figure 2.1: An illustration of the Norwegian Power System.

There are also different topologies to consider when designing grid systems. Their lines can be connected in a radial configuration or a meshed configuration. A radial grid can be compared to a tree. The electricity travels along the tree trunk before it divides into smaller branches, always going strictly in one direction [19]. At the distribution level, this means that there is a voltage drop at each consumer, leading to lower voltages for the last consumer in the line, as illustrated in Figure 2.2. Also, if there is a fault on the line, the consumers located downstream of the fault loses power. The other option is to use a so-called meshed system. A meshed network is more robust because the electricity has several routes it can take to the consumers. If one route has a fault, the electricity can use another way. On the other hand, it is more complex to isolate faults because electricity can flow in both directions [19]. In general, the radial configuration is often used in distribution grids and meshed configuration in the regional- and transmission networks [18].

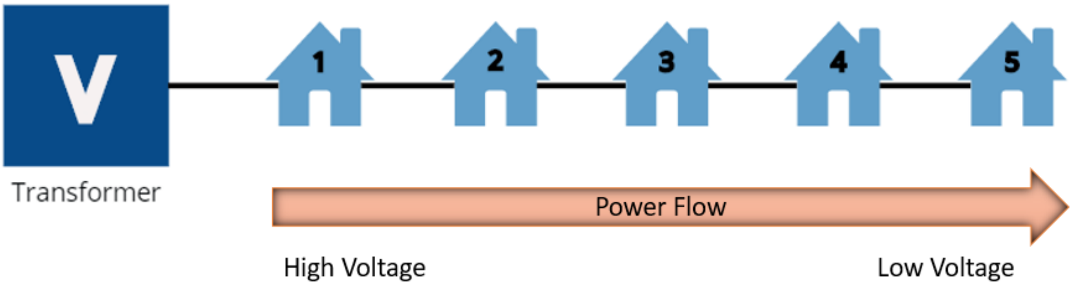


Figure 2.2: Radial configuration of the distribution grid. The electricity flows in one direction, leading to voltage drops. The voltage at the last consumer is lower than the voltage at the first consumer.

2.1.2 The Three-phase System

The electric power system is based on a three-phase system. This means that instead of one line that transmits electricity, there are three. In each line (or phase), there is alternating current (AC), meaning that the magnitude of the current and voltage oscillates between a minimum and a maximum value. In a balanced system, the current and voltage in the three phases oscillate between the same values, but they are separated by 120° in time from one another [19]. This is illustrated in Figure 2.3. Regular households are normally connected to one of the phases, while large scale industries often connect to all three. To keep the system balanced, the loads on each phase should be as equal as possible.

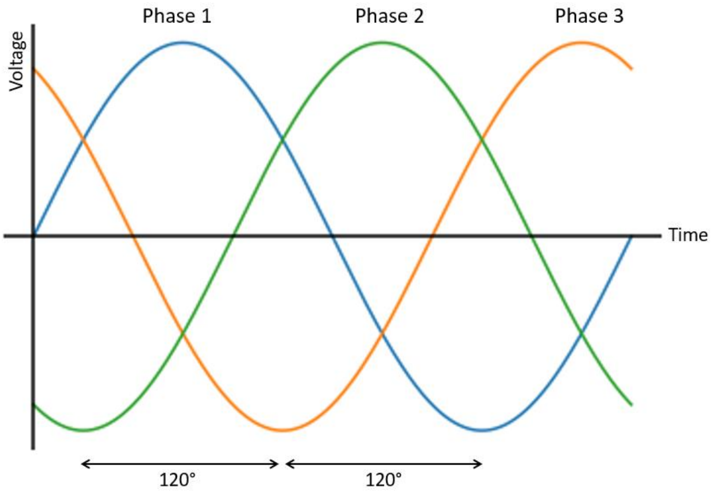


Figure 2.3: Voltage oscillations in a three-phase system. In a balanced system, the voltage in the three phases oscillates between the same maximum and minimum value, but they are separated by 120°.

When using alternating current, there is another power component that must be considered, known as reactive power. The amount of reactive power is given in Volt-Ampere reactive (VAr). The reactive power stems from coils that consume reactive power and capacitors that produce reactive power in the power systems. It is of no practical use for the consumers, but it affects the amount of active power that can be transmitted. Because of the existence of two power components, the total power transmitted is defined through apparent power, which is given in Volt-Ampere (VA). Apparent power, S, is defined as:

$$S = \sqrt{P^2 + Q^2}, \tag{2.1}$$

where P is active power, and Q is reactive power. The ratio between active power and apparent power is known as the power factor, $\cos\phi$, where ϕ represents the phase angle, which is the angle between the voltage and the current. The phase angle is given by:

$$\cos\phi = \frac{P}{S} \text{ [20].} \tag{2.2}$$

Ideally, the power factor should be 1 but is typically around 0.9 [19].

2.1.3 Power Regulation and Peak Demand

The power regulation is closely related to the frequency of the power system, which is decided by the rotational speed of the system's generators. The essential rule in the power system is that at every moment, the electricity production equals the electricity consumption. If the production is larger than the consumption, the frequency increases, and if the consumption is larger than the production, the frequency drops. As TSO, Statnett is responsible for keeping the frequency at 50 Hz ± 0.1 Hz [21]. The Norwegian power system is interlinked with the power systems in the Nordic countries, and soon with the systems in Germany and the United Kingdom (UK) too [16, 17]. Thus, the overall balance, if one disregards losses, is as follows:

$$Production + Import = Consumption + Export \tag{2.3}$$

In Norway, consumption varies throughout the day. During the weekdays, the demand is typically higher in the morning hours and afternoon/evening. In between these peaks and during the night, the power demand is lower. At the weekends, the patterns are similar but somewhat delayed. The demand also varies with the seasons. Because Norwegians mostly use electricity for heating, the power demand increases during the winter and is lower in the summer months.

2.1.4 Battery Storage for Power System Applications

As imbalances in the grid can be expected to grow due to the rapid increase of renewable energies in Europe, batteries have been proposed as one possible solution. With the gaining interest in batteries, numerous possible applications have been suggested, from utility-scale frequency regulation to behind the meter peak shaving. A list of applications and how they are defined is presented in Table 2.1.

Table 2.1: Suggested power system applications for batteries [22, 23].

Application	*Description*
Utility	
Frequency Regulation	Keeping the frequency within its defined tolerance range.
Voltage Regulation	Keeping the voltage within its defined tolerance range.
Fast Reserve	Keeping production and consumption balanced.
Transmission and Distribution Deferral	Postponing grid investments due to impending overload of components.
Black Start	Assisting the grid in coming back online after an outage.
Asset Optimization	Increasing thermal power plants' reaction time.
Peak Shaving	Reducing power demand peaks.
Redispatch	Preventing bottlenecks.
Renewable Energy Integration	Enabling integration of renewable energy.
Behind the Meter	
Backup Power	Secondary power supply in case of outages.
Increased PV[1] Self-consumption	Becoming energy independent.
Energy Arbitrage	Buying electricity when it is cheap and using it when it is expensive.
Grid Rental Fee Reduction	Reducing the power component of the grid rental fee.
Peak Shaving	Reducing power consumption peaks.

[1] Photovoltaic (solar cell).

2.2 Batteries

2.2.1 The Li-ion Battery

Several different battery chemistries are currently used in grid services around the world: lead-acid, sodium-sulfur (NaS), nickel-cadmium (NiCd), lithium-ion, and flow batteries [24]. In general, a battery cell consists of a positive and negative electrode, an electrolyte, a separator, and a casing for the components. The chemical reaction takes place on the electrodes, which is composed of an active material that undergoes reaction, and a conducting material. The separator and electrolyte can be found between the electrodes, with the purpose of keeping the electrodes apart and conducting ions, respectively. The flow battery differs somewhat from this general build since the reactant of these batteries is in external reservoirs. This gives these batteries the benefit of separating its power and energy capabilities [25].

Most electric vehicle batteries have Li-ion cell chemistry [22]. These cells have the same main components as a regular battery – a negative and a positive electrode, an electrolyte, and a separator. During discharge, Li-ions flow from the negative electrode, through the electrolyte, to the positive electrode. At the same time, electrons travel through the negative electrode's current collector to a load before it reaches the positive electrode's current collector. The process is reversible, which means that the opposite happens during charge [26], as shown in Figure 2.4.

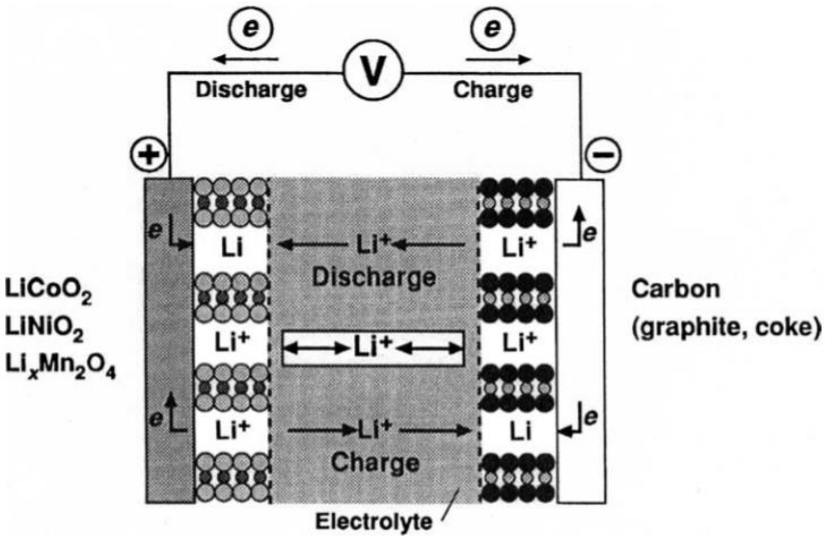


Figure 2.4: Illustration of a Li-ion battery cell and its working mechanism. Image obtained from [27].

The negative electrode is commonly composed of a carbon (C) material, often in the form of graphite [28]. The positive electrode can consist of a wide range of materials, commonly lithium combined with a metal such as cobalt (Co), nickel (Ni), or manganese (Mn) [29]. Because lithium reacts with water and produces hydrogen (H), a non-aqueous electrolyte, like organic liquid electrolyte or solid polymer electrolyte, must be used [26].

The Li-ion cell can be expected to have an energy density of 100-250 Wh/kg and a lifetime of over 6000 cycles. In comparison, the lead-acid battery has an energy density of 25-40 Wh/kg and a lifespan of around 500 cycles. Also, the Li-ion battery has a wide temperature operating range of 0-40 °C [22].

The build and characteristics of electric vehicle batteries will be described further in Section 3.1.1.

2.2.2 Battery Specifications

Voltage

The open-circuit voltage of a cell is defined as the difference in potential between the positive and negative electrodes. However, due to internal impedance, the voltage is lower when discharged and higher when charged. Since the internal impedance depends on the current, lower currents lead to reduced voltage losses [25].

When buying a battery, the term nominal voltage is used. The nominal voltage is an approximation of the voltage made by the manufacturers, and not the actual operating voltage [27].

Capacity and C-rate

The capacity, C, of a battery is the amount of charge available in the battery and is given in ampere-hours (Ah). As the unit suggests, it depends on the current drawn and the time of discharge, as shown in the following equation:

$$C = I_{discharge} \cdot t_{discharge}, \tag{2.4}$$

where $I_{discharge}$ is the discharge current given in ampere, and $t_{discharge}$ is the discharge time given in hours. In addition to varying with discharge time and current, the capacity is also influenced by the ambient temperature and aging [25].

The rated capacity (or nominal capacity) of a new battery is given for one specific discharge rate, known as *C-rate*, usually at 25 °C. The *C-rate* is given in amperes and is defined as:

$$C - rate = \frac{C}{t_{discharge}}. \tag{2.5}$$

Hence, a 10-hour discharge rate would correspond to C/10 [25]. A 1 C rate is commonly used when defining a battery's nominal capacity, meaning that the value of the nominal capacity is the same as the discharge current the battery can provide for one hour from full to empty [30]. *C-rate* is also sometimes used for charging rates.

State of Charge (SOC) and Depth of Discharge (DOD)

To describe the current capacity of a battery when in use, the terms state-of-charge (SOC) and depth-of-discharge (DOD) are used. They are ratios that define how much of the battery's capacity is remaining and how much is used, respectively. The *SOC* and *DOD* are defined as:

$$SOC = \frac{C_{remaining}}{C_{initial}} \tag{2.6}$$

and

$$DOD = 1 - SOC. \tag{2.7}$$

$C_{remaining}$ is the capacity remaining in the battery after some discharge and $C_{initial}$ is the capacity of the battery when it is fully charged. When the battery is new, $C_{initial}$ corresponds to the nominal capacity [13].

Energy and Power Content

The capacity can be used to compare batteries of similar voltages, but when comparing batteries of different voltages or sizing according to energy consumption, the energy content (or energy capacity), E, gives a clearer picture. It is given in watt-hours (Wh), or more often kilowatt-hours (kWh), and is defined as:

$$E = V_{battery} \cdot C, \tag{2.8}$$

where $V_{battery}$ is the battery voltage [25]. In this thesis, the energy capacity will often be referred to as the battery's capacity.

In many applications, size and weight matter. In the battery industry, the terms specific energy and energy density is used to describe the amount of stored energy in comparison to its size (volume) or weight, respectively. The specific energy, e_m, with the unit Wh/kg, is given by:

$$e_m = \frac{E}{m} \tag{2.9}$$

and the energy density, e_V, with the unit Wh/l or Wh/dm^3, is defined as:

$$e_V = \frac{E}{V}. \tag{2.10}$$

V is the volume of the battery, and m is the mass of the battery [25].

As with specific energy and energy density, specific power and power density describes the amount of output power per unit mass or unit volume, respectively. Because of the design required to achieve a high-power output, it usually means that these batteries have a reduced amount of stored energy [25].

Temperature Range

The performance of a battery is highly dependent on the ambient temperature [25]. Each battery has an ideal temperature range that varies with cell chemistry [26]. In general, most batteries perform best at indoor temperatures, between 15° C and 30° C, and worst at temperatures below -20 °C [25].

Efficiency

The energy retrieved at discharge is less than the energy used to charge the battery. This is due to losses caused by side reactions, such as corrosion and gassing, and the internal impedance of the cell. The overall efficiency, η, is given by:

$$\eta = \frac{E_{discharge}}{E_{charge}}, \tag{2.11}$$

where E_{charge} is the amount of energy used to charge the battery and $E_{discharge}$ is the amount of discharged energy. The efficiency is not constant because the losses depend on the ambient temperature and charge- and discharge rates. They also vary within a charge-discharge cycle [25].

Cycling

If a battery starts at one initial SOC, discharges and then charges back to the initial SOC, it has completed a cycle. The same is true for the opposite, from one initial SOC, charging and then discharging back to the initial SOC. In real life, however, cycling is rarely this straightforward, as there often are several smaller cycles within one larger cycle. There are ways of determining the cycles [31], but that is outside the scope of this thesis. The depth-of-cycle (DOC) is important when it comes to the cycle life and how much energy the battery can deliver. In general, shallower cycles leads to a higher cycle count and more energy delivered throughout the battery's lifetime [31].

Self-discharge

During storage, the batteries experience self-discharge. It varies with cell chemistries and is affected by temperature, age, and how the battery is cycled. A lead-acid battery will typically self-discharge 5 % each month, while a lithium-ion battery self-discharges 5 % in the first 24 h, followed by 1-2 % each month [32].

2.2.3 Aging and End of Life (EOL)

Over time the resistance in a battery cell will increase, and the capacity will decrease. This is due to unwanted side reactions and is known as aging [33]. In addition to capacity loss, aging will lead to a lower operating voltage and reduced power capabilities [34]. Aging is often split into two. The aging that occurs during use is called cycle aging, while the aging effects during rest is called calendar aging [13].

To get an impression of the overall degradation, the battery state-of-health (SOH) is often used [33]. The *SOH* is the ratio between the measured capacity and the nominal capacity, as shown in the following equation:

$$SOH = \frac{C_{measured}}{C_{nominal}}, \tag{2.12}$$

where $C_{measured}$ is the measured fully charged capacity of the battery and $C_{nominal}$ is the nominal capacity of the battery [13].

A battery's end-of-life (EOL) is a matter of definition. In the automotive industry, a battery's EOL is defined to be when 80 % of the initial capacity remains, which would translate to a SOH of 0.8. It is also possible to determine the EOL based on the battery's power capability, typically when the power density has dropped to 80 % of nominal power density at 80 % DOD [13].

2.3 Costs

2.3.1 Electricity Prices and Power Tariffs

In Norway, the electricity cost has traditionally been divided into a grid rental fee, an energy tariff, taxes, and fees. The grid rental fee has a fixed component and a variable component. The variable component is based on how much energy the customer uses. In the last three months of 2019, the average total cost per kWh was 112.3 øre[2]. Of that, 28.9 øre were the grid rental fee [35].

The energy tariff is dependent on the balance between production and demand and varies throughout the day, meaning that the prices change each hour, as illustrated in Figure 2.5. Typically, the prices are higher during the day than during the night. Still, the variations are not that large because the Norwegian power system has a large amount of flexible hydropower in its power mix. In 2015 the average difference was 18 Norwegian øre/kWh in Germany and 4,3 Norwegian øre/kWh in Norway. Towards 2030 it is predicted that the price will vary more, mainly because of the planned cables from Norway to Germany and the UK. In these countries, the power systems are characterized by less flexible power production than in Norway, which creates larger price differences between night and day. The linking of our power systems means that our systems will become more similar, and the prices likewise [36].

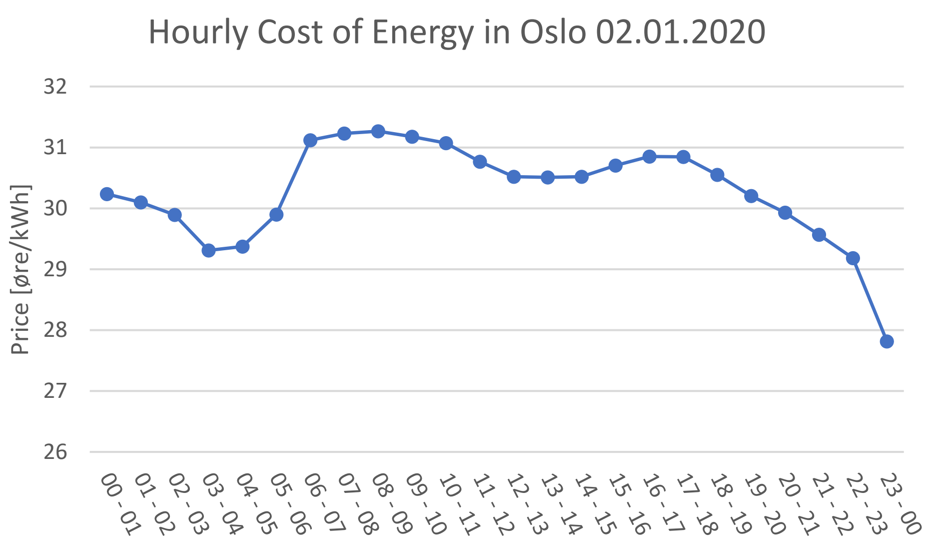


Figure 2.5: Hourly electricity spot prices in Oslo on 02.01.2020. Data supplied by Nord Pool[3] [37].

[2] 100 øre = 1 NOK.
[3] Nordic Power Market.

With the expected increase in the number of applications that use electricity and simultaneous consumption, the interest in power tariffs has grown. Today, the customers pay for the energy they use, not for the power capacity they use. Since grids must be dimensioned for peak power demand, a power tariff could reduce peaks and lead to fewer grid upgrades and investments. The idea is not entirely new, as power-intensive industries and businesses and customers connected to higher-level voltage grids have paid according to power tariffs for decades [38].

In February 2020, the Norwegian Water Resources and Energy Directorate (NVE) finished their second draft for a new electricity price regulation, where suggestions on how power components could be implemented in the grid rental fee in the Norwegian distribution grids. In this draft, they suggest that each DSO can choose from three different grid rental fee models. Customers would pay a grid rental fee based on the highest daily peak power, the average power consumption, or the fuse size, in addition to the energy component. The energy component in the grid rental fee will be lower than today, but with the option to increase the cost during peak hours. The goal of the possible new regulation is not to make the customers pay more, but to avoid unnecessary grid investments. Based on the average power consumption grid rental fee model, around 90 % of the household customers will experience less than 10 % increase in the yearly grid rental fee cost. Over time it is expected that the grid rental fee for the customers will be lower than it is currently. A cost example, based on data from 383 households at Ringerikskraft Nett, for the different models is shown in Table 2.2 [38].

Table 2.2: A cost example of the new methods for grid rental fee pricing versus the current practice. The example is based on data from 383 households at Ringerikskraft Nett. Table adapted from [38].

Grid Rental Fee Method	*Energy Component [NOK/kWh]*	*Power Component [NOK/kWh/h]*	*Fixed Component [NOK/year]*
Current	0.1859		2046
Average Power	0.05	1.00	1350 + 675 per kWh/h
Peak Power	0.05	1.49 (summer) 2.25 (winter)	1850
Fuse Size	0.05		1750 + 343 per kWh/h

2.3.2 Energy Economics

Payback Time

A simple way of evaluating an investment is to calculate the *payback time*. It is calculated by dividing the investment cost, C_{inv}, by the revenue, R, achieved per year, month, or day, as shown in Equation 2.13 [39].

$$Payback\ time = \frac{C_{inv}}{R}\,. \tag{2.13}$$

For a Battery Energy Storage System (BESS), the investment cost would be the initial cost of an operational BESS, and the revenues could include savings due to lower electricity bills or transmission/distribution deferral, in addition to revenue from storage services. However, this method does not consider any of the lifetime costs one must expect in any energy-related project.

Life Cycle Cost (LCC) and Levelized Cost of Energy (LCOE)

The Life Cycle Cost (LCC) does consider the lifetime costs. The *LCC* for a BESS should include the investment cost, the operation, and maintenance cost and the decommissioning cost [40]. The investment cost entails the initial investment cost of all the system's components and the installation cost. In the operation and maintenance cost component, the cost of repairs and replacements is included, in addition to the cost of electricity. Disposal and recycling costs are a part of the decommissioning cost. A basic *LCC*, given in NOK, can be defined as:

$$LCC = C_{inv} + C_{O\&M} + C_{dec}, \tag{2.14}$$

where C_{inv} is the investment cost, $C_{O\&M}$ is the operation and maintenance cost and C_{dec} is the decommissioning cost. These costs are subject to interest rates, and the performance and lifespan of the BESS [40].

The Levelized Cost of Energy (LCOE) defines the cost per unit energy (NOK/kWh) for the system [40]. Over the system's lifetime, the *LCOE* can be defined as:

$$LCOE = \frac{LCC}{Total\ Energy\ Production}, \tag{2.15}$$

where *total energy production* is the amount of energy that the system returns during its lifetime. In the case of a battery system, it is the amount of energy discharged from the battery during its lifetime.

Internal Rate of Return (IRR) and Net Present Value (NPV)

Internal Rate of Return (IRR) and Net Present Value (NPV) are cost evaluation methods that consider the time value of money. The *NPV* calculates the total worth of a project by finding the present value of all incoming and outgoing cash flows within a given period. It is defined as follows:

$$NPV = \sum_{t=1}^{N} \frac{(R_t - C_t)}{(1+i)^t} - C_{inv}. \tag{2.16}$$

R_t is the revenue of year t, C_t is the costs in year t, i is the discount rate and N the number of years. If the *NPV* is positive, it is considered an acceptable project. When choosing between several projects, the one with the highest *NPV* is the best alternative [39].

If the discount rate is unknown, one could find the discount rate where the incoming cash flow equals the outgoing cash flow. This rate corresponds to an NPV of zero. This discount rate is known as the IRR. If the IRR is higher than the cost of capital[4], it is considered an attractive investment [39].

[4] The rate of return that could have been achieved in another investment with equal risk.

3 The Electric Vehicle Battery as a Second-Life Battery

This chapter sheds light on factors that influence the viability of second-life battery systems in the Norwegian power system. The different factors are presented in subsections. In Subsection 3.1, the electric vehicle battery and its second-life capabilities are considered. Subsection 3.2 examines the availability of batteries. It is followed by a section containing laws and regulations that will influence suppliers and customers. A current process and some statistics for repurposing electric vehicle batteries in Norway are presented in Subsection 3.4. Subsection 3.5 introduces suppliers and projects using second-life battery systems from this decade, before costs is reviewed in Subsection 3.6. The chapter is discussed at length in Subsection 3.7. It is mostly discussed according the chapter's subsections, with corresponding parts, which makes it possible to read the discussion one part at the time as one progresses through this chapter.

The research in this chapter was conducted as a literature review. A wide search was implemented, using many different combinations of search words, and thus not relying on set searches. This was chosen to reach as much information as possible, as the field seemed new and somewhat limited. Though set searches were not implemented, some words or phrases, including "second-life," "electric vehicle battery," "battery," and "Li-ion," were used frequently. Journal articles and reports were preferred sources. However, as the second-life battery field is relatively new and first-hand knowledge was needed, personal communications and several internet sources were also used. Since these sources are considered less reliable, care was taken to choose information coming from credible sources.

In the subsection regarding costs, prices have been converted from USD and EUR to NOK, by using average 2019-exchange rates.[5] The exchange rates applied are 8.80 NOK/USD and 9.85 NOK/EUR. If the prices were higher than 100 NOK, they were rounded to the nearest 10 NOK.

[5] The average rates were obtained from www.valuta-kurser.no.

3.1 The Electric Vehicle Battery

3.1.1 Build and Specifications

As previously mentioned, the Li-ion cell is the common choice when building an electric vehicle battery pack. Different cell chemistries are used, but the most common are lithium-nickel-manganese-cobalt (NMC) and lithium-nickel-cobalt-aluminum (NCA). Other chemistries seen in electric vehicles are lithium-iron-phosphate-cobalt (LFP), lithium-titanate (LTO), and lithium-manganese-oxide (LMO) [22, 41]. The properties of the cell vary with chemistry, as illustrated in Figure 3.1.

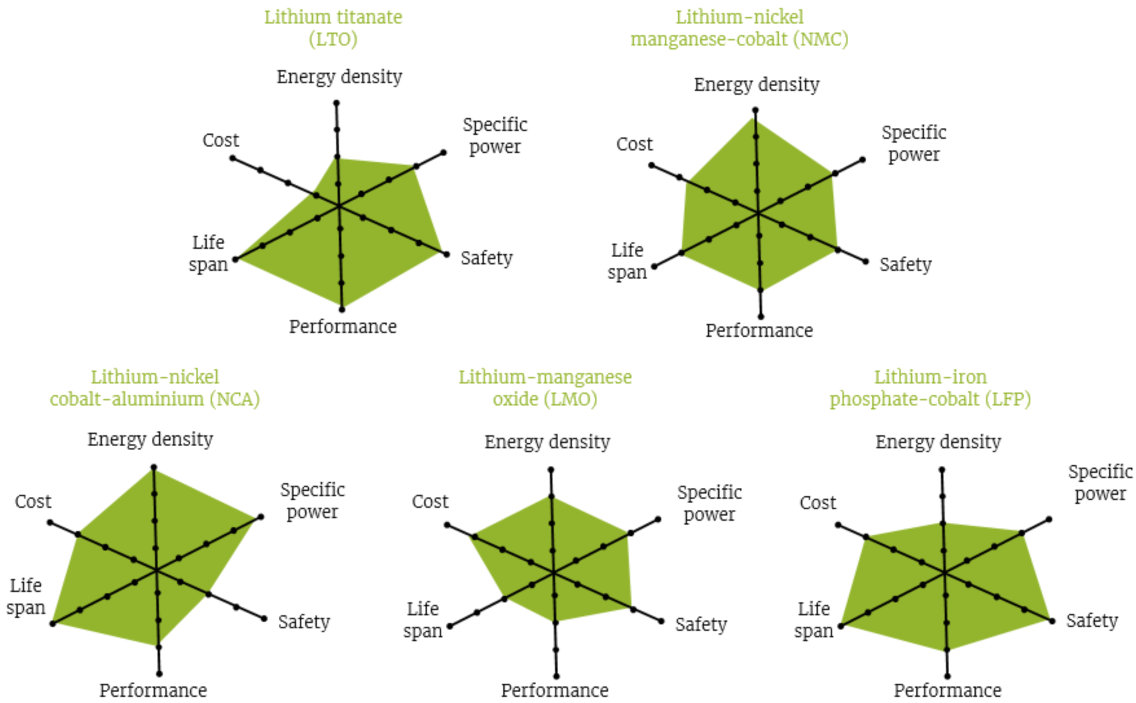


Figure 3.1: Performance comparison of different Li-ion chemistries. Figure acquired from [22].

In addition to having different chemistries, there is no standard when it comes to the build of the battery pack, which means that how the battery pack is put together will vary. In general, a battery pack consists of a cluster of modules, a Battery Management System (BMS), and a cooling system. The modules are made up of several cells placed inside a protecting frame. As an example, the BMW i3 has 12 cells per module and 8 modules per pack [42]. The different chemistries and builds lead to different characteristics and specifications for the individual battery packs. A selection of electric vehicle models and their specifications are shown in Table 3.1. There are several other models on the market, and even within the mentioned models in Table 3.1, there often exist older models, newer models, or models with different energy capacities (or ranges).

Table 3.1: A selection of electric vehicle models and their specifications [43-50].

Car Model	*Energy Capacity [kWh]*	*Maximum Charge Rate [kW DC]*	*Production Years*	*Expected Battery Lifespan[6] [years]*
Nissan Leaf	24	50	2011-2017	5
	40	50	2018-	8
BMW i3	22	50	2013-2018	8
	42	50	2019-	8
Tesla Model S	75	150	2016-2019	8
Tesla Model 3	50	170	2019-	8
Volkswagen e-golf	36	40	2017-	8
Audi e-tron	95	150	2019-	8

3.1.2 Aging

The specifications an EV battery has when it is new, cannot be expected to last, as aging mechanisms will degrade the battery during both cycling and storage. This degradation is what defines the lifespan of the battery. In the case of the EV application, the battery is commonly considered to have reached its end of usefulness at 80 % of the initial capacity [13]. The battery might still be viable in another application, in which the aging process will continue. Since EV battery packs are generally made of Li-ion cells, the aging of these cells is investigated.

Aging occurs in all the Li-ion cell's components (electrolyte, current collectors and electrodes) [13]. Still, electrode degradation is considered to be the most significant contributor to the aging of the cell [51]. On the negative electrode, the degradation is mainly a result of the formation and further development of a Solid Electrolyte Interface (SEI) [6]. In fact, it is thought of as the primary cause of aging in a Li-ion battery cell [7]. The solid electrolyte interface is formed at the surface of the electrode during the first cycle and keeps developing through the life of the battery, both during storage and cycling. It is caused by electrolyte side reactions, but the process is very complex and not fully understood [52]. Although the SEI is vital to the battery's function, by hindering additional side reactions and sustaining the electrochemical reaction, the SEI is also associated with aging. This is because the SEI is an imperfect barrier, meaning that

[6] Valid guarantee if the vehicle does not surpass a given number of driven kilometers. Typically, one can drive at least 100 000 km.

some side reactions will still occur, leading to the continued growth of the SEI layer. The continued growth of the SEI is associated with the reduction of cyclable lithium and an impedance increase, and hence, a decrease in capacity [53].

On the positive electrode, the aging is not as pronounced as in the negative electrode, but effects are still seen. In addition to electrolyte decomposition and SEI layer formation, electrode corrosion, and the interaction between dissolved electrode material and the negative electrode are the largest contributors. These effects will affect one another and are dependent on the material used in the electrode [51].

Aging is highly dependent on temperature. During storage, both high and low temperatures can have detrimental effects, by increasing side reactions and reducing the diffusion of Li-ions, respectively [51]. Temperature also affects the battery when cycling. Zhang et al. showed that the capacity fade and power fade in a deep cycled LFP cell are larger in lower temperatures. The cell tested at 45 °C had a capacity fade of 14.3 %, and minimal power fade after 600 cycles. At -10 °C, the capacity fade was 25.8 % and the power fade 77.2 % [54].

Another factor that has a high impact on aging is the SOC (as defined in Chapter 2.2.2). Because a high SOC translates to a significant imbalance in the Li-ion dispersion, which promotes side reactions, a high storage SOC is associated with capacity loss [55]. The effects were shown by Wu and Lee by storing Li-ion batteries at different SOCs and temperatures. As shown in Figure 3.2, a high storage SOC, which corresponds to a low DOD[7], is more susceptible to capacity fade than a low storage SOC. Also, the figure clearly shows the harmful effect high storage temperatures have on the Li-ion battery [56]. The detrimental effect of high SOCs during storage was also found by Ecker et al. They found that for cells stored at 50 °C, a SOC of 100 % lead to an expected lifetime of 107 days. In comparison, a cell stored with 0 % SOC had an expected lifetime of 4 years [57].

[7] The DOD is the inverse of the SOC, meaning that a SOC of 100 % corresponds to a DOD of 0 %.

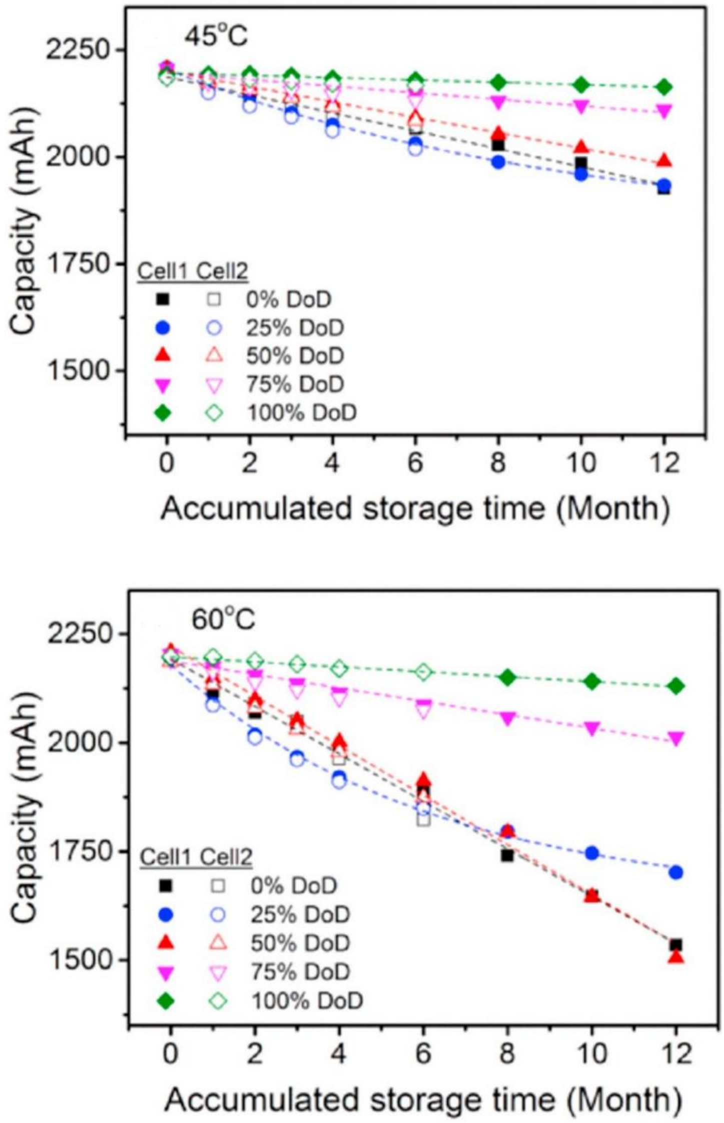


Figure 3.2: A high storage SOC (or low storage DOD) is associated with capacity fade. The higher the SOC during storage, the larger the capacity fade. High storage temperatures also have an evident detrimental effect on the cell's capacity. Figure obtained from [56].

Cycle depth and charge- and discharge rates also influence the cycle aging. Choi and Lim found that for lithium-cobalt-oxide cells cycled at 25 °C, increased charge- and discharge currents lead to faster degradation of the cell. A cell charged at 1 C would degrade from 900 mAh to around 800 mAh after 500 cycles, while one discharged at 1.4 C would degrade to around 250 mAh after the same number of cycles. The same pattern was observed with increasing discharge rates. At a 1 C discharge rate, the capacity declined from 900 mAh to around 775 mAh after 500 cycles. At 2 C, the capacity reached 500 mAh [58].

In a study by Ecker et al., the effects of cycle depth were studied. So-called Wöhler curves were found for cells cycled at 1 C at 35 °C around different average voltages, as shown in Figure 3.3. The figure shows the number of cycles until the battery has degraded to 80 % of the nominal capacity plotted against the cycle depth. For each average voltage, the cycle life drops for higher DODs. For an average voltage of 3.699 V, the cycle life drops from around 8500 cycles for a DOD of around 5 % to around 500 cycles for a DOD of 100 %. In addition to cycle depth, they showed that the SOC-range used will affect the degradation. Figure 3.4 illustrates that the capacity fade is smallest in the 45-55 % SOC-range and largest in the lowest and highest SOC-range [57].

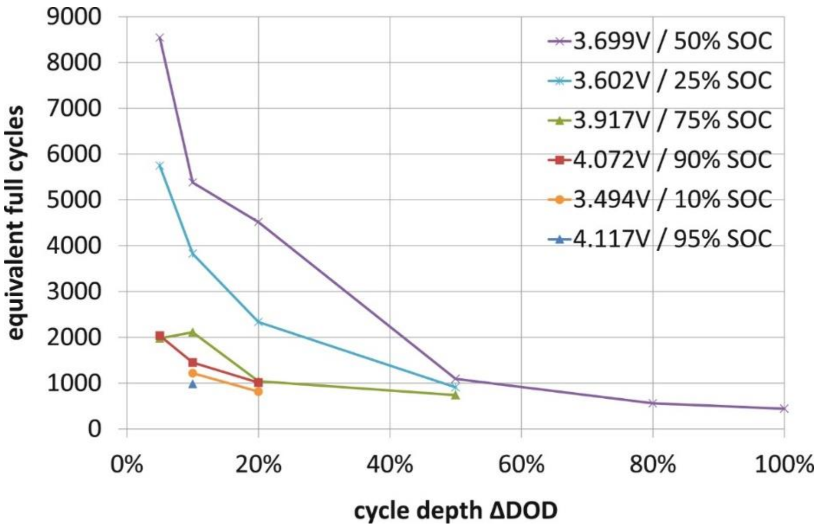


Figure 3.3: Wöhler curves for cells at different average voltages, cycled with 1 C at 35 °C. EOL is at 80 % of nominal capacity. The figure is obtained from [57].

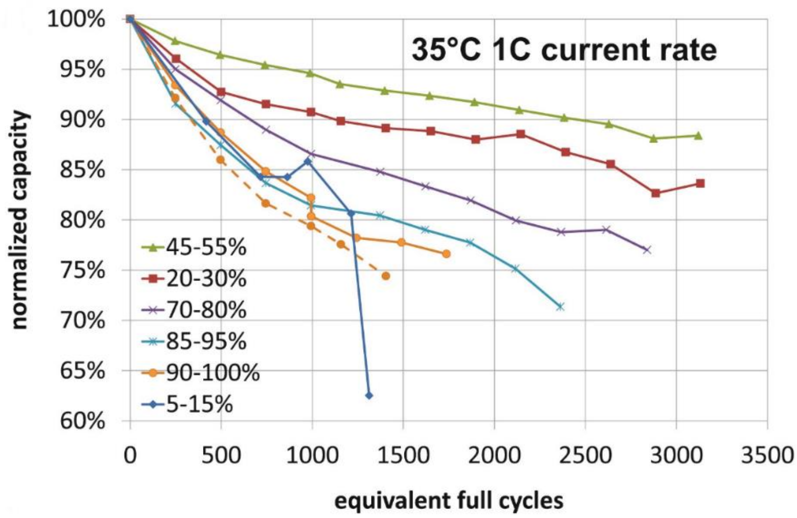


Figure 3.4: SOC-range's effect on capacity degradation. Figure obtained from [57].

3.1.3 The Sudden Death Phenomenon

Since the idea of second-life batteries is relatively new, most research that exists on aging assumes that the EOL is at 80 % of initial capacity, but some studies have researched the aging beyond this and discovered the sudden death phenomenon.

When the battery has degraded to around 80 % of its nominal capacity or has developed a resistance which is 1.5 times higher than the nominal resistance, the sudden death phenomenon may occur [57]. The aging per cycle up until this point is usually nearly linear, but if sudden death occurs, the capacity decrease per cycle increases strongly, as Figure 3.5 illustrates. This phenomenon is linked to the dominant aging mechanism moving from SEI formation to lithium metal deposition on the negative electrode, also known as lithium plating [59]. The main reason for the lithium plating is thought to be clogging of the pores due to the SEI film, which obstructs the Li-ions' journey into the negative electrode, leading to further lithium plating [34]. In addition to the capacity fade, the resistance increase and possible dendrite growth may affect the safety of the cell [60]. It has been thought that lithium plating only occurs when the battery is cycled in an unfavorable way (e.g., overcharging and low temperatures) [61], but it has been shown that lithium plating may occur in regular operating conditions as well, if local pore closures occur [62]. Although the effect of lithium plating is severe, Petzl et al. showed that the capacity reduction is smaller after long-term cycling and that the lithium plating effect is somewhat reversible after low-temperature cycling if the temperature is increased [60].

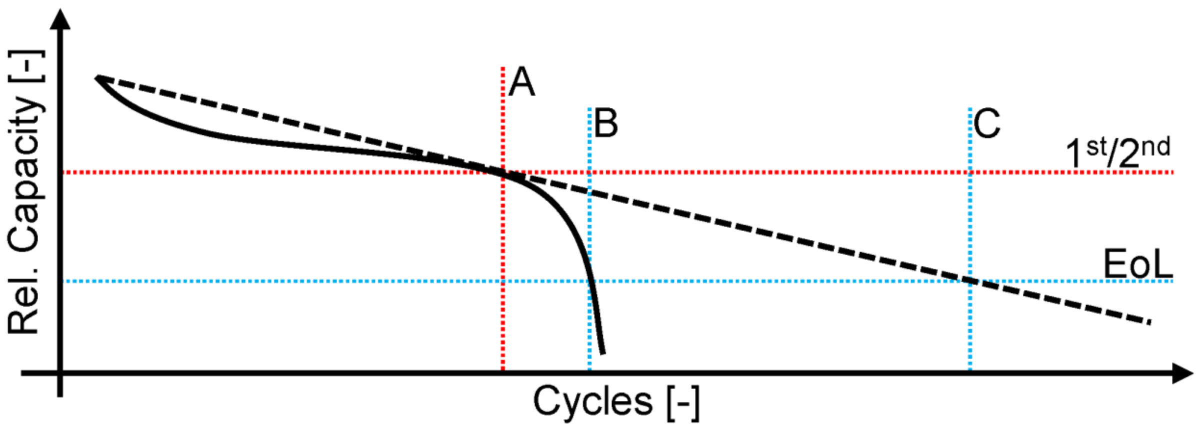


Figure 3.5: The sudden-death effect. The dashed line illustrates a linear decrease in capacity, while the solid line illustrates the capacity development when sudden death occurs. The red line represents the boundary between the first and second life of the battery. In blue, point A and B show the EOL point for linear and sudden-death aging for some defined EOL. Figure acquired from [59].

3.1.4 Thermal Runaway

Although the Li-ion battery is considered safe, safety hazards must be considered. The most apparent hazard is the danger of rupture and explosion, which is commonly due to thermal runaway. Thermal runaway begins when the cell reaches 80 °C, where decomposition of the SEI layer occurs [63]. With the SEI layer gone, accelerating reactions between the electrode materials and electrolyte leads to a further increase in the temperature [64]. As the temperature increases, the pressure builds and might lead to a rupture of the cell. In addition, the reactions keep producing oxygen [65], making fires hard to extinguish. The initial temperature increase is usually due to short-circuits, external heating, and overcharge [66]. If thermal runaway occurs, it can be a severe event, but because of safety measures taken, the rate of failures is only 0.3 per million (per 2003) [63].

3.2 Availability

3.2.1 Number of Electric Vehicle Batteries

For second-life batteries to be commercially possible, there must be an adequate supply of first-life batteries to repurpose them from. In this case, the supply is connected to the number of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) in Norway.

At the end of 2019, the total number of vehicles registered in Norway was 5 623 196. Of these, 2 768 991 were passenger cars [67]. The number of passenger cars in 2010 was 2 304 853 [68], meaning that the number of passenger cars has increased by roughly 50 000 vehicles each year from 2010 to 2019. 2019-numbers from Statistics Norway identified 18.1 years as the average age on passenger cars when they reached wreckage status [69].

According to the Norwegian Electric Vehicle Association, there were 267 990 BEVs[8] in Norway in 2019. In comparison, the number was 3347 in 2010. Figure 3.6 shows that the number of battery electric vehicles has grown increasingly in the years from 2010, with an increase in growth of almost 10 000-20 000 vehicles per year from 2012, except between 2015 and 2016. In 2019, BEVs made up 9.3 % of the passenger car fleet [70].

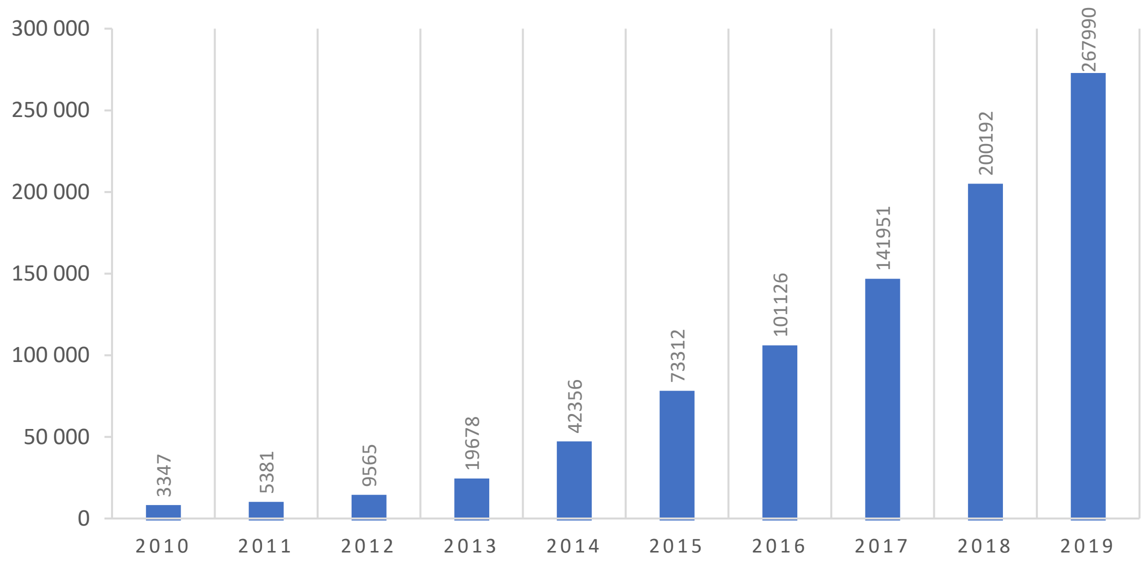


Figure 3.6: Number of BEVs in Norway from 2010 to 2019 [70].

When it comes to sales, Figure 3.7 shows the market shares of different passenger cars. In 2019, the battery electric vehicles had the largest market share at 42.4 %, hybrids, and plug-in hybrids 25.9%, and petrol and diesel-fueled cars had shares of 15.7 and 16.0 %, respectively. In the last

[8] Numbers are referring to passenger cars and vans.

two years (2018-2019), the market share of BEVs has increased with around 10 % each year [15]. In March 2020, 58.4 % of the passenger cars sold were BEVs [71].

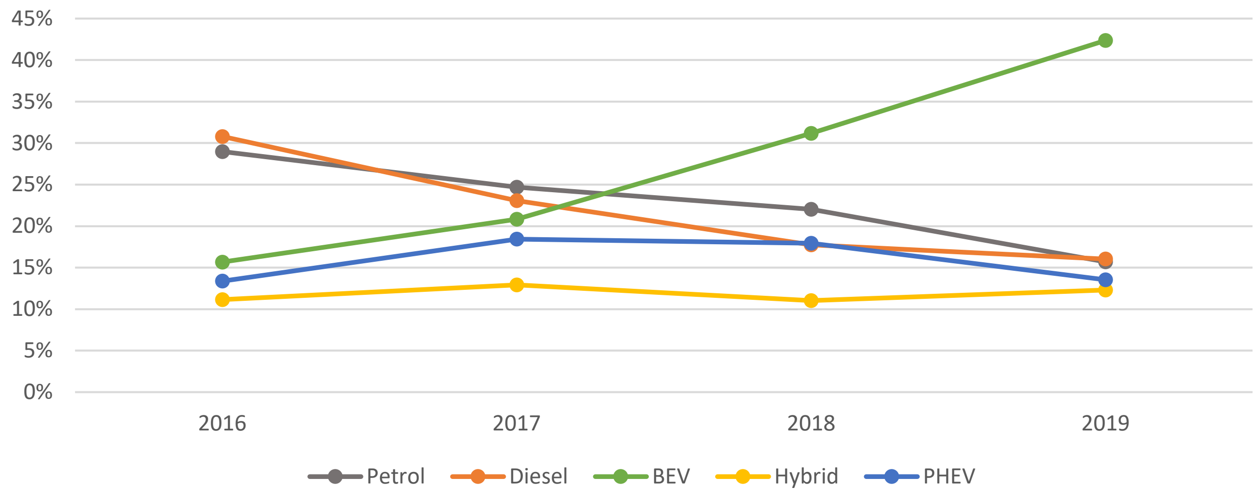


Figure 3.7: Market share of passenger cars sold from 2016 to 2019 [15].

3.2.2 The National Transport Plan (NTP)

The national transport plan is supporting the growth in the share of electric vehicles. In 2017, the Norwegian government presented the current national transport plan (NTP) for the following ten-year period. One of the goals of the Norwegian government is that all passenger cars and vans sold in 2025 will be zero-emissions vehicles. They will facilitate this transition but depend on the technology within the transportation sector to reach maturity for the goal to be achieved [72].

3.3 Laws and Regulations

If there are enough EV batteries in Norway to support a second-life battery industry and the batteries are deemed fit for a second life, laws and regulations regarding both ownership and handling must be considered next, as they might influence both suppliers and customers.

3.3.1 Ownership of Batteries

According to NVE, regular customers can freely own battery systems connected behind the meter, but if the systems require high voltage lines, approval is required [73]. Grid operators are also currently allowed ownership, as there are no specific laws or regulations for battery storages in the Norwegian grid. Batteries are simply considered a customer - feeding in or consuming energy [74]. However, NVE is signaling that the EU's Clean Energy Package could be used to model the Norwegian regulations dealing with energy storages. It states that DSOs must consider energy storage as an option to grid reinforcements and that energy storage owned by a third party could be used for grid services. It also states that DSOs and TSOs are not allowed to own or operate energy storages, except for in the following situations [74]:

1. The batteries are considered grid components and are critical for the operation of the grid. The regulatory authority must approve this.
2. A tendering process fails to deliver satisfactory results concerning time, cost, and quality.
3. Grid operators can own batteries already connected to the grid until depreciation is completed.

3.3.2 Handling of Electric Vehicle Batteries

Second-life battery systems require repurposing, and thus some processing and handling. Used electric vehicle propulsion batteries are currently treated as waste, meaning that the Norwegian Waste Regulations are the regulations determining how they are to be handled after their first life. Chapters 3 and 4 contain regulations about discarded batteries and vehicles, respectively, while hazardous waste regulations are found in Chapter 11 [75].

According to § 3-7 and 3-8, producers of batteries must be members of a recycling company approved by the Norwegian Environment Agency for collection, treatment, and recycling of discarded batteries. As stated in § 3-10, there must be systems for the collection of discarded batteries in areas where their member's products have been sold or delivered currently or in the past. At least 95 % of the total amount of the recycling company's member's imported and produced lead-acid batteries and industrial batteries, including electric vehicle propulsion batteries, must be collected each year according to § 3-11 [75].

§ 4-4 declares that producers of vehicles are responsible for their vehicles being collected and recycled at the end of their lifespans. The number of vehicles each producer is responsible for each year corresponds to their market share in Norway the same year. 95 % of this share, measured in weight, must be recycled, either as materials (85 %) or as energy. The collection system must be approved by the Norwegian Environment Agency, as stated in § 4-5 [75].

§ 3-15 and Appendix 1, part 3 in Chapter 4, says that companies collecting discarded vehicles must be able to extract and disassemble batteries from the vehicles. According to § 3-17, the spaces used for storage and treatment of the batteries must have impenetrable surfaces and with a weather-proof cover or in containers suited for the purpose. At least 50 % of the materials used in the battery, according to the battery's average weight, must be recycled. Higher percentages are demanded for nickel-cadmium and lead-acid chemistries [75].

According to § 11-2, the one possessing the waste is responsible for discerning if the waste is hazardous or not. Appendix 1 and 2, part 1 in Chapter 11, defines what is considered dangerous according to regulations. When it comes to batteries, lead-acid batteries, nickel-cadmium batteries, batteries containing mercury (Hg), and separately collected electrolyte solution are hazardous waste. Discarded vehicles are considered hazardous if dangerous fluids and components have not been removed. Explosive components like airbags and other non-specified dangerous components that are not otherwise mentioned are also considered unsafe. § 11-5 says that dangerous waste must be handled responsibly and that the people managing it must have written documentation of their competence [75]. According to the Pollution Control Act, approval from the pollution control authority is also needed [76]. Waste regarded to be explosive must be handled according to the Explosives, as stated in § 11-2 in the Waste Regulations [75].

3.4 Recycling and Reuse

In Norway, Batteriretur is the only company that recycles electric vehicle batteries. Currently, they receive several thousand such batteries each year. The batteries collected usually have some kind of malfunction due to production errors, accidents, or other reasons that are not related to natural aging. Batteriretur estimates that only a few percent of the batteries that they receive today are EOL batteries, but the number is expected to increase as the electric vehicles present in Norway age [77].

If battery packs from EVs are to be reused, they can, in theory, be dismantled and put back together in new battery packs, or the battery pack can be used more or less directly. Because of the state of the batteries that Batteriretur acquires today, the batteries must be dismantled for safety reasons. Another reason to dismantle is that most of the brands producing electric vehicles keep the battery management system separated from the battery, which means that a new BMS will be needed to operate the battery in its second life. However, Nissan has not separated the BMS from the battery pack, which means that these batteries, in theory, are good candidates for direct use [77].

Several steps are needed to make a second life battery out of an electric vehicle battery. Currently, the battery is usually recovered at a car dealership, but in the future, scrap yards will likely play a more significant role. At the brand garage, its function is analyzed before it is transported to Batteriretur. At Batteriretur, it is dismantled, and modules (and cells) are tested. The testing includes inspections of capacity, discharge- and charge rates, voltage, and heat production. The batteries deemed fit for a second life, are then put together to a new battery pack suited to the second life application. An estimation of 30-40 % of the batteries can be used in second-life applications. The rest is recycled. The process is shown in Figure 3.8, but it is still under development as new knowledge is gained. In 2020, three battery packs have been made from used electric vehicle batteries at Batteriretur. These are mostly used for research purposes, which means that the batteries are not yet commercialized [77].

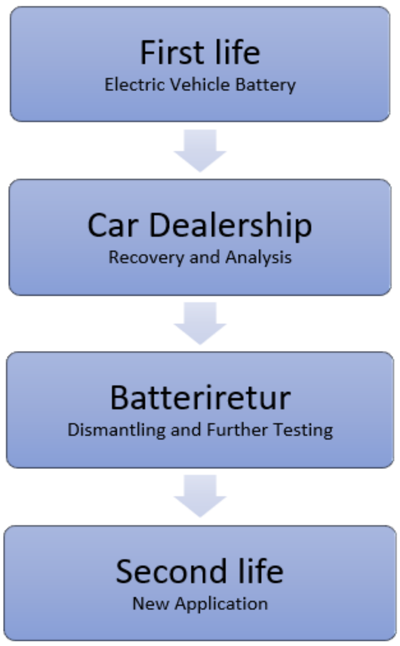


Figure 3.8: Batteriretur's process of preparing electric vehicle batteries for second-life applications [77].

3.5 Suppliers and Projects

Existing second-life battery systems can provide information about viability, possible applications, battery system specifications, and lifespans. In this subsection, a selection of current suppliers and projects from this decade are presented.

3.5.1 Eaton xStorage

In 2016, Eaton started a collaboration with Nissan to develop a second-life battery system for the private market. The result, called xStorage Home, is made up of 12 Nissan Leaf EV-modules, has a capacity of 4.2 kWh and a starting price of 40 000 NOK[9], including an inverter. An xStorage Home unit is exhibited in Figure 3.9. According to the Eaton press release, it can be connected to solar panels and reduce electricity costs by charging and discharging according to the electricity price. Furthermore, it can act as a backup energy system in case of blackouts [78]. Today, there are different sizes to choose from, from 4.2 to 10.08 kWh [79], but according to the datasheet in Appendix A, only the 4.2 kWh system is made of second-life batteries. It also shows that the second-life version of the battery system comes with a 5-year warranty, while the first-life versions come with a 10-year warranty.

Figure 3.9: Eaton's xStorage Home unit. The second-life version has a capacity of 4.2 kWh and a 5-year warranty. Image obtained from [79].

[9] This price was confirmed by Eaton customer service in April 2020 and is valid for the battery system with the smallest inverter of 3.6 kW.

xStorage Home units were used in the EU-funded Horizon 2020 project INVADE, which aims to use smart energy storage systems to manage the increasing share of renewable energies and electric vehicles [80]. Project pilots exist in Spain, Germany, Bulgaria, Norway, and the Netherlands, with different approaches and goals [10].

The pilot in Norway investigates the effect of battery systems, Vehicle to Home (V2H), and water boilers, intending to avoid high loads, both for the DSO and the end-user. The management system provides information, feedback, and interaction possibilities [81]. Battery systems from Eaton were used to examine economic profitability, how energy consumption relates to power and optimization of systems generating electricity. 20 different households in Rogaland, Norway, have Eaton's xStorage Home battery systems installed. Both new and second-life batteries from Nissan Leaf have been used, offering 6 and 4.2 kWh, respectively [82].

Eaton has also introduced xStorage Buildings, with capacities ranging from 20 kWh to 10 megawatt-hours (MWh). These batteries are intended for services like enabling the integration of renewable energies and EV-charging points, demand response, and using and storing energy according to electricity prices [83].

A 109 kWh/100 kW xStorage Building system is installed at Bislett Stadium in Oslo, Norway. It is made up of second-life Nissan Leaf batteries and consists of three racks of 30 battery packs. The aim was to reduce power consumption peaks and emissions and to exploit the 1100 m^2 on-site solar power facility. In addition, the battery system provides backup power services [84]. The arena is shown in Figure 3.10.

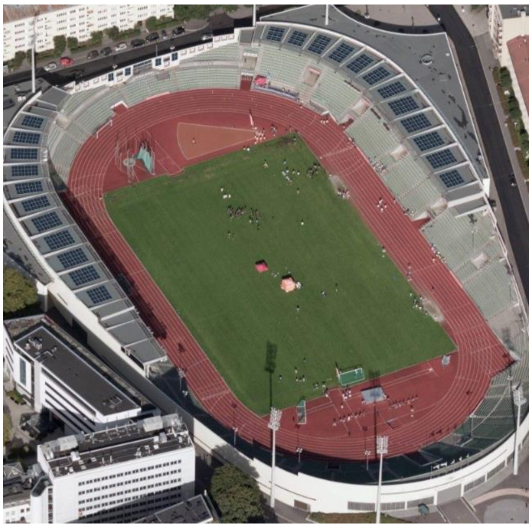


Figure 3.10: Bislett Stadium in Oslo, Norway. A 100 kW/109 kWh battery system consisting of second-life Nissan Leaf batteries is paired with the 1100 m2 solar power facility, reducing power consumption peaks and emissions. Image acquired from [84].

3.5.2 ECO HOME/ECO STOR

A company based in Norway, ECO HOME/ECO STOR AS, was established in 2018. Their goal was to "commercialise intellectual property and knowledge gained from "Second Life" energy storage development." They offer systems for developers, builders, and homeowners, and according to the company's web page, they have secured several contracts for energy storage delivery already [85].

3.5.3 Connected Energy E-STOR

Connected Energy, a subsidiary company of Future Transport Systems, provides commercially available second-life batteries to "catalyse new approaches to grid decarbonization" [86]. Their British-designed batteries are made of used EV batteries from Renault, Nissan, and Jaguar Land Rover. By giving the batteries a second life, they claim to double the lifespan of the EV batteries. Furthermore, the reduced system costs supposedly make the E-STOR systems a financially viable option for a wide range of end-users [86].

According to Connected Energy, the E-STOR units can be used in commercial, industrial and utility applications [87]. Uses suggested include grid stabilization, peak shaving, and pairing with renewable energy installations [88]. Since 2014, the storage systems have been a part of 11 projects throughout Europe [89, 90], some of which are introduced below. The total installed capacity has reached 2285 kW/2280 kWh in 2020 [90].

In Germany, a 60 kW/90kWh E-STOR battery system is used to provide support to the local grid at a fast 50 kW EV-charging point [91]. A similar system is used in Wanlin, Belgium [92], as shown in Figure 3.11. A research and development project in Norfolk, UK, uses a 200 kW/300 kWh battery system in a microgrid with EV-chargers of 22 and 50 kW, a small wind turbine and solar panels. The main applications are energy system optimization, peak shaving, EV-charging, and reducing the cost of energy [93]. In Dundee, UK, a 60 kW/90 kWh battery system is used for optimizing on-site PV, which will be used for charging EVs at a charging hub with 22 and 50 kW chargers [94]. Also in the UK, an E-STOR system was connected to Statkraft's Virtual Power Plant (VPP) [95], which can be defined as a collection of small-scale power producers acting as one large-scale supplier [96]. Based on forecasts of energy costs, the 60 kW/90 kWh battery system is charged and discharged [95]. In the Netherlands, a 150 kW/90kWh E-STOR system is used for frequency regulation via an aggregator. The local grid operator tested the system before it was put into operation [97]. Umicore, a global materials technology and recycling group, with energy-intensive industry in

Belgium, uses a 1200 kW/720 kWh system to provide reactive power and frequency regulation services to the grid. The batteries in this case came from Renault Kangoo vehicles, and have an expected second-life lifespan of around seven years [98]. The facility is shown in Figure 3.12.

Figure 3.11: A 60 kW/90 kWh E-STOR system used as a load management system at an EV-charge site in Belgium. Image obtained from Connected Energy.

Figure 3.12: A 1200 kW/720 kWh battery system providing reactive power and frequency regulation services to the grid at Umicore industrial site in Belgium. Image obtained from [99].

3.5.4 Bosch/Vattenfall/BMW

In 2013, Bosch, Vattenfall, and BMW started their second-life battery project, which was expected to last for five years. The trial operation commenced in September 2016. The project includes an electricity storage facility, located in Hamburg, made up of batteries from over 100 BMW vehicles, with 2600 modules in total. The facility is shown in Figure 3.13. It can deliver 2 MW of power and store up to 2800 kWh. Vattenfall sells this electricity on the primary control reserve market, to stabilize the grid by frequency regulation. The goal of the project was to learn more about Li-ion batteries' second-life performance, especially considering storage capacity and how the batteries age [100].

Figure 3.13: The BMW/Vattenfall/Bosch storage facility, located in Hamburg, is made up of over 100 BEV batteries, with a capacity of 2800 kWh and a power output of 2 MW. It is used for frequency regulation. Image acquired from [100].

3.5.5 Endesa/SEAT SUNBATT

Endesa, a Spanish power company, and the car manufacturer SEAT introduced the second-life battery lab called SUNBATT in 2016. The goal of the SUNBATT lab is to study the behavior of second-life EV batteries, demonstrate applications for these, and develop business models [101].

The system consists of four used PHEV batteries with two 20 kW bi-directional converters [102], three EV-charging points, a 14 kW solar array, connected to the local distribution grid, which offers 90 kW peak power. The lab is shown in Figure 3.14. The batteries consist of NMC-cells and had an overall energy capacity of 8.8 kWh when they were new. These cells are used by the Volkswagen group, using 25 Ah-cells in groups of 6 or 12 to create each module in their PHEV and BEV batteries. They reside in a temperature-controlled environment, and the SOC range goes from 95 % to 10 %, as defined by the manufacturer [103]. A computer uses machine learning to predict consumption and decide how the electric vehicles are to be charged – directly from the grid, from the solar panels, or from the used PHEV batteries. Also, the condition of the batteries, and actual consumption and generation are monitored [101].

Figure 3.14: The SUNBATT living lab. Four used PHEV batteries are visible in the 15 m^2 container. The lab is also connected to a solar array, three EV-chargers, and the distribution grid. Image obtained from [101].

According to the 2016-press release, preliminary findings show that in technical terms, an EV battery can have a second life, and manufacturers should take the possibility of a second life into account when making new EV batteries. Possible applications suggested include household use, storage of renewable energy, off-grid applications, and offer distribution services [101].

As a part of the SUNBATT project, Casals et al. ran computer simulations with the same batteries as used in the lab to predict the lifespan of the batteries in four different applications. The model is based on several accelerated aging tests and incorporates important aging factors such as SOC, DOD, temperature, and C-rate, in addition to the time spent under each condition. The temperature was set to 25 °C in the simulations. Based on the defined SOC range of the batteries in SUNBATT, a functional EOL was defined to be reached when more than 85 % DOD is demanded from the application. The four applications and their results are presented below [103].

- *Transmission Deferral:* The batteries will supply power to a grid transformer in the neighborhood when the transformer would be operating above capacity meeting electricity demand. Charging occurs during off-peak periods. In this case, the energy demand is assumed to increase over the years. Because of this, more than 200 PHEV batteries or 80 BEV batteries are needed. The number of batteries was determined by finding the number that where the functional EOL would be reached at 60 % SOH. A lifespan of 20 years is expected, but within this period, two replacements are assumed. The first pack reaches its EOL after close to 11 years, the next 5 and the last 3.8 years [103].
- *Self-consumption:* A solar array generates electricity, which is stored in a 6 kWh battery system. 1 BEV battery of 24 kWh was used. With an EOL of 60 % SOH, a lifespan of 5.9 years was found. At 40 %, the lifespan was 11.6 years. The functional EOL is reached when cycled at this point, meaning that it would have trouble meeting demand with continued use [103].
- *Area Regulation:* In addition to maintaining self-consumption, grid stability services are provided. The energy exchange increases to 11 kWh. 1 BEV battery of 24 kWh were used. 60 % of the initial capacity is reached after 4.7 years. The functional EOL is reached after 5.7 years [103].
- *Fast EV-charge:* The batteries supply extra power needed during fast charges. In this case, a grid connection of 70 kW peak was assumed. Simulations indicated that an additional 20 kW was needed in short periods, which were supplied by the batteries. 1 PHEV battery was needed to fulfill the requirements. The simulation results in a lifespan of 29 years in this application, assuming an EOL of 40 % SOH. The functional EOL is still not reached, but the authors of the study do not dare go lower due to the possibility of the sudden death phenomenon [103].

3.6 Costs

3.6.1 Battery Price Development

For battery energy storages to be an option, they must be profitable. Because this thesis examines the use of discarded EV batteries, the cost development of these batteries is of special interest. Figure 3.15 shows that these batteries have decreased rapidly in price this decade, from above 10 200 NOK/kWh in 2010 to around 1550 NOK/kWh in 2018. This translates to a decrease of 85 % [14]. In stationary applications, the installed battery cost for Li-ion batteries is higher than in EVs. This is mainly due to more challenging cycles, which leads to a need for more expensive BMSs and hardware. However, because of the EV battery growth, the International Renewable Energy Agency (IRENA) expects the cost for stationary Li-ion systems to decrease by 54-61% from 2017 to 2030, depending on cell chemistry. If so, the expected installed cost for these systems would be between 1280 NOK/kWh and 3960 NOK/kWh. A decrease in cost for other battery chemistries is also expected. Flow batteries are expected to reduce their installed cost from 2770-14 780 NOK/kWh in 2016 to 950-5070 NOK/kWh in 2030. High-temperature sodium-sulfur batteries had a typical installed cost of below 3520 NOK/kWh in 2017, and it is expected to be reduced to 1060-2900 NOK/kWh by 2030 [104].

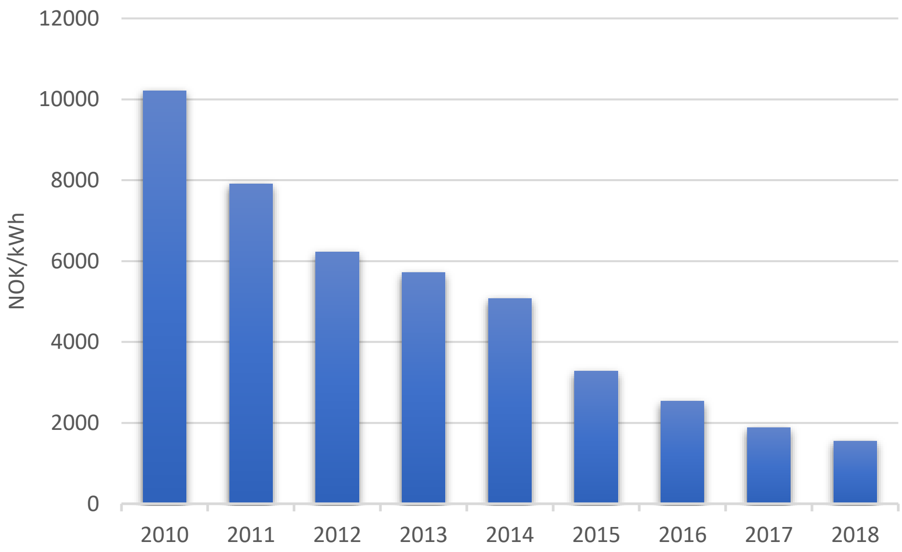


Figure 3.15: Volume-weighted average lithium-ion pack price [14].

3.6.2 Battery Repurposing Cost

The cost of repurposing a battery influences the selling price of the second-life battery and is thus important to the economic viability. It was found that several factors contribute to the overall repurposing cost.

A study by the United States (US)-based National Renewable Energy Laboratory (NREL) in 2015 points to the cost of battery purchase as the largest contributor to the overall cost, and the technician handling time to be the most expensive at the repurposing facility. Furthermore, the size of the module plays a large role in repurposing costs. It was found that the handling cost will be the same up until a certain optimal battery size, but beyond this optimal size, the probability of finding faulty cells increases, reducing earnings. Fault rates below 0.001 % have been shown to increase earnings and make the repurposing of larger modules possible in a cost perspective. To accomplish this, the batteries must either be tested efficiently before purchase or be engineered to decrease fault rates from the beginning [105].

The baseline scenario of the study found a repurposed battery price of 390-1580 NOK/kWh, with a corresponding repurposing cost of 220-430 NOK/kWh. These prices were based on the following assumptions [105]:

- 0.001 % fault rates
- The processing of 600 000 kWh/year (or approximately 25 000 BEV batteries/year)
- A salvage cost higher than the battery extraction cost
- 5 kWh battery modules with 3-hour handling time

In another scenario, with the assumptions of a 35-minute handling time, a processing of 1 000 000 kWh/year and a salvage cost equal to the battery extraction cost, the repurposing cost amounted to 180 NOK/kWh. This was the repurposing cost leading to the lowest feasible second-life battery selling price of 350 NOK/kWh [105]. How the annual costs were distributed in this case is shown in Figure 3.16.

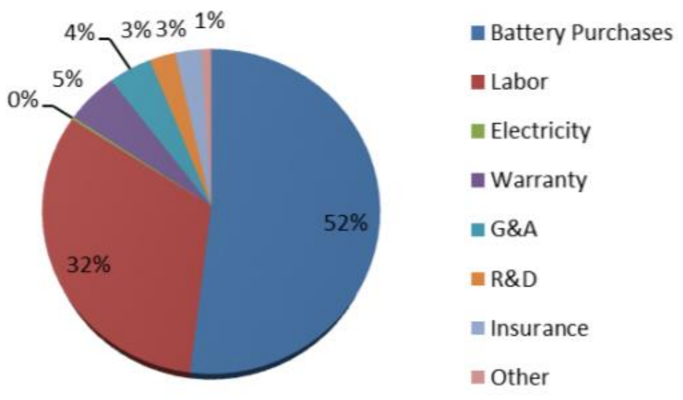


Figure 3.16: Annual costs with a selling price of 350 NOK/kWh. G&A = General and Administration and R&D = Research and Development. Figure acquired from [105].

A US-based study from 2011 indicates that a lot of the battery management system in an electric vehicle can be reused. If these systems could be used to determine which modules are fit for a second life, repurposing costs could be avoided or limited. The study made the following assumptions to decide the repurposing costs of an EV battery [106]:

- 1.4 million used batteries are available in 2020
- Around 10 repurposing plants are placed in strategical locations and are thus able to execute the refurbishing
- 142 300 batteries will be repurposed by each repurposing plant each year
- A plant size of 945 m^2 is adequate for the refurbishing process

Based on these assumptions, the fixed costs can roughly be split into the following cost categories: staff, general and administrative, travel and transportation, and tooling and equipment. The share of each category is shown in Figure 3.17. The total cost for 142 300 batteries adds up to a total of 42 659 710 NOK, or a pack price of 300 NOK. Since this is the pack price, the price per kWh is dependent on the battery size. If all batteries were 24 kWh Nissan Leaf batteries with 80 % of their capacity left, the fixed cost of refurbishing would be 16 NOK/kWh. However, there are variable costs associated with US shipping regulations. Electric vehicle batteries must pass a series of safety tests, including altitude simulations, thermal and vibration tests, and be shipped as hazardous waste. The transportation cost alone, excluding the testing, would be 1170 NOK/kWh for a Nissan Leaf 24 kWh battery pack [106].

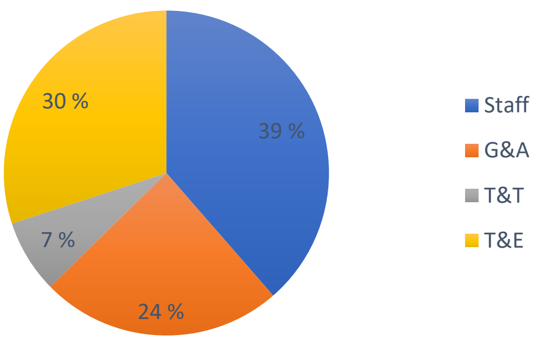


Figure 3.17: Shares of fixed costs for the refurbishment of 142 300 batteries, with a total fixed cost of 42 659 710 NOK. G&A = General and Administration, T&T = Travel and Transportation, and T&E = Tooling and Equipment [106].

Several other studies have proposed estimates. In 2016, Bloomberg New Energy Finance (BNEF) estimated that the repurposing of an electric vehicle battery could cost 430 NOK/kWh in 2018 [107]. In 2012, Williams and Lipman found that the repurposing cost for battery packs from a Toyota Prius, Chevy Volt, and Nissan Leaf would be 6550, 10 120, and 15 660 NOK, respectively. These results were based on a 2003-study done by Cready et al., including costs for packaging materials, testing equipment, labor, rent, insurance, general and administrative, warranty, capital recovery, earnings and taxes. The costs were adjusted to 2010 currency, and a cost of 4400 NOK for extraction of the battery was added. They also found that since the prices for new batteries are declining, the total cost of a second-life battery must be significantly lower. If a Chevy Volt battery reaches its end-of-first-life at 8 years, the repurposed battery, including BMS, could not cost more than 36 080 NOK if it is to be competitive [108].

3.6.3 Applications and Economic Feasibility

As a part of the IntegER project, a Norwegian project aiming to "contribute with new knowledge and practical guidelines that enable energy storage (mainly electric batteries) to be used and integrated into the Norwegian distribution grid" [9], a techno-economic analysis was performed on different use cases [109].

The first use case considered the use of batteries to decrease the grid rental fee by reducing the monthly peak load. An industrial load with a yearly peak of 150 kW and a grid rental fee consisting of an energy component, a power component and a fixed component was assumed, as shown in Table 3.2. In this case, an investment cost of 1970 NOK/kWh was found to be feasible. The second use case considered the same load, battery system, and electricity prices as in the first use case, but with a 287 kilo-watt-peak (kWp) PV-installation in addition. Peak shaving and feeding in electricity to the grid were investigated, resulting in a feasible battery investment cost of 3000 NOK/kWh. Frequency regulation services, based on French TSO data, were examined in the third use case. 2017-regulation prices from the Norwegian TSO, Statnett, were used. In this scenario, the battery cost was found to be feasible at around 13 790 NOK/kWh. All three cases used an NPV/IRR approach (as described in Chapter 2.3.2). The results depend on different factors, like battery rest value, grid costs, discount rates, and interest rates. For example, the feasible investment cost increases with increasing grid costs [109]. Assumptions made and results for these three cases are shown in Table 3.3.

Table 3.2: Grid Rental Fee Component Costs. Table adapted from [109].

	Fixed Component [NOK/month]	*Energy Component [øre/kWh]*	*Power Component [NOK/kW]*
Summer	22 110	3.6	58.5
Winter		4.2	68.0

Table 3.3: Assumptions and results for three different use cases in the techno-economic analysis in the IntegER project. Table adapted from [109].

	Peak Shaving for Industrial Load	*Peak Shaving and PV-infeed for Industrial Load*	*Frequency Containment Reserve*
Discount Rate	5 %	5 %	5 %
Loan	70 % of investment	70 % of investment	70 % of investment
Interest Rate	2.24 %	2.24 %	2.24 %
Project Lifetime	10 years	10 years	10 years
Operation and Maintenance Cost	1 % of investment	1 % of investment	49 437 EUR + 1 % of investment/year
Rest Value of Battery After 10 Years	20 % of investment	20 % of investment	
Battery Capacity	30 kWh	30 kWh	400 kWh
Battery Output	18 kW	18 kW	1000 kW
Roundtrip Efficiency	83 %	83 %	
Savings on Power Tariff	5800 NOK/year	7770 NOK/year	
Increase in Energy Tariff	120 NOK/year	150 NOK/year	
Savings from Spot Market + Losses	340 NOK/year	1420 NOK/year	
Revenues			647 140 NOK/year
Feasible Battery Price	1970 NOK/kWh	3000 NOK/kWh	13 790 NOK/kWh

The last case in the IntegER study examined grid support services. In this case, the battery is used for both frequency regulation services as in the third use case, and power relief and voltage regulation in a DSO network a small number of hours per year. A virtual power plant of several 30 kWh/18 kW batteries, adding up to a 1 MW-battery, is assumed. With the revenue result from the third case and an assumed power factor of 0.95, the cost per kVA/hour is 8 øre. If the

DSO needed 30 kVA for 200 hours of the year, the yearly cost would add up to 490 NOK. In comparison, the replacement cost of a 315 kVA distribution line ranges from 301 410 NOK/km to 673 740 NOK/km, depending on the area [109].

Song et al. performed two case studies in the US and Denmark to investigate if second-life batteries can be profitable in a wind farm. Their cost function included revenue of wind power sales, the cost of scheduling and dispatching conventional reserves, and the cost of meeting power demand when the wind power fluctuates. For the US-case, a capacity of 600 MWh for a new battery was decided to be the optimal size profit-wise. The second-life battery's initial capacity is thus 480 MWh, if it has 80 % of nominal capacity. The accumulated profit depends on how long the battery is in operation, the battery investment cost, and the wind power price. It was concluded that a second-life battery could not compete with a new battery if one assumes a wind energy price of 18 NOK/MWh or above, a battery investment cost of 1260 NOK/kWh for a new battery and that the refurbishment of the battery costs around 350 NOK/kWh. However, if the wind energy price is 9 NOK/MWh, the second-life battery can be profitable, if it can be cycled to a SOH of 60 % or further. At the time of this study (2019), the wind energy price was assumed to be 180 NOK/MWh, and the price for a new battery 2260 NOK/kWh. The authors concluded that for the second-life battery to be profitable, the wind energy price must decline much faster than the price for new batteries. If the battery investment cost is 1260 NOK/kWh, the refurbishing cost is 350 NOK/kWh and the wind energy price is 9 NOK/MWh, the second-life battery can cost 250 NOK/kWh and be profitable. The use case in Denmark confirms the findings in the US use case. With a new battery with an initial capacity of 3.75 MWh and a wind energy price of 200 NOK/MWh, second-life batteries would not be profitable compared to a new battery [110].

The economic viability of second-life batteries for residential applications, namely peak shaving and load shifting, was studied in [111]. A PV-connected household with second-life batteries was assumed in a simulation model, which takes battery degradation into account. It was assumed that the household consisted of three people and that it was located in southern Germany. An NPV approach was used [111]. The model's input parameters are shown in Table 3.4.

Table 3.4: Simulation model parameters for residential applications. The table is adapted from [111].

Location	Stuttgart, Germany
Installed PV peak power	5 kWp
Annual electricity consumption	3892 kWh
Battery size at beginning of life	4 kWh to 8 kWh
Battery capacity at the beginning of the second life	80 %
Inflation per year	1.742 %
Nominal discount rate	4 %
Feed-in tariff	1.21 NOK/kWh
Battery selling price	340-1150 NOK/kWh
Battery power conditioning, controls and interface	880 NOK/kWh
Battery installation and startup costs	450 NOK/kWh
Battery maintenance costs	3 % of the investment costs

Three scenarios were examined, with electricity prices increasing 2, 4, or 6 % per year from 2015 to 2025. Figure 3.18 shows that the NPV is highest at low battery cost and high electricity cost. In scenario 3, with a yearly increase in electricity price of 6 %, the NPV is positive throughout. For the middle scenario of a 4 % increase, also known as scenario 2, the NPV is positive at battery prices below 1050 NOK/kWh. If the electricity price only increases by 2 % per year, however, the battery price must be below 720 NOK/kWh, to have a positive NPV. It was also shown that as battery prices decrease, larger storage capacities yield higher NPVs. At 1150 NOK/kWh, the most profitable capacity is around 5.5 kWh, while at 340 NOK/kWh, the highest NPV is found at 7-8 kWh [111].

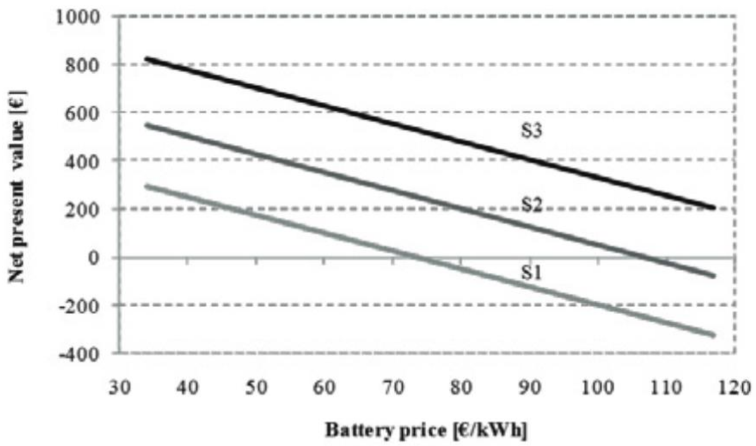


Figure 3.18: NPV for different battery prices in residential applications given in EUR. Figure acquired from [111].

3.7 Discussion

3.7.1 The Electric Vehicle Battery

There exists a wide variety of EV batteries [43-50], with various energy capacities, charging capabilities and builds. Because battery cells and modules can be connected in series or parallel to increase both voltage and capacity, it is possible to make many different configurations of batteries with distinct capabilities. In theory, one could make the batteries as large as one wanted, if enough EV batteries were used, making the technological opportunities almost unlimited. With its initial second life capabilities, battery packs from electric vehicles used directly or as a part of a new second life battery pack should be able to serve in any of the grid applications new batteries do. The real question is how it performs over time.

The Li-ion battery ages throughout its first life and continues to do so in its second life. However, aging is difficult to predict because of the aging mechanisms' complexity and interdependency. Many factors come into play: temperature, C-rate, SOC, DOD, and chemistry, amongst others. To be certain of how a battery ages and how many cycles it will be able to deliver, tests need to be completed. These tests must be as close to the actual situation as possible, where one examines the battery chemistry in question and the specific operating conditions the battery is expected to perform under. Certain general considerations have been found, however. In general, the Li-ion battery shows less degradation if it is stored and cycled in room temperatures, uses charge-and discharge rates of 1 C or below, is stored with a low SOC, and is cycled at certain SOC intervals and with a low DOD.

Most aging studies have been performed with an assumption that the EOL is at a capacity of 70-80 % of the initial capacity. This makes the aging somewhat uncertain when the battery reaches its second life. One phenomenon that has been studied is the sudden death phenomenon, which usually occurs at the point between a first and second life [57]. With a sudden drop in capacity, the second life batteries might be rendered useless. Even though the effect is somewhat reversible, the best path seems to be to avoid overcharge and below-zero temperatures, which appear to be the main reason for sudden death occurrence. Care must also be taken in the design and manufacture of the batteries so that the electrode pores are not susceptible to SEI clogging.

With the ongoing development in the battery industry, future batteries might be less influenced by these aging factors, but since the second life batteries available in the next years will be the batteries used today, more research seems to be needed on the second life aging and life expectancy of chemistries and batteries existing today.

3.7.2 Availability

If electric vehicles have the same lifespan as an average car today, the first wave of batteries due to EOL considerations will not be available until somewhere between 2025 and 2030 in Norway. However, according to Table 3.1, the car manufacturers generally guarantee a lifespan of 8 years [43-50], meaning that the EVs that entered the market in the early 2010s might have discarded their batteries already. Based on Batteriretur reports, several thousand batteries are delivered each year, but over 95 % of these are malfunctioned ones or from condemned cars [77]. This suggests that most of the batteries in the EVs are not discarded after 8 years. Remembering that the number of BEVs did not reach numbers above 100 000 before 2016 [70], it seems there will not be larger quantities of EOL batteries available until after 2025 at the earliest. From then on, all seem to point to a larger and larger amount of batteries available for second-life applications.

If the number of passenger cars continues to increase in the same fashion as it has up until 2019, there will be roughly 3 million passenger cars in Norway by 2025. However, it is unlikely that all these cars and the rest of the vehicle fleet will be electric by then. First, even if all the new passenger vehicles and vans sold were electric this year, it would still take almost two decades before the last fossil-fueled cars were gone. Secondly, vehicles like trucks and buses might take longer to reach zero emissions and could choose other technologies, like biofuels or hydrogen. Fuel cell technology may also be of interest to those buying passenger cars and vans, but the figures in Figure 3.7 does suggest that BEV is the most popular choice, with a share of 42 % of all cars sold in 2019 [15]. And the number is increasing [71]. Considering that the Norwegian government is facilitating a transition to emission-free transportation [72], and the fact that there are rising numbers of models of electric vehicles with longer driving ranges, it seems likely the share of new BEVs sold will continue to increase. If the number of BEVs increases with 10 000 more vehicles than the previous year, as Figure 3.6 suggests, the number of BEVs in 2025 will be close to 900 000 vehicles. This means that even though it will take several decades before the last fossil-fueled vehicle is gone, there will likely be more than enough batteries on the roads in 5 years to support an EV second-life battery industry in the future.

3.7.3 Laws and Regulations

Currently, there are no laws or regulations prohibiting households, industry, or grid operators from owning battery storage systems. However, with NVE signaling that Norwegian regulations will be modeled after EU's Clean Energy Package, grid operators will probably be prohibited from owning, or at least making money off, such grid-connected energy storage in the future. Since third parties are allowed to own battery storages, it seems likely that the TSO and DSOs for the most part must buy the services such storage might provide in the future. This means that companies offering flexibility services, households, and industry might be the most likely customers of second-life battery systems in the future.

The regulations concerning the producers of batteries and vehicles are clear. Producers are responsible for their products when they are no longer useful to the consumer. They must make sure that the vehicles and batteries are collected and recycled in a way that is approved by authorities. This means that the products cannot simply disappear without any trace. Since 95 % of the vehicles and batteries must be collected [75] and the systems for collection are not new, most vehicles and batteries sold should be available for recycling at their end of life.

Regulations concerning EV propulsion batteries after collection is not as clear, as EV batteries are not explicitly mentioned in the regulations regarding the treatment of batteries in the recycling process. They say that the companies collecting discarded vehicles must be able to extract batteries from the vehicle, but it seems likely that extracting a starter battery in a traditional fossil-fueled vehicle and extracting a propulsion battery from an electric vehicle is two different things. However, since most electric vehicle batteries are Li-ion batteries and this chemistry is not defined as a hazardous one in the regulations, it seems electric vehicle batteries are not considered dangerous in the eyes of the law, at least not explicitly. This means that it is up to the person collecting and recycling the battery to decide if it is hazardous or not. Considering that these are high energy batteries, which might not be empty upon collection, combined with the potential risk of thermal runaway, the batteries should be treated as dangerous to the humans handling them as well as their surroundings during storage and treatment, and it should not be possible to misinterpret it.

If the batteries are judged as hazardous, proof of competence is needed to handle and transport them, but what this competence entails is difficult to discern from the regulations. With the large number of electric vehicles entering the market, clearer regulations and guidelines are needed to safely recycle, and possibly reuse, the batteries.

3.7.4 Recycling and Reuse

Batteriretur is gaining valuable experience in the battery repurposing field, both by executing the refurbishment of the batteries and by using their second-life batteries in research projects. They could thus provide the much-needed guidelines for the handling and repurposing of EV batteries in the near future, and maybe influence the regulations, so that safe handling could be assured. It is important to note, however, that the type of batteries collected likely will shift from mainly being malfunctioned, or from condemned cars, to mainly being EOL batteries within the next decade. Also, it is expected that more and more batteries will end up at scrap yards [77]. This means that any guidelines and repurposing processes developed today might be lacking in a few years. Thus, to ensure safe and efficient handling of the batteries, recommendations must be updated along the way and adjusted according to the situations that might occur.

As the only company in Norway to recycle EV batteries, they are in a unique position. The number of EV batteries available in Norway is on the rise and will likely reach volumes that could lead to reasonable refurbishment costs according to repurposing cost studies within a few years. With batteries moving towards being EOL batteries, the testing procedures could likely be simplified, and some batteries could be used in a more direct manner, which would reduce costs. It thus seems that given the experience level and the market development, Batteriretur could commercialize second-life batteries within this decade if the batteries prove viable.

3.7.5 Suppliers and Projects

The number of ongoing projects and emerging suppliers in this decade suggests a growing interest in second-life battery storage systems throughout Europe. It seems both renowned companies like Bosch and Statkraft, and emerging companies like ECO HOME/ECO STOR, believes second-life battery systems could be part of tomorrow's power systems. In these projects alone, five different car manufacturers have contributed. This suggests a certain positivity towards the subject of second-life battery systems. The willingness from the car industry might lead to the creation of batteries intended for second-life applications, as suggested by the SUNBATT project [101]. If so, these batteries might be even better suited for second-life services in the future. At the very least, with car manufacturers on board, it seems likely that systems will be put in place to facilitate a second life for the EV batteries.

There is a wide range of second-life battery systems currently in use. With capacities from 4.2 kWh to 2800 kWh [79, 100], these systems confirm that the capacity of the second-life battery systems is not an issue. However, with the larger sizes, one must be prepared that a container-sized area is needed, as seen in Figures 3.12 and 3.13. The systems are used for many different purposes, from residential services to grid management services [78, 83, 88, 100, 101], suggesting that the second-life systems could be suitable for a wide array of applications.

Considering that the development seems to have begun in the last few years, the experience level concerning these systems are likely still low. The ongoing projects will, therefore, provide valuable information about the performance of these systems. Since some of them have been in operation for several years already, preliminary results should be available soon, and as the years go on, the experience and knowledge should grow further, assuming the development and operation continues.

Initially, the second-life battery systems seem to perform their tasks satisfactorily. The question is how they age and perform over time. This cannot be known for sure until more experience is gathered, but the suppliers do suggest certain lifespans at their web pages, meaning they must be fairly certain that the batteries should be able to operate satisfactorily for the timespan mentioned. xStorage Home by Eaton operates with a guaranteed lifespan of five years (Appendix A), while Connected Energy says they will double an EV battery's lifespan by giving it a second life [86]. However, the lifespan of the batteries seems to be very dependent on the application, in addition to the conditions. For the battery system at Umicore industrial site, offering frequency and voltage regulation services, a second life of seven years is stated [98]. In the simulation study performed by Casals et al. based on the SUNBATT system, a lifespan of between 3.8 and 11 years were found for transmission deferral services, 5.9 to 11.6 years for self-consumption, 4.7 to 5.7 for area regulation and 29 years in fast EV-charge [103]. This clearly suggests that different lifespans must be expected for different applications and that some applications might be better suited for second life services than others in a lifespan perspective. It is also important to note that how the EOL point is defined will affect the lifespan. The defined EOL is not necessarily the system's functional EOL. This could raise the discussion of how EOL should be defined in first-life applications, and maybe even third-life applications as well, especially with battery sizes increasing.

It is difficult to tell how these second-life systems perform in reality since little research results regarding the battery performance have been published. The same is true for the cost-effectiveness of the systems. Apart from the Eaton xStorage Home units, it was challenging to find any price estimations of the systems used, making it hard to consider if the systems described are at all profitable to use. The secrecy and competition between companies do seem to slow down the development and implementation of second-life battery systems. To expedite the process, more collaboration and openness is needed.

In this section, internet sources were the main origin of the information used. Care was taken to use the projects' or suppliers' own web pages when gathering information, to increase the probability of the information being accurate and updated. But the information might still be biased. This is probably especially true for sites belonging to suppliers and others who have a financial interest in the product, like Eaton and Connected Energy. Ideally, independent research should be conducted on the battery systems to verify their capabilities.

3.7.6 Costs

The EV battery cost has decreased rapidly this decade – 85 % in eight years [14]. This is a considerable reduction, and as the world turns to greener solutions, it seems likely that even larger volumes of EV batteries will be needed, leading to further development in manufacturing efficiency. Mass production is known to reduce costs, which means one can expect a further decrease in EV battery cost. A reduced EV battery cost should mean a reduced second-life battery cost, making these batteries more desirable cost-wise. However, as the manufacturing processes are developing, the prices for first life Li-ion battery storages will also benefit, leading to cheaper first life battery storage options. According to IRENA, the 2030 installed cost of such storage systems could be between 1280 and 3960 NOK/kWh [104]. With a 2018 EV battery price of 1550 NOK/kWh [14], it seems likely that the second life batteries will cost considerably less than this in 2030, meaning that in applications in which little refurbishment is needed, they could be a preferable option to first-life systems.

Other battery chemistries might also compete with the second-life batteries. High-temperature NaS batteries could cost 1060 NOK/kWh according to IRENA [104], but because they are high-temperature batteries and Li-ion batteries are not, it is probable that these batteries will have different working applications, and hence not be direct competitors. Flow batteries may compete with the Li-ion chemistry, considering that the cost might be as low as 950 NOK/kWh [104], which is lower than what is expected for Li-ion batteries. Flow batteries can also separate their power and energy capabilities, which might be desirable in some applications. However, if the size and weight are of great importance, few batteries can currently compete with Li-ion chemistry. It seems like the second-life Li-ion batteries will have competitors, both from other chemistries and from first life Li-ion batteries, and that what system is preferred depends on the application.

One crucial factor in the economic viability of second-life batteries is the repurposing costs since this will influence the selling price of the battery. Several studies have addressed this, but it seems most of these are at least 5 years old, which points to a need for updated research. In addition, the studies described were mostly done in the US. There are different conditions in the US, which means that these studies might not be valid for Norwegian conditions. However, it is possible to draw some conclusions based on the findings in the studies. The repurposing cost ranges between 180 NOK/kWh and 1580 NOK/kWh [105-108]. The relatively large range is due to various assumptions. One example of different assumptions is the transportation cost. This is thought to be the largest component of the overall cost in one study [106], but in the study by NREL, the transportation cost is not considered as important. Either way, it can be assumed that the transportation cost may vary from area to area, depending on regulations and guidelines. This means that cost-effective transportation systems must be put in place to ensure a low repurposing cost. Since the regulations and guidelines regarding the collection and processing of EV batteries are currently somewhat unclear in Norway, it is difficult to predict these costs today, but it does seem likely that the costs will get higher the more regulations repurposers have to uphold. There does seem to be some consensus regarding the high cost of staff, but this is also subject to area-specific factors. One such factor is wages. In 2019, the average annual wage in Norway was 100 000 NOK higher than in the US [112, 113]. Thus, the staff- and labor costs would be higher if the repurposing facility is in Norway. If automated processes were implemented, this might be remedied to a certain extent.

To reduce repurposing costs, the following conditions were also identified as necessary:

- large volumes of batteries
- low battery price
- low fault rates [105, 106].

As already discussed, the cost of new EV batteries is rapidly decreasing, making it probable that their EOL price is also decreasing. To achieve low fault rates, efficient testing tools must exist, preferably that tests the battery pack before it is sold as possible second-life batteries. With the manufacturers increasing interest in second-life applications for their batteries, they might be willing to take responsibility for such testing, which would reduce costs for repurposers. When it comes to volumes, Batteriretur reports that several thousand EV batteries are collected each year [77]. This number is far from the volumes of up to 142 300 batteries/year discussed in the studies [106], especially considering that only 30-40 % of the batteries collected are fit for reuse [77]. However, if one considers the growth in the number of EVs in Norway these last few years and that the share that is fit for reuse will likely increase as the number of EOL batteries increase, larger volumes can be expected in the next few years. With the current growth, the volumes should be large enough sometime after 2025. This means that the repurposing costs in Norway will likely be higher than proposed in the studies today, but maybe not in the future - if automated processes are developed, and cost-efficient transportation is possible to achieve. With the EV batteries having different builds and chemistries, it might be challenging to make a cost-efficient and automated system to handle the processing of the batteries, however. It thus seems likely that to avoid expensive processing systems, EV battery manufacturers should agree on one standard, or the facilities should decide on using one type of battery pack. Although the last option influences the volumes of batteries available, and thus it may not be possible to differentiate in this way. It is evident that many factors influence the cost of repurposing and that they could be area specific. Hence, studies based on Norwegian conditions are needed to complete the picture.

A study that could shed some light on the Norwegian market is the study done by the IntegER project. It assumes the use of fresh batteries, but since the study investigates what battery price is feasible in different applications, the results can be valid in a second-life perspective as well. For the results to be valid for second-life batteries, the batteries must be able to deliver services satisfactorily for 10 years and have some rest value after their second life. As discussed previously, this cannot be guaranteed because of the possibility of the sudden death phenomenon and that the aging of the battery in its second life is not investigated extensively. However, it seems that favorable operation, knowledge of their first life, and testing of the batteries would make it possible. The study suggests that a battery price of 1970-13 790 NOK/kWh [109], depending on the application, is feasible. This means that even if the repurposing cost is significantly higher than proposed in the described studies, second-life battery systems could be economically feasible today in some applications.

In the IntegER project study, the frequency regulation services had a much higher feasible battery price, 13 790 NOK/kWh, than the industrial peak shaving applications [109]. This points to higher incoming cash flow in this application, making it more profitable. In the industrial applications, only the peak shaving case with the support of a PV-infeed seems somewhat feasible at current costs. Even with the PV-infeed, the cost of the batteries would have to be below 2880 NOK/kWh for it to be feasible at all [109], making the profitability at current prices low. Balancing services offered by a third party seems to be the most profitable to a DSO. If the yearly cost was 490 NOK as outlined in Subsection 3.6.3, it would take at least 600 years to reach the cost of replacing a line, assuming the costs did not change. This bodes well if one remembers that the TSO and DSOs in Norway will likely not be allowed to own battery energy storages in the future.

From the results in the IntegER study, it does seem that the battery size is worth considering. The battery is much larger in grid service applications than in the industrial applications, hundreds to thousands of kWh vs. 30 kWh [109]. This might mean that larger battery systems are more profitable. However, the study by Song et al. investigates the use of a 480 MWh battery system in wind power services and found that several factors influenced the feasibility of a second-life system, meaning that a system is not profitable only because it is large. They found that if the wind energy price is higher than 18 NOK/MWh, the battery investment cost of a new battery is 1260 NOK/kWh and that the refurbishment of the battery costs 350 NOK/kWh, it would not be feasible [110]. Considering that NVE estimated the LCOE for land-based wind energy plants in Norway to be 340 NOK/MWh in 2018 and expects it to be 210 NOK/MWh in 2040 [114], it seems unlikely that wind energy prices will get low enough to make second-life battery systems feasible in this application anytime soon, even if the battery investment costs and refurbishing costs meet the target in this study.

For residential applications, the electricity price is an important factor. A higher electricity price leads to a higher NPV, which opens for a higher battery investment cost. With an increase of 6 % in electricity price, the battery is profitable at a battery price of 1150 NOK/kWh [111]. This is only 400 NOK/kWh from the current price of EV batteries, but one must also take repurposing costs into account. Furthermore, electricity prices must be evaluated. According to Eurostat, the average price of electricity for a household, including taxes and fees in Germany, was 2.40 NOK/kWh in 2015 [115]. In Norway, the 2019-price was 1.12 NOK/kWh [35]. According to data from Statistics Norway, the electricity price for households increased by an average of 2.75 % from the beginning of 2012 to the end of 2019 [116]. One might think that the prices will increase substantially with the proposed new power tariffs, but it is actually expected that the grid rental fee will decrease with time [38]. It thus seems unlikely that any of the electricity price scenarios described in the study will occur in Norway within the next few years - even with the possible increased daily variability in electricity prices. In addition, the study assumed a feed-in tariff of 1.15 NOK/kWh. Eidsiva, a Norwegian power company, suggests a feed-in tariff that equals the spot price [117]. Since the average spot price in 2019 was 0.387 NOK/kWh [37], the revenue from PV electricity sales is considerably lower in Norway than in Germany. Also, the average yearly energy consumption in Norway is higher than 3892 kWh, which might mean that less of the PV power is sold. This all makes it seem less feasible in Norway, calling for lower battery prices than even the lowest battery price of 680 NOK/kWh in Germany [111]. However, the higher energy consumption in Norway might offset some of the factors mentioned, making it difficult to decide what battery price would be feasible in Norwegian conditions. Area-specific studies are thus needed in order to examine economic viability of second-life battery storages for different residential applications. One such study is performed and discussed in the use case in this thesis.

3.7.7 Other Aspects and Considerations

Some of the most relevant aspects of second-life battery viability in Norway. However, there are other factors not mentioned in this chapter that is worth examining when deciding if second-life batteries should have a future in the Norwegian power system. A few are discussed briefly below.

Recycling and environmental impact are worth mentioning. Today, most batteries are recycled, and materials reused indirectly when possible. The discussion is whether one should continue this recycling scheme or reuse. Most likely, the answer lies somewhere in between. As mentioned in Section 3.3.2, regulations only demand 50 % of the batteries to be recycled [75], which means that a lot of useful material might be lost, and energy wasted in the process. Reusing batteries could thus be a way to exploit the usefulness of such materials to a larger degree and save energy, leading to environmental benefits. However, a question of material availability also exists. With the increasing demand for Li-ion batteries, there might be a shortage of the metals used in the future. In that case, recycling could be the more reasonable choice.

Another factor to consider is the competition of other energy storage technologies. There is a wide array of options in addition to different battery storages: flywheels, capacitors, compressed air, hydrogen, and pumped hydro, to mention some. Furthermore, new technology is continuously being developed. The individual storage technologies have distinct strengths and weaknesses, which makes them suitable for different applications. One should thus identify the direct competitors to second-life battery systems and evaluate them against one another.

In addition to these, the safety of second-life Li-ion batteries need to be examined. Since these systems are new and relatively few systems have been tested in real-life applications, there might be some unexpected reactions leading to dangerous situations. One such example is thermal runaway. It has been described as a possible hazard in first life Li-ion batteries, and it seems that the probability for it might increase as the battery ages. If an increase in possibly dangerous situations occurs, the use of second-life batteries might not be possible. However, this author is not aware of any such reports for second-life batteries currently, which suggests that they are no more unsafe than what one would expect of other storage systems.

4 Use Case: Peak Shaving

This chapter presents a use case of the peak shaving application in Hvaler, Norway. Subsection 4.1 contains an area- and data description. It is followed by a methodology subsection, before the results are presented in Subsection 4.3. The chapter is discussed in Subsection 4.4.

4.1 Data and Area Description

The data was retrieved from a transformer substation located at Hvaler, an island group off the coast of Fredrikstad, in the south-eastern part of Norway, as shown in Figure 4.1.

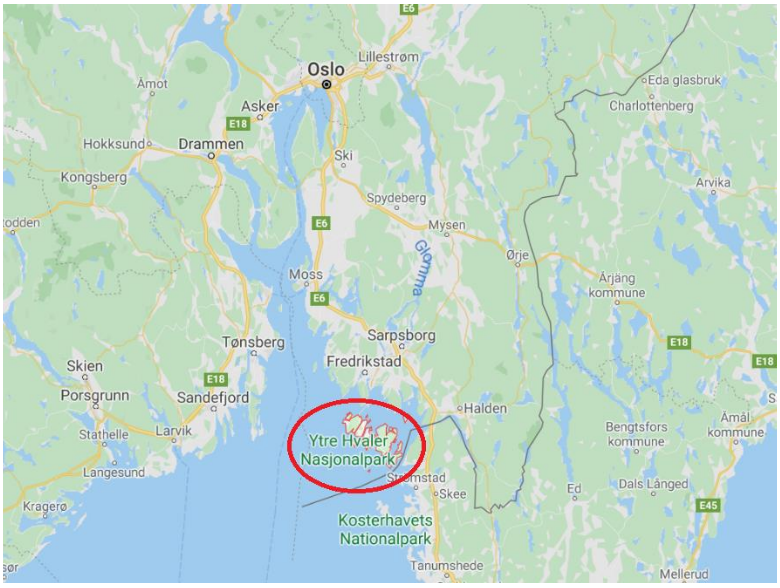


Figure 4.1: The substation investigated in this use case is located at Hvaler, in the south-eastern part of Norway. Image retrieved from Google Maps.

The substation has a rated apparent power capacity of 315 kVA and is connected to 69 consumers, where 35 are characterized as households, 10 as small businesses, and 24 as cabins.

The data is composed of hourly energy consumption over almost three years, from 01.01.2017 to 29.11.2019, for each consumer.

4.2 Methodology

4.2.1 Data Processing

The data was received from Norgesnett as a csv-file, with hourly energy consumption values given in kWh for each consumer node. Each value is an average of the power consumption for the previous hour. Python and its Pandas and Matplotlib libraries were used for data processing and analysis.

The data was loaded into a data frame with English column titles, the delimiter changed to a comma, and the kWh-values changed into float numbers. Midnight time 00:00:00 was also added throughout. To simplify calculations, the midnight hour was counted as the date it turns into at midnight.

Time was given in UTC+2. Since Norway has summertime UTC+2 and wintertime UTC+1, the data was shifted one hour during the winter months. To have the same number of hours for each date, the dates where summertime changes to wintertime, and opposite, were removed from the data set. The dates removed are March 26 and October 29 in 2017, March 25 and October 28 in 2018, and March 31 and October 27 in 2019. In addition, September 12, 2019, was removed due to outlier values. This is true for all calculations and graphs, except for the total duration curve, where all these values are included and not shifted according to summer- and wintertime.

4.2.2 Daily and Hourly Consumption

For daily consumption, the processed data was split into the different consumer categories – businesses, households, and cabins, by making new data frames for each category based on the consumer nodes' designation. Next, a list of data frames, where each data frame contains the values for one specific date, was created. The energy consumption values in each data frame were summed and plotted for each category. For the total daily consumption, all the values for one specific date were summed up and plotted.

The total hourly consumption at the substation was found for an average winter week. Winter was defined to be in the months of December, January and February. A data frame of hourly values for the three years were created from the processed data, by summing all the consumer nodes' values for each hour. To find the averages during winter, the different weekdays' dates were identified for the winter months over the three years and used to calculate average hourly values for each day of the week. The hourly averages for each weekday were then plotted in the same figure.

4.2.3 Duration Curves

Data without time shift was used to create a duration curve for the entire three-year period. The last value in the data set, which was a single midnight value, was removed. The total energy consumption value was calculated for each hour and sorted in descending order. Percentage points were found by dividing 100 by the number of hours. The percentage points were sorted in ascending order and plotted against the kWh-values.

Total duration curves with and without household batteries were created for an average winter week. With batteries, the new total energy consumption values were found by subtracting the difference between the old and the new hourly total household energy consumption values from the original hourly total energy consumption values. Next, percentage points were found, values sorted, and plotted as explained for the total duration curve.

4.2.4 Peak Shaving Simulation

Battery Algorithm

To simulate peak shaving, a battery class was constructed, containing charge- and discharge functions. This algorithm can be found in Appendix B. A battery is generated by entering the nominal capacity, C_n, the remaining capacity, C_r, and the DOD-limit, DOD_{lim}. The capacities are given in kWh. The battery's useful capacity is decided by the DOD-limit. The capacity limit, C_{lim}, determines how much the battery can be discharged and is defined as:

$$C_{lim} = C_n \cdot (1 - DOD_{lim}). \tag{4.1}$$

There are two charge functions within the class. One assumes that charging occurs upstream of the substation and the other that charging occurs downstream of the substation. The first charges regardless of current energy consumption and is only constricted by the charge power and charge efficiency. The latter does not charge if the hourly energy consumption value entered is not lower than a pre-defined value. It cannot charge above a given energy consumption value or charge the battery above its nominal battery capacity. The algorithm is illustrated in the flow chart in Figure 4.2.

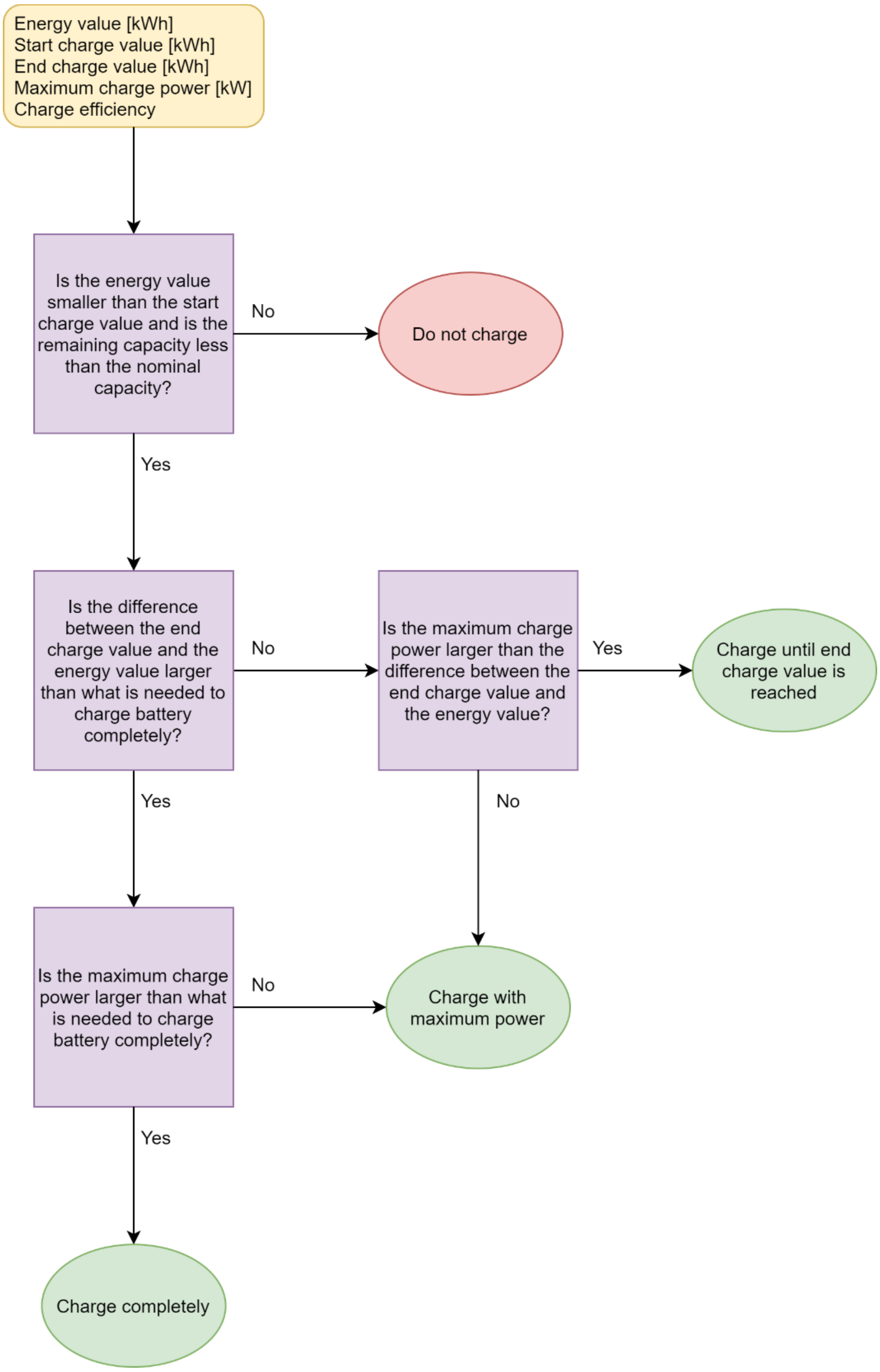


Figure 4.2: Charging algorithm. Battery charges when above a pre-defined energy consumption value. It cannot charge above a given value or above the battery's nominal capacity. The maximum charge rate is defined by the maximum charge power.

The discharge function discharges according to a set of constraints. First, the entered hourly consumption value must be above a given value for the battery to discharge. It does not discharge below a pre-defined hourly energy consumption value or below the battery's capacity limit. It also takes the discharge efficiency into account. The discharge function is displayed in the flow chart in Figure 4.3.

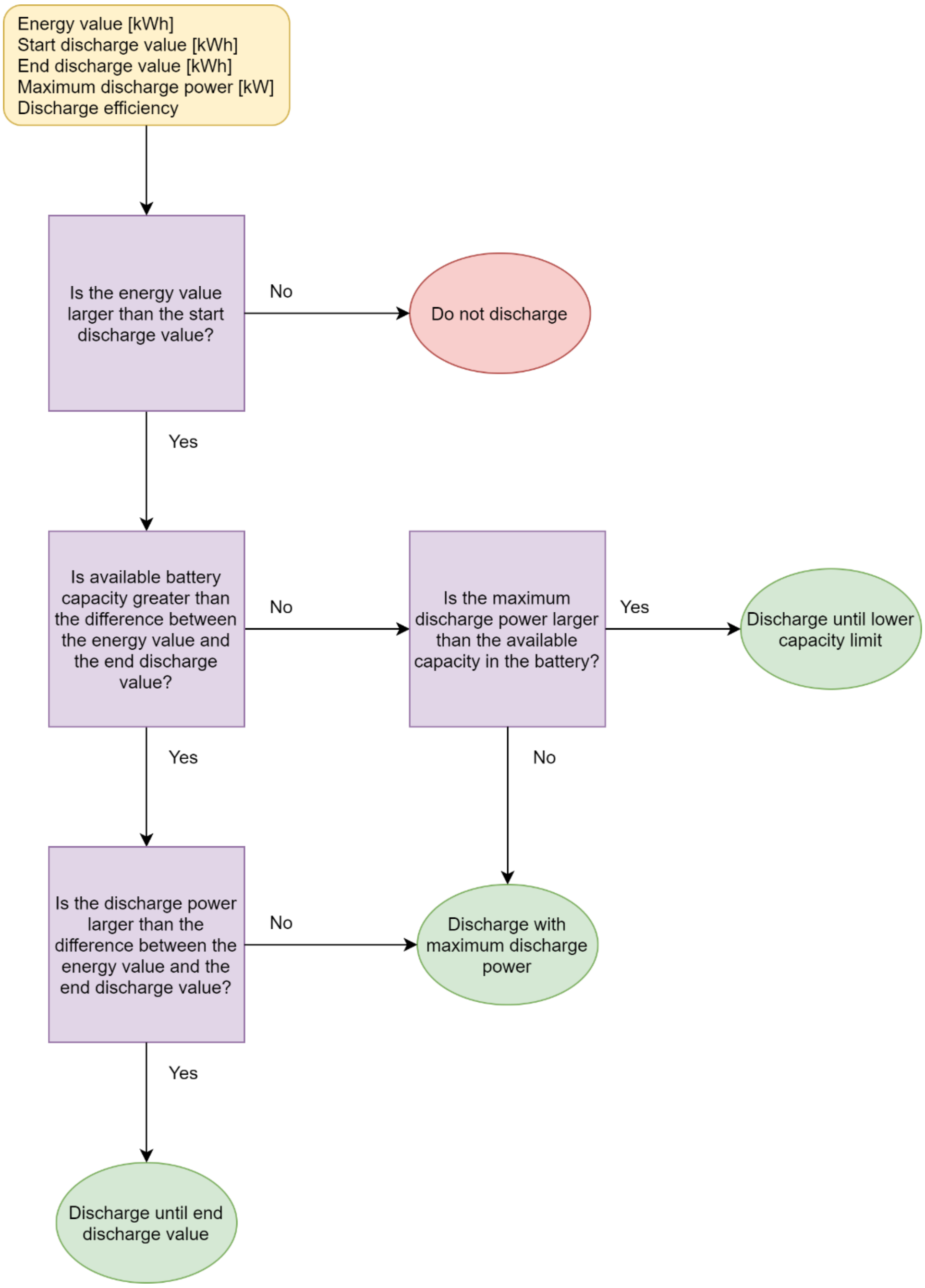


Figure 4.3: Discharge algorithm. The battery discharges when above a given hourly energy consumption value. It cannot discharge below a pre-defined value or below the capacity limit of the battery. The maximum discharge rate is determined by the maximum discharge power.

Assumptions and limitations

The household batteries are based on Eaton's xStorage Home units, shown in Appendix A, with an energy capacity of 4.2 kWh and a maximum charge power of 3.6 kW. For the 8.4 kWh battery, two of the 4.2 kWh battery packs with one inverter were simulated. For both batteries, it was assumed that the maximum discharge power equals the maximum charge power. Since the datasheet suggests a DOD of 0.9 and reports discharge efficiencies of above 90 %, 0.9 was used as DOD limit and discharge and charge efficiency in the household simulations. For the substation simulations, the 109 kWh battery was based on the Eaton xStorage Buildings battery used at Bislett Stadium [84], with an assumed charge- and discharge power of 40 kW, charge and discharge efficiency of 0.9 and a DOD-limit of 0.8. The 350 kWh battery was chosen arbitrarily with the same charge and discharge specifications as the 109 kWh battery. The self-discharge was assumed to be negligible due to short storage periods in all scenarios. Different SOH was not investigated in any of the simulations.

For charging and discharging of the household batteries, it was assumed that the batteries charge between 00:00 and 05:00 and discharge between 06:00 and 23:00. They cannot do both at any time. For the substation battery, it was assumed that it was charged from a source upstream of the substation between 00:00 and 05:00 and that it discharged as the household batteries between 06:00 and 23:00. The two different simulation algorithms are shown in Appendix B. Before the first charge, the household batteries were assumed to be at their lower capacity limit, while the substation batteries were assumed to be fully charged.

In the simulations with household batteries, the goal was to even out the consumption down to a pre-defined level, meaning that peak shaving was not considered to be complete if every hourly energy consumption value was not on or below this given value unless the time constraints hindered it or the energy consumption was simply too low. The peak shaving was inspected visually by investigating the graphs after the simulation. The level was adjusted with one decimal accuracy until complete peak shaving was achieved.

4.2.5 Cost Calculations

Grid Rental Fee

In Hvaler, the grid rental fee is composed of a fixed component, an energy component, and a power component. The power component is found by taking the average of the three highest values for three different hours in three different days per month. The grid rental fee, as stated in 2020 by the local DSO, is given in Table 4.1 [118].

Table 4.1: The grid rental fee in Hvaler is split into three components: a fixed component, an energy component, and a power component. Table adapted from [118].

Type of Consumer	*Fixed Component [NOK/year]*	*Energy Component May – October [Øre/kWh]*	*Energy Component November – April [Øre/kWh]*	*Power Component January - December [NOK/kW/month]*
Household	809	25.79	27.66	76.17
Cabin	1613	25.79	27.66	76.17

Based on the prices displayed in Table 4.1, the yearly grid rental fee, GRF_{yearly}, was calculated by using the following equation:

$$GRF_{yearly} = GRF_{fixed} + GRF_e + GRF_p. \tag{4.2}$$

GRF_{fixed} is the fixed component, GRF_e is the energy component, and GRF_p is the power component. The energy component was calculated by finding the total weekly energy consumption. To find the monthly consumption, the value was multiplied with the number of weeks in a year and divided by the number of months. Since the prices and energy use vary with the seasons, the energy and power components were split into summer and winter costs. It was assumed that the average weekly summer consumption lasted from May to October and that the average weekly winter consumption lasted from November to April. Hence the energy component was calculated as follows:

$$GRF_e = \left(c_{e,summer} \cdot E_{m,summer} + c_{e,winter} \cdot E_{m,winter}\right) \cdot 6\,months, \tag{4.3}$$

where $c_{e,summer}$ and $c_{e,winter}$ are the price for energy given in øre/kWh and $E_{m,summer}$ and $E_{m,winter}$ are the monthly energy consumption given in kWh during summer and winter, respectively. The power component was calculated by finding the three highest hourly energy consumption values on three different days during the week. Since average weeks were found, it was assumed that these values also were the highest values during either summer months or winter months.

The mean of these three values then served as the peak values for summer, $P_{p,summer}$, and winter months, $P_{p,winter}$, given in kW and the power component cost was determined by:

$$GRF_p = (c_{p,summer} \cdot P_{p,summer} + c_{p,winter} \cdot P_{p,winter}) \cdot 6\ months, \tag{4.4}$$

where $c_{p,summer}$ and $c_{p,winter}$ are the power component price given in NOK/kW/month.

Electricity Cost

To find the cheapest electricity supplier for Hvaler, a website comparing electricity prices and suppliers was used[10]. The supplier chosen was Agva, with a spot price deal which follows Nord Pool, plus an added fee of 8.9 øre/kWh and a monthly fee of 19 NOK/month [119]. Average hourly price values were found for both a winter week and a summer week by analyzing hourly spot price data for 2019 from Nord Pool. As before, winter was defined to be December, January and February. Summer was defined as June, July, and August. The summer cost was used from May to October, while the winter cost was used from November to April. The weekly cost, EC_{weekly}, was calculated with the following equation:

$$EC_{weekly} = \sum_{i=1}^{n} (c_{h,i} + c_{fee}) \cdot E_{h,i}, \tag{4.5}$$

where n is the total amount of hours in a week, making $c_{h,i}$ the cost for hour i and $E_{h,i}$ the energy consumption for hour i. c_{fee} is the added fee per kWh from Agva. Monthly prices for winter and summer were found by multiplying the weekly cost with 52 weeks and dividing by 12 months. The yearly price, EC_{yearly}, was defined as:

$$EC_{yearly} = (c_{el,ms} + c_{el,mw}) \cdot 6\ months + (c_{el,mf} \cdot 12\ months), \tag{4.6}$$

[10] www.elskling.no.

where $c_{el,ms}$ is the monthly electricity cost during summer, $c_{el,mw}$ is the monthly electricity cost during winter and $c_{el,mf}$ is the monthly added fee from Agva.

Cost of System Components

The price for a complete 4.2 kWh battery system, including inverter, is assumed to be 40 000 NOK [78]. In the case of the 8.4 kWh battery system, the price of two 4.2 kWh systems are used.

Upgrading a similar substation as the one in the case is assumed to cost 200.000-500.000 NOK [120].

4.3 Results

The following section presents the results of the use case. First, the total energy consumption at the substation is considered in Subsection 4.3.1. The next subsection investigates the use of batteries for peak shaving in the households connected to the substation. A few selected households are examined in addition to studying the effect on the substation if all households had batteries. Subsection 4.3.3 examines the use of one large battery at the substation in peak shaving application. The last subsection considers the cost and payback time of the use of batteries in peak shaving application in two selected households.

4.3.1 Energy Consumption

As shown in Figure 4.4, the total load at the substation varies with the seasons of the year, from around 1300 kWh per day during the summer to around 4500 kWh per day during winter. The cabins and small businesses consume considerably less than the households, with around 500 kWh per day year-round with some seasonal variation. The rest of the total consumption is due to the households. The duration curve in Figure 4.5 shows that the substation never delivers more than 250 kWh/h and that it supplies more than 175 kWh/h 5 % of the time.

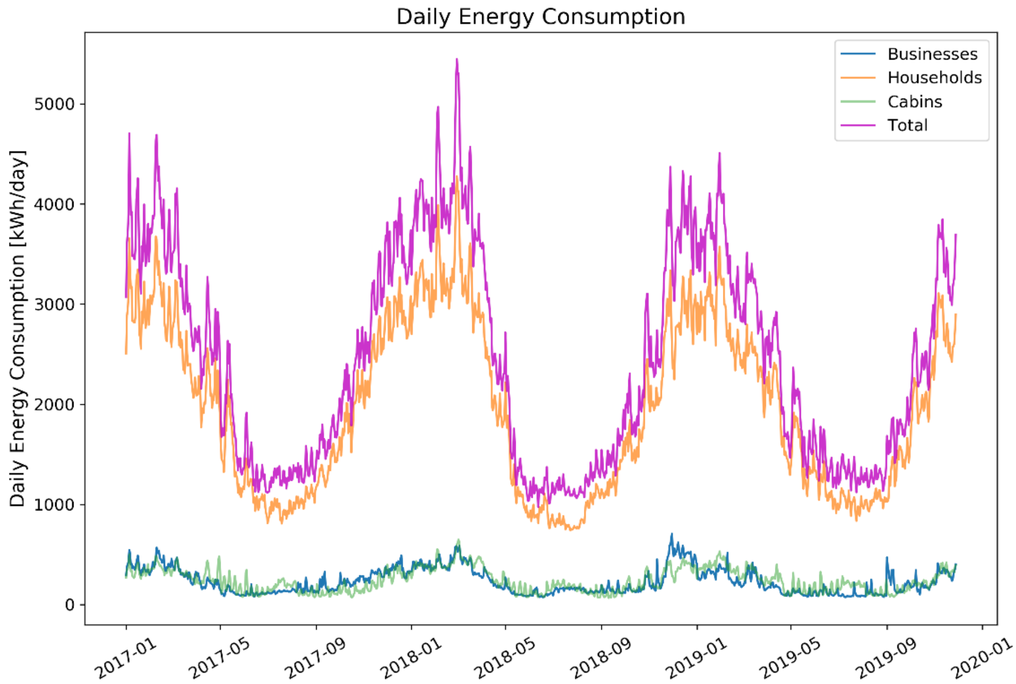


Figure 4.4: Daily energy consumption. The total load at the substation varies from around 1300 kWh/day during summer to around 4500 kWh/day during winter. The main contributors to the total load are the households.

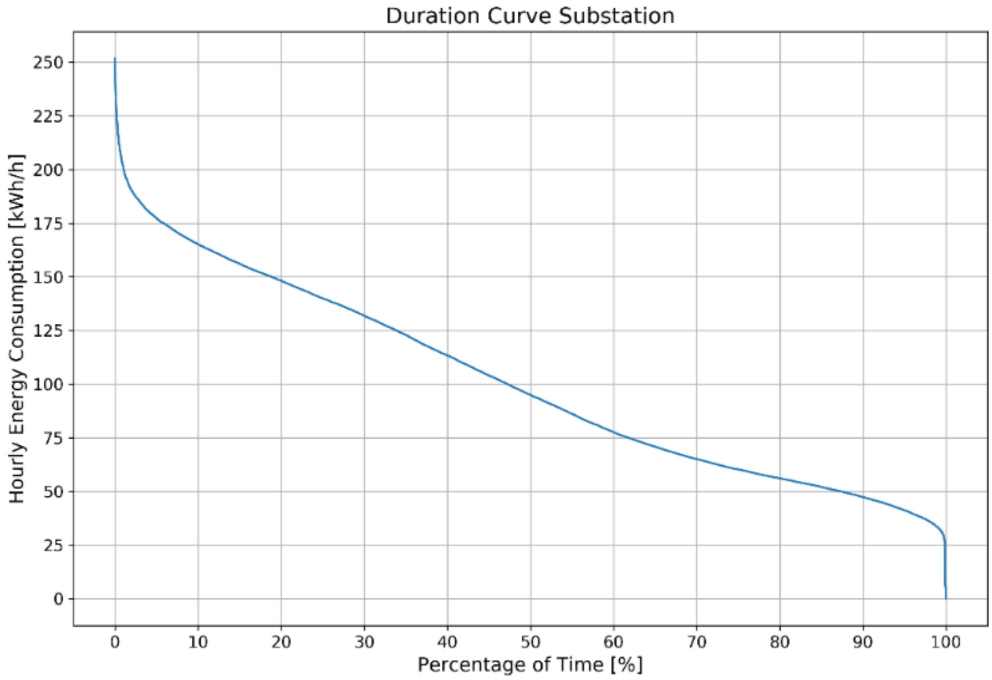


Figure 4.5: Substation duration curve.

Since the consumption is largest during the winter months and might provide higher energy savings, these months were chosen for further consideration. During the winter months, December to February, the consumption follows a clear daily pattern. Figure 4.6 illustrates the hourly average throughout a winter week. On weekdays, the utilization of energy is typically below 140 kWh between midnight and 6 a.m., and above 170 kWh between 4 and 7 p.m. At weekends the consumption is shifted to the right, meaning that the use of energy peaks at later times. In addition, the consumption increases throughout the day. At night the consumption is about 5 kWh higher and in the afternoon about 10 kWh higher. Most pronounced, however, is the increase during daytime, which is about 15 kWh higher, compared to the weekday consumption.

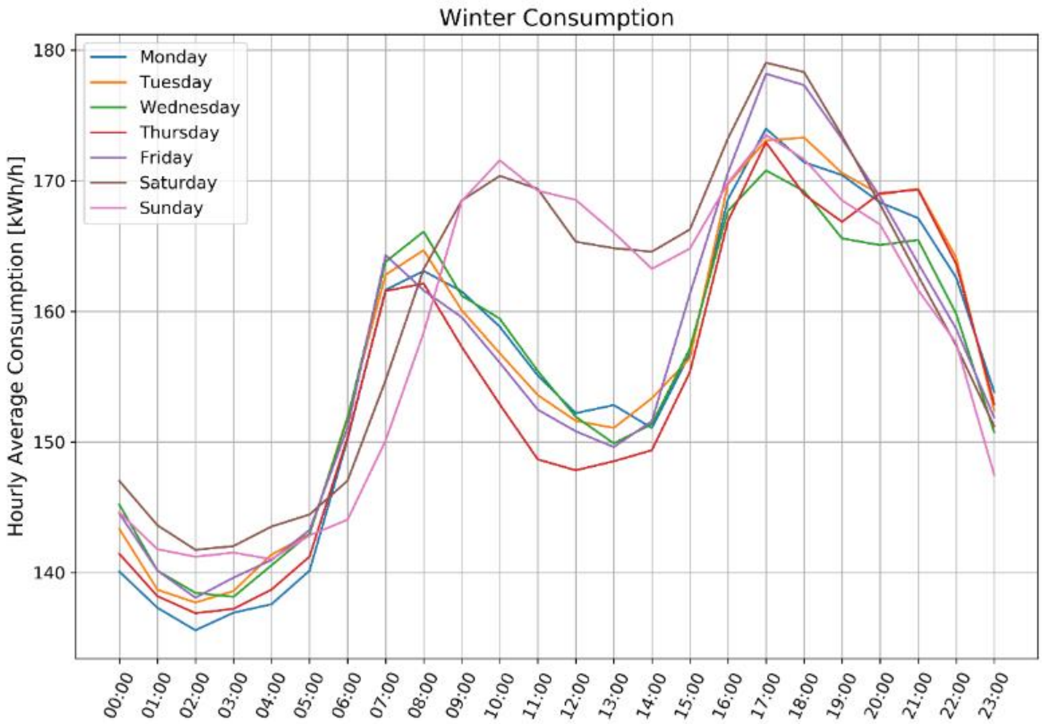


Figure 4.6: Hourly average total consumption during a winter week, where winter is defined to be December, January, and February.

4.3.2 Case 1: Batteries in Households

Households were the largest contributors to the load at the substation and were thus chosen for further investigation. During a winter week, the consumption varies with the households. Figure 4.7 shows average hourly values for each household. Household 34 has an energy use of close to 0 kWh, while household 20 has an average above 8 kWh. 29 of the households have hourly average values between 2 kWh and 6 kWh. Notice also that the times and durations for energy bottoms and peaks differ between households when investigating the graphs of selected households below.

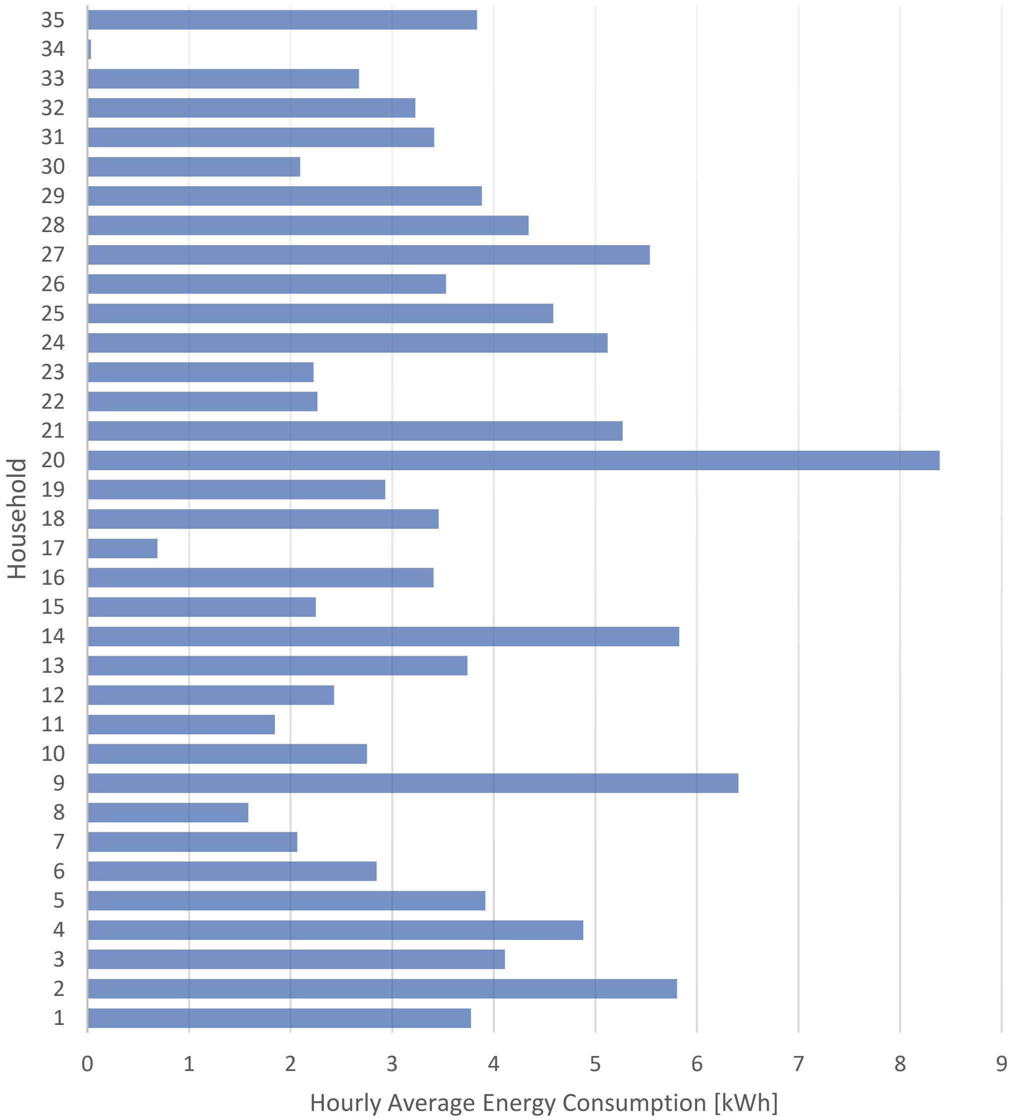


Figure 4.7: Average hourly energy consumption for each household during a winter week.

A few households were selected for more consideration. They were chosen because of their different consumption patterns, so that several types of households could be examined. The battery systems used were based on the Eaton xStorage Home Units of 4.2 kWh. A battery size of 8.4 kWh was also considered.

Household 32 had a large difference between its daily bottom and peak consumption. As shown in Figures 4.8 and 4.9, a battery can reduce the household's peaks and even out its consumption. With a 4.2 kWh battery installed, household 32 shaves its peaks down to 5.1 kWh, reducing the daily peak consumption with 0.4-1.8 kWh. New nightly peaks occur, with a size connected to the SOC of the battery, as it recharges fully every night. The capacity of the battery is below 20 % SOC Wednesdays between 18.00 and midnight. Otherwise, its SOC does not reach values below 40 %. This is shown in Figure A.3 in Appendix C. With an 8.4 kWh battery, the peaks are shaved 0.7 kWh more than with a 4.2 kWh battery, down to 4.4 kWh. The nightly peaks increase and reach 4.4 kWh every night. These peaks also last for several hours. The battery recharges completely all nights and reaches below 20 % SOC values on Wednesdays between 18.00 and midnight. All other nights, except Thursdays, it reaches 40 % SOC or below. This can be seen in Figure A.4 in Appendix C.

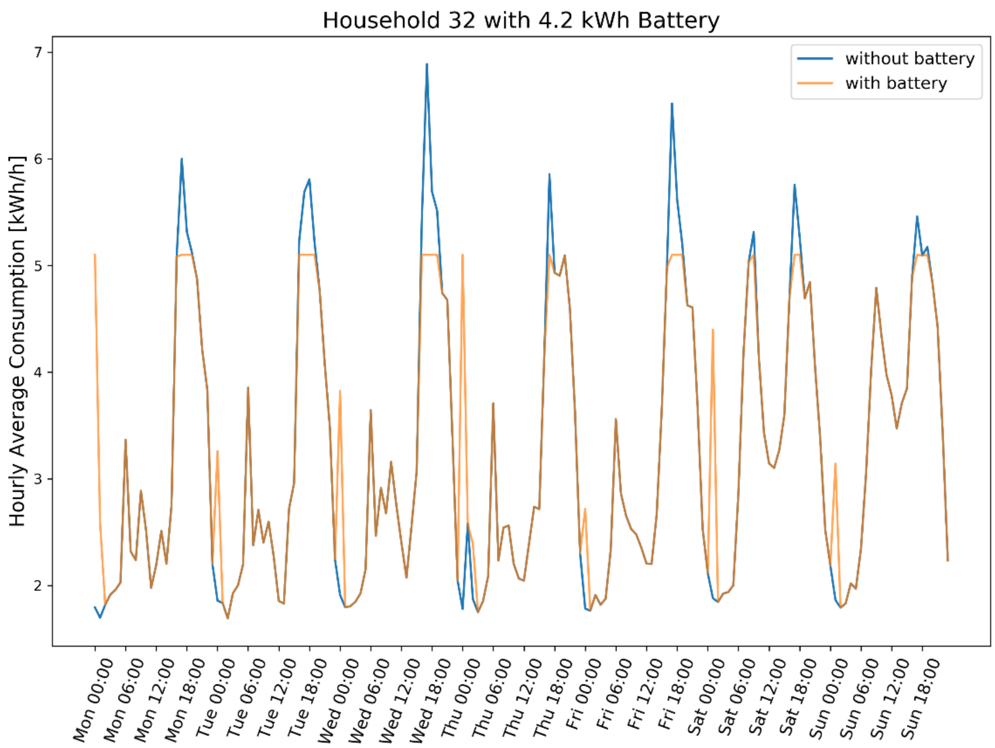


Figure 4.8: Hourly energy consumption for household 32. With a 4.2 kWh battery, the peaks are shaved down to 5.1 kWh/h, which translates to a peak reduction of 0.4-1.8 kWh.

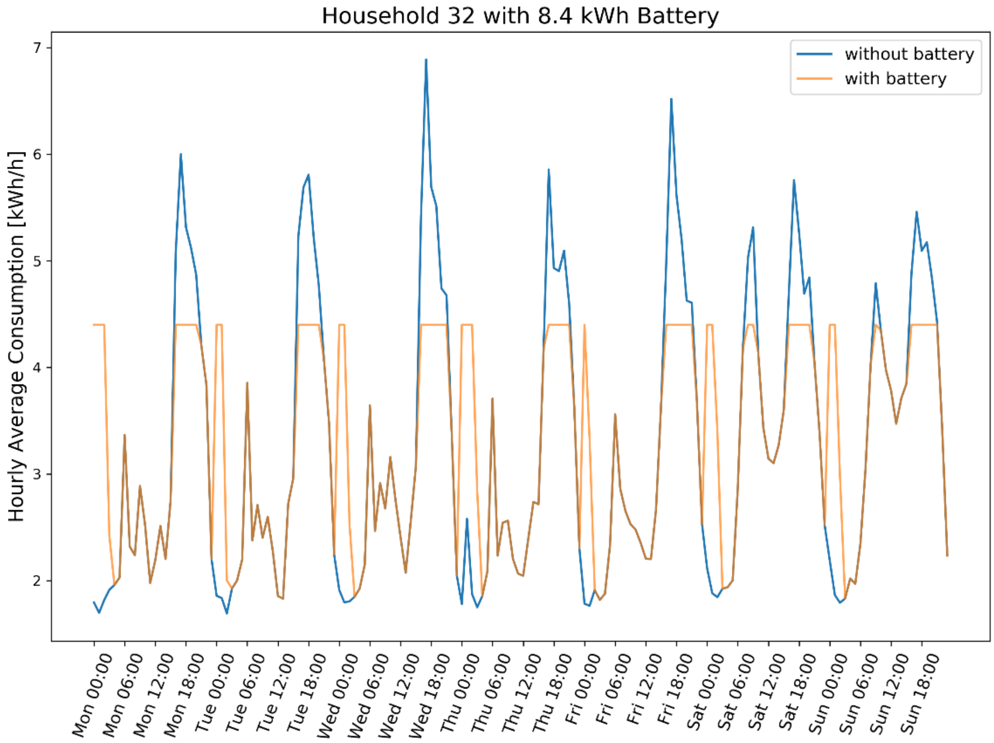


Figure 4.9: Hourly energy consumption for household 32 with an 8.4 kWh battery installed. The peaks are shaved down to 4.4 kWh/h, which is 0.7 kWh/h more than with a 4.2 kWh battery.

For household 1, the hourly consumption varies between 3.2 and 4.4 kWh/h. Thus, the consumption is significantly more even than household 32's consumption. As shown in Figures 4.10 and 4.11, the peak reduction with batteries is below 0.4 kWh/h, and the 8.4 kWh battery is not able to shave more than the 4.2 kWh battery. With a 4.2 kWh battery, the battery charges to 100 % SOC every night from Tuesday and never discharges further than 30 % SOC. The 8.4 kWh battery is not fully charged before Friday but stays above 40 % SOC from Wednesday. The battery capacity graphs can be seen in Figures A.1 and A.2 in Appendix C. When attempted to reduce the peak with another 0.1 kWh, the battery is unable to maintain the defined limit throughout the week, and on Tuesday and Wednesday, there are peaks of 4.3 kWh/h and 4.2 kWh/h, respectively. In this case, the battery never reaches 100 % SOC during the week. This situation is illustrated in Figure 4.12.

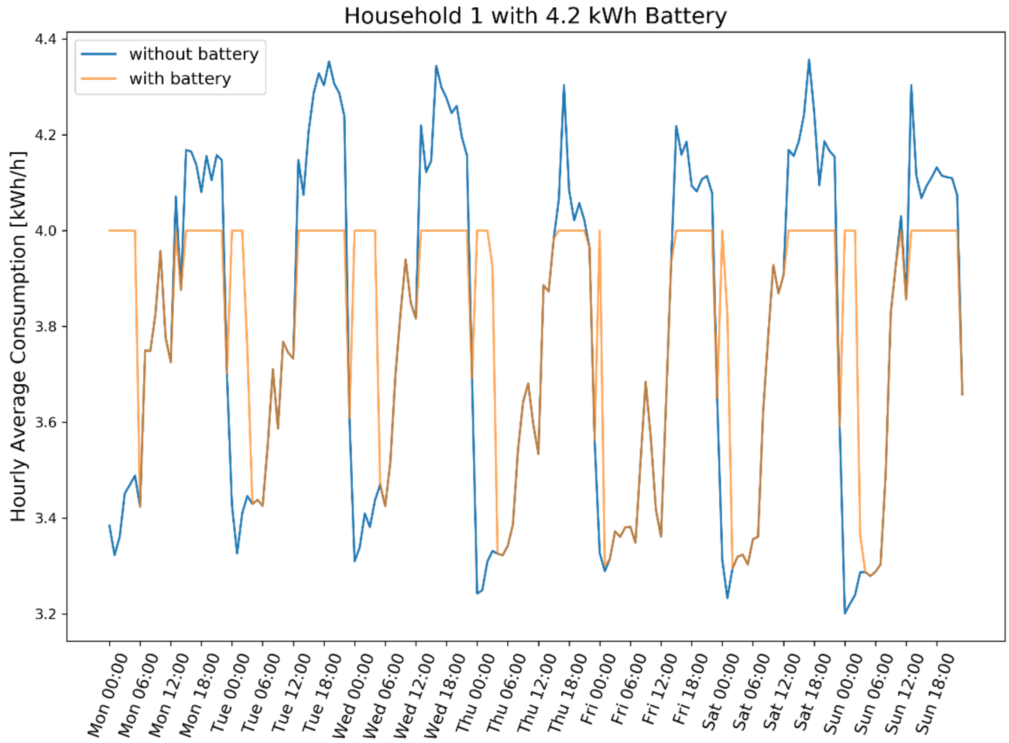


Figure 4.10: Hourly energy consumption for household 1. With a 4.2 kWh battery, the peaks are shaved down to 4.0 kWh/h.

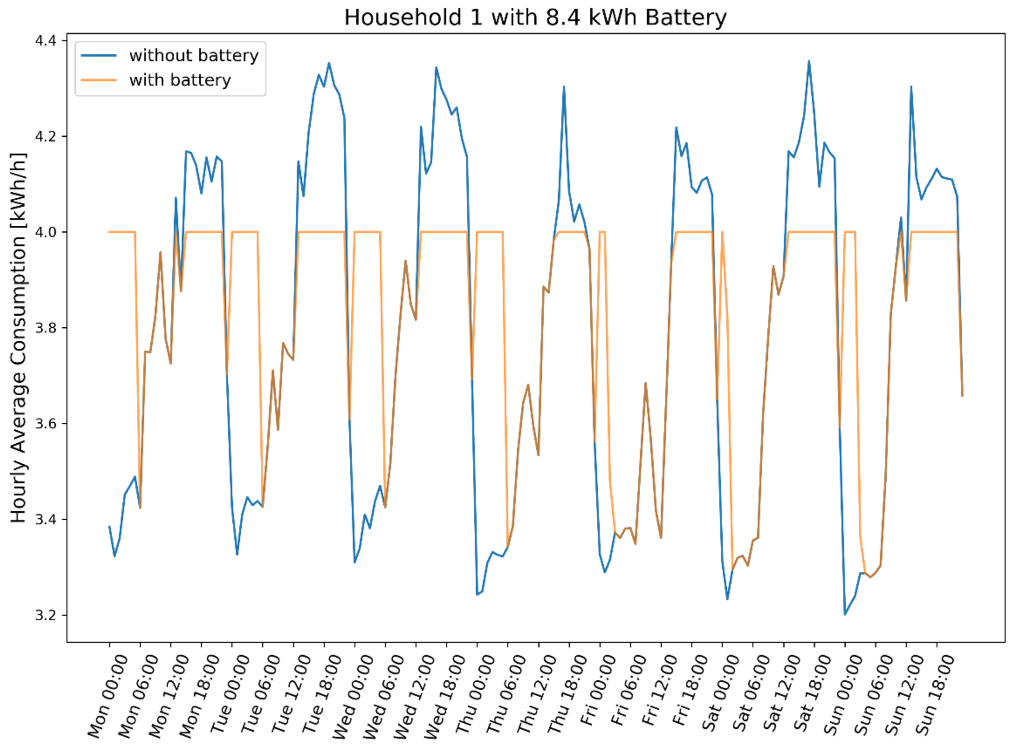
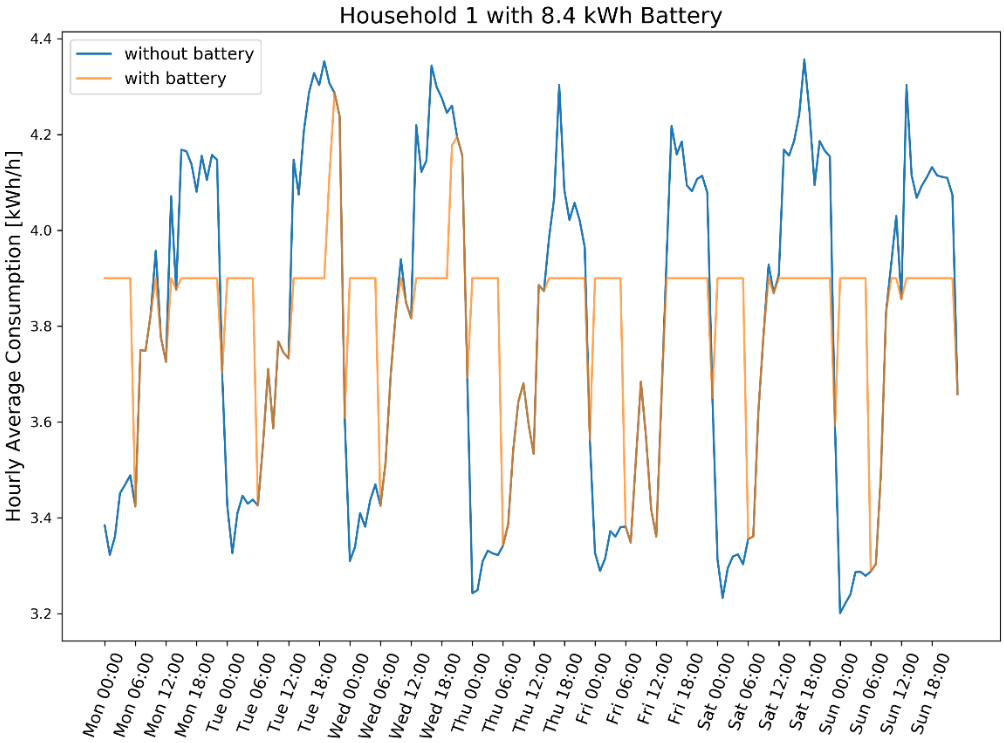


Figure 4.11: Hourly energy consumption for household 1 with an 8.4 kWh battery. It shaves the same amount as the 4.2 kWh battery.



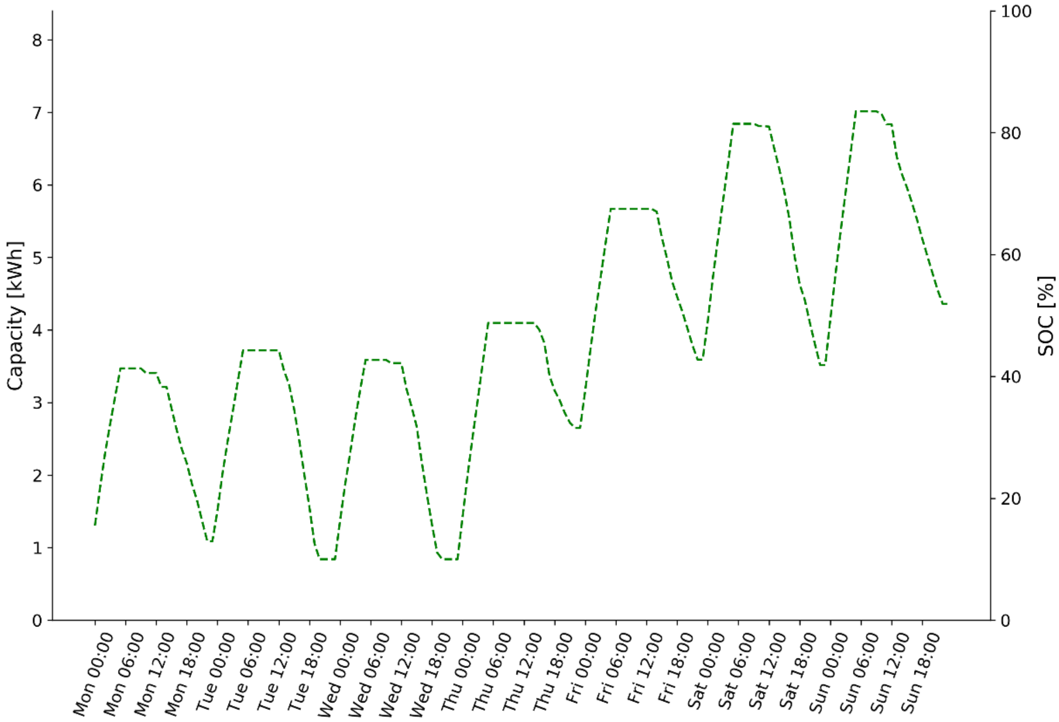


Figure 4.12: The upper graph shows the hourly energy consumption with an 8.4 kWh battery when attempting to peak shave down to 3.9 kWh/h, which is 0.1 kWh/h more than the battery has been shown to accomplish. The battery is unable to shave all the peaks to the defined limit, resulting in unshaved peaks on Tuesday and Wednesday. The corresponding battery capacity graph is illustrated below, showing that the battery never reaches a SOC of 100 % during the week.

The pattern of household 19 is shifted somewhat in comparison with the other two households. It has its peaks at 6 or 7 in the mornings, depending on it being a weekday or weekend. However, the consumption increases to above 3.0 kWh at 4 or 5 at night. The batteries are not able to reduce the peaks down to the limit, but the peaks are shifted one hour to the left and is reduced to the pre-existing value at that time. The smaller peaks during the day are reduced to the limit. Capacity-wise, the battery never goes below 30 % SOC. The hourly consumption and the corresponding battery capacity are demonstrated in Figure 4.13.

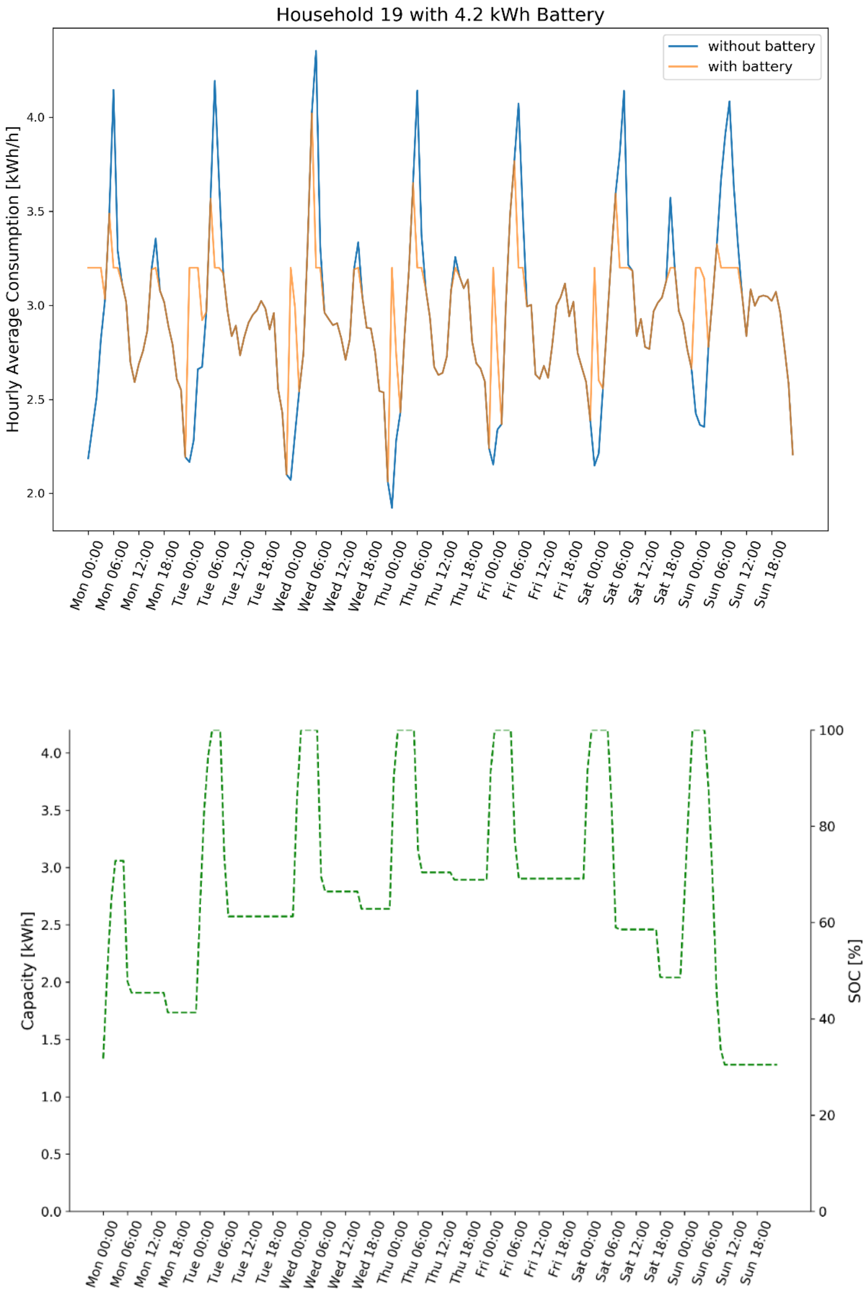


Figure 4.13: The hourly average consumption and battery capacity curve for household 19 with a 4.2 kWh battery installed. The battery is unable to peak shave down to the defined limit, even though the battery never reaches its lower capacity limit.

The average effect on the weekly winter consumption at the substation of installing batteries of 4.2 kWh and 8.4 kWh in every household are shown in Figures 4.14 and 4.15, respectively. With 4.2 kWh batteries, the highest daily peaks are reduced with 4-7 kWh/h, from 171-179 kWh/h to 166-172 kWh/h. At the same time, the previous lowest points increase with a similar amount, and 160-163 kWh-spikes occur when the battery charges at night. For the case with 8.4 kWh batteries, the total consumption curve changes noticeably, with a reduction of 7-11 kWh/h of the highest daily peaks, from 171-179 kWh/h to 164-169 kWh/h, and the previous bottoms now reaching values close to the new peaks.

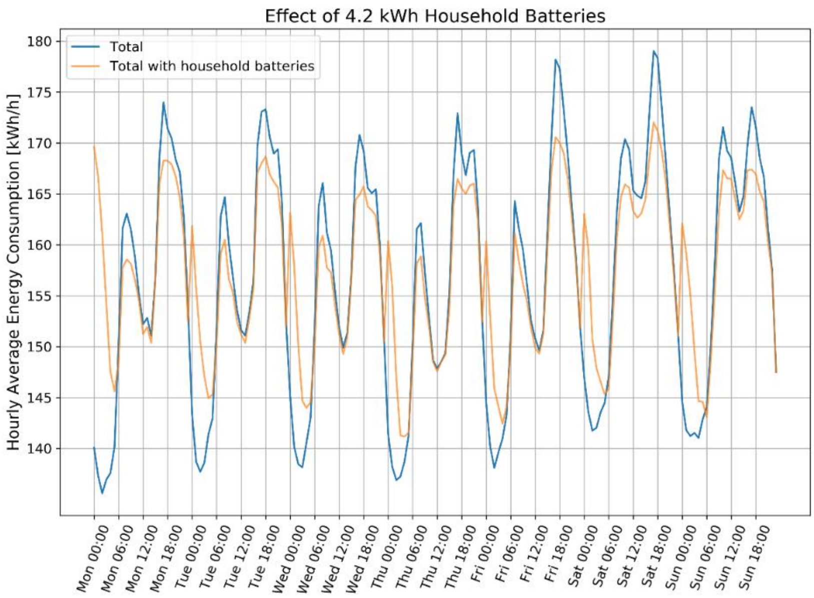


Figure 4.14: The effect of 4.2 kWh household batteries in every household on the total consumption.

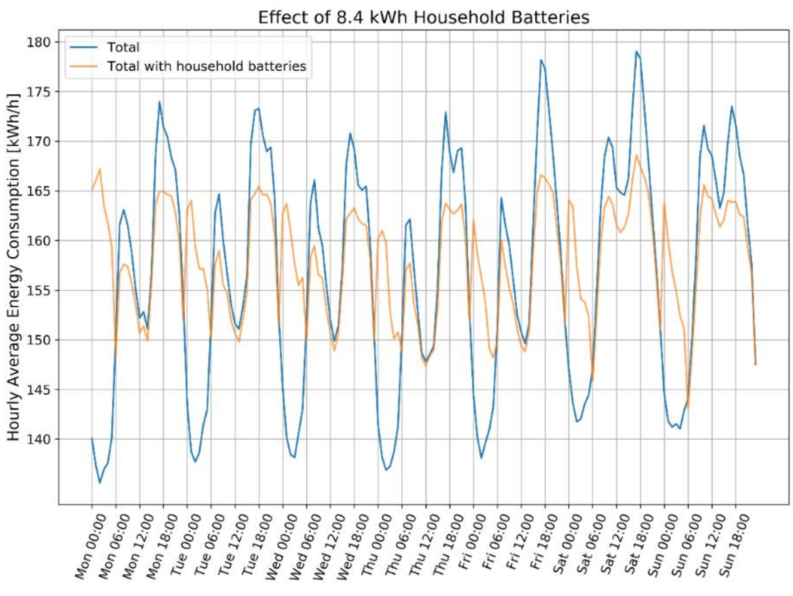


Figure 4.15: The effect of 8.4 kWh household batteries in every household on the total consumption.

Figure 4.16 displays the duration curves for the substation with and without household batteries during an average winter week. Without household batteries, the substation is supplying above 150 kWh 70 % of the time and above 170 kWh 10 % of the time. With batteries, the curve gets more horizontal. With 4.2 kWh household batteries, it must supply over 150 kWh 75 % of the time and over 170 kWh 1-2 % of the time. The trend of flattening the duration curve continues with the 8.4 kWh household batteries, where the substation must deliver above 150 kWh 85-90 % of the time and above 170 kWh 0 % of the time.

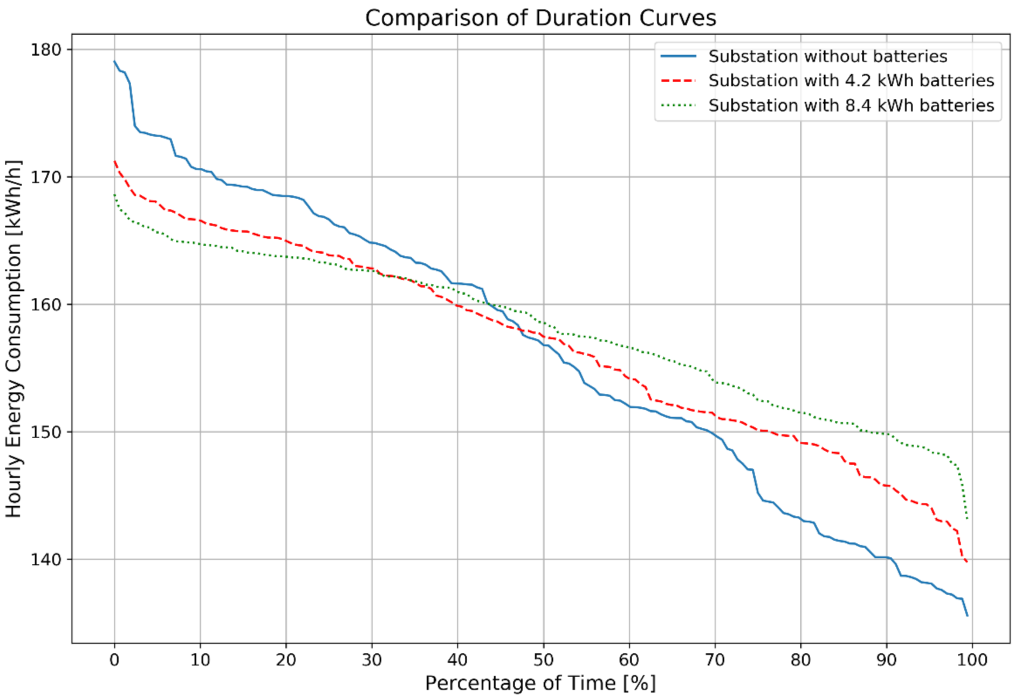


Figure 4.16: Duration curve with and without household batteries during an average winter week.

4.3.3 Case 2: Battery at Substation

The use of one larger battery for peak shaving at the substation was also examined. Two different battery sizes were considered. One based on the xStorage Buildings battery located at the Bislett Stadium and one chosen arbitrarily.

With a 109 kWh battery, as the one at Bislett Stadium, the peaks can be reduced to 164 kWh/h. At the maximum, this translates to a reduction of 7-15 kWh/h off the highest daily peaks. The values below 164 kWh/h is unchanged. 50 % or less of the battery's capacity is used during the weekdays, while close to 80 % of the battery's capacity is used on Saturdays and 60 % on

Sundays. This is illustrated in Figure 4.17. With a battery of 350 kWh, the energy consumption is reduced to 153 kWh/h. The highest daily peaks are decreased with 18-26 kWh/h. The battery uses 50 % of its capacity during weekdays, close to 80 % on Saturdays and Sundays. The peak shaving and battery capacity of the 350 kWh battery is illustrated in Figure 4.18.

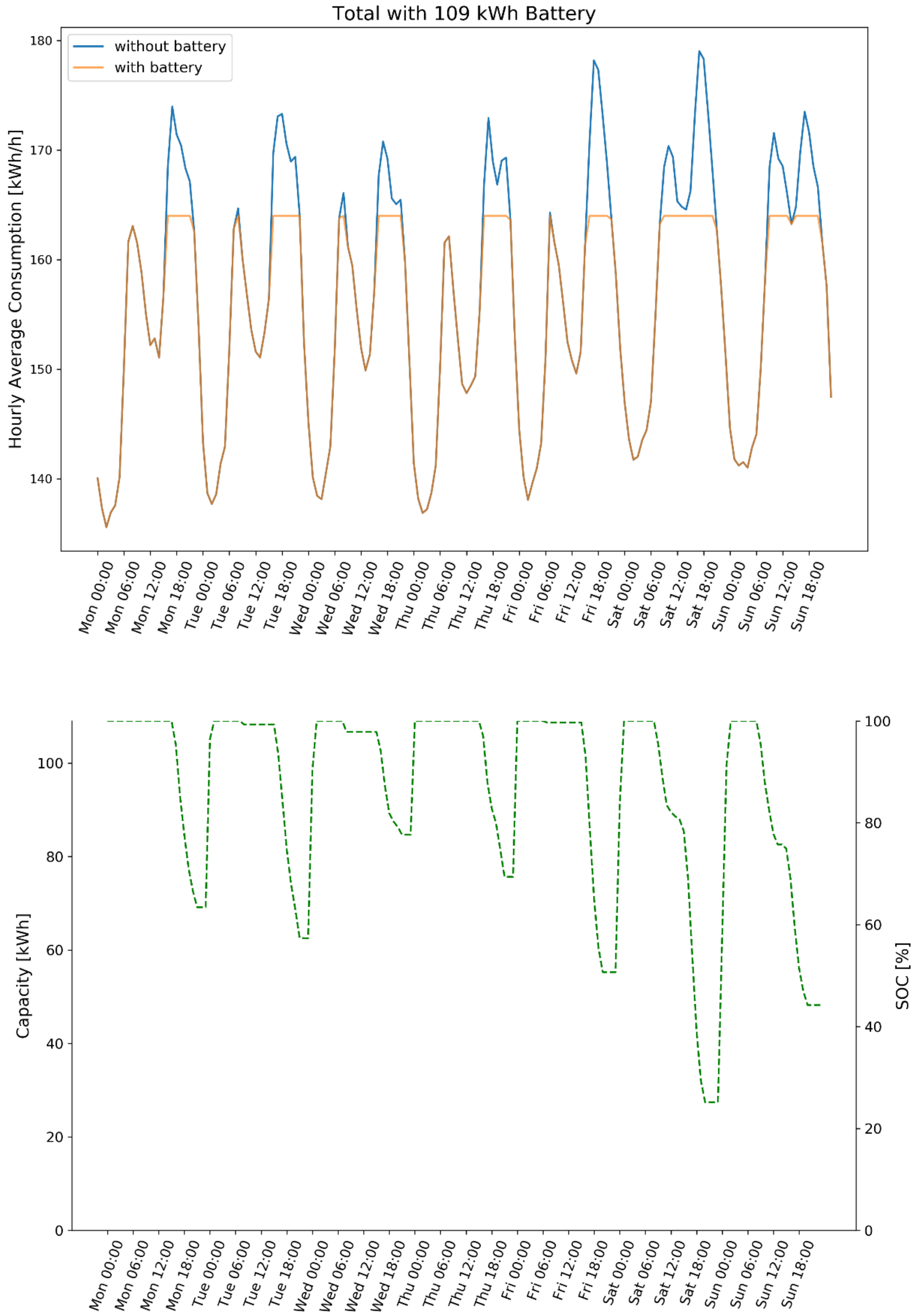


Figure 4.17: The hourly average consumption and battery capacity curve for the substation with a 109 kWh battery installed. A 109 kWh battery can peak shave down to 164 kWh/h, which translates to a daily peak reduction of 7-15 kWh/h.

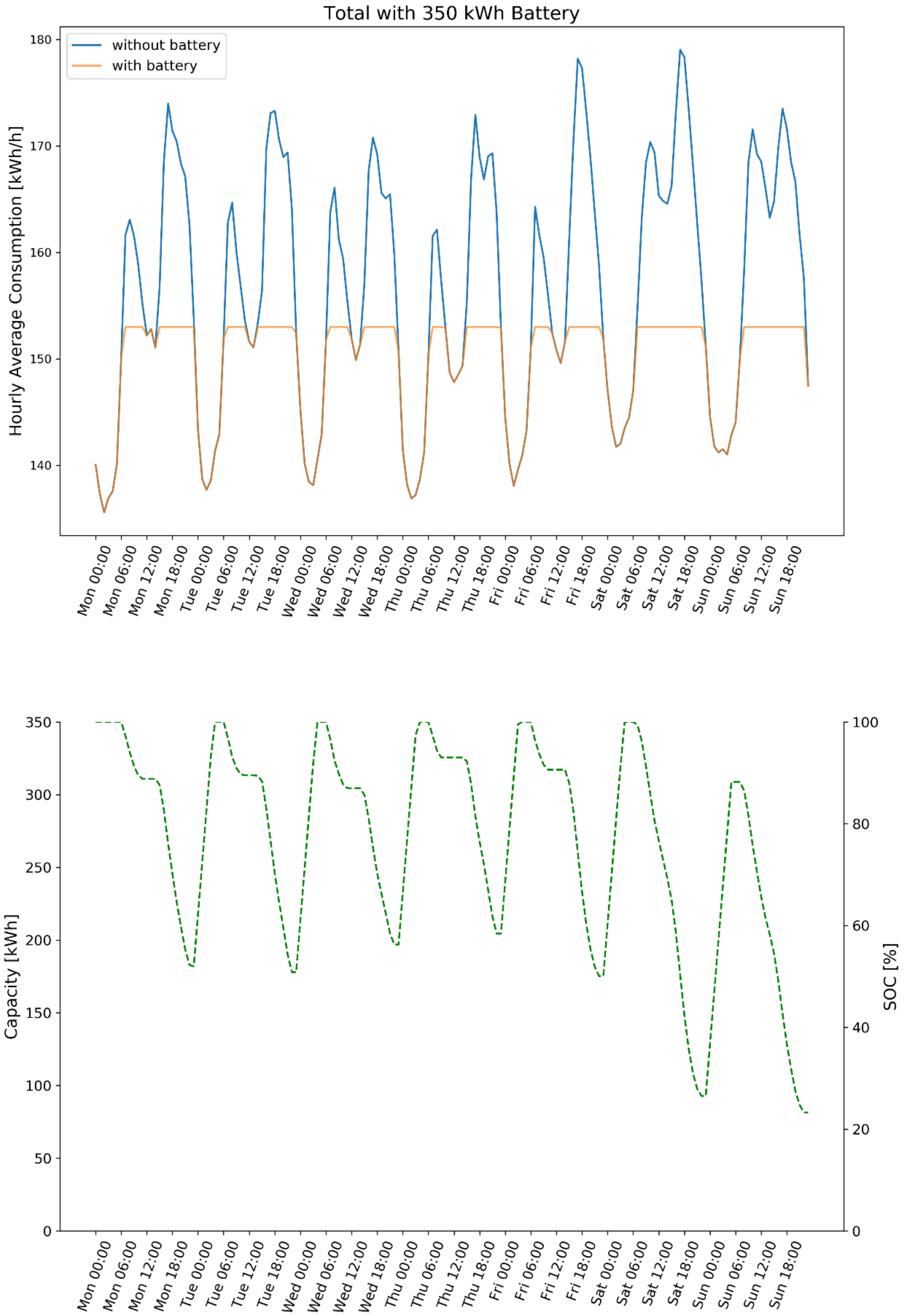


Figure 4.18: The hourly average consumption and battery capacity curve for the substation with a 350 kWh battery installed. The 350 kWh battery can shave the peaks down to 153 kWh/h - a reduction of 18-26 kWh/h off of the highest daily peaks.

4.3.4 Cost

The average of the three highest daily peaks, energy consumption per month, the power component cost and energy component cost of the grid rental fee for households 1 and 32 are shown for winter and summer in Tables 4.2 and 4.3, respectively. The component costs were calculated by using Equations 4.3 and 4.4, and the prices shown for the grid rental fee at Hvaler in Table 4.1. Tables 4.2 and 4.3 show that the energy requirement increases with 26-48 kWh/month when 8.4 kWh batteries are installed in the households, which increases the energy component cost by 6-13 NOK/month. The power component cost difference is largest for household 32 during winter, with a reduction of 160 NOK/month with an 8.4 kWh battery. Household 1 reduces the power component cost by 30 NOK/month in summer and winter.

Table 4.2: Average value of the three highest daily peaks, monthly energy consumption, and monthly power and energy component cost in the winter months for households 1 and 32.

Winter	*Highest Peaks Average [kW]*	*Energy Consumption [kWh/month]*	*Power Component Cost [NOK/month]*	*Energy Component Cost [NOK/month]*
Household 32				
Without battery	6.5	2353	495	651
4.2 kWh battery	5.1	2379	388	658
8.4 kWh battery	4.4	2401	335	664
Household 1				
Without battery	4.4	2747	335	760
4.2 kWh battery	4.0	2769	305	766
8.4 kWh battery	4.0	2791	305	772

Table 4.3: Average value of the three highest daily peaks, monthly energy consumption, and monthly power and energy component cost in the summer months for households 1 and 32.

Summer	*Highest Peaks Average [kW]*	*Energy Consumption [kWh/month]*	*Power Component Cost [NOK/month]*	*Energy Component Cost [NOK/month]*
Household 32				
Without battery	2.7	1200	206	310
4.2 kWh battery	2.1	1213	160	313
8.4 kWh battery	1.9	1226	145	316

Household 1				
Without battery	2.3	1205	175	311
4.2 kWh battery	1.9	1222	145	315
8.4 kWh battery	1.9	1239	145	320

Through Equation 4.2, the yearly total grid rental fees were calculated. The yearly electricity cost was found through Equations 4.5 and 4.6. The results are displayed in Table 4.4 and reveal that the amount saved per year on the total electricity cost is highest for household 32 with an 8.4 kWh battery. In this situation, 1056 NOK/year is saved compared to not having a battery. If household 32 were to install a 4.2 kWh battery, the amount saved per year would be 780 NOK. For household 1, the numbers are 48 and 222 NOK/year, respectively. Household 32 would have the shortest payback time according to Equation 2.13, with 52 years for the 4.2 kWh battery system.

Table 4.4: Yearly grid rental fee, yearly electricity cost, yearly total, and amount saved on the battery system for households 1 and 32.

	Yearly Grid Rental Fee [NOK/year]	*Yearly Electricity Cost [NOK/year]*	*Yearly Total [NOK/year]*	*Amount Saved [NOK/year]*
Household 32				
Without battery	10781	11070	21851	0
4.2 kWh battery	9923	11148	21071	780
8.4 kWh battery	9569	11226	20795	1056
Household 1				
Without battery	10295	12318	22613	0
4.2 kWh battery	9995	12396	22391	222
8.4 kWh battery	10061	12504	22565	48

4.4 Discussion

4.4.1 Energy Consumption

As expected, there are large seasonal variations in the daily total energy consumption, with a consumption of around 3200 kWh more during winter than during summer. This means the peak shaving potential is larger during the winter months. Since the cabins and businesses only contribute with around 500 kWh each, peak shaving at these consumers would likely not have the largest effect on the amount of energy the substation must deliver. Still, these consumers might be able to shave an adequate amount off the total daily consumption at a lower cost than household batteries, if smaller batteries can be used efficiently due to their lower energy usage. In this use case, however, household batteries were chosen due to their larger peak shaving potential.

During the winter months, there is a clear daily pattern to the consumption. It follows the traditional energy use pattern, where the lowest consumption occurs during the night, followed by a peak in the morning, lower consumption during the day, and another peak in the afternoon. Based on this, it should be possible to shave consumption peaks or to level out the load by charging at night and discharging during the day.

4.4.2 Case 1: Household Batteries

The utilization of energy varies with the households, with average hourly values between approximately zero to above 8 kWh. In addition, the hourly variation is different from household to household. In household 32, the minimum value is below 2 kWh/h, while the maximum value is close to 7 kWh/h. The same numbers for household 1 are 3.2 kWh/h and 4.4 kWh/h, respectively. Household 32 shaves its highest peak from 6.9 kWh/h to 5.1 kWh/h with a 4.2 kWh battery and to 4.4 kWh/h with an 8.4 kWh battery. Household 1, on the other hand, shaves its highest peak from 4.4 kWh/h to 4.0 kWh/h with both batteries. This suggests that households with small variations in hourly energy consumption will be able to reduce their peaks considerably less than households with larger variations. Furthermore, there is no gain from increasing battery size in households with small fluctuations in their consumption. The reason seems to be that the difference between the peak and the desired consumption limit is so small that the amount of energy charged into the battery is not enough to charge the battery completely in the allotted time. This is supported by the battery capacity graph for an attempt to reduce to 3.9 kWh/h with an 8.4 kWh battery in Figure 4.12. It shows that the battery never fully charges. Moreover, the peaks generally last from around 12 to around 22 each day, which means that an increase in reduction of 0.1 kWh/h affects the battery's capacity noticeably.

In addition to varying average values, the times when the households draw power differs somewhat from household to household. Household 19 has its daily peaks earlier than household 1 or 32, leading to the battery not being able to peak shave completely. Since the 4.2 kWh battery of household 19 never reaches its lower capacity discharge limit, it is likely that it would be able to peak shave more of the consumption, had it not been for the battery only being allowed to discharge between 06:00 and 23:00. In addition, the household's energy use declines between 18:00 and 00:00, meaning that it could use this time to charge the battery if needed. Being able to charge more than once a day and at times suited to its consumption might lead to a larger reduction in consumption and more efficient use of the battery's capacity. Also, in this algorithm, one decimal accuracy was chosen, meaning that the battery might be able to shave more if this was not a constraint. The battery capacity curves for the different households show that the battery generally reaches its lower discharge limit 1-2 times per week, meaning that there is unused capacity for the rest of the week. This means that individual algorithms with higher resolution accuracy should be developed according to each household's energy use, to maximize peak shaving.

With batteries in every household, 4.2 kWh batteries reduce the highest peaks of total consumption at the substation with 4-7 kWh/h and 8.4 kWh batteries with 7-11 kWh/h. Since the energy capacity of the battery doubles, one could expect that the reduction would also double. However, this is not the case because some of the households did not increase their reduction in consumption when increasing battery size and double the size does not necessarily mean double the reduction, as seen above. This suggests that individual sizing of batteries is needed for every household to maximize the effect and minimize the cost.

Since household 1 shaves the same amount its consumption with double the battery capacity, it would make no sense investing in an 8.4 kWh battery system. The 4.2 kWh battery system is not profitable either. In fact, with it saving a mere 222 NOK/year, it seems one can conclude that a battery system no matter the size for this household would be an unprofitable undertaking. Household 32 saves more money on its systems but bearing in mind that the most cost-effective solution has a payback time of over 50 years and the fact that the battery system only has a guaranteed lifespan of 5 years (as stated in Appendix A), the investment cost of the battery is simply too high to be an attractive option today.

The power component in the grid rental fee is where the money is saved. Considering that this component is priced according to the highest monthly peaks, the deciding factor of how much one can save is how much the batteries can shave off the highest peaks and how high the power component price is. If another of the proposed grid rental fee models are chosen, however, fuse size or average power consumption will play a larger role. Since the DSO in the Hvaler-area includes a power tariff in the grid rental fee already, it seems unlikely that this cost will change considerably in the next few years. The energy component of the grid rental fee and the electricity cost is higher for the cases with batteries, even though the batteries are charged at night when the spot price for electricity is lower. This is likely due to the higher overall energy consumption when batteries are used and the relatively small difference in spot price throughout the day. As the linking of European power systems continue, this is expected to change to larger variations, meaning that there might be more money to save on charging at low-priced times in the future. Either way, it seems the battery price must be reduced significantly for these systems to be feasible in the future.

In a substation perspective, the peak shaving achieved with household batteries might not seem substantial. This substation was never operating above capacity, but in a given scenario where it was and assuming a power factor of unity, the capacity could not have been above 172 kVA for the 4.2 kWh battery case and 169 kVA for the 8.4 kWh battery case for it to always be able to reduce peaks down to or below substation capacity. During the winter months, the hourly total energy use is above 172 kWh/h 7 % of the time and above 169 kWh/h 16 % of the time, meaning that it might offer some support. Nevertheless, this solution would be too expensive in comparison to upgrading the substation if the DSO was to cover the cost of the household batteries. If every household were to have 4.2 kWh batteries, the total cost would be 1 400 000 NOK, compared to a cost of 200 000-500 000 NOK for a substation upgrade [120]. However, since it seems DSOs will not be allowed to own grid-connected batteries in the future, the household owners would have to cover this cost themselves. If so, the DSO would benefit.

The duration curve for the winter week clearly flattens when batteries are introduced. This is due to the increased hourly consumption at night when the batteries are charged. This increase is not a problem, as the substation is working below capacity, but in a hypothetical case where it was close to capacity or above capacity, this increase could lead to the substation working above capacity more of the time than before batteries were installed if the capacity was low enough. In this case, a capacity of 150 kVA would be exceeded 70 % of the time without batteries and 90 % of the time with 8.2 kWh household batteries. If the capacity was 165 kVA, it would be exceeded 30 % at the time without batteries and 7-20 % of the time with batteries, meaning that there exists a limit where batteries start reducing time above capacity. Because larger batteries need more time to charge, it is reasonable to assume that larger batteries would flatten the curve even further, which is supported by the curves of the 4.2 kWh battery case and the 8.4 kWh battery case. If the battery cannot charge above a given limit, this means that household batteries cannot be infinitely large if the goal is to keep substations below capacity.

4.4.3 Case 2: Substation Battery

For the battery simulation at the substation, a battery size of 109 kWh shaves between 7 kWh/h and 15 kWh/h off the highest daily peaks, which is a little more than what the 8.4 kWh household batteries can deliver. With a combined energy capacity of 294 kWh for the 35 households, it is clear that for peak shaving of the total consumption, a battery connected directly to the substation is more efficient, being a third of the size and still being able to outperform the 35 household batteries. Furthermore, based on the review of second-life battery costs in Section 3.6, the cost is considerably lower. If one assumes that the second-life battery selling price is 3000 NOK/kWh, the battery cost would be 327 000 NOK. Thus, it could be an option to upgrading the substation, given that the installation, operation and maintenance costs were low enough. However, considering that the expected lifespan for second-life batteries in most applications ranges from 4-11 years [98, 103], a substation upgrade would likely have a much longer lifespan. Another factor to examine is the effects of the upstream charging. Since the battery is charged upstream of the substation, components there could be influenced or even overloaded. Therefore, an analysis of the load and capacity of the different components are needed before deciding where such a battery should be located.

Increasing the size of the battery at the substation increases the peak shaving capabilities of the battery. With a 350 kWh battery at the substation, the highest daily peaks are reduced between 18 kWh/h and 26 kWh/h. This reduction is notable and suggests that substation batteries could be used as an alternative to upgrading the station. As Section 3.5.4 shows, larger systems than this is already operational [98, 100], meaning that the size is not an issue. Yet, the costs must be discussed. If one assumes the same battery price as for the 109 kWh battery, the battery price would amount to 1 050 000 NOK, meaning that this battery would only be an option if the cost per kWh is substantially reduced for larger systems.

Investigating the battery capacity curves of the substation batteries, one can clearly see that the use of the battery varies during the week, as expected when compared with the weekly consumption. The batteries discharge close to the lower capacity limit during the weekend, while the SOC stays on or above 50 % the rest of the week. This means that the highest consumption during the week, in this case the weekend consumption, is the limiting factor for the battery's overall peak shaving capabilities. On the plus side, the shallower cycles will most likely lead to an increase in cycle life, meaning that the overall energy stored and delivered might end up being higher than it would have if it discharged to the lower capacity limit each day.

4.4.4 Assumptions and Limitations

The midnight hour was assigned to the date it turns into at midnight. However, since the value corresponds to the energy consumed in the previous hour, from 23:00 to 00:00, this value does belong to the previous date. This means that the calculated daily values are not completely correct, but assuming the midnight values are similar from one day to the other, the discrepancy is expected to be small enough to show trends in a satisfactory way.

Since the data is given in hourly values, it was assumed that the power was the same value throughout the hour. This is highly unlikely and might have led to discrepancies between actual values and the ones used. This means that the consumption could have been higher or lower than assumed at each instant. That could have influenced the charging and discharging of the batteries, in addition to the duration and consumption curves. It could also mean that the batteries are unable to peak shave as much as is shown in these simulations. The effect of higher resolution has been seen in a Norwegian demo, where they found peaks of 8 kW with 10-second resolution. With 1-hour resolution the peaks were between 2.5 and 5 kW [121]. Thus, in further simulations, data with higher resolution should be used.

Average hourly energy consumption values are used in calculations. Comparing the substation duration curve that includes all the individual values with the winter substation duration curve using average values, one can see that the highest values have disappeared. It is likely that the highest values occurred during winter, meaning that the peaks of some months are higher than those used in calculations. For these months, the amount of money saved might be underestimated. At the same time, the battery might not be able to shave higher peaks, and thus shave less overall, meaning that this part might be overestimated. In addition, averages were made from six months of the year in total, three months for winter, and three months for summer, meaning that spring and autumn values are disregarded. However, since the energy use values in autumn and spring rise and fall sharply and winter values and summer values are generally more evenly distributed, it seems likely that by assuming winter averages one half of the year and summer values in another half of the year, the values will even each other out and simulate an entire year satisfactorily. The same method was used when finding the spot prices, meaning that the prices could have been both higher and lower than the values used, but again the approximation was assumed to be satisfactory. To get an accurate answer, simulations with individual values throughout the year should be executed.

The simulations are only run with the initial SOH, which means that aging is not considered. The battery will age, leading to lower peak shaving capabilities over the years. This means that the battery may not be able to perform its task satisfactorily after a few years and that the lifespan is uncertain. Thus, a degradation model should be included in further simulations.

5 Conclusion and Further Research

This thesis sought to investigate if second-life battery systems have a future in the Norwegian power system. Numerous factors, many interdependent, influence the answer to this question, making it a very complex mission. Thus, the task was divided into sub-questions, which focused on the following factors: suitability, costs, availability, laws and regulations, and repurposing. A literature review and an in-depth use case were conducted. In short, it seems second-life battery systems could have a future in the Norwegian Power System, given the right conditions and developments. However, most factors indicate that the systems will likely not be viable until 2025 at the earliest.

The energy capacity is not an issue at the beginning of a second life for the electric vehicle battery. How it performs over time is more uncertain, as the aging of the Li-ion cell is dependent on several factors, including temperature, cycle depth, charge- and discharge rates, chemistry, and state-of-charge. Certain conditions have proven favorable, but since most aging studies have a first-life perspective, further studies regarding second-life aging are needed.

With the wide range of capabilities second-life systems offer, they could, in theory, be used in many applications. This is largely confirmed by suppliers of second-life battery systems and projects using such systems in a wide array of applications, including self-consumption in households, EV-charging, frequency regulation, balancing the grid, backup power, renewable energy integration, and peak shaving [78, 83, 88, 100, 101]. However, the lifespan depends on the application [103], which could make the second-life battery systems more suitable in some implementations. The array of projects and suppliers could increase the experience level and answer questions about technical viability, aging, and lifespans in the next few years, but openness is required to accelerate the process.

Currently, the volumes of batteries available for repurposing are low – a few thousand batteries at most [77], but larger quantities should be available from 2025-2030, depending on the first-life lifespan. Norwegian laws and regulations state that all the vehicles and 95 % of the batteries must be collected at the end of their lifespan [75], which means that few electric vehicle batteries will disappear from the supply.

One recycling company for electric vehicle batteries exist in Norway – Batteriretur. They are gaining valuable experience in repurposing and reusing batteries and have developed a repurposing process [77]. This process must be further developed as more batteries will be end-of-life batteries in the future. Another challenge in the repurposing process is unclear laws and regulations regarding the handling of electric vehicle batteries. Guidelines and updated regulations should be put in place to ensure safety.

The cost is currently a challenge for second-life battery systems. The selling price is dependent on the repurposing cost, which seems to be undetermined for Norwegian conditions. In the US, studies suggested a refurbishing cost of 180-1580 NOK/kWh [105-108]. Transportation, handling time, battery price, battery volume, and fault rates were considered important factors [105, 106]. Due to low volumes of batteries and higher staff wages, it seems likely that the refurbishing cost is currently higher in Norway. However, the rapidly decreasing electric vehicle battery price [14], increasing battery volumes and experience level, and automated processes could make the cost competitive within the decade.

What selling price is feasible depends on the application. Frequency regulation services and balancing services could be profitable today. For industrial peak shaving applications, the feasibility is currently more uncertain, and likely not profitable. Current electric vehicle battery price trends could make it increasingly feasible within this decade if repurposing costs can be kept low. An implementation where it seems unlikely that a second-life battery system will be realizable soon is in wind energy plant services. Residential applications also seem to be an unprofitable undertaking, unless electricity prices increase rapidly and the battery selling price decrease to below 1150 NOK/kWh [111]. Nevertheless, it was examined further in the use case.

The use case considered the utilization of second-life battery systems for peak shaving in south-eastern Norway. The implementation was examined for a substation and the households connected to it. A household with considerable peak shaving potential would have a payback time of at least 50 years for an Eaton xStorage Home battery system. The reason is the high cost of the battery system – over 9500 NOK/kWh [78], including inverter, and low electricity prices, thus confirming the preliminary conclusion of residential applications.

Substation peak shaving could be achieved by an on-site battery or by using the aggregated effect of the household batteries. An on-site battery proved to be both more efficient and more economically feasible, but not necessarily a better option than substation upgrades. However, peak shaving services would probably have to be bought by a third party, since DSOs most likely cannot own batteries in the future.

For the individual households, the effectiveness depended on the consumption. It was shown that larger variations in daily energy use led to more efficient peak shaving, meaning that such households had more to gain from installing battery systems. Also, an increase in battery size did not lead to a proportional increase in peak reduction for a household with little variation in daily consumption. Thus, individual sizing is crucial. Furthermore, the battery management system must be adapted to each household's use of energy to maximize peak shaving.

In conclusion, it is not possible to predict the future of second-life batteries with absolute certainty today, as the idea of using electric vehicle batteries in other applications is relatively new. Thus, the experience is limited, and the systems in their infancy. However, the research does suggest that the main obstacles currently seem to be the need for more knowledge regarding aging and lifespans, a lack of cost estimations in the Norwegian market – especially considering the repurposing and insufficient regulations and guidelines concerning the handling of electric vehicle batteries. Thus, further research should focus on gathering experiences from projects and suppliers, in addition to performing individual studies of the use of second-life battery systems in different applications. Constructed scenarios can be simulated, but the level of certainty would increase by using an experimental approach. Guidelines for repurposing should be further developed and the costs identified. Ideally, different repurposing strategies for the Norwegian market and the costs in these scenarios should be outlined and then tested in real operation. Research focusing on the economic feasibility of used electric vehicle batteries in different power system applications could shed light on specific economic constraints. Cost estimates of ongoing or finished Norwegian projects would be of high value.

The use case could also be improved or developed further. Improvements could include making individual algorithms for each household, optimize the sizing of the batteries, and using data with higher resolution. One could also investigate the effects of aging and upstream charging and add components to the system. Such components could be PV-arrays, EV-chargers, or boilers. Another possibility is to examine how the household-sized batteries could be used for grid services if a third party owned them.

Bibliography

[1] "*Paris Agreement*," European Commission. Accessed: May 15, 2020. [Online]. Available: https://ec.europa.eu/clima/policies/international/negotiations/paris_en

[2] "*A European Green Deal*," European Commission. Accessed: May 15, 2020. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[3] "*Powerwall*," Tesla. Accessed: May 15, 2020. [Online]. Available: https://www.tesla.com/powerwall

[4] "*Introducing Megapack: Utility-Scale Energy Storage* " Tesla, July 29, 2010. Accessed: May 15, 2020. [Online]. Available: https://www.tesla.com/blog/introducing-megapack-utility-scale-energy-storage

[5] J. Leadbetter and L. G. Swan, "Selection of battery technology to support grid-integrated renewable electricity," *Journal of Power Sources*, vol. 216, pp. 376-386, 2012, doi: https://doi.org/10.1016/j.jpowsour.2012.05.081.

[6] J. Leadbetter and L. Swan, "Battery storage system for residential electricity peak demand shaving," *Energy & Buildings*, vol. 55, pp. 685-692, 2012, doi: https://doi.org/10.1016/j.enbuild.2012.09.035.

[7] E. L. Ratnam, S. R. Weller, and C. M. Kellett, "An optimization-based approach to scheduling residential battery storage with solar PV: Assessing customer benefit," *Renewable Energy*, vol. 75, pp. 123-134, 2015, doi: https://doi.org/10.1016/j.renene.2014.09.008.

[8] M. Arifujjaman, "A comprehensive power loss, efficiency, reliability and cost calculation of a 1 MW/500 kWh battery based energy storage system for frequency regulation application," *Renewable Energy*, vol. 74, pp. 158-169, 2015, doi: https://doi.org/10.1016/j.renene.2014.07.046.

[9] "*IntegER - Integration of energy storage in the distribution grid*," SINTEF, 2017. Accessed: April 29, 2020. [Online]. Available: https://www.sintef.no/en/projects/integer-integration-of-energy-storage-in-the-distribution-grid/

[10] "*The INVADE project*," INVADE. Accessed: April 21, 2020. [Online]. Available: https://h2020invade.eu/the-project/

[11] J. R. Martinez-Bolanos, M. E. M. Udaeta, A. L. V. Gimenes, and V. O. d. Silva, "Economic feasibility of battery energy storage systems for replacing peak power

plants for commercial consumers under energy time of use tariffs," *Journal of Energy Storage,* vol. 29, p. 101373, 2020, doi: https://doi.org/10.1016/j.est.2020.101373.

[12] C. Yianni, M. Florides, S. Afxentis, V. Efthymiou, and G. E. Georghiou, "Economic viability of battery energy storage system applications," in *2018 IEEE International Energy Conference (ENERGYCON)*, 3-7 June, 2018, pp. 1-6, doi: 10.1109/ENERGYCON.2018.8398740.

[13] E. Hossain, D. Murtaugh, J. Mody, H. M. R. Faruque, M. S. H. Sunny, and N. Mohammad, "A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies," *IEEE Access,* vol. 7, pp. 73215-73252, 2019, doi: 10.1109/ACCESS.2019.2917859.

[14] C. McKerracher *et al.*, "*Electric Vehicle Outlook 2019*," BloombergNEF, 2019. Accessed: April 28, 2020. [Online]. Available: https://about.bnef.com/electric-vehicle-outlook/#toc-viewreport

[15] "*Elbilsalg*," Norsk elbilforening, 2019. Accessed: April 8, 2020. [Online]. Available: https://elbil.no/elbilstatistikk/elbilsalg/

[16] "*NordLink*," Statnett. Accessed: February 27, 2020. [Online]. Available: https://www.statnett.no/vare-prosjekter/mellomlandsforbindelser/nordlink/

[17] "*North Sea Link*," Statnett. Accessed: February 27, 2020. [Online]. Available: https://www.statnett.no/vare-prosjekter/mellomlandsforbindelser/north-sea-link/

[18] "*The Norwegian power system. Grid connection and licensing*," NVE, 2018. Accessed: February 19, 2020. [Online]. Available: http://publikasjoner.nve.no/faktaark/2018/faktaark2018_03.pdf

[19] A. v. Meier, *Electric Power Systems. A conceptual Introduction.* New Jersey: John Wiley & Sons, Inc., 2006.

[20] T. Wildi, *Electrical Machines, Drives and Power Systems*, 6th ed. New Jersey: Pearson Education, Inc., 2006.

[21] "*Tall og data fra kraftsystemet. Import og eksport*," Statnett. Accessed: February 27, 2020. [Online]. Available: https://www.statnett.no/for-aktorer-i-kraftbransjen/tall-og-data-fra-kraftsystemet/#nordisk-kraftbalanse

[22] G. Reid and J. Julve, "*Second Life-Batteries As Flexible Storage For Renewable Energies*," Bundesverbandes Erneuerbare Energie E.V. and Hannover Messe, 2016. Accessed: April 23, 2020. [Online]. Available: https://www.bee-

ev.de/fileadmin/Publikationen/Studien/201604_Second_Life-Batterien_als_flexible_Speicher.pdf

[23] G. Fitzgerald, J. Mandel, J. Morris, and H. Touati, "*The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid*," Rocky Mountain Institute, 2015. Accessed: April 23, 2020. [Online]. Available: https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf

[24] K. Buss, P. Wrobel, and C. Doetsch, "Global distribution of grid connected electrical energy storage systems," *International Journal of Sustainable Energy Planning and Management*, vol. 9, pp. 31-56, 2016, doi: 10.5278/ijsepm.2016.9.4.

[25] R. M. Dell and D. A. J. Rand, *Understanding Batteries*. Cambridge: The Royal Society of Chemistry, 2001.

[26] M. Yu, P. Hynan, A. v. Jouanne, and A. Yokochi, "Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements," *Energies*, vol. 12, no. 6, pp. 1074-1094, 2019, doi: 10.3390/en12061074.

[27] H. A. Kiehne, *Battery Technology Handbook*, 2nd ed. Renningen-Malsheim: Expert Verlag, 2003.

[28] S. J. An, J. Li, C. Daniel, D. Mohanty, S. Nagpure, and D. L. Wood, "The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling," *Carbon*, vol. 105, pp. 52-76, 2016, doi: 10.1016/j.carbon.2016.04.008.

[29] Y. Wang and H.-Y. Huang, "An Overview of Lithium-Ion Battery Cathode Materials," *MRS Proceedings*, vol. 1363, 2011, doi: 10.1557/opl.2011.1363.

[30] "*BU-402: What Is C-rate?*," Battery University, 2020. Accessed: February 17, 2020. [Online]. Available: https://batteryuniversity.com/index.php/learn/article/what_is_the_c_rate

[31] A. Jossen, "Energy Storage. Lecture notes," Technische Universität München, Compendium, April 24, 2019.

[32] "*BU-802b: What does Elevated Self-discharge Do?*," Battery University. Accessed: February 18, 2020. [Online]. Available: https://batteryuniversity.com/learn/article/elevating_self_discharge

[33] H. Hesse, M. Schimpe, D. Kucevic, and A. Jossen, "Lithium-Ion Battery Storage for the Grid-A Review of Stationary Battery Storage System Design Tailored for

Applications in Modern Power Grids," *Energies*, vol. 10, no. 12, p. 2107, 2017, doi: 10.3390/en10122107.

[34] M. Broussely *et al.*, "Main aging mechanisms in Li ion batteries," *Journal of Power Sources*, vol. 146, no. 1, pp. 90-96, 2005, doi: https://doi.org/10.1016/j.jpowsour.2005.03.172.

[35] "*Elektrisitetspriser*," Statistisk sentralbyrå (SSB), 2020. Accessed: February 21, 2020. [Online]. Available: https://www.ssb.no/elkraftpris

[36] L. Henden *et al.*, "*Batterier i bygg kan få betydning for det norske kraftsystemet*," NVE, 2017. Accessed: February 7, 2020. [Online]. Available: http://publikasjoner.nve.no/rapport/2017/rapport2017_66.pdf

[37] "*Historical Market Data*," Nord Pool, 2020. Accessed: February 24, 2020. [Online]. Available: https://www.nordpoolgroup.com/historical-market-data/

[38] A. B. Eriksen *et al.*, "*RME Høringsdokument. Nr 01/2020. Endringer i nettleiestrukturen*," NVE, 2020. Accessed: February 25, 2020. [Online]. Available: http://publikasjoner.nve.no/rme_hoeringsdokument/2020/rme_hoeringsdokument2020_01.pdf

[39] S. C. Bhattacharyya, *Energy Economics: Concepts, Issues, Markets and Governance*. London: Springer, 2011.

[40] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 569-596, 2015, doi: https://doi.org/10.1016/j.rser.2014.10.011.

[41] F. Baronti, M.-Y. Chow, C. Ma, H. Rahimi-Eichi, and R. Saletti, "E-transportation: the role of embedded systems in electric energy transfer from grid to vehicle," *EURASIP Journal on Embedded Systems*, vol. 2016, no. 1, p. 11, 2016, doi: 10.1186/s13639-016-0032-z.

[42] "*Technology*," Samsung SDI. Accessed: May 5, 2020. [Online]. Available: https://www.samsungsdi.com/column/all/detail/54344.html

[43] "*Nissan LEAF 24/30 kWh (2011-2017)*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/nissan-leaf/

[44] "*Nissan LEAF 40 kWh (2018)*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/nissan-leaf-40-kwh-2018/

[45] "*BMW i3 60Ah / 94Ah (2013-2018)*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/bmw-i3/

[46] "*BMW i3 / i3S 120Ah (2019)*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/bmw-i3-i3s-120ah-2019/

[47] "*Tesla Model S Standard Range (75, 2016-2019)*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/tesla-model-s-75-d/

[48] "*Tesla Model 3 Standard Range Plus*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/tesla-model-3-standard-range-plus/

[49] "*Volkswagen e-Golf*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/vw-e-golf/

[50] "*Audi e-tron 50 / 55 quattro*," Norsk elbilforening. Accessed: February 18, 2020. [Online]. Available: https://elbil.no/elbil/audi-e-tron-55-quattro/

[51] A. Barré, B. Deguilhem, S. Grolleau, M. Gérard, F. Suard, and D. Riu, "A review on lithium-ion battery ageing mechanisms and estimations for automotive applications," *Journal of Power Sources,* vol. 241, no. C, pp. 680-689, 2013, doi: 10.1016/j.jpowsour.2013.05.040.

[52] H. Buqa, A. Würsig, J. Vetter, M. E. Spahr, F. Krumeich, and P. Novák, "SEI film formation on highly crystalline graphitic materials in lithium-ion batteries," *Journal of Power Sources,* vol. 153, no. 2, pp. 385-390, 2006, doi: 10.1016/j.jpowsour.2005.05.036.

[53] C. Delacourt and M. Safari, "Mathematical Modeling of Aging of Li-Ion Batteries," in *Physical Multiscale Modeling and Numerical Simulation of Electrochemical Devices for Energy Conversion and Storage: From Theory to Engineering to Practice*, A. A. Franco, M. L. Doublet, and W. G. Bessler Eds. London: Springer London, 2016, pp. 151-190.

[54] Y. Zhang, C.-Y. Wang, and X. Tang, "Cycling degradation of an automotive LiFePO 4 lithium-ion battery," *Journal of Power Sources,* vol. 196, no. 3, pp. 1513-1520, 2011, doi: 10.1016/j.jpowsour.2010.08.070.

[55] M. Kassem, J. Bernard, R. Revel, S. Pélissier, F. Duclaud, and C. Delacourt, "Calendar aging of a graphite/LiFePO4 cell," *Journal of Power Sources,* vol. 208, no. C, pp. 296-305, 2012, doi: 10.1016/j.jpowsour.2012.02.068.

[56] S.-H. Wu and P.-H. Lee, "Storage fading of a commercial 18650 cell comprised with NMC/LMO cathode and graphite anode," *Journal of Power Sources,* vol. 349, pp. 27-36, 2017, doi: 10.1016/j.jpowsour.2017.03.002.

[57] M. Ecker *et al.*, "Calendar and cycle life study of Li(NiMnCo)O2-based 18650 lithium-ion batteries," *Journal of Power Sources,* vol. 248, pp. 839-851, 2014, doi: https://doi.org/10.1016/j.jpowsour.2013.09.143.

[58] S. S. Choi and H. S. Lim, "Factors that affect cycle-life and possible degradation mechanisms of a Li-ion cell based on LiCoO2," *Journal of Power Sources,* vol. 111, no. 1, pp. 130-136, 2002, doi: https://doi.org/10.1016/S0378-7753(02)00305-1.

[59] M. Daniel, D. Thomas, and B. Kai Peter, "Model-Based Investigation of Porosity Profiles in Graphite Anodes Regarding Sudden-Death and Second-Life of Lithium Ion Cells," *Batteries,* vol. 5, no. 2, p. 49, 2019, doi: 10.3390/batteries5020049.

[60] M. Petzl, M. Kasper, and M. A. Danzer, "Lithium plating in a commercial lithium-ion battery – A low-temperature aging study," *Journal of Power Sources,* vol. 275, pp. 799-807, 2015, doi: https://doi.org/10.1016/j.jpowsour.2014.11.065.

[61] Z. Li, J. Huang, B. Yann Liaw, V. Metzler, and J. Zhang, "A review of lithium deposition in lithium-ion and lithium metal secondary batteries," *Journal of Power Sources,* vol. 254, pp. 168-182, 2014, doi: https://doi.org/10.1016/j.jpowsour.2013.12.099.

[62] J. Cannarella and C. B. Arnold, "The effects of defects on localized plating in lithium-ion batteries," *Journal of The Electrochemical Society,* vol. 162, no. 7, pp. A1365-A1373, 2015, doi: https://doi.org/10.1149/2.1051507jes.

[63] A. Hammami, N. Raymond, and M. Armand, "Runaway risk of forming toxic compounds," *Nature,* vol. 424, no. 6949, pp. 635-636, 2003, doi: https://doi.org/10.1038/424635b.

[64] D. D. MacNeil, L. Christensen, J. Landucci, J. M. Paulsen, and J. R. Dahn, "An Autocatalytic Mechanism for the Reaction of Li_xCoO_2 in Electrolyte at Elevated Temperature," *The Electrochemical Society,* vol. 147, no. 3, pp. 970-979, 2000, doi: https://doi.org/10.1149/1.1393299.

[65] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, and C. Chen, "Thermal runaway caused fire and explosion of lithium ion battery," *Journal of Power Sources,* vol. 208, pp. 210-224, 2012, doi: https://doi.org/10.1016/j.jpowsour.2012.02.038.

[66] Y.-W. Wang and C.-M. Shu, "Hazard Characterizations of Li-Ion Batteries: Thermal Runaway Evaluation by Calorimetry Methodology," in *Rechargeable Batteries: Materials, Technologies and New Trends,* Z. Zhang and S. S. Zhang Eds. Cham: Springer International Publishing, 2015, pp. 419-454.

[67] "*Kjøretøybestanden per 31. desember 2019*," Opplysningsrådet for veitrafikken (OFV). Accessed: April 8, 2020. [Online]. Available: https://ofv.no/kjoretoybestanden/kj%C3%B8ret%C3%B8ybestanden-31-12-2019

[68] "*Kjøretøybestanden 2010*," Opplysningsrådet for veitrafikken (OFV). Accessed: April 8, 2020. [Online]. Available: https://ofv.no/kjoretoybestanden/kjoretoybestanden-2010

[69] "*Bilparken*," SSB. Accessed: May 6, 2020. [Online]. Available: https://www.ssb.no/statbank/table/05522/

[70] "*Elbilbestand*," Norsk elbilforening, 2019. Accessed: April 8, 2020. [Online]. Available: https://elbil.no/elbilstatistikk/elbilbestand/

[71] "*Norway reaches historical electric car market share*," Norsk elbilforening, 2020. Accessed: April 8, 2020. [Online]. Available: https://elbil.no/norway-reaches-historic-electric-car-market-share/

[72] D. K. Samferdselsdepartement, "Meld. St. 33 Nasjonal Transportplan 2018–2029," *Oslo, Norway*, 2017.

[73] Personal communication with Senior Advisor B. A. Fladen at Section for Regulation of Network Services at NVE, April 29 2020.

[74] B. A. Fladen, "*Regulatoriske føringer i Europa og Norge for bruk av batterier i nettet*," NVE, Trondheim, January 30, 2020.

[75] *Forskrift om gjenvinning og behandling av avfall (Avfallsforskriften)*, 2004. Accessed: April 13, 2020. [Online]. Available: https://lovdata.no/dokument/SF/forskrift/2004-06-01-930

[76] *Lov om vern mot forurensninger og om avfall (Forurensningsloven)*, 1983. Accessed: April 13, 2020. [Online]. Available: https://lovdata.no/dokument/NL/lov/1981-03-13-6

[77] Personal communication with Operation Manager T. H. Svendsen at Batteriretur, February 2, 2020.

[78] "*Nyheter og hendelser*," Eaton, 2016. Accessed: April 2, 2020. [Online]. Available: http://www.eaton.no/EatonNO/OurCompany/NewsEvents/NewsReleases/PCT_2976767

[79] "*xStorage Home*," Eaton. Accessed: April 23, 2020. [Online]. Available: https://www.eaton.com/no/no-no/catalog/energy-storage/xstorage-home.html

[80] "*INVADE Horizon 2020*," INVADE. Accessed: April 23, 2020. [Online]. Available: https://h2020invade.eu/

[81] "*Norway*," INVADE. Accessed: April 21, 2020. [Online]. Available: https://h2020invade.eu/the-project/norway/

[82] "*xStorage Home supports the energy transition*," Eaton. Accessed: April 21, 2020. [Online]. Available: https://www.eaton.com/gb/en-gb/products/energy-storage/xstorage-home-supports-the-energy-transition.html

[83] "*xStorage Buildings*," Eaton. Accessed: April 23, 2020. [Online]. Available: https://www.eaton.com/no/no-no/catalog/energy-storage/xstorage-buildings.html

[84] "*Norges første idrettsanlegg med Eaton xStorage Buildings*," Eaton. Accessed: April 23, 2020. [Online]. Available: https://www.eaton.com/no/no-no/products/energy-storage/bislett-stadium-success-story.html

[85] "*A Second Life for Electric Vehicle Batteries*," ECO STOR. Accessed: April 23, 2020. [Online]. Available: https://eco-stor.com/

[86] "*FAQs + Answers*," Connected Energy. Accessed: April 23, 2020. [Online]. Available: https://www.c-e-int.com/resources/faqs/

[87] "*Opportunities for E-STOR*," Connected Energy. Accessed: April 22, 2020. [Online]. Available: https://www.c-e-int.com/product/uses-for-estor/

[88] "*Features + Benefits*," Connected Energy. Accessed: April 22, 2020. [Online]. Available: https://www.c-e-int.com/product/e-stor-benefits/

[89] "*Collaborative, Ambitious, Credible*," Connected Energy. Accessed: April 24, 2020. [Online]. Available: https://www.c-e-int.com/technology/history/

[90] "*2nd Life Battery Storage Systems*," Connected Energy. Accessed: April 22, 2020. [Online]. Available: https://www.c-e-int.com/

[91] "*Connected Energy + Allego Germany*," Connected Energy. Accessed: April 23, 2020. [Online]. Available: https://www.c-e-int.com/technology/our-projects/allego-germany/

[92] "*Connected Energy + Allego Belgium*," Connected Energy. Accessed: April 23, 2020. [Online]. Available: https://www.c-e-int.com/technology/our-projects/allego-belgium/

[93] "*Connected Energy + The Norfolk Microgrid*," Connected Energy. Accessed: April 23, 2020. [Online]. Available: https://www.c-e-int.com/technology/our-projects/norfolk-microgrid/

[94] "*Connected Energy + Dundee City Council*," Connected Energy. Accessed: April 23, 2020. [Online]. Available: https://www.c-e-int.com/technology/our-projects/dundee-city-council/

[95] "*Connected Energy + Bryt Energy*," Connected Energy. Accessed: April 22, 2020. [Online]. Available: https://www.c-e-int.com/technology/our-projects/bryt-energy-wales/

[96] "*Virtual power plant: Europe's biggest power plant is 100 % renewable*," Explained by Statkraft. Accessed: April 22, 2020. [Online]. Available: https://explained.statkraft.com/articles/2018/virtual-power-plant-europes-biggest-power-plant-is-100-renewable/

[97] "*Connected Energy + Engie Netherlands*," Connected Energy. Accessed: April 23, 2020. [Online]. Available: https://www.c-e-int.com/technology/our-projects/engie-netherlands/

[98] "*Connected Energy + Umicore*," Connected Energy. Accessed: April 22, 2020. [Online]. Available: https://www.c-e-int.com/technology/our-projects/umicore/

[99] "*Renault batteries find "megawatt-scale" second life use in Belgium*," List Solar. Accessed: April 23, 2020. [Online]. Available: https://list.solar/news/renault-batteries/

[100] "*A second life for used batteries*," Bosch, 2016. Accessed: April 22, 2020. [Online]. Available: https://www.bosch-presse.de/pressportal/de/en/a-second-life-for-used-batteries-64192.html

[101] "*Endesa conducting electric vehicle battery second life study in living energy lab*," Endesa, 2016. Accessed: April 20, 2020. [Online]. Available: https://www.endesa.com/en/press/press-room/news/energy-transition/electric-mobility/endesa-is-carrying-out-an-electric-vehicle-second-life-study-in-an-energy-living-lab

[102] "*SUNBATT*," Research Centre for Energy Resources and Consumption (CIRCE), 2015. Accessed: April 20, 2020. [Online]. Available: https://www.fcirce.es/en/smart-mobility-en-en/sunbatt-2

[103] L. C. Casals, B. Amante García, and C. Canal, "Second life batteries lifespan: Rest of useful life and environmental analysis," *Journal of Environmental Management*, vol. 232, pp. 354-363, 2019, doi: 10.1016/j.jenvman.2018.11.046.

[104] "*Electricity Storage and Renewables: Costs and Markets to 2030*," International Renewable Energy Agency (IRENA), Abu Dhabi, 2017. Accessed: April 28, 2020. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017_Summary.pdf

[105] J. Neubauer, K. Smith, E. Wood, and A. Pesaran, "*Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries*," National Renewable Energy Laboratory (NREL), 2015. Accessed: April 28, 2020. [Online]. Available: https://www.nrel.gov/docs/fy15osti/63332.pdf

[106] C. K. Narula, R. Martinez, O. Onar, M. R. Starke, and G. Andrews, "*Economic Analyses of Deploying Used Batteries in Power System*," Oak Ridge National Laboratory, 2011. Accessed: April 29, 2020. [Online]. Available: http://www.ehcar.net/library/rapport/rapport124.pdf

[107] "*KCBS: BNEF's Curry on EV batteries' second life*," Bloomberg New Energy Finance (BNEF), 2016. Accessed: April 30, 2020. [Online]. Available: https://about.bnef.com/blog/kcbs-bnef-curry-on-ev-batteries-second-life/

[108] B. Williams and T. Lipman, "*Analysis of the Combined Vehicle- and Post-vehicle-use Value of Lithium-ion Plug-in-vehicle Propulsion Batteries*," University of California - Transportation Sustainability Research Center, 2012. Accessed: April 30, 2020. [Online]. Available: https://ww2.energy.ca.gov/2013publications/CEC-500-2013-088/CEC-500-2013-088.pdf

[109] P. Ahčin, K. Berg, and I. Petersen, "Techno-economic analyis of battery storage for peak shaving and frequency containment reserve," in *2019 16th International Conference on the European Energy Market (EEM)*, 18-20 Sept. 2019 2019, pp. 1-5, doi: 10.1109/EEM.2019.8916380.

[110] Z. Song, S. Feng, L. Zhang, Z. Hu, X. Hu, and R. Yao, "Economy analysis of second-life battery in wind power systems considering battery degradation in dynamic processes: Real case scenarios," *Applied Energy*, vol. 251, p. 113411, 2019, doi: https://doi.org/10.1016/j.apenergy.2019.113411.

[111] R. Madlener and A. Kirmas, "Economic Viability of Second Use Electric Vehicle Batteries for Energy Storage in Residential Applications," *Energy Procedia*, vol. 105, pp. 3806-3815, 2017, doi: 10.1016/j.egypro.2017.03.890.

[112] "*Lønn*," Statistisk sentralbyrå (SSB), 2020. Accessed: May 4, 2020. [Online]. Available: https://www.ssb.no/arbeid-og-lonn/statistikker/lonnansatt

[113] "*Occupational Employment Statistics*," U.S. Bureau of Labor Statistics, 2020. Accessed: May 4, 2020. [Online]. Available: https://www.bls.gov/oes/current/oes_nat.htm

[114] "*Kostnader i energisektoren*," NVE, 2019. Accessed: May 5, 2020. [Online]. Available: https://www.nve.no/energiforsyning/energiforsyningsdata/kostnader-i-energisektoren

[115] "*Energy prices in the EU in 2015*," Eurostat, 2016. Accessed: May 5th, 2020. [Online]. Available: https://ec.europa.eu/eurostat/documents/2995521/7405554/8-27052016-AP-EN.pdf/b5652235-2df1-47ed-84c6-701614849b3a

[116] "*Høyeste strømpris på sju år*," Statistisk sentralbyrå (SSB), 2018. Accessed: May 6, 2020. [Online]. Available: https://www.ssb.no/energi-og-industri/artikler-og-publikasjoner/hoyeste-strompris-pa-sju-ar

[117] "*Salg av overskudd på strøm/plusskunde*," Eidsiva Energi. Accessed: May 5, 2020. [Online]. Available: https://www.eidsivaenergi.no/solceller/salg-av-overskudd-strom--plusskunde/

[118] "*Effektbasert nettleie*," Norgesnett AS, 2020. Accessed: February 18, 2020. [Online]. Available: https://norgesnett.no/nettleie/#/effektbasert-nettleie/

[119] "*AGVA Spotpris*," Agva. Accessed: April 6, 2020. [Online]. Available: https://www.agva.no/stromavtale/agva-spotpris/

[120] Personal communication with Vidar Kristoffersen, department manager for grid development at Norgesnett, January-April 2020.

[121] K. Berg, "*Webinar februar 2020: Demoer for batterier i nettet*," SINTEF, February 28, 2020. Accessed: May 12, 2020. [Online]. Available: https://www.youtube.com/watch?v=dB_sBCO9PD0&feature=youtu.be

Appendix A: Eaton xStorage Home Datasheet

xStorage Home single phase system combinations overview

Battery Capacity (nominal)	AC Inverter Power (nominal)			Max. Recommended PV input power	Full system weight (appr.)	Full system dimensions (appr.)
4.2 kWh						
6 kWh	3.6 kW	4.6 kW	6 kW	4.8 kW	135 kg	1230 x 890 x 220 mm (H x W x D)
7.5 kWh						

Battery pack	BATTERY TYPE		
	SECOND LIFE	NEW	
Nominal	4.2 kWh	6 kWh	7.5 kWh
Cell chemistry	LMO (Lithium Manganese Oxide)		NMC (lithium nickel manganese cobalt oxide)
Max charge/discharge current DC	42 A	54 A	70 A
DC battery input voltage	74.4 - 98.4 V		
Overcharge protection	Fuse + Contactor		
DoD	90%		
Standards	IEC 62619; UN 34.81; UN 38.3; CE		
Warranty – battery life time	5 years (1 full cycle per day i.e., charge and discharge)	10 years (1 full cycle per day i.e., charge and discharge)	10 years (1 full cycle per day i.e., charge and discharge)
Physical properties			
Dimensions	442 x 781 x 175 mm (HxWxD)		
Weight	83 kg		
Hybrid inverter	INVERTER POWER RANGE		
	3.6 kW	4.6 kW	6 kW
PV INPUT (DC)			
Max. DC power	4.8 kW		
Maximum DC Voltage	500 V		
Nominal DC operating voltage	100 - 500 V		
MPPT max. voltage range	240 - 500 V		
Max. Input current	20 A		
Initial feeding voltage	150 V		
Number of MPP Trackers	1		
DC insulation resistance	VDE0126 & VDE0126-1-1/A1: Riso > 1.5 MΩ, Others: Riso > 200 kΩ		
LOAD/GRID OUTPUT (AC)			
Nominal Output Power	3600 W	4600 W	6000 W
Max Critical Load	70% of nominal output power		
Nominal AC Grid Voltage	230 V (Grid-Tie), 230 V ± 3% (Off-Grid)		
Nominal frequency	AC Synchronized operation 50 Hz / 60 Hz ± 1 Hz		
Nominal AC output current	15.7 A	20 A	26.1 A
Max. AC current	17.4 A	22.3 A	29 A
AC wiring system	Single phase/N/PE, TN, TT, IT (additional fuse or CB required)		
Total Harmonic Distortion (THD)	<3%		
Power Factor	0.99 (Grid-Tie), ±0.9 (Off-Grid)		
Metering capability	Power meter for critical load and PV production (not meter-grade)		
EFFICIENCY			
MPPT efficiency	>99%		
Maximum efficiency (battery to AC)	>90%		
PV to grid max. efficiency	97%		
Standby Losses	<10 W		
INTERFACE			
Communication	LAN, RS-485, USB Host (with USB WIFI dongle) USB: Type B receptacle for firmware upgrade CAN BUS: Only for battery pack - inverter internal comms		
Comms Protocols	HTTP REST API		
LED indicators	Green (ON): Normal status Red (ON): Fault status. Inverter is unable to connect to the grid Green (Blinking): Communication activity		
Display	LCM display: Character 16 words, 2 lines, 3 Function keys		
STANDARDS			
EMC/EMI standard	EN 61000-6-2: 2005/EN 61000-6-3: 2007+A1: 2011		
CE	LVD: 2014/35/EU; EMC: 2014/30/EU; 2011/65/EU RoHS		
Physical properties			
Dimensions	515 x 796 x 182 mm (HxWxD)		
Weight	37 kg		
General system specs	XSTORAGE		
	Applicable for all system combinations		
SAFETY			
Degree of protection	IP20 (Indoor)		
Hazard substance restriction	Lead free, compliance with RoHS GP2		
Standards	IEC 62109-1:2010; IEC 62109-2:2011; IEC 62619:2017		
OPERATING CONDITIONS			
Storage temperature range	from -10 – 40°C		
Operating temperature	0 – 30°C		
Humidity	5% to 95% Relative Humidity (Non condensing)		
Acoustic noise	35 dB (indoor application)		
Altitude	Elevation: max 3000 meters		
Cooling	Natural airflow		
OTHERS			
Solar DC Switch	Integrated		
Topology	Transformerless		
Grid integration	AC coupled		
Grid certificates	UK (G83/2, G59/3-2); FR (UTE C15-712-1, SEI REF 04, V6 or CRAE, Mainland/Island); IT (CEI 0-21: pending)		
Common use cases	Grid tie: self-consumption; Off-grid: backup		
OV category	OVCII and OVCIII in common mode		
Degree of pollution	2		

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Appendix B: Battery Algorithm and Simulation Code

```python
# -*- coding: utf-8 -*-

__author__ = "Karin Tråer"
__email__ = "karin.traer@nmbu.no"

import matplotlib.pyplot as plt


class Battery:
    """
    Class handling the battery charge and discharge.
    """

    def __init__(self, nom_capacity, remaining_capacity, DOD_limit):
        """
        Establishing battery.

        Parameters
        ----------
        nom_capacity : Nominal energy capacity of battery, given in kWh.
        remaining_capacity : Current capacity of battery, given in kWh.
        DOD_limit : Lower limit of battery discharge, given as float between 0
        and 1.

        Returns
        -------
        None.

        """
        self.nom_capacity = nom_capacity
        self.remaining_capacity = remaining_capacity
        self.capacity_limit = nom_capacity * (1-DOD_limit)


    def charge (self, kwh_value, start_charge, end_charge, charge_power,
                c_efficiency):
        """
        Charging the battery.

        Parameters
        ----------
        kwh_value : Energy value, float given in kWh.
        start_charge : Energy value where charging can start,
                       float given in kWh.
        end_charge : Energy value where charging should end,
                     float given in kWh.
        charge_power : Maximum charging power, float given in kW.
        c_efficiency : Charging efficiency, float between 0 and 1.

        Returns
        -------
        new_kwh_value : Energy value after charge, float given in kWh.

        """
        if (kwh_value < start_charge) and (self.remaining_capacity <
                                           self.nom_capacity):
            start_capacity = self.remaining_capacity

            if ((self.nom_capacity - start_capacity)/c_efficiency) <= \
                (end_charge - kwh_value):
                if charge_power >= ((self.nom_capacity - start_capacity)/
```

```
                                    c_efficiency):
                    self.remaining_capacity = self.nom_capacity
                    new_kwh_value = kwh_value + ((self.nom_capacity -
                                                  start_capacity)/c_efficiency)
                else:
                    self.remaining_capacity += (charge_power*c_efficiency)
                    new_kwh_value = kwh_value + charge_power

            else:
                if charge_power >= (end_charge - kwh_value):
                    self.remaining_capacity += ((end_charge - kwh_value)*
                                                c_efficiency)
                    new_kwh_value = end_charge
                else:
                    self.remaining_capacity += (charge_power*c_efficiency)
                    new_kwh_value = kwh_value + charge_power
        else:
            new_kwh_value = kwh_value

        return new_kwh_value


    def charge_outside(self, kwh_value, charge_power, c_efficiency):
        """
        Charging battery outside system.

        Parameters
        ----------
        kwh_value : Energy value, float given in kWh.
        charge_power : Maximum charge power, float given in kW.
        c_efficiency : Charge efficiency, float between 0 and 1.

        Returns
        -------
        new_kwh_value : Energy value after charge, float given in kWh.

        """
        if self.remaining_capacity < self.nom_capacity:
                   new_capacity = self.remaining_capacity + (charge_power*
                                                             c_efficiency)
                   if new_capacity > self.nom_capacity:
                       self.remaining_capacity = self.nom_capacity
                   else:
                       self.remaining_capacity += (charge_power*c_efficiency)

               new_kwh_value = kwh_value

               return new_kwh_value


           def discharge(self, kwh_value, start_discharge, end_discharge,
                         discharge_power, d_efficiency):
               """
               Discharging battery.

               Parameters
               ----------
               kwh_value : Energy value, float given in kWh.
               start_discharge : Energy value where discharge can commence,
                                 float given in kWh.
               end_discharge : Energy value where discharge should end,
                               float given in kWh.
               discharge_power : Maximum discharge power, float given in kW.
               d_efficiency : Discharge efficiency, float between 0 and 1.

               Returns
```

```
            -------
            new_kwh_value : Energy value after discharge, float given in kWh.

            """
            if kwh_value > start_discharge:
                start_capacity = self.remaining_capacity

                if ((start_capacity - self.capacity_limit)*d_efficiency) >= \
                    (kwh_value - end_discharge):
                    if discharge_power >= (kwh_value - end_discharge):
                        new_kwh_value = end_discharge
                        self.remaining_capacity = start_capacity - \
                            ((kwh_value - end_discharge)/
                             d_efficiency)
                    else:
                        new_kwh_value = kwh_value - discharge_power
                        self.remaining_capacity -= (discharge_power/
                                                    d_efficiency)
                else:
                    if discharge_power >= ((start_capacity - self.capacity_limit)
                                           *d_efficiency):
                        new_kwh_value = kwh_value - \
                            ((start_capacity - self.capacity_limit)*d_efficiency)
                        self.remaining_capacity = self.capacity_limit
                    else:
                        new_kwh_value = kwh_value - discharge_power
                        self.remaining_capacity -= (discharge_power/
                                                    d_efficiency)
            else:
                new_kwh_value = kwh_value

            return new_kwh_value


    def battery_simulation(df_of_households,household_no, nominal_capacity,
                           available_capacity, DOD_limit, start_charge,
                           end_charge, charge_power, c_efficiency,
                           start_discharge, end_discharge, discharge_power,
                           d_efficiency):
        """
        Function taking a dataframe containing columns of hourly
        kwh-averages for different households during winter week (Dec-Feb).
        Simulation with battery defined.
        Returns kwh-list of kwh values after simulation and a list of
        the battery's remaining capacity after each hour.

        Parameters
        ----------
        df_of_households : Dataframe containing hourly average
                           for winter week for different households.
                           Must have columns 'Household no' (where no is an
                           integer) and 'time'.
        household_no : Integer. Household number in question.
        nominal_capacity : Float. Nominal capacity of battery (kWh).
        available_capacity : Float. Remaining capacity in battery (kWh).
        DOD_limit : Float between 1 and 0. How far the battery is allowed
                    to discharge.
        start_charge : Float. kWh-value where charge commences.
        end_charge : Float. kWh-value where charge ends.
        charge_power : Float. Charging power (kW).
        c_efficiency : Float between 1 and 0. Charging efficiency.
        start_discharge : Float. Kwh-value where discharge commences.
        end_discharge : Float. Kwh-value where discharge ends.
        discharge_power : Float. Discharge power (kW).
```

```
        d_efficiency : Float between 1 and 0. Discharging efficiency.

        Returns
        -------
        kwh_values: List of original kwh-values.
        kwh_values_with_battery : List of floats, where floats are kwh values
                                  after simulation.
        capacity_battery : List of floats, where floats are the remaining
                           capacity in the battery.

        """

        kwh_values = df_of_households['Household {0}'.format(household_no)].\
                                                      tolist()
        times = df_of_households['time'].tolist()

        battery = Battery(nominal_capacity,available_capacity,DOD_limit)

        kwh_values_with_battery = []
        capacity_battery = []

        for i in range(len(kwh_values)):
            if times[i] <= '05:00:00':
                kwh_values_with_battery.append(battery.charge(kwh_values[i],
                                                              start_charge,
                                                              end_charge,
                                                              charge_power,
                                                              c_efficiency))
            else:
                kwh_values_with_battery.append(battery.discharge(kwh_values[i],
                                                                 start_discharge,
                                                                 end_discharge,
                                                                 discharge_power,
                                                                 d_efficiency))
            capacity_battery.append(battery.remaining_capacity)

        return kwh_values, kwh_values_with_battery, capacity_battery


    def battery_simulation_total(df_total, nominal_capacity, available_capacity,
                                 DOD_limit, charge_power, c_efficiency,
                                 start_discharge, end_discharge,
                                 discharge_power, d_efficiency):
        """
        Function taking a dataframe containing columns of hourly kwh-averages
        during winter weeks (Dec-Feb). Simulation with battery defined.
        Returns kwh-list of kwh values after simulation and a list of
        the battery's remaining capacity after each hour.

        Parameters
        ----------
        df_total: Dataframe. Total average hourly consumption. Must have
                    columns 'time' and 'kwh'.
        nominal_capacity : Float. Nominal capacity of battery (kWh).
        available_capacity : Float. Remaining capacity in battery (kWh).
        DOD_limit : Float between 1 and 0. How far the battery is allowed
                    to discharge.
        charge_power : Float. Charging power (kW).
        c_efficiency : Float between 1 and 0. Charging efficiency.
        start_discharge : Float. kWh-value where discharge commences.
        end_discharge : Float. kWh-value where discharge ends.
        discharge_power : Float. Discharge power (kW).
        d_efficiency : Float between 0 and 1. Discharge efficiency of battery.
```

```python

        Returns
        -------
        kwh_values: List of original kwh-values.
        kwh_values_with_battery : List of floats, where floats are kwh values
                                  after simulation.
        capacity_battery : List of floats, where floats are the remaining capacity
                           in the battery.

        """

        kwh_values = df_total['kwh'].tolist()
        times = df_total['time'].tolist()

        battery = Battery(nominal_capacity,available_capacity,DOD_limit)

        kwh_values_with_battery = []
        capacity_battery = []

        for i in range(len(kwh_values)):
            if times[i] <= '05:00:00':
                kwh_values_with_battery.append\
                    (battery.charge_outside(kwh_values[i],
                                            charge_power,
                                            c_efficiency))
            elif kwh_values[i] > start_discharge:
                kwh_values_with_battery.append(battery.discharge(kwh_values[i],
                                                                 start_discharge,
                                                                 end_discharge,
                                                                 discharge_power,
                                                                 d_efficiency))
            else:
                kwh_values_with_battery.append(kwh_values[i])

            capacity_battery.append(battery.remaining_capacity)

        return kwh_values, kwh_values_with_battery, capacity_battery
```

Appendix C: Battery Capacity Curves

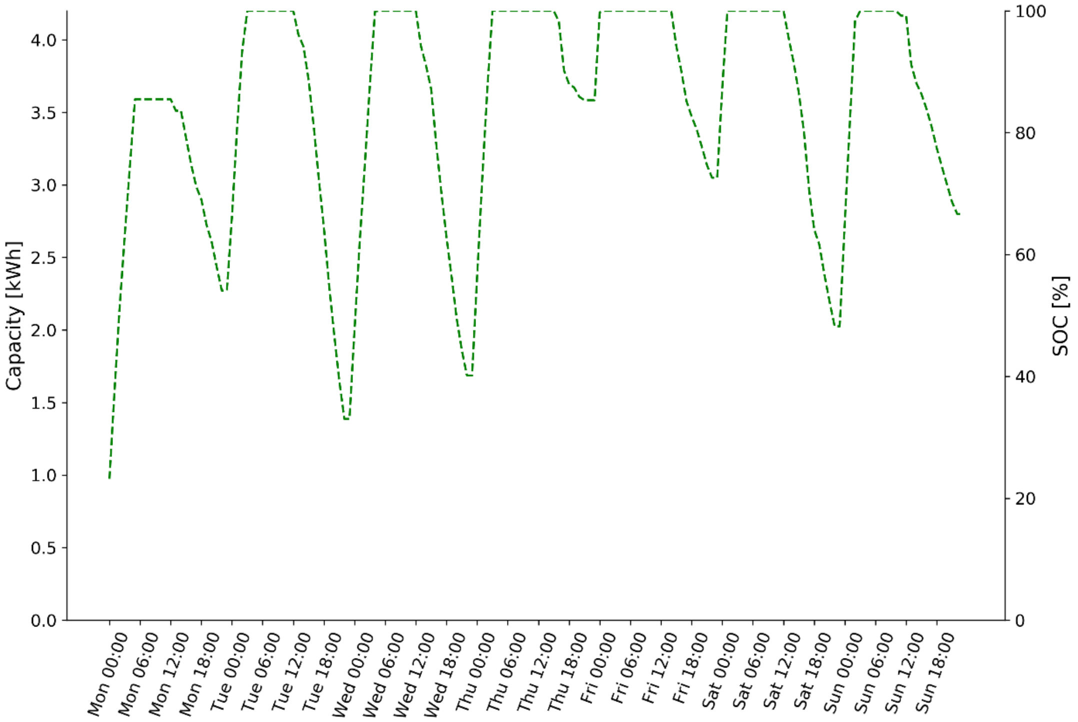

Figure A.1: Battery capacity curve for household 1 with a 4.2 kWh battery system, which reduces peaks down to 4.0 kWh/h.

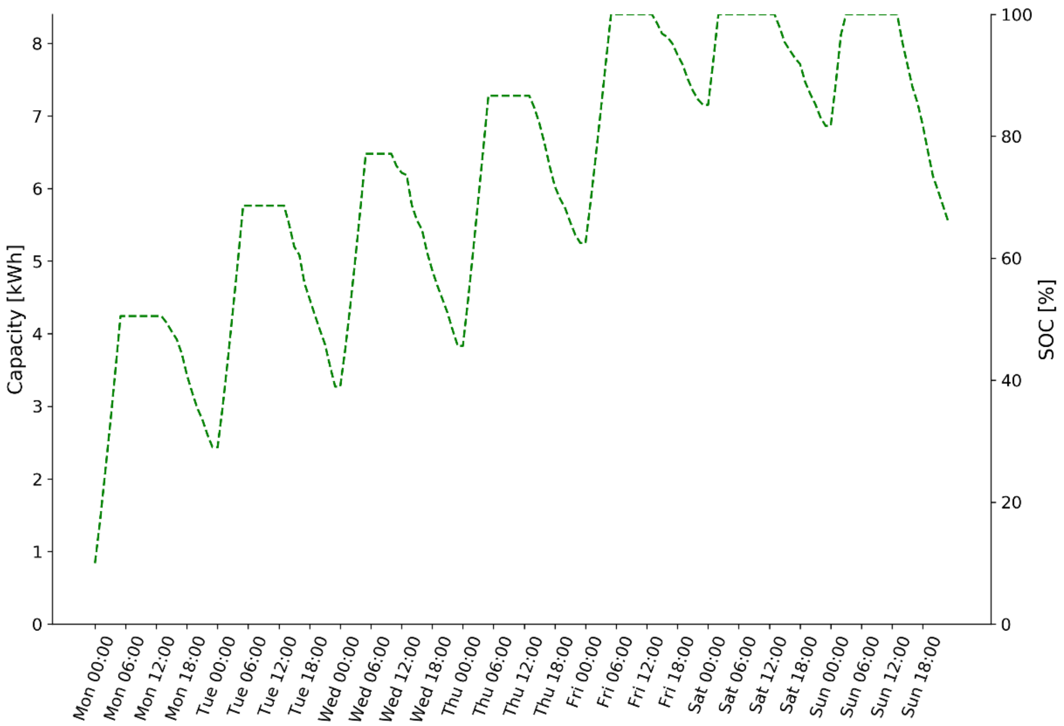

Figure A.2: Battery capacity curve for household 1 with an 8.4 kWh battery system, which reduces peaks down to 4.0 kWh/h.

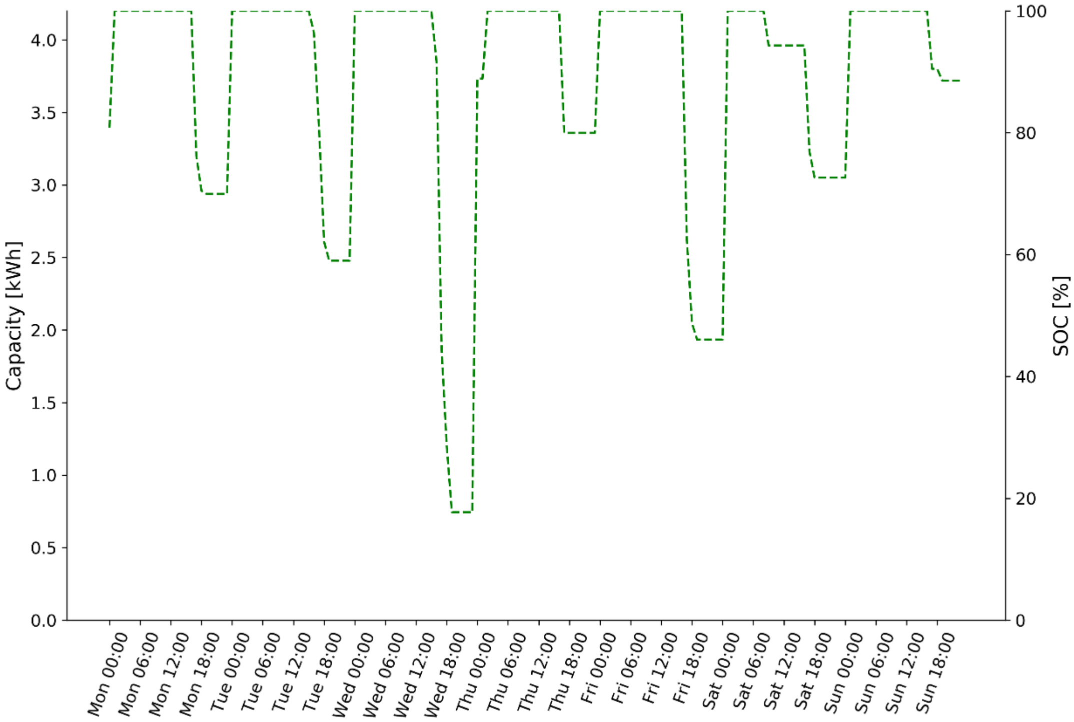

Figure A.3: Battery capacity curve for household 32 with a 4.2 kWh battery system, which reduces peaks down to 5.1 kWh/h.

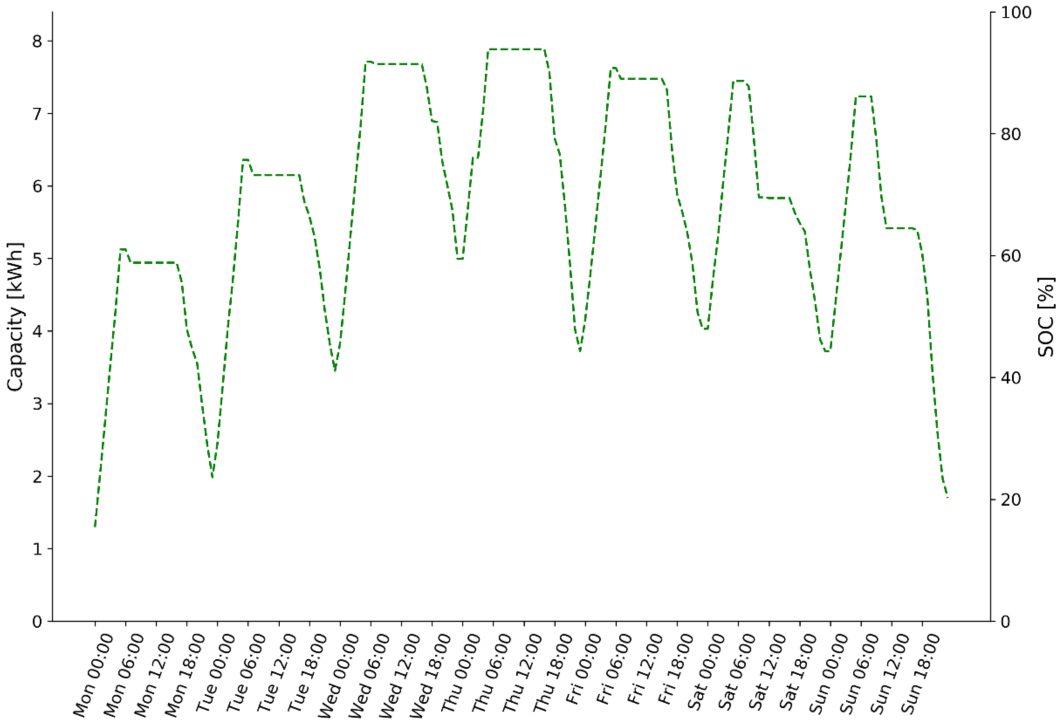

Figure A.4: Battery capacity curve for household 32 with an 8.4 kWh battery system, which reduces peaks down to 4.4 kWh/h.

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway