Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

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Utilization of energy storage systems in ports

Case studies of three Norwegian ports

Master's thesis in Energy and Environmental Engineering
Supervisor: Kjetil Uhlen
June 2020

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Problem Description

With the maritime sector's ambitions to lower emissions, efforts to increase energy efficiency and implement new fuel-technologies in the international shipping fleet are rising. One of the favorable developments is the increased electrification of maritime traffic. Electrification refers to the utilization of alternative marine power (AMP), partly electrification of propulsion/operation and total electrification of propulsion/operation. Common for the three segments within electrification is the fundamental requirement of a sufficient and reliable power supply.

Ports are undeniably affected by technological development in the maritime industry and new technological and environmental demands arise from both governmental and private actors. Within a decade, Norwegian ports are expected to supply AMP to almost all vessels, and the government is working hard to facilitate hybrid and total-electric solutions. This development introduces new challenges for ports. Some of these challenges are related to the costs of the required AMP and charging equipment, while others are related to constraints in grid capacities. A third challenge that has been highlighted lately is the high energy costs that are caused by AMP-and charging loads. The high costs weaken the competitiveness of AMP, hybridization, and total-electrification, as the ports are forced to charge more for AMP and charging-power.

To enhance the competitiveness of electric solutions, energy storage can be implemented into ports. Energy storage systems can reduce energy costs, as well as provide an alternative to grid investments. In this report, the potential of utilizing energy storage systems (ESSs) in Norwegian ports is studied. The candidate shall:

- give a description of relevant system theory prioritizing analysis of energy storage technology
- study the economic feasibility of utilizing energy storage systems in ports to cut costs of supplying vessels with electrical energy
- study what energy storage technologies and ESS dimensions are most favorable for a selection of port loads
- conduct a sensitivity analysis to determine how variations in model parameters impact the feasibility of energy storage in ports

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Abstract

With the electrification of the maritime industry, ports are challenged by new obligations to supply alternative marine power (AMP) and power for the charging of batteries on-board vessels. This report seeks to study whether the utilization of energy storage systems (ESSs) in ports can help meet these challenges, what energy storage technologies are preferred, and how the feasibility varies with different types of ports and system-parameters.

The report starts with an introduction to energy storage technologies that analyze the potential applications, use-cases, characteristics, costs, and models for the cost of energy storage. Technical characteristics and cost-elements of energy storage technologies for 2016 and 2030 are derived, and the utilization of NaS, NaNiCl, VRFB, and NCA stands out as most advantageous. Further, the Norwegian regulatory environment and the expected electrification of vessel traffic in Norwegian waters are studied to determine what applications of ESSs in Norwegian ports are convenient. The Norwegian regulations concerning ESSs are immature and the benefits of several of the potential grid-applications are uncertain. Combining behind-the-meter applications give fewer regulatory boundaries, and an evaluation of the Norwegian grid tariff scheme reveals strong incentives to reduce monthly peak powers. A combination of load leveling and energy arbitrage is found to be the most promising combination of applications, as this can also be used for ports with constrained grid power capacity.

To study the economical feasibility of ESSs in Norwegian ports, an optimization model is constructed. The optimization model is shaped into the Norwegian regulatory environment and finds the optimal ESS capacity and power rating that minimized the annual costs of supplying a load. The input to the model is yearly load, grid tariff coefficients, and a selection of energy storage characteristics and cost-elements. The optimization model is applied to case studies that constitute two potential future loads of a City port dominated by passenger traffic, a Cargo port, and an Offshore/subsea base. The case studies are conducted under normal operation and with constraints in grid power capacity.

The results of the case studies indicate that with the current characteristics and costs of energy storage technologies, the utilization of ESSs in the ports is generally not feasible for even the most aggressive electrification scenarios. With the expected development in energy storage technologies, the economical feasibility of implementing ESSs into ports is greatly enhanced, first of all for the Cargo and City port which experience cost reductions. Further, several energy storage technologies show high potential in deferring upgrades in the grid capacity of City and Cargo ports. The employment of ESSs in the Offshore port is proven to be economically less feasible. As expected, NaS gives the best results.

Through sensitivity analyses, the impact of variations in grid tariffs, electricity prices, and end-of-life return values are studied. The sensitivity analyses show a clear correlation between grid tariffs and the feasibility of ESSs. Further, the deficiency of energy arbitrage with the spot prices of the Norwegian market, compared to other European markets, is demonstrated. Finally, the increasing benefits of ESSs with the advancement in end-of-life return values are illustrated.

Sammendrag

Ved en elektrifisering av maritim industri møter havner nye utfordringer knyttet til leveranse av landstrøm og ladestrøm til skip. Denne rapporten forsøker å undersøke om bruk av elektrisk energilagring i havner kan bidra til å møte disse utfordringene, hvilke teknologier som er foretrukne og hvordan lønnsomhet varierer mellom havner og ulike systemparametre.

Oppgaven starter med en introduksjon av energilagring som analyserer potensielle bruksområder, eksempler av bruk, teknisk karakteristikk, kostnadselementer og kostnadsmodeller. Videre blir teknisk karakteristikk og kostnadselementer for energilagringsteknologier i 2016 og 2030 utledet, hvor bruk av NaS, NaNiCl, VRFB og Litium-ion NCA gir mest lovende resultater. Videre blir det norske regulatoriske landskapet og forventet elektrifisering av skipstrafikk i norsk farvann undersøkt for å avgjøre hvilke bruksområder av energilagring i norske havner som har størst potensiale. De norske reguleringene som omhandler energilagring er fortsatt umodne og fordelene ved flere av de mulige bruksområdene er derfor usikre. En kombinasjon av markedsapplikasjoner gir færre regulatoriske utfordringer og en evaluering av norske tariffer tydeliggjør sterke insentiver for å redusere månedlige effekttopper. Basert på dette blir en kombinasjon av reduksjon av effekttopper og energiarbitrasje valgt som den mest lovende kombinasjonen av bruksområder. Denne kombinasjonen kan også brukes for havner med begrenset effektkapasitet i nettet.

For å undersøke potensialet av å bruke energilagring i havner, blir en optimeringsmodell, som kan brukes til casestudier, laget. Optimeringsmodellen er formet av det norske regulatoriske landskapet, og finner den optimale kapasiteten og effekten til et energilagringssystem som minimerer de årlige kostnadene for å dekke en last. Modellen tar inn årlig last, koeffisienter for nettariff og utvalgte karakteristikker og kostnadselementer for en energilagringsteknologi. Casestudiene representerer potensielle fremtidige laster i en byhavn dominert av passasjertrafikk, en lastehavn og en offshore/subsea-base. Casestudiene er utført under normale forhold og med begrensninger i nettkapasitet.

Resultatene fra casestudiene indikerer at med nåværende tekniske karakteristikker og kostnader for de ulike teknologiene, så vil ikke bruken av energilagring i havner være økonomisk lønnsom, selv for de mest ambisiøse scenariene for elektrifisering. Med den forventede teknologiske og kostnadsrelaterte utviklingen vil derimot den økonomiske lønnsomheten øke drastisk, spesielt i by- og lastehavnene som oppnår kostnadsreduksjoner. Flere teknologier viser høyt potensiale for å kunne utsette investeringer i nettkapasitet rundt by- og lastehavnene. Implementering av energilagring i Offshore/subsea-basen er bevist mindre lønnsomt. Som forventet gir NaS de beste resultatene i alle casestudiene.

Gjennom sensitivitetsanalyser blir påvirkningen fra variasjoner i nettariffer, elektrisitetspriser og økonomisk restverdi studert. Sensitivitetsanalysene viser en klar korrelasjon mellom netttariff og økonomisk lønnsomhet av energilagring. Videre tydeliggjøres en svakhet i energi arbitrasje med norske strømpriser sammenlignet med flere andre europeiske strømpriser. Til slutt illustreres fordelene ved en økning i økonomisk restverdi for systemer for energilagring.

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Abbreviations

DSO = Distribution system operator
ESS(s) = energy storage system(s)
ESU = energy storage unit
EV = electrical vehicle
IMO = International Maritime Organization
ISO = independent system operator
NOx = generic term for the nitrogen oxides
PCU = power conversion unit
PPM = parts per million
PV = photo voltaic
RTO = regional transmission organization
SOx = sulfur and oxygen containing compounds
TSO = transmission system operator

Chapter 1

Introduction

1.1 Background and motivation

A port can be defined as ”a maritime facility which may comprise one or more wharves where ships may dock to load and discharge passengers and cargo” [2]. The most common types of ports are seaports that manage passenger ships and/or cargo. In addition to passenger and cargo ports, some ports operate as bases for different types of vessels like fishing vessels, offshore supply vessels, and subsea supply vessels. Traditionally, ports were built in a time with ”exclusive focus on local trade, with often a characterized polluted industry, deficient transport, and little interest in public health, citizen welfare and no awareness for environmental issues” ([3], page 1). In the industrial revolution, ports were established close to cities or in some cases, the areas surrounding the ports grew into cities. The ports created jobs and became vital for trade and the port-nations’ economies ([3], page 1-2).

Throughout history, the role of ports in society has changed dramatically. Today, ports serve as economic backbones in many communities. Although many ports have high shares of private ownership, they are normally owned by government entities through port authorities. The public ownership of ports is justified by the fact that ports play a key role in national economies, but through this ownership, the ports also become tools for reaching federal or local goals. Today, this is shaping ports to become more environmentally friendly.

1.1.1 Emission-driven development in the maritime sector

One of the strategic and economic interests that have been of particular importance for governments in recent years, is the reduction of emissions. Lately, the focus on the negative effects of the activities associated with traditional port development and operation has been enhanced. These activities include land reclamation, dredging, and large-scale construction, but the negative impact vessel traffic has on local health and environment has been especially emphasized. This has lead local, regional, and national governmental bodies to pursue emission reductions from ports. This emission reduction is pursued through the ownership of ports as well as through new regulations, directives, or financial support-programs.

As the emissions from ports mainly origin from the ships using the ports, it's evident that ports need to work together with ship owners and operators to reduce them. Further, this has to be done in a way that doesn't endanger ports' competitiveness. If a port has very strict requirements, vessel owners or operators are more likely to choose to use other ports. This is why it's also crucial that the ports work together to force the ship-owners to take measures. The International Association of Ports and Harbors (IAPH) is an arena for this collaboration, with initiatives like the World Port Sustainability Program (WPSP) and coordination with organizations like the International Maritime Organization (IMO), the United Nations Conference on Trade and Development (UNCTAD) and the World Association for Waterborne Transport Infrastructure (PIANC) [4].

Although the ports need to adapt their environmental initiatives to what the shipping-industry will tolerate, it does not mean that the shipping industry is not working to reduce emissions on their own. One example of this is how the shipping- and cruise industry is currently working to reduce the pollution of sulfur to cope with the introduction of IMO 2020. IMO 2020 is a new regulation introduced by the International Maritime Organization (IMO) that limits the allowed share of sulfur in fuel oil used on board all ships to 0.50% [5]. Regulations that reduce the allowed emissions from ships in international and national waters are expected to become stricter, something that has lead the marine industry to research exhaust-cleaning methods, new fuel-technologies, and the use of shore-power.

The combined efforts of ports, vessel owners/operators, organizations and governmental bodies to reduce emissions are expected to facilitate the implementation of new emission-friendly technologies. These new technologies will impact the role of ports, drastically changing the operation and requirements of the ports of the future.

1.1.2 New infrastructure requirements in ports

According to [6], the three main fuel-technology trends that will be used to reduce emissions from ships in the coming years is the use of hydrogen storage combined with fuel cells, the use of bio-fuel and the use of battery-electric operation. All of these trends have the potential of drastically changing the infrastructure requirements in ports, but the impact of increased electrification of the shipping fleet is in main focus in this report. In literature, the electrification of the shipping fleet is typically divided into three segments ([6], page 20):

- alternative marine power (AMP) to supply ship operations in port
- partly electrification of propulsion and operation (hybridization)
- total electrification of propulsion and operation

Common for all these segments is that they all use electrical energy from shore to replace the use of petroleum. In practice, this means that a sufficient, reliable, and cost-effective power supply in ports becomes a critical success factor.

The electrification-development constitutes a major challenge for ports. First of all, the need for AMP- and charging-power introduces new costs for the required equipment and facilities. Second, the grid surrounding many ports are in general not dimensioned for high power demands and this is imminent to trigger investments in grid infrastructure. A third challenge, that origins in the large power demands of ships, is the high energy costs due to high grid tariffs (peak power tariffs). Combined, these challenges endanger the competitiveness of the electrified solutions, as the resulting high investment and operating costs force the ports to charge accordingly.

1.1.3 Electrification segments

Below, the three electrification segments are shortly described.

Alternative marine power (AMP)

AMP is based on the concept of ships using shore-power to replace the use of own auxiliary engines in ports. This results in an elimination of all local pollution (SOx, NOx, and PPM) and a reduction of CO_2-emissions relative to the electricity mix of the shore connection and the energy efficiency of the ship engines ([7], page 3). The main benefit of utilizing shore-power is the mitigation of local pollution, as the ship pollution has negative health effects to the areas surrounding the ports, which can often be characterized by having high population densities ([7], page 17).

The electrical load of a ship that is portcalling primarily consists of the ”hotel load”, which is the load that originates from lighting, heating/cooling, and auxiliaries, etc. In addition to this, there may be load related to safety systems, cargo-handling, or other processes that are ship-specific. For cruise ships, the electrical load in port has been experienced to be quite constant, and this can be assumed to be the case for other ship types as well. For ships with cranes or other energy-intensive equipment, typically container ships or offshore supply ships, the load can be expected to fluctuate more.

With the development and adoption of the high-voltage international standard for AMP (IEC/IEEE 80005-1), stricter national and international regulations towards marine emissions and emerging public pressure towards ports and shipping companies, the use of AMP is expected to increase in the next few years ([7], page 53). The standard is extremely important as it ensures connectivity across countries and continents, which makes the investment in AMP-technology safer for both port- and shipping-stakeholders. The use of AMP today is growing significantly in the cruise and container sector, with companies like Carnival Cruise Line, A.P. Møller – Mærsk A/S, China Ocean Shipping company, and the Mediterranean Shipping Company taking a lead ([7], page 9). There is also significant use of AMP by ro-ro ferries and ro-ro cargo lines, especially in the Scandinavian countries.

Hybridization

A partly electrification of propulsion and operation, also known as hybridization, is much easier to achieve than total electrification and is also feasible for many more vessel types and routes. A hybridization is realized by combining electrification of propulsion and operation with the use of other fuels by using energy storage technologies like batteries.

When dealing with partly electrification of propulsion and operation it's important to separate conventional hybridization and plug-in hybridization. A plug-in hybrid ship uses shore-power to charge it's batteries, while in conventional hybridization, the on-board energy storage is charged by the ship's engines to achieve increased engine performance. This means that conventional hybridization has no impact on ports.

In addition to allowing a ship to sail emission-free for a period of time, the use of large batteries with optimized power control can reduce the fuel consumption, maintenance, and emissions from ships ([8], page 4). In future ships, some scientists also assume that the energy infrastructure aboard will be a combination of many different types of fuel ([8], page 14), which is likely to require energy storage to achieve optimal operation.

Total electrification of propulsion and operation

Total electrification of propulsion and operation of a ship refers to using electrical energy storage to supply all ship activities. To achieve this, the electrical energy storage system that supplies the ship must be charged by power from shore. A total electrified ship can in many ways be compared to an electrical vehicle (EV), as the battery and electric systems are similar. A major difference is however the dimensions; many vessel types, like cruise ships and container ships that sail long distances, are improbable to fully electrify because the size of the required energy storage would be immense.

There are however types of vessels and vessel traffic that is feasible to completely electrify, already today. Smaller vessels that sail shorter routes, like ferries and some ro-ro vessels, need much smaller energy storage systems to run fully electric. There are already some ferries that sail fully electric - one example is *MV Ampere*, the World's first battery-electric passenger and car ferry. *MV Ampere* has a storage capacity of 1.09 MWh, but charges in only 10 minutes, which results in a power need of approximately 6 MW.

1.1.4 Motivation for the introduction of energy storage in ports

With the challenges related to the electrification of marine traffic, ports need innovative solutions to help fulfill their new requirements at a controlled cost. One of these innovative solutions is to implement energy storage systems into ports with high AMP or charging loads. This can lower the costs of importing electricity into the port and reduce or diminish the required investments in the electricity grid infrastructure surrounding the port. Further, the implementation of energy storage systems in ports will reduce the stress on the grid and benefit the DSOs and TSOs as well. There are several benefits of including energy storage into systems that supply AMP or charging-power to ships, but the main ones are:

- reduction of peak power demands (peak shaving)
- increased power and energy capacity
- possibility of energy arbitrage /load shifting

1.2 Objective

This objective of this report is to study whether the utilization of ESSs in ports can help meet the challenges related to power and energy requirements from the electrification of maritime traffic. The report aims to give descriptions of relevant theory concerning energy storage technologies, regulations, and development in electrification. Further, an optimization model is constructed to study the feasibility of implementing ESSs into a selection of Norwegian ports. These case studies seek to analyze how optimal ESS capacities, power ratings, and cost savings vary in different ports and for different scenarios for the electrification of maritime traffic. Lastly, the sensitivity of the most important optimization parameters should be studied to determine how these impact the feasibility of port ESSs.

1.3 Approach

To study the feasibility of ESSs in ports, the analysis begins with a study of relevant theory, primarily of energy storage technologies. This theory is then applied to an analysis of the Norwegian regulatory environment and expected electrification development to derive potential applications in Norwegian ports. An optimization problem is defined to describe the utilization of these applications and a corresponding optimization model is constructed both mathematically and in Python. This optimization model is then used to perform case studies of a selection of port loads. The port loads are modeled using the port's schedules for vessel traffic in combination with both given and derived power needs. The model is solved using Gurobi and can be altered for specified input-parameters. The output of the model is the cost-optimal energy storage capacity and power rating, various cost-components, and the operation pattern of the system. The optimal energy storage capacity and power rating, together with the various cost-components, are printed to Excel, while the operation patterns are plotted in Python. This allows swift modeling of multiple combinations of input-parameters. The results of the case studies are used as a rationale for the feasibility of ESS in ports.

1.4 Structure

The structure of the report is given below.

- Chapter 2, *Energy storage*, gives an introduction to energy storage technologies, typical applications and characteristics, cost development and derives a cost-model according to required specifications.
- Chapter 3, *Utilization of energy storage in Norwegian ports*, studies how the application of energy storage fits with Norwegian regulations and expected electrification-development. Based on the analyses, a combination of applications are chosen for the case studies.
- In Chapter 4, *Mathematical modeling of problem*, an optimization model that sizes ESSs, based on energy storage characteristics, Norwegian regulations, and a given load, is composed.

- In Chapter 5, *Description of cases*, the vessel traffic of a selection of ports is studied, and yearly loads are modelled based on two chosen scenarios.
- In Chapter 6, *Results*, the main results of the case studies are presented and sensitivity analyses are conducted.
- In Chapter 8, *Discussion*, the optimization model, estimation of case study port loads, the results of the initial analysis and the sensitivity analysis are criticized and discussed.
- In Chapter 9, *Conclusion*, the main points of the report are summarized and suggestions for further works are made.

Chapter 2

Energy storage

2.1 Introduction

To study the potential of using ESSs in the ports, it's imperative to study what energy storage technologies are relevant, what applications and use-cases exist, and what the characteristics of different technologies are today and how the characteristics are expected to change. Additionally, different cost models of ESSs are compared and a cost model that can be used for estimation-purposes is derived.

Today, the most established energy storage technologies can be divided into three categories, as presented in Figure 2.1 ([1], page 36). The three categories for energy storage are electrical, mechanical, and chemical technologies. The electrical storage technologies

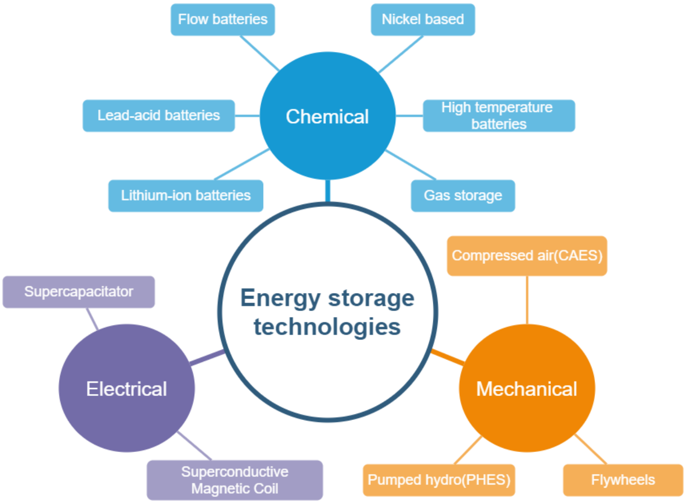


Figure 2.1: Established energy storage technologies

consist of supercapacitors and superconductive magnetic coils, which can both be identified by high power-to-energy ratios. The mechanical energy storage technologies are pumped hydro-electric storage (PHES), compressed air energy storage (CAES), and flywheels. PHES, together with CAES, constitute the largest ESSs in the world measured in both power and energy capacity. Flywheels, on the other hand, typically supply high power over short durations, similar to the electrical energy storage technologies. The electrical and mechanical energy storage technologies are unsuitable for implementation in ports and accordingly, these technologies are not studied further in this report.

Chemical energy storage includes conventional electrochemical battery technologies, gas storage, and flow batteries. The general concept of chemical energy storage is common for all these technologies; the electrical energy is stored through chemical reactions, but the way these chemical reactions are triggered varies. The conventional electrochemical batteries consist of one or more electrochemical cell(s) [9]. The flow batteries work by passing a solution over a membrane where ions are exchanged to charge or discharge the cell [9]. In gas storage, electrical energy is stored through the production of gases, typically hydrogen or methane [9]. The electrochemical battery technologies, together with the flow batteries, will be the focus of this report. The electrochemical batteries are the batteries known from vehicles and electrical appliances, typically Lead-acid, Lithium-ion, or Nickel based batteries, as well as high-temperature molten-salt batteries.

Lead-acid and Li-ion batteries are the most common electrochemical battery technologies and both offer a range of different compositions. The two most common Lead-acid batteries are flooded Lead-acid and valve-regulated Lead-acid (VRLA), while for Li-ion batteries, there are five important compositions; Lithium-Iron Phosphate (LFP), Lithium titanate (LTO), Lithium Nickel Cobalt Aluminum oxide (NCA), lithium nickel manganese cobalt oxide (NMC) and lithium manganese oxide (LMO). The Nickel based batteries are primarily Nickel-Cadmium (NiCd), which was one of the first batteries that were invented (1899) [10], and Nickel-metal-hydride (NiMH). The high-temperature batteries operate at typically more than 150°C ([1], page 96). Two well known high-temperature battery technologies are based on sodium Sulfur (NaS) and sodium nickel chloride(NaNiCl). Two interesting types of flow batteries make use of vanadium cells (VRFB) and zinc-bromine (ZBFB) and have market shares that are expected to grow significantly in the next years [11]. According to ([12], page 293-294), the most mature energy storage technologies are pumped hydroelectric energy storage(PHES), followed by Ni-Cd, NiMH, Li-ion, NaS, NaNiCl, and flywheels.

2.2 Applications

In literature, the services that energy storage can provide are described variously, depending on what regulatory environment is prevailing and what categories are being used to divide the different services and applications. One example is ([12], page 295), which divides the applications of energy storage into the following three categories; Bulk energy storage, Distributed storage, and Power quality. Another example is the classification that is performed by ([13], page 5), where the applications are divided into categories specifying what stakeholder the service benefits; ISO/RTO (TSO/DSO) services, Utility services, and Customer services. One last example is ([1], page 40), which divides the applications into potential locations in the grid and desired discharge durations. The three desired discharge duration-categories are short-term storage, daily storage, and long-term storage/seasonal storage.

In this report, dividing the applications into grid services and behind-the-meter services is appropriate. Here, behind-the-meter applications refer to all applications that use energy storage behind the meter, i.e. both commercial and private customers. The grid applications are all applications that require energy storage in either the DSO's or TSO's grid. The energy storage applications for islands or remote networks are disregarded. A collection of all the relevant energy storage applications in literature, divided into grid services and behind-the-meter services, is given below.

- Grid applications
    - Energy Shifting / Load Levelling
    - Generation, distribution or transmission investment deferral
    - Transmission congestion relief
    - Frequency regulation
    - Spin/Non-spin reserves
    - Black start support
    - Voltage support
- Behind-the-meter applications
    - Energy Shifting / Load Levelling
    - Increased PV self-consumption
    - Increased Power Quality
    - Backup power
    - Bill management (time-of-use, energy arbitrage)

Grid applications

Energy shifting or load leveling normally refers to storing energy at low load periods and releasing the energy at high load periods, hence leveling or making the load more even [14]. This application can be used both in the grid and behind-the-meter. Grid operators can use load leveling to defer investments in increased generation, distribution, and transmission capacities, as well as for transmission congestion relief. Transmission congestion relief refers to the process of using load leveling to store energy downstream of a line to reduce or prevent congestions in that line. The energy is stored when there is no congestion and discharged if the congestion occurs.

Frequency regulation, spin/non-spin reserves, and black start support rely on a completely different working principle than energy shifting/load leveling. Instead of storing and releasing energy based on capacity or load patterns, these applications store energy to help keep the power grid stable in case a sudden change in frequency, an unexpected generation contingency event or a grid failure occurs([13], page 15). These applications are normally controlled by the TSO or DSO, depending on what regulations apply. Voltage support, on the other hand, is advantageous if a system experiences a combination of low load and high PV or wind power production; to help prevent the voltage from rising downstream of the power production, a share of the produced energy can be stored temporarily using energy storage ([15], page 1).

Behind-the-meter applications

Energy shifting or load leveling can also be used behind-the-meter, but the purpose of the use is different. The purpose of using energy storage to shift energy for private or commercial customers is mainly bill management. Here, instead of shifting energy from low-load periods to high-load periods, the energy is shifted from low-price periods to high price periods. Depending on local regulation, these high and low price periods can occur due to varying electricity prices, but also due to time-of-use rates. This is also known as energy arbitrage or time-of-use management. As the low-load and high-load periods often come together with the low-price and high-price periods, energy shifting or load leveling behind the meter will in most cases also be beneficial for the grid operators.

To increase PV self-consumption, energy storage can be used to store excessive energy from periods where production is higher than consumption, to periods where consumption is higher than production (instead of selling this energy to the grid). By doing this, the share of a costumer's consumption that is being supplied by the customer's production will increase, and the total energy costs can be reduced. Energy storage can also provide backup power in case of grid failure and improve power quality for private and commercial customers. For most private customers, these applications don't necessarily give any financial benefits, but for commercial customers, the increased reliability and quality of supply can be decisive.

2.3 Use-cases

For many years, stationary energy storage has been dominated by pumped hydro storage, but in recent years, this has started to change with the inclusion of chemical energy storage. According to IRENA, the annual battery storage capacity will rise from 360 MW to 14 GW from 2014 to 2023. For utility-scale projects, 37% is expected to be from battery use for load shifting applications, 29% for renewable integration, 15% for peak shaving, and the rest for ancillary services and other services ([16], page 24). The leading countries when it comes to chemical energy storage are China, Japan, Germany, and the United States.

The dominating battery storage technology in the power market is NaS, followed by Lithium-ion, advanced Lead-acid, VRFB, and Ni-Cd ([16], page 24). The market is however moving towards using more Lithium-ion due to cost and performance advantages, as well as further development of the industry ([16], page 26-27). In general, the largest battery storage systems are implemented together with large wind or PV energy production facilities, isolated grids or to handle the peak demands of large regions or cities. In the US, Germany, and China, most of the operational and planned projects are either Lithium-ion or Lead-acid, while in Japan, large NaS-installations by the Tokyo Electric Power Company dominate ([16], page 96).

As the battery storage industry has evolved, numerous battery use-cases have emerged around the world. To illustrate the variations within a battery storage application and the use of different technologies for similar purposes, four utility-scale battery storage use-cases are studied. All the use-cases are incorporated into wind farms and have similar applications, but the resulting choices of technologies and characteristics are very different.

- The first use-case is in Rokkasho, Japan, where a 34 MW/204 MWh NaS battery system was commissioned in 2008 ([16], page 27). The battery system is connected to a 51 MW wind farm for energy time-shifting and frequency response. The battery system is charged in the night when the demand is low, and discharged during the day, when the demand is higher, with a storage capability of up to 6 hours.
- Similarly, a 36 MW/24 MWh advanced Lead-acid battery system is incorporated into a 153 MW wind farm in West Texas. The applications of this storage system are similar to the system in Japan, but it has a maximum discharge duration of only 15 minutes ([17], page 14).
- A third battery system that is incorporated into a wind farm, is the 0.5 MW/1 MWh VRFB system that belongs to a 78 MW wind and 640 kW solar photovoltaics site in Zhangbei, China ([17], page 15).
- The fourth use-case is in Hawaii, where an 11 MW/4.3 MWh LFP battery system is installed to manage that wind farm ramp rates comply with the local interconnection requirements ([17], page 5).

In the four use-cases described above, four different technologies and varying energy and power capacities are used, although all the systems are connected to similar systems. This shows that within the same applications, the desired impact of incorporating a battery system will vary and the desired application will also depend on the local grid and regulations. It also shows that multiple technologies can be used for similar applications. This is emphasized in Figure 2.2 that presents a Ragone-plot of several energy storage technologies. The Ragone-plot shows possible system power ratings on the x-axis and discharge times at rated power on the y-axis. In the upper right corner, the technologies with very high system power ratings and discharge times are placed, namely pumped hydro and compressed air energy storage. In the lower-left section the technologies with very low discharge times, like flywheels, supercapacitors, and SMES, are placed. In between, the battery technologies, flow batteries, and the high-energy supercapacitors are placed. In general, most of the battery technologies have very similar system power ratings, but there are greater differences in the discharge times at rated power.

2.4 Characteristics

As a result of the different physical and chemical features of materials, the characteristics of battery technologies vary significantly. When comparing energy storage technologies, typical characteristics that are decisive are power and energy density, power and storage

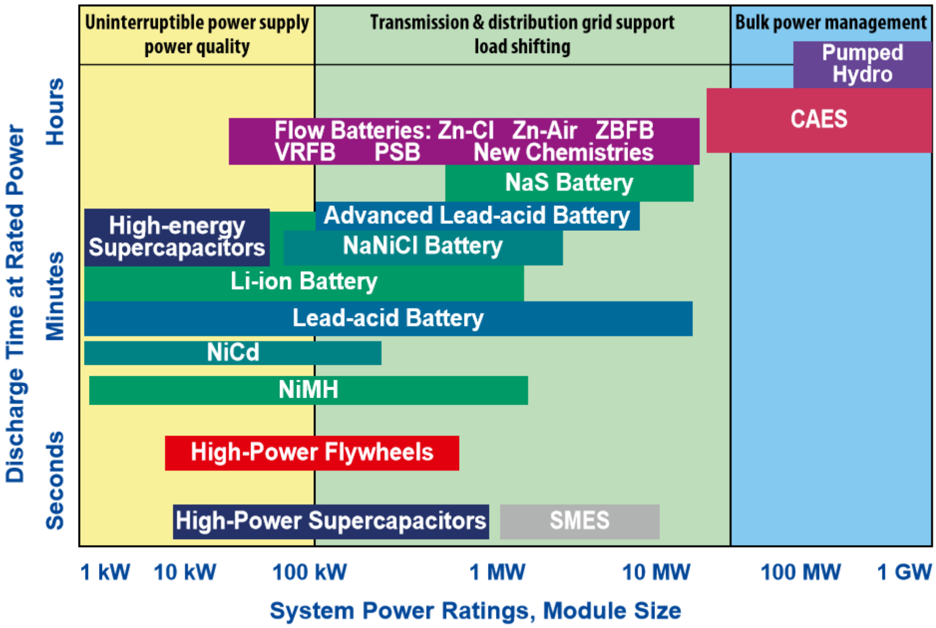


Figure 2.2: IRENA's Positioning of diverse energy storage technologies per their power rating and discharge times at rated power. Source: [1], page 41

capability, reliability, response time, durability, and cost. In general, there is no ”best” energy storage technology - the choice of technology is application-specific and depends on what characteristics are most influential.

In Table 2.1 and 2.2, typical characteristics of ten different battery technologies are presented: VRFB, ZBFB, NaNiCl, NaS, Flooded Lead-acid, VRLA, Li-ion LFP, Li-ion LTO, Li-ion NCA and Li-ion NMC/LMO. Each technology has specific values related to energy density, power density, calendar life, cycle life, depth of discharge (B^{dod}), round-trip efficiency (B^{eff}) and self discharge (B^{sd}). The values are the reference characteristics estimated by IRENA ([1], page 124-125) for 2016 and for 2030.

Technology	E. den. [Wh/l]	P. den. [W/l]	Cal. life [y]	Cyc. life [-]	B^{dod} [%]	B^{eff} [%]	B^{sd} [%/day]
VRFB	15-70	1-2	12	13,000	100	70	0.15
ZBFB	20-70	1-25	10	10,000	100	70	15
NaNiCl	150-280	150-270	15	3,000	100	84	5
NaS	140-300	120-160	17	5,000	100	80	0.05
F. Lead-acid	50-100	10-700	9	1,500	50	82	0.25
VRLA	50-100	10-700	9	1,500	50	80	0.25
LFP	200-620	100-10,000	12	2,500	90	92	0.1
LTO	200-620	100-10,000	15	10,000	95	96	0.05
NCA	200-620	100-10,000	12	1,000	90	95	0.2
NMC/LMO	200-735	100-10,000	12	2,000	90	95	0.1

Table 2.1: Battery specific parameters - 2016 values

Technology	E. den. [Wh/l]	P. den.[W/l]	Cal. life [y]	Cyc. life [-]	B^{dod} [%]	B^{eff} [%]	B^{sd} [%/day]
VRFB	15-70	1-2	19	13,000	100	78	0.15
ZBFB	20-70	1-25	16	10,000	100	78	15
NaNiCl	150-280	150-270	23	4,538	100	87	5
NaS	140-300	120-160	24	7,500	100	85	0.05
F. Lead-acid	50-100	10-700	13	3,225	50	85	0.25
VRLA	50-100	10-700	13	3,225	50	83	0.25
LFP	200-620	100-10,000	18	4,774	90	94	0.1
LTO	200-620	100-10,000	23	19,097	95	98	0.05
NCA	200-620	100-10,000	18	1,910	90	97	0.2
NMC/LMO	200-735	100-10,000	18	3,819	90	97	0.1

Table 2.2: Battery specific parameters - 2030 values

As can be seen in Table 2.1 and 2.2, there are considerable differences in the characteristics of the different storage characteristics. The technologies that are the most energy and power dense, are the Lithium-ion batteries. The Lithium-ion batteries are followed by the molten-salt batteries, NaS and NaNiCl, and then the Lead-acid batteries, Flooded Lead-acid and VRLA. The flow batteries, VRFB and ZBFB, have the lowest power and energy densities. The energy and power densities are expected to remain unchanged for all technologies towards 2030.

The estimated lifetime in years and the cycle life also vary greatly, with the flow batteries leading in the number of cycles, while the molten-salt batteries lead in the calendar life. The Lithium-ion LTO battery also has very high durability, with 10,000 cycles and an estimated 15-year calendar life. The Lead-acid batteries have the shortest lifetime in both calendar life and cycle life, together with Lithium-ion NCA and LFP. When dealing with the durability measured in calendar years, it's important to remember that this metric is dependent on the utilization pattern of the battery. The durability is expected to increase greatly towards 2030 for all of the technologies, but the rankings between the technologies are expected to remain the same.

The depth of discharge (DoD), which is a measure of the maximum recommended discharge for peak performance of the battery, is close to 100% for all batteries except the Lead-acid batteries. The Lead-acid batteries have recommended DoDs of 50%, which highlights a major deficit of these technologies. The DoDs are expected to remain the same towards 2030. The round-trip efficiencies of all the technologies are quite similar, but the Lithium-ion technologies are the only ones with efficiencies above 90%. The round-trip efficiency refers to the DC-to-storage-to-DC energy efficiency, i.e the share of energy that is put into the battery that can be exported and used. Followed by the Lithium-ion batteries, the molten-salt and Lead-acid batteries all have efficiencies above 80%. The flow-batteries have major deficits in terms of efficiency with reference values of 70%. Towards 2030, the efficiency of all technologies is expected to increase, but the flow batteries are expected to increase the most, with 8 percentage points.

The self-discharge of a chemical storage technology refers to the energy lost from internal chemical reactions that inevitably occur within the storage system. Most of the storage technologies have self-discharges below or equal to 0.25 %/day, but ZBFB and NaNiCl have self-discharge rates as high as 15 and 5 %/day. This effectively makes these technologies unsuitable for storage over long durations. The self-discharge rate of each technology is expected to remain the same towards 2030.

Based on the comparison of physical characteristics of the ten storage technologies in Table 2.1 and Table 2.2, LTO stands out as the favorable technology. There are however small differences between the Li-ion batteries in many of the characteristics, like energy density, power density, and efficiency. The molten-salt batteries and flow-batteries do well in many of the metrics, but the low efficiencies and self-discharge of ZBFB and NaNiCl are alarming. The Lead-acid and flow batteries stand out as the inferior technologies in terms of energy density and power density.

2.5 Cost development

The cost of energy storage has declined significantly in the last 10 years and this development is expected to continue. According to ([18], page 13), the capital cost of energy storage can be expected to decline with cost reductions in 2025 of 10-52% and in 2030 of 31%-80%. There are significant differences in the cost of different battery technologies and even within the same technology the variation is notable when comparing the cheapest to the most expensive supplier. Although the cost reductions have been significant, batteries are still ”expensive” and the main use of batteries is still quite limited to off-grid purposes, transport, and some behind-the-meter uses ([1], page 15).

In addition to the price variations that occur from different suppliers, the costs of different ESSs will also differ significantly depending on what applications the systems are made for. The price of energy storage used in EVs is not necessarily comparable to the price of stationary storage used for grid or home-purposes, even given the same system size. According to ([19], page 2), prices related to EV-batteries may differ significantly from the prices of stationary batteries because the prices of batteries used in EVs are excluded the control system and power electronics that are necessary for stationary batteries. This consideration is especially critical when working with Li-ion batteries, as this is the most used technology in the EV-industry.

In Table 2.3 and 2.4, estimated values of the energy installation cost (B^{eic}), power installation cost of PCU (B^{pic}) and fixed yearly OPEX cost ($B^{opex,f}$) of a selection of storage technologies are given. The cost-elements are given for 2016 and projected for 2030. The energy installation costs are estimates of different stationary storage technologies conducted by the World Energy Organization (IRENA) in 2019 ([20], page 13). The power installation cost of the PCU and the fixed yearly OPEX cost are averages derived in 2014 by ([21], page 590-591). The power installation costs of 2016 are assumed to be equal to the values derived in 2014, and from 2016 to 2030, the power installation cost of the PCU and the fixed yearly OPEX cost are assumed to experience similar reductions as the energy installation costs. This means that each technology has equal percentage reductions in energy installation cost, power installation cost, and OPEX from 2016 to 2030. This methodology is equal to the one used in ([18], page 9) for Lithium-ion. To obtain values in NOK for the cost components, average currency rates of 8.8003 NOK/USD in 2017 and 8.9500 NOK/EUR in 2015 have been used.

Technology	B^{eic} [NOK/kWh]	B^{pic} [NOK/kW]	$B^{opex,f}$ [NOK/kW/year]
VRFB	3,054	4,386	76
ZBFB	7,920	3,974	38
NaNiCl	3,511	4,224	49
NaS	3,239	3,276	32
F. Lead-acid	1294	4,162	30
VRLA	2,314	4,162	30
LFP	5,087	4,144	62
LTO	9,240	4,144	62
NCA	3,098	4,144	62
NMC/LMO	3,696	4,144	62

Table 2.3: Estimated battery cost-elements for 2016

Technology	B^{eic} [NOK/kWh]	B^{pic} [NOK/kW]	$B^{opex,f}$ [NOK/kW/year]
VRFB	1,047	4,386	76
ZBFB	2,719	3,974	38
NaNiCl	1,417	4,224	49
NaS	1,426	3,276	32
F. Lead-acid	651	4,162	30
VRLA	1,162	4,162	30
LFP	1,971	4,144	62
LTO	4,207	4,144	62
NCA	1,276	4,144	62
NMC/LMO	1,470	4,144	62

Table 2.4: Estimated battery cost-elements for 2030

As can be seen in Table 2.3, there are considerable differences in the energy costs of different technologies. The technology with the lowest energy installation cost in 2016 was flooded Lead-acid and VRLA at 1,294 and 2,314 NOK/kWh, followed by VRFB, NCA, NaS, NaNiCl, and NMC/LMO at 3,054, 3,098, 3,239, 3,511 and 3,696 NOK/kWh, respectively. The technology with the highest energy installation cost was LTO at 9,240 NOK/kWh, followed by ZBFB at 7,920 NOK/kWh and LFP at 5,087 NOK/kWh. There are also large differences in the yearly fixed operational expenditures, ranging from 30 NOK/kW/year for the Lead-acid batteries to 76 NOK/kW/year for VRFB. NaS has the second-lowest fixed OPEX at 32 NOK/kW/year, while the Lithium-ion batteries have fixed OPEXs at 62 NOK/kW/year. The power installation costs of the power conversion units are much more similar, ranging from 3276 NOK/kW for NaS to 4,386 for VRFB. The reference cost of all battery types are expected to decrease significantly towards 2030; flooded Lead-acid is expected to have the cheapest energy installation cost at 651 NOK/kWh, but VRFB is expected to pass VRLA to become the second cheapest at 1,047 NOK/kWh. Following VRFB is VRLA at 1,162 NOK/kWh, NCA at 1,276 NOK/kWh, NaS at 1426 NOK/kWh and NMC/LMO at 1470 NOK/kWh. The greatest expected reference cost decreases are by VRFB, LFP, and NMC/LMO with cost reductions of more than 60%.

2.6 Modeling cost of energy storage

When comparing the costs of energy storage systems a typical metric to use is the energy installation cost per kWh. This refers to the investment cost of the ESS per kWh, which is often extracted from the real costs of several projects. In addition to the energy capacity, the investment cost of energy storage for a given application is also dependent on the rated power and what power electronics the application requires. These costs are typically labeled by the power installation cost of the energy storage unit, and the power installation cost of the power conversion unit.

In reality, the costs of an ESS are far more complex. In addition to investment costs, both fixed and variable operational costs depend on the given application. Further complications origin in the fact that the durability of an ESS depends on the number of cycles, and the charging and discharging pattern. This will in turn impact the lifetime of the system. To cope with the many varying cost-parameters, multiple models have been developed to aid users in the estimation of costs related to different applications and technologies.

According to ([21], page 572), there are two main approaches to studying energy storage costs in literature; the first one is to study the total capital costs (TTC) and the second is to study the life cycle costs (LCC). While the TTC includes ”the costs related to the purchase, installation, and delivery of an energy storage unit,” the LLC includes the TCC, as well as ”the expenses related to fixed operation and maintenance (O&M), variable O&M, replacement, disposal and recycling” ([21], page 572). The LLC is often the most relevant approach, as this provides the levelized annual costs, which is the annualized yearly cost of the whole ESS during the system’s lifetime. There are different ways of estimating the LLC, depending on what parameters are included. One popular way of modeling the cost of electricity from energy storage is the Levelized Cost of Storage (LCOS).

The Levelized Cost of Storage (LCOS) is similar to the Levelized Cost of Electricity (LCOE) that is used when estimating the expected cost of electricity generation from electricity production. The LCOE can be defined as ([22], page 539):

> ”the present value of the price of the produced electrical energy (usually expressed in units of cents per kilowatt hour), considering the economic life of the plant and the costs incurred in the construction, operation and maintenance, and the fuel costs”

Similarly, the Levelized Cost of Storage (LCOS) gives ”the total lifetime cost of the investment in an electricity storage technology divided by its cumulative delivered electricity”([23], page 82). In effect, this means that the LCOS is the total lifetime cost of the ESS, including electricity losses, divided by the total electricity the storage system has delivered during its lifetime. The result is an estimated cost per ”discharged” kWh or kW, which can be interpreted as the minimum price that electricity from the storage system can be sold at.

According to ([24], page 5-6), the advantages of using LCOS is the familiarity of the metric and the possibility of comparing storage costs with generation costs and possible revenue. One of the major drawbacks of using LCOS compared to using LCOE is the arbitrariness of LCOS; the amount of energy stored and discharged over a period will depend on an assumed application, which does not necessarily reflect the actual use ([24], page 5-6). The other drawback of using LCOS is that the methodology is still incomplete and the resulting estimations that are performed will also be incomplete. The LCOS can, however, be used for both electrical energy (cost/kWh) and electrical power (cost/kW), which is beneficial.

Although there exist several studies on LCOS, there is still no one ”shared” definition ([23], page 81). Some studies neglect end-of-life costs like replacement or disposal, while others neglect performance parameters like capacity degradation. One last major drawback of using LCOS is that LCOS can’t manage systems that perform multiple applications, and as the LCOS is system- and application-specific, there are a lot of different estimations. An example definition of LCOS is given in equation (2.1) ([25], page 1596). In this definition, the LCOS over the calculation time of N years is given by the initial investment cost, TCC, the annual costs, C_t^{ESU}, the annual energy output of the storage system, E_t^{ESU}, and the discounting factor $\alpha_{r,N}$.

$$LCOS = \frac{TCC + \sum_{t=1}^{N} C_t^{ESU} \cdot \alpha_{r,t}}{\sum_{t=1}^{n} E_t^{ESU} \cdot \alpha_{r,t}} \tag{2.1}$$

In equation (2.1), the annual costs (C_t^{ESU}) are defined as the sum of the annual operational costs ($OPEX_t$), the costs of reinvestments in storage system components ($CAPEX^{re}$), the average electricity price (C_{el}), the annual electricity input (W_{in}), and the end of life recovery value (R_N^{eof}). The annual costs are hence defined in equation (2.2).

$$C_t^{ESU} = OPEX_t + CAPEX^{re} + C^{el} \cdot W^{in} - R_N^{eof} \tag{2.2}$$

Chapter 3

Utilization of ESSs in Norwegian ports

3.1 Introduction

The objective of this chapter is to study how electrical energy storage can be utilized in Norwegian ports. First, the Norwegian regulatory environment is studied and then an inquiry of the expected electrification development in marine traffic is conducted. Based on these analyses, relevant ESS applications in Norwegian ports are discussed and a combination of two applications is chosen for further analysis.

3.2 Regulatory environment

To understand how electrical energy storage can be utilized in Norwegian ports, the regulatory environment of the Norwegian electricity system must be studied. The Norwegian electricity system is subject to extensive regulations, particularly through The Norwegian Energy act. The Norwegian Energy Act shall ”ensure that energy is generated, converted, transmitted, traded, distributed and used rationally and in the best interests of society” [26]. This has lead to a system based on the principle that electricity production and trading should be market-based, while grid operations should be regulated [27]. The reasoning for this is that the market-mechanisms for production and trading of electricity ensures effective use of resources and reasonable prices, while electricity transmission and distribution is a natural monopoly and is hence not suited for competition. The regulations and models that decide how a consumer or producer participates in the market are discussed in the following sections.

3.2.1 Power Market Organization

To understand how different actors can participate in the Norwegian power market, the organization of it must be studied. The Norwegian power market can be divided into wholesale and end-user markets [27]. In the wholesale market, power producers, brokers, power suppliers, energy companies and large industrial costumers trade, while in the end-user market, the consumers (end-users) of electricity can choose their power supplier.

The wholesale market

The wholesale market primarily consists of three different market-types: the day-ahead market, the intraday market and the balancing markets. The day-ahead market and the intraday market are run by Nordpool, while the balancing markets are run by the TSO, Statnett. In addition to these three markets, market actors can also make bilateral agreements on the purchase or sale of specific volumes of electricity at an agreed price in an agreed period [27].

The day-ahead market is an auction-based market for contracts with delivery of physical power, where market actors can sell or buy energy for the next 24 hours. The market sets bidding zone prices for each hour, which means that the price for each hour is set according to the price and volume that the market actors are willing to sell and buy-in that particular hour. The auction is cleared to maximize social welfare while still keeping transmissions in the grid within the given constraints. In the day-ahead market, no market participants are forced to generate or consume energy ([28], page 26). This means that if a market participant succeeds in making a trade in the day-ahead market, the market participant is not obligated to meet this trade by producing or consuming the energy itself [29].

There are always deviations in generation and consumption from the day-ahead market-clearing to the actual operations. These deviations can come from physical failures in generation, consumption or grid, or uncertainties related to the estimation of consumption and generation. If the traded quantity does not correspond to the true generation or consumption, the obligation of power delivery or consumption can be met in three different ways: re-dispatching of own generation or consumption, making agreements with other market actors in the intraday-market or let the system operator put the market back to balance through the balancing market. While the day-ahead market is auction-based and uses centralized trading, the intraday market is based on bilateral trading. This type of trading differs significantly from centralized trading as it's based on the direct exchange of power between a buyer and a seller ([28], page 7). The purpose of the intraday market is for market actors to be able to reduce any imbalances in their own generation or consumption that has occurred after the closing of the day-ahead market. The intraday market is hence a continuous market where trading happens at all times from the clearance of the day-ahead market until one hour before ”delivery” and in some cases right up until ”delivery” [30]. The bilateral trading that is typically performed in the intraday market is ”over-the-counter” trading or electronic trading, which is handled by Nordpool.

The balancing markets are used by Statnett to regulate generation or production to maintain an instantaneous balance in the power grid. The Norwegian balancing markets consist of primary reserves (FCR), secondary reserves (FRR-A) and tertiary reserves

(FRR-m) [27]. The use of primary and secondary reserves are automated, while tertiary reserves are activated manually by Statnett. Primary reserves are traded in different hourly and weekly markets, while secondary reserves are traded in a weekly market. The tertiary reserves are traded in the regulating power market (RK), which is a common market for all the Nordic countries [27].

End-user market

The end-users in the Norwegian power market, that purchase electricity for private consumption, are free to choose between power suppliers. Small end-users, like private consumers or small businesses, usually make agreements with power suppliers, while large end-users, like industrial companies, often purchase directly in the wholesale market [27]. In general, the end-users that purchase energy from a power supplier can choose between three different types of contracts; fixed-price, standard variable price, and spot price [27]. In a fixed-price contract, the consumer pays a fixed price for a certain period, while in a spot price contract, the consumer pays the Nordpool spot price with a mark-up. The standard variable price is a combination of the two, where the consumer pays a fixed price, but the power supplier can change this fixed price if informing the customer 14 days ahead. There are also examples of other types of contracts, but these will not be taken into further consideration.

3.2.2 Grid tariffs

In addition to paying for the price of consumed electricity, all electricity consumers in the Norwegian power market have to pay a grid tariff. The grid tariff gives the DSO and TSO revenue to cover the costs of transporting electricity and as the grid companies are monopolies, the allowed profit is strictly controlled by The Norwegian Water Resources and Energy Directorate (NVE). In addition to the grid tariffs, there is a consumption tax on electricity, a value-added tax, a fee earmarked for the Energy fund, and payment for electricity certificates [27].

Each DSO determines the grid tariff based on allowed revenue, and due to differences in prerequisites and operation of grid companies, the grid tariffs can vary significantly between different regions [31]. In addition to the variation in grid tariffs between DSOs, there is also a differentiation of grid tariffs between customer groups. This differentiation has to be non-discriminatory and objective, and it should be based on relevant grid-parameters. One of these parameters is customer utilization time, which is the basis of the differentiation of grid tariffs between private households, vacation homes, and commercial consumers. The main difference of these tariffs is that vacation homes have a higher fixed tariff and that as of now, commercial consumers also pay a tariff associated with the peak power consumption.

Today, almost all grid tariffs for private customers consist of a fixed cost and a cost of consumed energy. This model is however expected to change, as NVE wants to include a tariff associated with the peak power consumption. The structure of this tariff is not decided yet, but the intent is to make it more profitable for costumers to reduce private consumption in periods where the load in the grid is high [32]. Even though the tariff has not been introduced yet, customers of some grid companies can already choose this tariff-model.

The grid tariff of a commercial customer typically consists of a fixed part, an energy-related part, and a peak power-related part, as presented in equation (3.1). The total monthly grid tariff is denoted as Gt_m and is dependent on the fixed cost (C^{fixed}), the energy price (C^{ep}), the consumption tax (C^{ct}), the monthly peak power cost (C^{pt}), the total monthly energy consumption (E_m), and the monthly peak power consumption (P_m^{peak}).

$$Gt_m = C^{fixed} + (C^{ep} + C^{ct}) \cdot E_m + C^{pt} \cdot P_m^{peak} \tag{3.1}$$

Even though this is a typical setup, there are significant variations between DSOs. The peak power cost coefficient is typically between 40 and 60 NOK per kW (peak) per month, depending on the peak power consumption and the time of the year. Most DSOs have separate coefficients for winter and summer, and the size of the coefficient typically decreases with increasing voltage level and peak power consumption. To illustrate the variations, a selection of cost coefficients (fixed cost, energy price, and peak power cost) for high voltage / high consumption commercial customers is presented in Table 3.1. The cost coefficients have been retrieved from four different Norwegian grid companies and an average has been estimated assuming summer months of April-September and winter months of October to Mars. DSO 1 operates with November to February as winter months, DSO 2 and 3 with October to Mars, while DSO 4 operates with November to Mars. In Table 3.1, C^{fixed} is the annual fixed cost, $C^{s,ep}$ is the energy price for summer months, $C^{w,ep}$ is the energy price for winter months, $P_m^{s,peak}$ is the peak power coefficient for summer months, and $P_m^{w,peak}$ is the peak power coefficient for winter months.

	DSO 1	DSO 2	DSO 3	DSO 4	Avg.
C^{fixed} $[NOK]$	20,800	25,000	11,000	10,800	16,900
$C^{s,ep}$ $[NOK/kWh]$	0.028	0.02	0.07	0.015	0.033
$C^{w,ep}$ $[NOK/kWh]$	0.028	0.02	0.08	0.035	0.040
$P_m^{s,peak}$ $[NOK/kW]$	28	50.10	30	17	31.28
$P_m^{w,peak}$ $[NOK/kW]$	38	63.30	35	122 / 52	53.53

Table 3.1: Grid tariff cost coefficients for high voltage commercial customers for a selection of Norwegian DSOs

As can be seen in Table 3.1, there are major differences in how DSOs charge commercial customers. The fixed costs of DSO 1 and 2 are about twice as high as the fixed costs of DSO 3 and 4, while DSO 5 has a fixed cost of less than one-fifth of DSO 3 and 4. The energy prices are all low compared to the electricity price, but here DSO 5 has an energy price that is much higher than the others. The summer peak power cost coefficients range from 17 NOK/kW per month to 50.10 NOK/kW per month, while the winter coefficients range from 38 NOK/kW to 122 NOK/kW, but here DSO 4 separates between the winter months of December, January and February and the winter months of October, November, and Mars.

To illustrate the differences in the grid tariffs, the yearly costs of an example customer are calculated. The example customer has a consumption of 500 MWh combined with a peak power of 1 MW in the summer months and consumption of 1500 MWh combined with a peak power of 1.5 MW in the winter months. This resulting grid tariffs for the different DSOs are given in table 3.2.

	DSO 1	DSO 2	DSO 3	DSO 4	Avg.
Summer mth. [NOK]	42,000	60,100	65,000	24,500	47,780
Winter mth. [NOK]	52,000	73,300	75,000	139,500/69,500	73,530
Yearly cost [NOK]	564,800	825,400	851,000	784,800	744,760

Table 3.2: Monthly and yearly grid tariff for example high voltage commercial customer

The yearly grid tariff varies from 564,800 NOK for the cheapest, to 851,000 NOK for the most expensive. This shows that there are major differences in the grid tariff of similar customers between DSOs. Table 3.2 also shows what elements are driving the cost of the grid tariff. The fixed yearly cost is insignificant, while the peak tariff is the element that is driving the cost in 3 of the 4 cases. This means that if a commercial customer with high peak demands manages to reduce the peaks, this can result in considerable savings. The energy consumptions and peaks are however randomly selected in this example, which means that in practice, the allocation of costs may be different.

3.2.3 Power Market participation

One of the fundamental principles of the Norwegian electricity system is that everyone that wants to take part in the power market should be able to at non-discriminating and objective tariffs and terms [33]. This means that the grid companies have duties to connect to power producers and consumers, as long as the producers or consumers agree to pay the necessary tariffs and contribute to cover the costs of connection. The grid companies in Norway are in fact obligated to require investment contributions from a customer to cover costs of new grid investments and grid upgrades that are triggered by the customer [34]. This includes investments that are related to when a customer gets connected to the grid, receives increased capacity, or receives improved quality. The purpose of this regulation is to highlight the costs of grid investments and to allocate the costs of grid investments between the customer(s) that trigger the investments and the other customers of the grid company. The size of the investment contribution depends on the cost of the grid upgrade and the customer's share of the grid upgrade, which is case-to-case specific.

The Norwegian Energy act regulates the building, owning, and operation of electrical installations, as well as the trading of electrical energy, through licensing. The Norwegian Energy act states that:

- ”Installations for the generation, conversion, transmission and distribution of high voltage electrical energy, may not be built or operated without a license. The same applies to the rebuilding or expansion of existing installations.” [35]

- ”No one but the State may engage in the trade in electrical energy without a license. In case of doubt, the Ministry decides whether a license is mandatory.” [35]

There are some minor exceptions to the requirement of licenses. This includes farms without high voltage facilities and private customers with peak production of less than 100kW, but in general, the concession includes all types of delivery and trade of electrical energy [36].

Participation for ESSs

There are several regulatory challenges with the inclusion of ESSs into the grid or behind-the-meter. Some key challenges regarding the regulations of energy storage are:

- The typical operation of an ESS involves an electrical installation and the trading of energy, which means licenses are required.
- Energy storage for grid applications can be owned by the grid company, by third parties (not grid companies) or a combination of these ([37], page 22-23). DSOs or TSOs should however in general not own or operate ESSs ([37], page 4).
- Having energy storage performing both behind-the-meter applications and grid applications is problematic ([37], page 22-23).
- The charges for grid access of ESSs are uncertain. Three different principles are viable ([37], page 24).

3.3 Future loads in Norwegian ports

The current and future electrical loads in Norwegian ports are heavily dependent on the electrification-development in the maritime sector. The Norwegian government has, together with the municipalities and port authorities, a goal of having zero-emission ports where feasible by the end of 2030 ([38], page 7). This goal refers to the emissions from port activities like cargo-handling and resource processing, but more importantly, it refers to the emissions that originate from the ships that use the ports. This indicates that the implementation of AMP will be greatly increased. Further, in the Norwegian action plan for green shipping, Norway has committed to reducing the emissions from domestic shipping and fishing with 50% by 2030 ([38], page 6). To accomplish this, plug-in hybridization or total electrification is required. Through stimulation of zero- and low-emission solutions to vessels and ports, the government aims to keep Norway's leading position within green shipping. The technologies that are stimulated include new fuel-technologies like LNG, hydrogen, and biofuels, as well as AMP, hybridization, total-electrification, and new technical and operational measures [39].

According to [40], the feasible measures to reduce emissions vary significantly between vessel types. The reason for this is that the vessels that sail in Norwegian waters differ in the length of sailing routes, age of ships, operational profiles, and type of ownership, and this varies severely between vessel types. In a five-year perspective, achieving zero emissions is only realistic for ferries and some express-boats, while achieving low emissions (40% reduction) is realistic for all vessel types through battery-hybridization, use of LNG and increased energy efficiency measures ([40], page 3). Below, a selection of vessel types is studied according to the analyzes performed in [40], and an expected electrification-development is deduced.

Cargo ships

The cargo ship-segment includes general cargo ships, container ships, refrigerated vessels, and ro-ro cargo ships. According to ([40], page 13), cargo ships are highly relevant in terms of battery hybridization, due to a varying operation profile with frequent portcalls and high loads in port caused by cargo-handling. Battery hybridization of these ships is technically feasible, but for economical reasons, the possibility for retrofits is much lower than for new-builds: the cargo ship-segment is dominated by numerous old and small general cargo ships, which are often owned by small and little robust companies ([40], page 13-14). These small cargo ships that mostly operate domestically are however technically more suited for hybridization. With governmental incentives and the demand for zero-emission transport of goods purchased by the public where feasible ([38], page 42) this segment can be expected to experience modest plug-in hybridization.

Bulk ships

The bulk ship-segment includes dry bulk, oil tankers, chemical/product-tankers, and gas tankers. These ships have limited possibilities to become fully electric within the next five years, due to the high energy demands ([40], page 19). As for the cargo ships, the smaller vessels that sail shorter routes are more suited for hybridization, but these are also typically older than the vessels sailing international routes. This segment can be expected to experience a development similar to the cargo ship-segment.

Offshore ships

The offshore ship segment includes supply vessels, subsea vessels, and a range of other ships that supply and handle different tasks for the offshore industry. These ships are in general advanced and quite modern and the segment is leading when it comes to environmental-friendly solutions. More than 20 offshore ships that operate in Norway already have battery-hybrid solutions ([40], page 24). The Norwegian government has committed to consider a demand for low- and zero-emission solutions for new ships connected to petroleum production ([38], page 44). Based on this, the offshore ship segment can be expected to experience a plug-in hybridization that exceeds the cargo and bulk ship segments, but complete electrification of vessels is not likely.

Cruise ships

As for the other ship segments, cruise ships also have limited possibilities in terms of total electrification due to large energy needs and long sailing routes. For cruise ships, the most realistic solution for emission reductions is the use of LNG, which is already the chosen fuel-technology for 25% of today's ordered ships ([40], page 33). There are however also cruise lines, like Norwegian Hurtigruten and German AIDA cruises, that have started to implement battery-hybrid solutions into their ships. Stricter regulations of the cruise industry may facilitate the electrification further. Based on this, the cruise ship segment can be expected to experience a battery-hybridization that is more moderate than for the cargo ship segment.

Express boats

For express boats, complete electrification is only viable for a few routes, because of the required energy to maintain the high speed. Most express boats are however eligible for a change in fuel technology or battery hybridization to reduce emissions. Because of county ownership, the express boats are more likely to be hybridized or totally electrified, than for example cargo ships. There are however few or no solutions commercially available for total electrification ([41], page 11).

Shore side port-operations

The shore-side port-operations, like cargo and passenger handling equipment, are also expected to become more environmentally friendly by transitioning to an altered energy system. Cargo handling equipment is especially significant; according to [42], approximately 20% of diesel fuel emissions from cargo handling operations in ports come from RTG-cranes and other cargo handling equipment. This means that reducing the emissions from cargo handling equipment has significant potential in reducing a port's sustainability performance. With the Norwegian goal of having zero-emission ports by 2030, total electrification of shore-side port-operations is compulsory.

3.4 ESS applications in Norwegian ports

To cope with the complex regulations surrounding the ownership and operation of energy storage, the ESSs in ports should be owned and operated by the ports themselves, or by third party companies. In some Norwegian ports, the port authorities have created new companies together with the local grid companies to own and operate AMP-systems [43]. This is a procedure that could work for port ESSs as well. Further, to prevent conflicts of interest, the applications of ESSs should be market-based. An alternative is performing grid applications that are bound by detailed contracts between energy storage owner/operator and grid operator. The grid applications are further complicated as many of the services energy storage can provide to the grid or grid operator are not easily quantifiable. Besides, many of the grid-services require a certain amount of available energy to be stored at all times, which is difficult to appraise. This includes black start support, frequency regulation and spin/non-spin reserves.

With market-based applications, the ESSs are expected to have grid tariffs similar to normal commercial customers, but this may change in the future. In most cases, an ESS can and should be used for multiple applications and several of the behind-the-meter and grid applications can technically be combined. Combining behind-the-meter applications with grid applications is however complex, as described above. In the future, ESSs should however be able to participate in the balancing markets as primary, secondary, or tertiary reserves, as this has already been tested in Finland ([44], page 39).

With the Norwegian grid tariff scheme, leveling of monthly peak demand is strongly incentivized. With the high power demands from maritime vessels, this is likely to be one of the major drivers of energy costs in Norwegian ports. Load leveling can be combined with energy arbitrage, as long as the objective is bill management, i.e to reduce energy costs. This combination is beneficial as both applications are easily quantifiable and the market can help guide the optimal operation. Additionally, in ports with restricted power capacity, energy storage can be used for peak shaving/load leveling in periods where the constraint is active. This can help defer or reduce the investment contributions of grid upgrades. The applications require trading licenses and access to the day-ahead or intraday markets unless the trading is handled by a power supplier or similar.

Chapter 4

Mathematical modeling of problem

4.1 Objective

Based on the current Norwegian regulative environment and the expected development in electrification, a battery system that performs bill management through load leveling and energy arbitrage is chosen for further study. The feasibility of this system is studied through a mathematical model that finds the optimal ESS capacity and power rating based on a given energy storage technology, load, and choice of energy cost parameters. The model ensures that the battery system trades with the grid in a cost-optimal way, allowing both load-leveling and energy arbitrage. Further, the model compares the estimated annual costs of the ESS with the annual cost savings from the operation of the battery. The main objectives of the mathematical model are hence to study whether an investment in a battery system is cost-effective, and what battery capacities and power ratings are optimal.

4.2 System description

The model is based on a simple system setup, which increases flexibility and allows easy analysis of multiple cases. The system consists of a connection to the grid, a battery bank, and a load. The system can easily be modified for different grid power capacities and local energy production. As the control of the battery system is not important for the purpose of this study, this part is left as a black box. A presentation of the system set up is given in Figure 4.1.

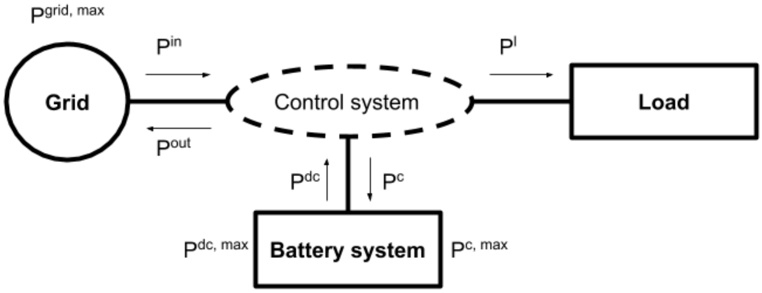


Figure 4.1: Illustration of system set up

4.2.1 Power and energy balance

An important prerequisite for the optimization problem to function is to sustain power and energy balance. By assuming that all power variables and parameters are positive reals, the power balance in the center node can be expressed by equation (4.1).

$$P_t^{in} + P_t^{dc} = P_t^{out} + P_t^c + P_t^l \tag{4.1}$$

To sustain the energy balance in the system, the energy of each time step has to be equal to the sum of the energy stored in the previous time step and the net energy change in the previous time step. In this system, the stored energy in the battery at time t has to be equal to the sum of the stored energy at time $t-1$, adjusted for battery self-discharge, and the energy injected into the battery at time $t-1$, adjusted for efficiency. The size of the timestep is denoted as Δt. The resulting energy balance is given in equation (4.2).

$$B_t^{SOC} = (1 - B^{SD}) \cdot B_{t-1}^{SOC} + (B^{EFF} \cdot P_{t-1}^c - P_{t-1}^{dc}) \cdot \Delta t \tag{4.2}$$

Another important aspect that involves the energy balance of the battery is that the discharged energy at time t can't exceed the stored energy at time $t-1$, adjusted for self-discharge. This is sustained by equation (4.3).

$$P_t^{dc} \cdot \Delta t \leq (1 - B^{SD}) \cdot B_{t-1}^{SOC} \tag{4.3}$$

4.2.2 Annual costs of energy and transmission

The system is assumed to be able to purchase electricity at spot price and sell at spot price, minus the feed-in tariff. The grid tariff is assumed to be as given in equation 3.1, but the fixed tariff is neglected as it is redundant for comparison-purposes. The resulting monthly total cost of energy and transmission is given by equation 4.4.

$$ET_m^{cost} = (G^{EC} + C^{spot}) \cdot E_m^{in} + G^{pt} \cdot P_m^{in,max} - (C^{spot} - G^{ft}) \cdot E_m^{out} \tag{4.4}$$

Here, ET_m^{cost} [NOK] is the total monthly energy and transmission costs, C^{ep} [NOK/kWh] is the DSO energy price, C^{spot} [NOK/kWh] is the spot price, G^{pt} [NOK/kW] is the monthly peak power coefficient and G^{ft} [NOK/kWh] is the feed-in tariff. Assuming the coefficients are constant, the total costs of energy and transmission will depend on three variables: the imported energy, the exported energy, and the monthly peak power.

4.2.3 Annual cost of ESS

Although the LCOS described in Section 2.6 helps provide a measure of the electricity costs of using a specific energy storage technology, it has to be modified to be applied to this system. The goal of the cost model is to derive a measure of annual total life cycle costs of an ESS, excluding all energy-related costs. This can in turn be used to dimension rated power and energy capacity of an ESS, given that the energy-related costs are included when performing the dimensioning. The energy-related costs that are excluded are efficiency-losses and self-discharge. The degradation of energy storage is neglected. The derivation is based on the LCOS and the methodology used in the IRENA cost-of-service tool ([1], page 126-129).

The present value of the total life cycle costs excluding energy-related costs, LCC^{pv}, is given by equation (4.5). The annuity of the life cycle costs, i.e. the annual cost if the present value at T=0 is divided into N parts of equal value, is given by equation (4.6).

$$LCC^{pv} = TCC + \lambda_{r,N} \cdot OPEX_t - \alpha_{r,N} \cdot R_N^{eof} \tag{4.5}$$

$$LCC^{ann} = OPEX_t + \epsilon_{r,N} \cdot \Big(TCC - \alpha_{r,N} \cdot R_N^{eof}\Big) \tag{4.6}$$

In equation (4.5) and (4.6), TCC [NOK] is the total capital costs, $OPEX_t$ [NOK/yr] is the annual non-energy related operation and maintenance costs and R_N [NOK] is the end of life residual value and N [yr] is the economic lifetime. Further, $\lambda_{r,N}$ is the capitalization factor, $\alpha_{r,N}$ is the discount factor and $\epsilon_{r,N}$ is the annuity factor given by equations (4.7), (4.8) and (4.9). In the subsections below, the different cost-elements in equations (4.5) and (4.6) are described briefly.

$$\lambda_{r,N} = \frac{1-(1+r)^{-N}}{r} \tag{4.7}$$

$$\alpha_{r,N} = (1+r)^{-N} \tag{4.8}$$

$$\epsilon_{r,N} = \frac{r}{1-(1+r)^{-N}} \tag{4.9}$$

Total capital costs (TCC)

The TCC is given by the sum of the TCC of the ESU (TCC_{ESU}), the TCC of the power conversion unit (TCC_{PC}), and the other costs related to the ESS (TCC_{Other}). This is defined in equation (4.10).

$$TCC = TCC^{esu} + TCC^{pcu} + TCC^{other} \tag{4.10}$$

The TCC of an ESU can be separated into two parts: one part includes the costs related to the energy installation and is dependent on the energy capacity, while the other part includes the costs related to the power installation of the ESU, and is dependent on the rated power. For battery systems, the power installation cost of an ESU is however zero ([1], page 126). The resulting TCC is presented in equation (4.11).

$$TCC^{esu} = C^{eic,esu} \cdot B^{cap} \tag{4.11}$$

In (4.11), $C^{eic,esu}$ is the energy installation cost of the ESU [NOK/kWh] and B^{cap} is the energy capacity of the ESU [kWh]. The total capital cost of a PCU is given by equation (4.12). Here, $C^{pic,pcu}$ [NOK/kW] is the power installation cost of the PCU, and B^{pow} [kW] is the rated power of the ESS.

$$TCC^{pcu} = C^{pic,pcu} \cdot B^{pow} \tag{4.12}$$

TCC^{other} represents all capital costs that are not related to the investment in the ESU or the PCU. These costs are typically related to purchasing and/or clearing of a suitable site, as well as system installation costs ([1], page 127). These costs are neglected in this analysis.

Operational expenditures

The operational expenditure of an ESS often includes the costs related to the energy loss from efficiency and self-discharge, but here, these costs are left out. This means that only the maintenance cost of the ESU and the PCU are included, as well as the other operational costs that come from maintaining or operating the system. According to [21], the operational costs of the ESU and power conversion can be separated into a fixed and variable part. The fixed part is dependent on the rated power of the ESS, while the variable part is dependent on the rated power times the yearly operating hours. In equation (4.13), the fixed OPEX per kW rated power is denoted as $C^{OPEX,f}$ and the variable OPEX per MWh is denoted as $C^{OPEX,v}$. The yearly operating hours are given as n.

$$OPEX_t = C^{OPEX,f} \cdot B^P + C^{OPEX,v} \cdot B^P \cdot n \tag{4.13}$$

End of life residual value

The end-of-life return value of the system at year N is denoted as R_N. This value is highly uncertain, but it can be modeled as a percent of the TCC. This results in equation (4.14), where C^{eof} is the percentage end-of-life return value.

$$R_N^{eof} = C^{eof} \cdot TCC \tag{4.14}$$

Complete equation for annual cost of ESS

Adding equations (4.10)-(4.14) to (4.6) gives equation (4.15). Here, the power installation cost of the ESU ($TCC^{pic,esu}$), the TCC related to ”other” costs (TCC^{other}) and the variable OPEX ($C^{OPEX,v}$) are neglected.

$$\begin{aligned} LCC_{ann} = \big(&B^{eic} \cdot B^{cap} + C^{pic} \cdot B^{pow}\big) \qquad (4.15)\\ &\cdot \big(\epsilon_{r,N} \cdot (1 - \alpha_{r,N} \cdot C^{eof}\big) + C^{opex,f} \cdot B^{pow} \qquad (4.16)\end{aligned}$$

Assuming all energy storage coefficients are known, the annual costs of battery storage become a function of the capacity and rated power of the battery system.

4.3 Optimization model

4.3.1 Simplifications

- The load is assumed to be known and purely active (reactive power is ignored)
- The number of days in each month is set to 30, meaning that the model is optimizing over 360 days, and not 365.
- For computational-purposes, the timestep is set to 1 hour.
- The round-trip efficiency of the battery is assumed to be constant, and the efficiency of the PCU is assumed to be 100%
- Max charging and discharging capacity is set to be equal.
- The maximum capacity of the grid is set to be equal for import and export.
- Battery degradation is ignored.

4.3.2 Notations

Sets

- m $\longrightarrow$ Month in year index (1, 2, ..., 12)
- d $\longrightarrow$ Day in month index (1, 2, ..., 30)
- h $\longrightarrow$ Hour in day index (0, 1, ..., 23)

Grid Parameters

- $P^{l}_{m,d,h}$ $\longrightarrow$ Active load at month m, day d and hour h [kW]
- $P^{grid,max}$ $\longrightarrow$ Max power capacity of grid [kW]

ESS specific parameters

- N $\longrightarrow$ Calendar life of ESS [years]
- B^{dod} $\longrightarrow$ Depth of discharge of ESU [%]
- B^{sd} $\longrightarrow$ Self discharge of ESU [%/day]
- B^{eff} $\longrightarrow$ Round-trip efficiency of ESU [%]
- B^{eic} $\longrightarrow$ Energy installation cost of ESU [NOK/kWh]
- B^{pic} $\longrightarrow$ Power installation cost of PCU [NOK/kW]
- $B^{opex,f}$ $\longrightarrow$ Fixed yearly OPEX cost coefficient [NOK/kW per year]

Economical parameters

- $C^{d,h\,spot}$ ⟶ Spot price of electricity at month m, day d and hour h
- $G^{ec,s}$ ⟶ Grid energy cost for summer months [NOK/kWh]
- $G^{ec,w}$ ⟶ Grid energy cost for winter months [NOK/kWh]
- $G^{pt,s}$ ⟶ Monthly grid peak power tariff for summer months [NOK/kW/month]
- $G^{pt,w}$ ⟶ Monthly grid power tariff for winter months[NOK/kW/month]
- G^{ft} ⟶ Feed-in tariff [NOK/kWh]
- C^{eof} ⟶ End-of-life return value coefficient [% of TCC]
- $\alpha_{r,N}$ ⟶ Discounting factor of year N with interest rate r
- $\epsilon_{r,N}$ ⟶ Annuity factor of year N with interest rate r

Variables

- $P^{in}_{m,d,h}$ ⟶ Power from grid to system at month m, day d and hour h [kW]
- $P^{out}_{m,d,h}$ ⟶ Power from system to grid at month m, day d and hour h [kW]
- $P^{c}_{m,d,h}$ ⟶ Power to ESS at month m, day d and hour h [kW]
- $P^{dc}_{m,d,h}$ ⟶ Power from ESU at month m, day d and hour h [kW]
- $B^{SOC}_{m,d,h}$ ⟶ Energy available in battery bank at month m, day d and hour h [kWh]
- $P^{in,max}_{m}$ ⟶ Monthly peak power flow from grid [kW]
- G^{ft} ⟶ Monthly peak power coefficient of grid tariff [NOK/kW]
- G^{ec} ⟶ Monthly energy cost of grid tariff[NOK/kWh]
- B^{cap} ⟶ Energy capacity of battery [kWh]
- B^{pow} ⟶ Rated power capacity of battery [kW]

4.3.3 Objective function

The objective function of the problem is to minimize the annual costs of supplying the load. To determine whether the use of ESSs can help to lower the annual costs, the annual costs of energy storage must be included in the annual costs of energy and transmission. This means that if the inclusion of an ESS is profitable, the optimization model will dimension the energy capacity and power rating to the optimal sizes. On the other hand, if the inclusion of a battery storage system is not profitable, the optimization model will simply set the energy capacity and power rating to zero, which will result in an ESS cost of zero and the model will be solved as if the ESS was not connected.

$$min\left(ET^{cost} + B^{cost}\right) \tag{4.17}$$

4.3.4 Constraints

To control the behaviour of the variables in the optimization model, several constraints are added. In addition to controlling the variables, some constraints are used to perform necessary calculations and make the model more interpretable. The constraints can be divided into equations concerning *Energy and transmission related costs*, *Annual ESS costs*, *Power flow balance*, *Energy balance*, *Monthly peak power*, *Battery constraints* and *Miscellaneous*.

Annual energy and transmission related costs

The annual energy and transmission-related costs, that are a part of the objective function, are calculated using (4.18).

$$ET^{cost} = \sum_{m=1}^{12} \left(\sum_{d=1}^{30} \sum_{h=0}^{23} \left(P^{in}_{m,d,h} \cdot \left(C^{spot}_{m,d,h} + G^{ec} \right) - P^{out}_{m,d,h} \cdot \left(C^{spot}_{m,d,h} - G^{ft} \right) \right) + P^{in,max}_{m} \cdot G^{pt} \right) \tag{4.18}$$

Annual ESS costs

The costs of an ESS is dependent on the storage capacity and rated power, as derived in equation (4.15).

$$B^{COST} = \left(B^{eic} \cdot B^{cap} + C^{pic} \cdot B^{pow} \right) \cdot \left(\epsilon_{r,N} \cdot \left(1 - \alpha_{r,N} \cdot C^{eof} \right) \right) + B^{opex,f} \cdot B^{pow} \tag{4.19}$$

Power flow balance

The power flow balance is controlled by equation (4.20). As the power flow in each direction is separated and all the power flow variables are defined positive, this results in negative signs in front of $P^{out}_{m,d,h}$ and $P^{dc}_{m,d,h}$.

$$P^{in}_{m,d,h} - P^{out}_{m,d,h} = P^{l}_{m,d,h} + P^{c}_{m,d,h} - P^{dc}_{m,d,h} \tag{4.20}$$

Energy balance

The energy balance of the system is sustained by the constraints given in equations (4.21a) and (4.21b). Equation (4.2) and (4.3) proved that the energy balance is dependent on the stored energy and the net charged energy in the previous timestep. As the chosen time step is one hour, the battery capacity is modeled in kWh and all power flows are modeled in kW, the net charged energy can be directly interpreted as the power flow, adjusted for efficiency-losses.

$$B^{soc}_{m,d,h} = \begin{cases} B^{soc}_{m,d,h-1} \cdot (1 - B^{sd}) + \dots \\ \qquad P^{c}_{m,d,h-1} \cdot B^{eff} - P^{dc}_{m,d,h-1} & \text{if } h > 0 \\ B^{soc}_{m,d-1,23} \cdot (1 - B^{sd}) + \dots \\ \qquad P^{c}_{m,d-1,23} \cdot B^{eff} - P^{dc}_{m,d-1,23} & \text{if } d > 0 \text{ and } h = 0 \\ B^{soc}_{m-1,30,23} \cdot (1 - B^{sd}) + \dots \\ \qquad P^{c}_{m-1,30,23} \cdot B^{eff} - P^{dc}_{m-1,30,23} & \text{if } m > 0,\ d = 1 \text{ and } h = 0 \\ (1 - B^{dod}) \cdot B^{cap} & \text{if } m = 0,\ d = 1 \text{ and } h = 0 \end{cases} \tag{4.21a}$$

$$\begin{cases} P^{dc}_{m,d,h} \leq B^{soc}_{m,d,h-1} \cdot (1 - B^{sd}) & \text{if } h > 0 \\ P^{dc}_{m,d,h} \leq B^{soc}_{m,d-1,23} \cdot (1 - B^{sd}) & \text{if } d > 0 \text{ and } h = 0 \\ P^{dc}_{m,d,h} \leq B^{soc}_{m-1,30,23} \cdot (1 - B^{sd}) & m > 1, d = 1 \text{ and } h = 0 \\ P^{dc}_{m,d,h} \leq 0 & \text{if } m = 0,\ d = 1 \text{ and } h = 0 \end{cases} \tag{4.21b}$$

Monthly peak power

To calculate the power-related grid tariff, the monthly peak power is used. The peak power is simply the highest single value of $P^{in}_{m,d,h}$ for each month and as long as there's a cost related to increasing the peak value, equation 4.22 will constrain $P^{in,max}_{m}$ equal to the monthly peak.

$$P^{in,max}_{m} \geq P^{in}_{m,d,h} \tag{4.22}$$

4.3.5 Capacity constraint

Equation 4.23 controls that the SOC of the battery stays below the given storage capacity.

$$B^{soc}_{m,d,h} \leq B^{cap} \tag{4.23}$$

4.3.6 Miscellaneous

The last equations constrain the power flow variables to be positive and sets the correct grid tariffs according to winter and summer months.

$$P^{c}_{m,d,h}\ ,\ P^{dc}_{m,d,h}\ ,\ P^{in}_{m,d,h}\ ,\ P^{out}_{m,d,h} \geq 0 \tag{4.24}$$

$$G^{ec} = \begin{cases} G^{ec,s} & if\ 3 < m < 10 \\ G^{ec,w} & if\ m < 4\ or\ m > 9 \end{cases} \tag{4.25}$$

$$G^{pt} = \begin{cases} G^{pt,s} & if\ 3 < m < 10 \\ G^{pt,w} & if\ m < 4\ or\ m > 9 \end{cases} \tag{4.26}$$

Chapter 5

Description of case studies

5.1 Introduction

To study the potential of using energy storage in the ports of the future, three different ports have been selected for further analysis. These ports have been chosen because they have vessel traffic that differs substantially, something that should give a good insight into how the benefits of utilizing energy storage can vary. The first port is dominated by passenger traffic, the second port is a cargo port and the third port is an offshore/subsea vessel base. For each of these ports, two scenarios are studied for the development in electrification: the first scenario models an aggressive implementation of AMP, while the second scenario models an aggressive implementation of AMP and plug-in hybridization of parts of the fleet. Lastly, the power needs in the two scenarios for each of the three ports are presented.

5.2 Port 1 - City Port

5.2.1 Introduction

The first port that is studied represents a City port, which is a port dominated by passenger traffic like cruise traffic, passenger ro-ro vessels, ferries, and so on. As the example port, the passenger-vessel traffic of Trondheim Port has been used. Trondheim Port has a very strategic location close to the city center of Trondheim, with roads and railroad nearby. Trondheim Port is a hub for passenger-traffic along the west coast, with daily departures of Kystruta, ferries, and a steadily growing cruise-traffic. The port consists of Ila Pir, Pir I and II, Turistskipskaia, and several smaller quays [45].

5.2.2 Description of ship traffic

The ship traffic in Trondheim Port is dominated by three different segments: *Kystruta*, cruise traffic, and express boat traffic. Trondheim Port is one of the selected ports of *Kystruta*, which is a ro-ro ferry line that sails along the western coast of Norway. In

Trondheim, both the southbound and northbound ships berth for 3 hours and 15 minutes every day [46]. This means that the daily duration of stay for *Kystruta*-vessels is 6 hours and 30 minutes, accounting for a total of 2,372 hours and 30 minutes during the year. This equals a use factor of more than 25%. The portcalls are from 06:30 to 09:45 and from 10:00 to 13:15.

The cruise traffic in Trondheim Port is currently experiencing tremendous growth with 82 portcalls in 2019, 104 portcalls expected in 2020, and more than 125 portcalls registered for 2021 already. The typical cruise traffic in Trondheim can be described by using the cruise traffic of 2019, illustrated in Figure 5.1. The cruise traffic in Trondheim was studied in [7] and some key takeaways are summarized below. The peak season for cruise-traffic is, as expected, during the summer months of May, June, July, and August. The average duration of stay for cruise ships in 2019 was 9.09 hours, ranging from a minimum of approximately 5 hours to a maximum of 31 hours. The total utilization time, or the time there were cruise ships portcall, was roughly 764 hours in 2019, which amounts to a use factor of 8.7% (if all cruise ships are assumed to use the same quay). The average cruise ship size in 2019, measured in gross registered tonnage, was 60,114 GT, but the size of the biggest cruise ship that portcalled was 139,702 GT [7].

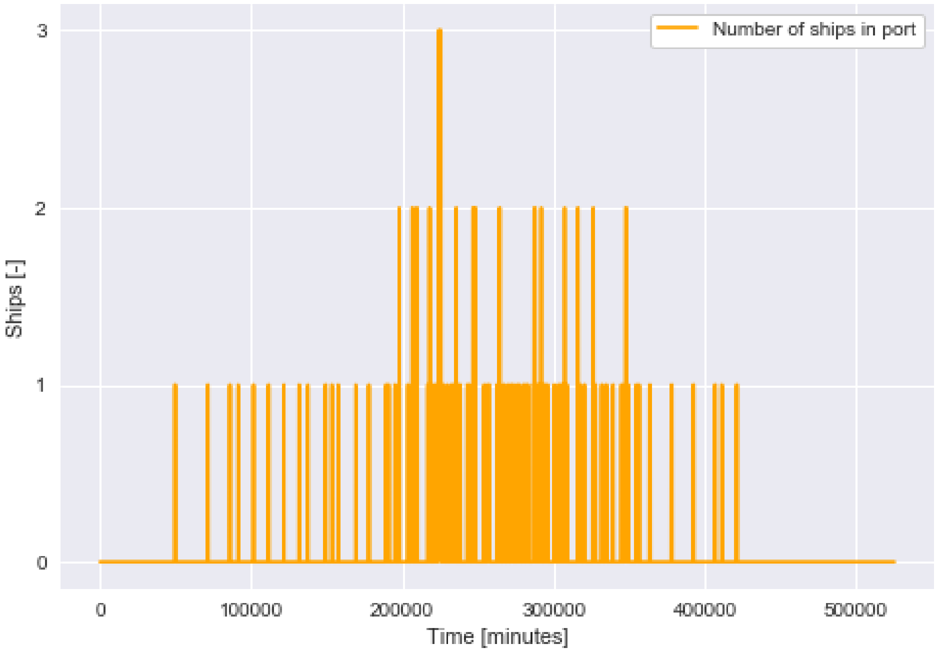


Figure 5.1: Cruise traffic in Trondheim Port in 2019

The last type of ship traffic in Trondheim port (in this analysis) is from express boats. From Trondheim there are two express boat-routes; one 25 minute route across the fjord and a longer route to Kristiansund with varying length depending on the stops. The short ferry has 13 daily departures from Monday to Friday and 8 daily departures in the weekend. Apart from the traffic from cruise ships and *Kystruta* there are also cement carriers, reefer ships, and other commercial ships that portcall in Trondheim. These ships, along with the express boats, will be ignored in this analysis.

5.3 Port 2 - Cargo Port

5.3.1 Introduction

The second port that is studied is a cargo port. A cargo port typically handles many types of cargo; containers, dry bulk, liquid bulk and breakbulk and operates both regular cargo ships and ro-ro vessels. As the example port, the vessel traffic of Haugesund Cargo Terminals Husøy has been used.

5.3.2 Description of ship traffic

Haugesund Cargo Terminals Husøy is Norway's third largest port area measured in cargo ([47], page 5). With 13 different berths, the port can offer specialized terminals for ro-ro, container, bulk, general cargo, breakbulk, and fishery. In 2018, Haugesund Cargo Terminals Husøy handled one million tonnes of goods, equivalent to 32,000 TEU. The amount of goods handled is expected to grow significantly to 50,000 TEU in 2020, 80,000 in 2025 and 100,000 in 2030 ([47], page 17-19). One of the main reasons for this expected growth is that the port is aiming to become a leading transshipment terminal between domestic and international routes, something that would greatly increase the cargo traffic. In the analysis, the growth in cargo traffic is neglected.

In 2018, Haugesund Cargo Terminals Husøy had a total of 850 portcalls by 96 different ships. In 2019, the number of portcalls rose to 892 by 100 ships. The traffic is dominated by several ro-ro vessels and cargo ships that use the cargo terminals frequently. The average duration of stay for all the ships calling is 5.85 hours in 2018 and 6.56 hours in 2019. The average size of the portcalls in 2018 is roughly 5,921 GT and in 2019 it is roughly 6,103 GT. The ship traffic of 2019 is presented in Figure 5.2, with the number of ships in port at each minute on the y-axis and the minutes throughout 2019 on the x-axis.

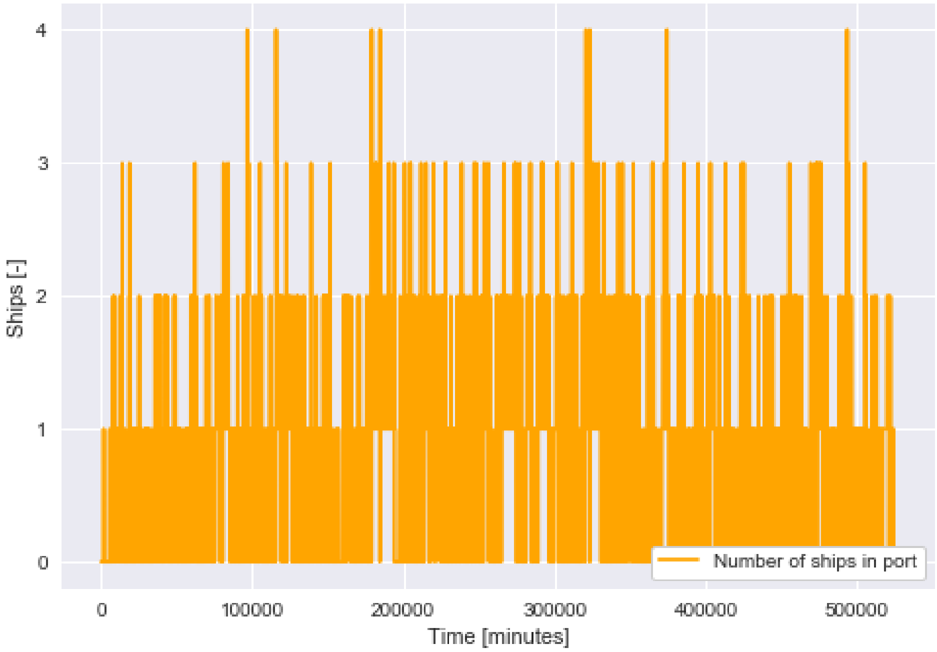


Figure 5.2: Number of ships portcalling in Husøy port in 2019

5.3.3 Cranes, conveyors and commercial vehicles

In addition to cargo ship traffic, the port on Husøy is also dominated by a lot of land-based activity to transport cargo around. This transport consists of a big harbor crane, belt conveyors, reach stackers, front loaders, forklifts, and various smaller vehicles. The impact of this traffic is not included in this report.

5.4 Port 3 - Subsea/offshore base

5.4.1 Introduction

The third port that is studied represents a subsea/offshore base with traffic from subsea and offshore supply ships. As the example port, Haugesund Subsea and offshore base Killingøyis used. Haugesund Subsea and offshore base Killingøy consists of four different companies that serve the subsea and offshore industry in western Norway [48]. The base consists of five different quays and some of these quays are already equipped with shore power systems [48].

5.4.2 Description of ship traffic

As a basis for the analysis, the ship traffic of 2019 is used. In 2019, Haugesund Subsea and Offshore base had 212 portcalls by 41 ships. The average duration of stay for all the ships calling is 90.1 hours in 2019. The average size of the ships portcalling in 2019 is roughly 6,956 GT. The ship traffic of 2019 is presented in Figure 5.3. The number of ships in port at each minute is presented on the y-axis, and the minutes during the year are on the x-axis.

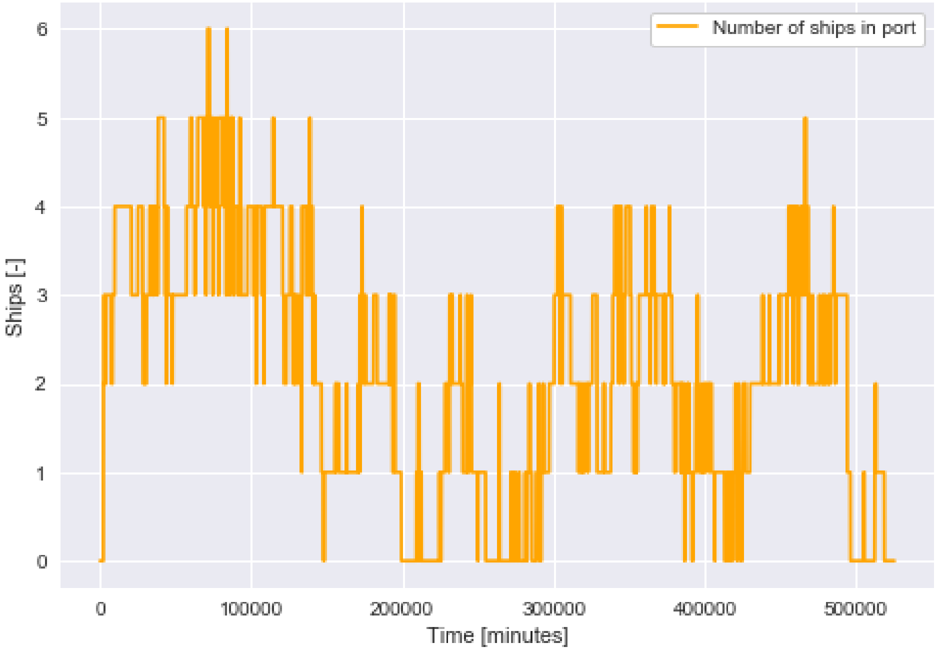


Figure 5.3: Number of ships in Killingøy port at each minute throughout 2019

5.5 Description of scenarios

To determine how the feasibility of using ESS in a port changes with different levels of maritime electrification, two scenarios for port loads are drawn and a scenario analysis is conducted. The scenario analysis is not an attempt to forecast the future electrification of maritime traffic, it's rather a tool to study how different levels of electrification will influence the business case of investing in port ESSs. The scenarios are drawn based on the deducted development in Norwegian maritime traffic according to Section 3.3. The two scenarios can be characterized as:

- Scenario 1: Aggressive implementation of AMP
- Scenario 2: Aggressive implementation of AMP and plug-in hybridization of parts of fleet

5.5.1 Scenario 1: Aggressive implementation of AMP

As introduced in Section 3.3, the Norwegian government has, together with the municipalities and port authorities, a goal of having zero-emission ports where feasible by the end of 2030 ([38], page 7). This goal indicates that the Norwegian government is planning to increase the utilization of AMP, as this is a relatively easy way to reduce or mitigate the port emissions. In Scenario 1, all the vessels that portcall in the three case ports are assumed to be using AMP.

When estimating the AMP-need of a ship, the gross tonnage, a standard measure of ship size, is often used. In the application process for financial aid from Enova Sf, the AMP-need is estimated using the coefficients presented in Table 5.1. The power consumption of all vessel types in Scenario 1 is calculated using the coefficients given in Table 5.1, except "Kystruta." The AMP need of the ships sailing *Kystruta* can be found by looking at the ships that have already installed AMP-equipment. According to TU, the power need of the Hurtigruta ships in port are approximately 1 MW, but this will of course vary from ship to ship [49]. To model this variation, the power need of each Hurtigruta ship is chosen as a random number between 900kW and 1100kW. The consumption during a port call is assumed to be constant for all vessel types and the connection and disconnection time of the AMP equipment is neglected. The ships with portcalls that are shorter than 60 minutes are ignored.

Size [GT]	Container ships	Offshore supply ships	Passenger vessels
$\leq$ 999	31 kW	45 kW	20 kW
1,000 - 4,999	121 kW	144 kW	119 kW
5,000-9,999	332 kW	345 kW	272 kW
10,000-24,999	473 kW	553 kW	570 kW
25,000-49,999	864 kW	912 kW	1,194 kW
50,000-99,999	1,535 kW	1,144 kW	2,100 kW
100,000 $\leq$	2,295 kW	1,248 kW	2,912 kW

Table 5.1: Estimated power need in port for a selection of vessel types

5.5.2 Scenario 2: Aggressive implementation of AMP and plug-in hybridization of parts of the fleet

In Scenario 2, a further continuation of the electrification in Scenario 1 is modeled. The degree of electrification is assumed to be dependent on the feasibility of reducing emissions, as described in Section 3.3. Implicitly, this results in plug-in hybridization of parts of the fleet. Also, the impact of the implementation of new fuel technologies and new technical and operational measures are ignored - only the implementation of AMP, hybridization, and complete-electrification is studied. Similarly to Scenario 1, the ships with portcalls that are shorter than 60 minutes are ignored.

The expected electrification-development is used to estimate the added future power need from plug-in hybrid and total-electric ships that are used in Scenario 2. For the vessel types where there are real examples of plug-in hybrid vessels that are planned or exist today, the battery capacity of each ship is estimated based on the "size per battery capacity”-factors of the real examples. For the vessel types that have no real examples of plug-in hybrid solutions, other assumptions are made to size the batteries. The electrical load from the charging of batteries is added to the AMP-need from Scenario 1. The charging loads are calculated with the capacity of the ESS, divided by the duration of each portcall, hence assuming a constant charging load through the portcall. For the vessel types where a share of plug-in hybrid ships are assumed, these shares are used to randomly select what portcalls are assumed plug-in hybrid.

Cargo ships

No examples of plug-in hybrid cargo ships were found, but a methodology corresponding to [40] is used. The shares of cargo ships assumed to be plug-in hybrid and the corresponding battery capacities in Scenario 2 are given in Table 5.2.

Size [GT]	≤ 999	1,000 - 4,999	5,000-9,999	10,000-24,999	25,000 $\leq$
Share	40%	40%	30%	25%	15%
Cap.	1 MWh	2 MWh	3 MWh	4 MWh	5 MWh

Table 5.2: Estimated battery capacity of plug-in hybrid cargo and bulk ships

Bulk ships

This segment is expected to experience a development similar to the cargo ship-segment and the same shares and capacities given in Table 5.2 are used.

Offshore ships

There are multiple battery-hybrid offshore ships in operation, but most of these are not plug-in hybrid. Viking energy, Normand Server, and Normand Supporter are however three examples of offshore ships that are plug-in hybrid. Viking energy is 5,073 GT and has a battery capacity of 653 kWh [50], while Normand Server and Normand Supporter are both 4,590 GT and have battery capacities of 560 kWh [51]. This means that Viking energy has about 7.8 GT/kWh battery capacity, while the Normand-ships have about 8.2 GT per kWh battery capacity. Assuming these ”size per battery capacity”-factors can be used as starting points, the gross tonnage per battery capacity of the offshore ships are assumed to be a random number in the range 7-9 GT per kWh. The share of ships that are plug-in hybrid is assumed to be 50%, irrelevant of the size of the ship.

Cruise ships

There are currently two famous plug-in hybrid ships that are either in operation or planned. AidaPerla, at 125,572 GT, has a battery system with a capacity of 10 MWh [52], while MS Roald Amundsen, at 20,889 GT, has a battery system with a capacity of 1,356 MWh [53]. This results in a ”size per battery capacity”-factor of 12.5 GT/kWh battery capacity for AidaPerla and 15.4 GT/kWh battery capacity for MS Roald Amundsen. Using these factors as a reference, and assuming greater variation in capacities than for the offshore vessels, the battery capacity of the plug-in hybrid cruise ships are assumed to be a random number in the range 10-18 GT per kWh. The share of ships that are plug-in hybrid is assumed to be 20%.

For ”Kystruta,” the ro-ro ferry line that sails along the western coast of Norway, a much more ambitious implementation of battery-hybrid solutions can be expected. In the period 2021-2030, the suppliers of Kystruta need to reduce the emissions by 25% compared to the levels of 2015, and both suppliers have chosen ships using gas in combination with batteries. Based on this, it can be expected that all the ships that sail Kystruta will need charging power, in addition to AMP. According to [54], the Havila ships will have battery systems with capacities of 6.1 MWh. This is assumed to be the battery capacity of all the ships sailing Kystruta.

Express boat

As there are no commercially available solutions for the plug-in hybridization or total electrification of express boats, these vessels are ignored in this analysis ([41], page 11).

5.6 Port loads

The resulting case port loads for the city, cargo and offshore port, based on the assumptions made in Scenario 1 and 2, are presented in Figures 5.4-5.9.

5.6.1 Scenario 1

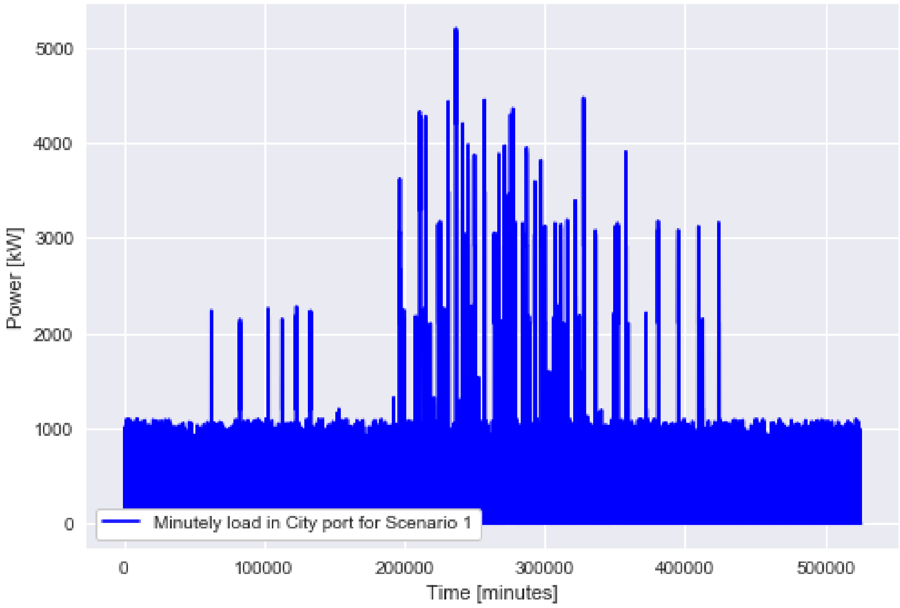


Figure 5.4: Minutely load in City port for Scenario 1

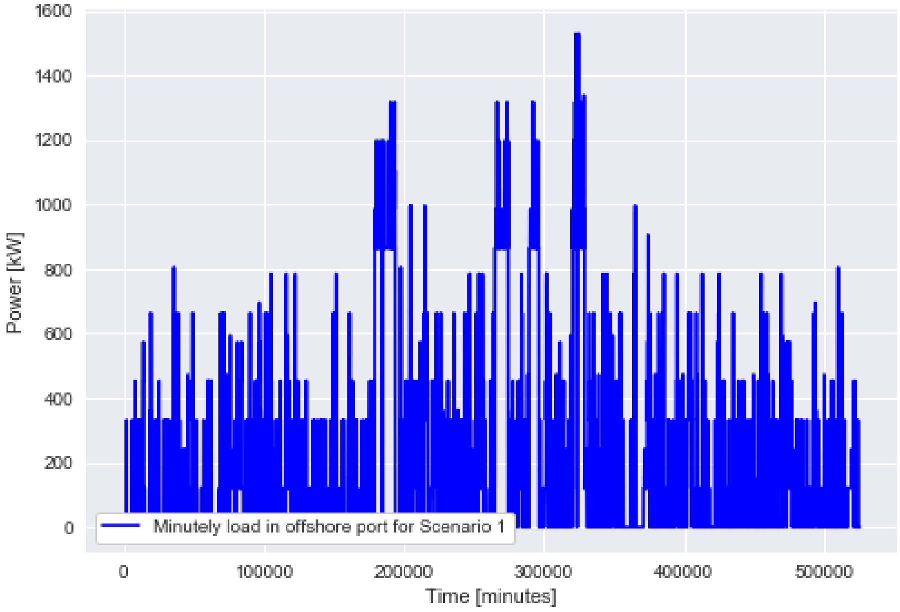


Figure 5.5: Minutely load in Cargo port for Scenario 1

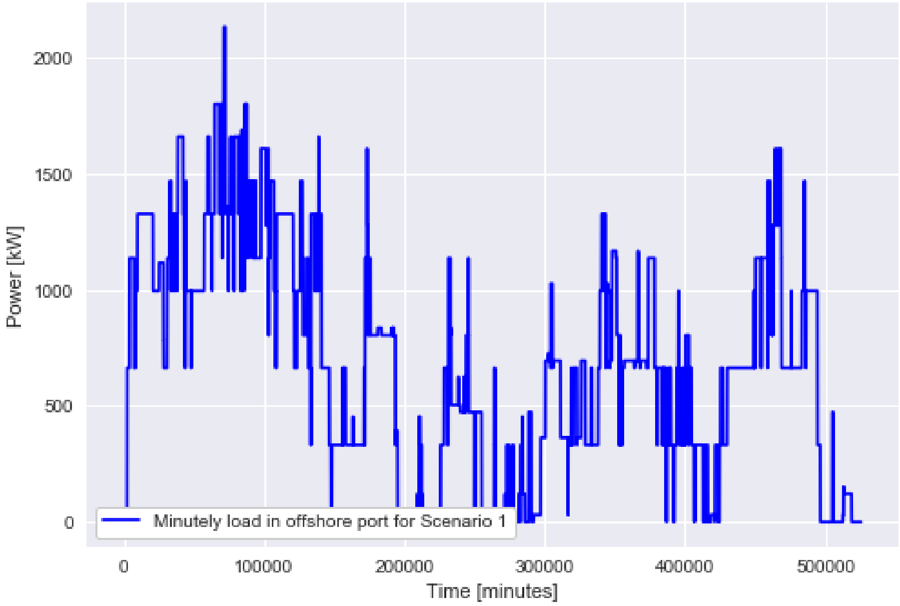


Figure 5.6: Minutely load in Offshore port for Scenario 1

5.6.2 Scenario 2

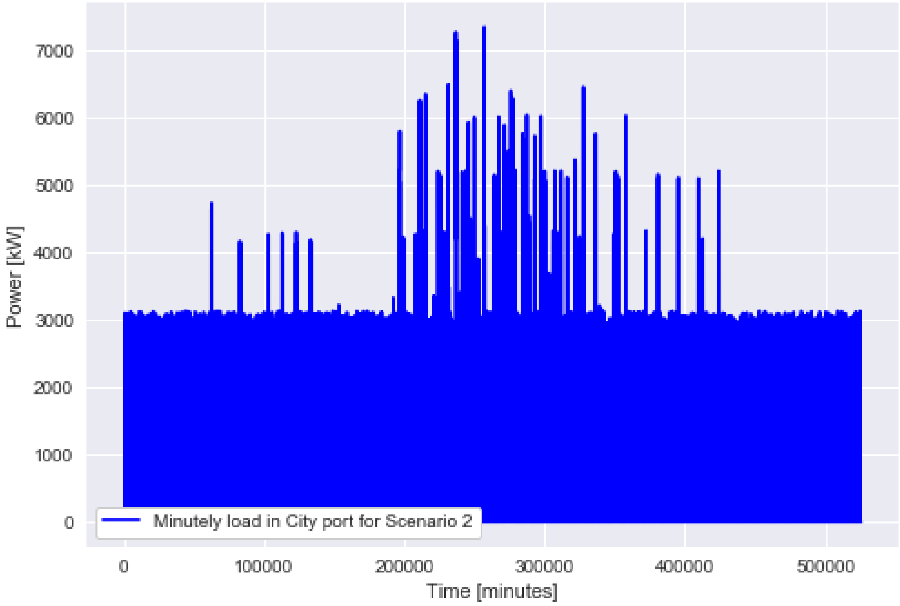


Figure 5.7: Minutely load in City port for Scenario 2

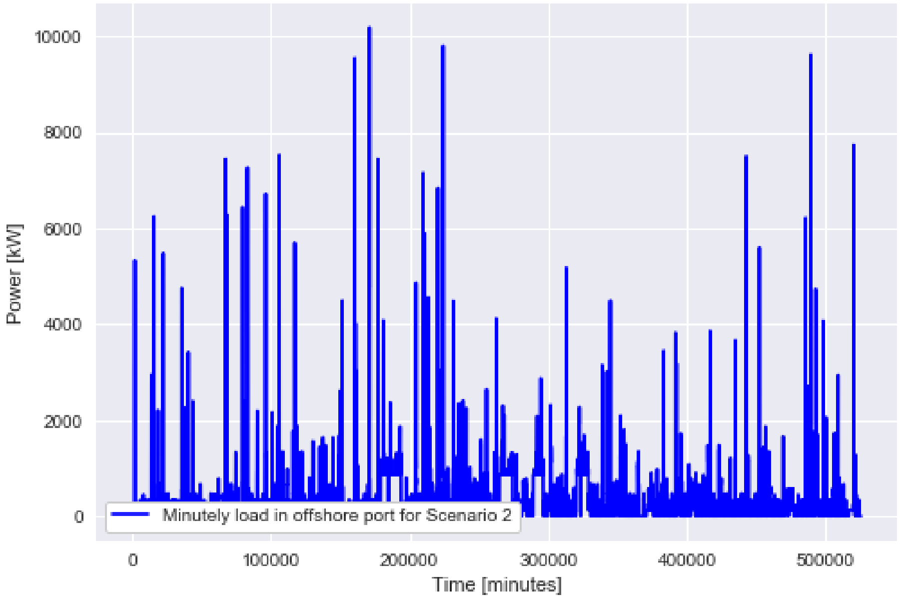


Figure 5.8: Minutely load in Cargo port for Scenario 2

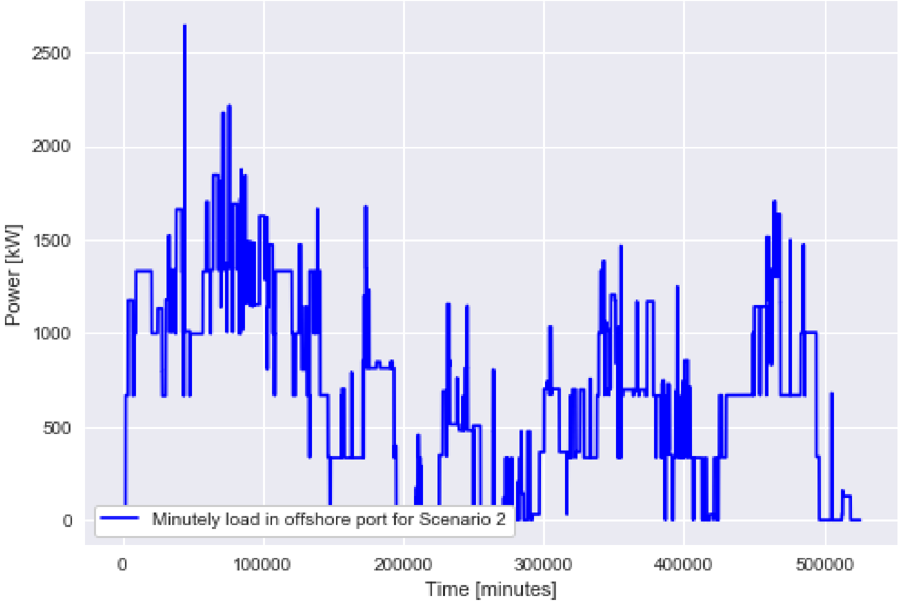


Figure 5.9: Minutely load in Offshore port for Scenario 2

Chapter 6

Results of case studies

6.1 Introduction

In this chapter, the results of the case studies are presented. First, the results of the initial analysis using both the 2016 and 2030 ESS characteristics are given. The operating patterns of these ESSs are presented in yearly and monthly plots. Second, the results of the case studies with constrained grid power capacities of 70%, 80%, and 90% of peak loads are given. The costs of using ESS to supply the loads are compared to the costs in the initial analysis - these costs can in turn be compared to the costs of upgrading the grid capacities. Third, a sensitivity analysis is conducted and the results are presented. The sensitivity of the grid tariffs, end-of-life return value, and the electricity spot price are examined.

6.2 Initial analysis

In the initial analysis, model specifications that reflect the current conditions in Norway are used. The interest rate is set to 4%, which is equal to the recommended rate used for social-economic calculations in Norway. As the end-of-life value of battery systems are highly uncertain, this parameter is set to be zero. The grid tariffs are set to the averages derived in Table 3.1. The model separates between the summer months of April to September and the winter months of October to Mars.

- Interest rate $\longrightarrow r = 4\%$
- End-of-life return value $\longrightarrow C^{eof} = 0\%$
- Summer grid tariff energy cost $\longrightarrow G^{ec,s} = 0.033 NOK/kWh$
- Winter grid tariff energy cost $\longrightarrow G^{ec,w} = 0.040 NOK/kWh$
- Summer grid tariff monthly peak power cost $\longrightarrow G^{pt,s} = 31.28 NOK/kW$

- Winter grid tariff monthly peak power cost $\longrightarrow G^{pt,w} = 53.53 NOK/kW$
- Grid feed-in tariff $\longrightarrow G^{ft} = 0.0134 NOK/kWh$
- Max power capacity of grid $\longrightarrow P^{grid,max} = inf$

The ESS characteristics that are used are given in Tables 2.1 and 2.2, while the costs are given in Tables 2.3 and 2.4. In the initial analysis, the Norwegian system price for 2019 is used as the spot-price. This is presented in Figure 6.1.

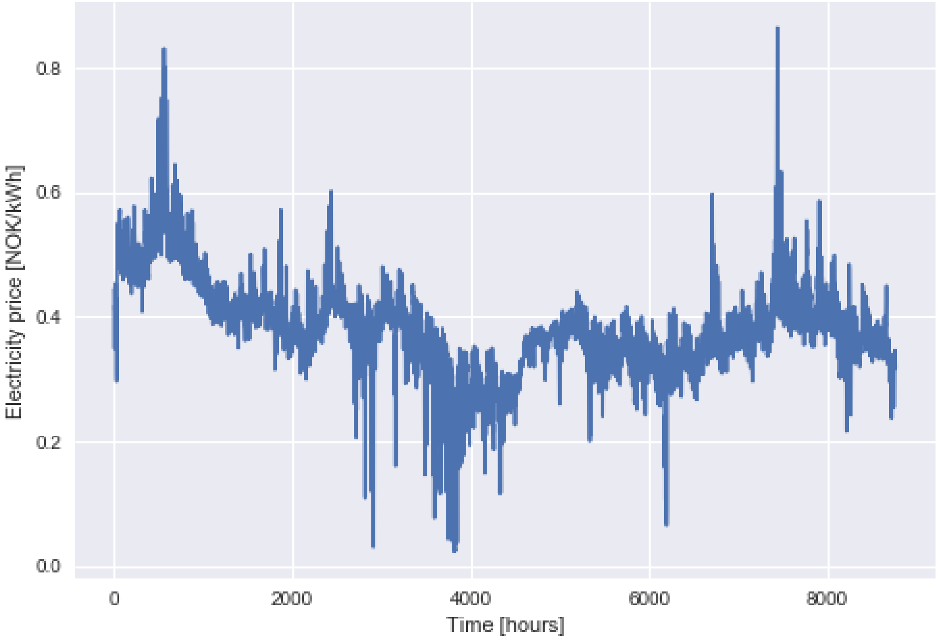


Figure 6.1: Norwegian system price 2019

6.2.1 Annual costs of supplying loads

The annual costs of supplying the loads in the two scenarios for all three ports for the cost-parameters in the initial analysis are given in Table 6.1.

Load/Cost element	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
Energy costs [NOK/yr]	1,406,470.3	3,401,255.6	703,475.0	1,012,843.1	2,652,979.2	2,688,038.8
Peak power cost [NOK/yr]	1,741,449.0	2,976,611.5	565,872.0	2,891,601.9	844,492.2	892,935.6
Total cost [NOK]	3,147,919.3	6,377,867.1	1,269,347.0	3,904,445.0	3,497,471.4	3,580,974.4

Table 6.1: Annual costs of supplying loads

6.3 Results of initial analysis using 2016 battery characteristics

The initial model specifications applied to the optimization problem for the six loads result in optimal battery capacities and rated powers of zero for all battery technologies except NaS for *Cargo port - Scenario 2*. The cost reductions of utilizing the NaS-system with 2016 battery parameters for *Cargo port - Scenario 2* are however minor. The optimal battery capacity, power rating and annual cost savings of the NaS-system for *Cargo port - Scenario 2* is presented in Table 6.2.

Port load	Tech.	Cap [kWh]	Power [kW]	Savings [NOK/yr]
Cargo port, S2	NaS	811.7	811.7	13,518.1

Table 6.2: Optimal battery capacity, rated power and annual savings of NaS battery system in scenario 2 for the Cargo port.

As can be seen in Table 6.2, the optimal ESS capacity is equal to the optimal rated power, which means that the system can discharge at rated power for one hour. It does however also mean that the ESS can be fully charged in a bit more than one hour (when taking the efficiency into account). The cost components of the initial system with the optimally sized 2016 NaS system and the difference from the initial system without ESS are presented in Table 6.3.

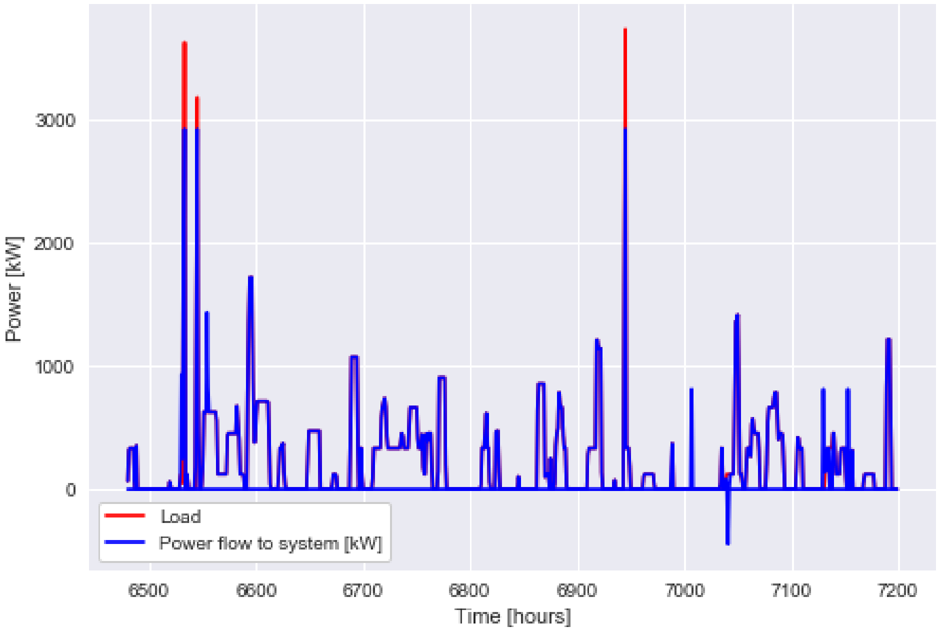
Cost component	With NaS	Diff.
Energy cost [NOK/yr]	1,007,947.1	-4,896
Peak power cost [NOK/yr]	2,422,210.0	-469,391.9
Battery-system cost [NOK/yr]	460,769.7	-460,769.7
Imported energy [kWh]	2,489,015.3	+24,393.9
Exported energy [kWh]	8046.2	+8046.2
Avg. spot price [NOK/kWh]	0.3671	-0.0046

Table 6.3: Optimal battery capacity, rated power and annual savings of NaS battery system for *Cargo port - Scenario 2*.

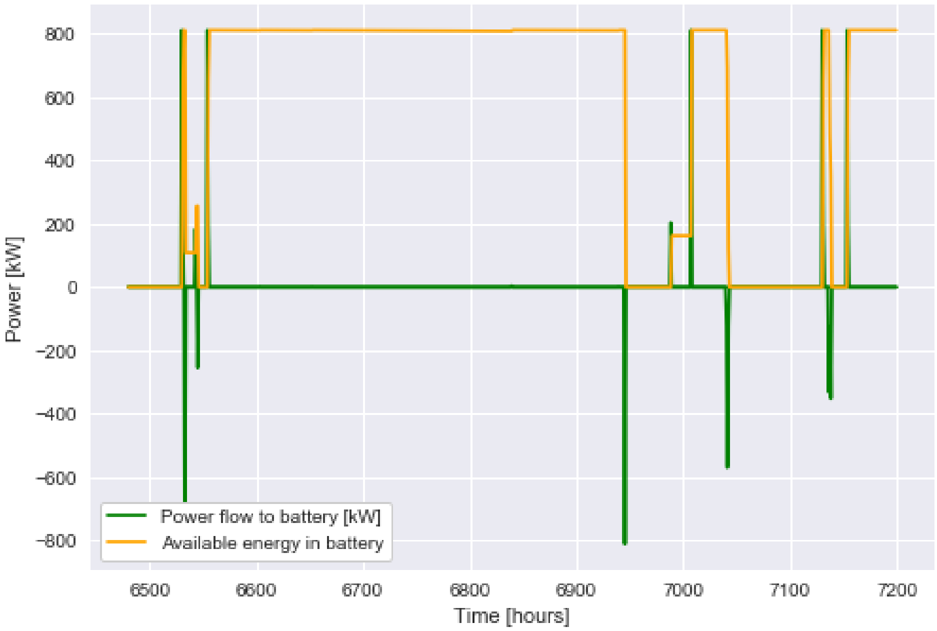
From the reduction in cost components between the initial system and the system with NaS, it's clear that the main advantage of implementing ESS in a port is the reduction of costs related to peak tariffs. The implementation of the NaS-system leads to a 16% decrease in annual costs related to peak tariff, but only a roughly 0.5% reduction in the costs related to energy. The battery system does however leverage importing energy at a lower spot price, but this difference is minor. The system with batteries imports roughly 24.39 MWh more energy than the initial system, but only exports about 8.05 MWh. This means that more than 16 MWh energy is lost due to inefficiencies and self-discharge in the ESS.

In Figure 8.1 in appendix, the yearly system power flow is modeled. The upper two plots show the hourly load and the power flow to the system, while the lower two plots show the power flow to and from the ESS and the available energy capacity in the energy storage unit. The peak-shaving effect of the ESS is clear, as many of the peaks are significantly lower in the plot showing the power flow to the system than in the plot showing the load. The charging and discharging of the energy storage unit varies through the year, with higher activity around the 4000th hour, i.e. mid-May to mid-June.

To better visualize the effects of the energy storage unit, a plot of the system for an arbitrary month is presented in Figure 6.3. In Figure 6.3, the upper plot shows load is displayed in red, while the power flow to the system is displayed in blue. The lower plot shows the corresponding charging and discharging activity. The plot clearly shows that the energy storage unit shaves the three peaks to the same level, which is a result of the Norwegian peak tariff scheme. Further, the plots show how the system charges the energy storage unit many hours ahead of the third peak, leveraging the lower price. In month eight, there's just one instance where the system chooses to export energy to the grid, which indicates that energy arbitrage is not very profitable.



(a) System load and power to/from system for month eight (August)



(a) Power to/from ESS and available energy for month eight (August)

Figure 6.3: Monthly power flow in system supplying Scenario 2 for the Cargo port using optimally sized NaS ESS

6.4 Results of initial analysis using 2030 battery characteristics

The annual costs of supplying the load in Scenario 1 and Scenario 2 for the City and Cargo port can be reduced significantly by utilizing the expected 2030 battery characteristics. In the City port, four battery technologies can reduce the annual costs; VRFB, NaNiCl, NaS, and Li-ion NCA. In the Cargo port, only NaS can reduce the annual costs in Scenario 1, while VRFB, NaNiCl, NaS, Flooded Lead-acid, Li-ion LFP, Li-ion NCA, and Li-ion NMC can reduce the annual costs in Scenario 2. The optimal capacities, power ratings, and annual savings of supplying the port loads using these battery technologies with the expected 2030 characteristics are given in Table 6.4.

Case	Tech.	Cap. [kWh]	Pow. [kW]	Savings [NOK/yr]
City, S1	VRFB	277.8	138.9	3,280.7
	NaNiCl	329.8	171.4	12,402.0
	NaS	379.4	189.7	28,619.1
	NCA	334.9	150.7	4,126.3
City, S2	VRFB	547.5	273.7	4,889.0
	NaNiCl	959.6	478.3	32,642.4
	NaS	1,040.2	520.1	77,991.4
	NCA	930.5	418.7	10,920.7
Cargo, S1	NaS	57.2	28.6	277.9
Cargo, S2	VRFB	3,508.3	2,695.5	157,495.8
	NaNiCl	4,122.2	3,053.9	323,277.4
	NaS	4,333.7	3,566.7	627,430.6
	F. Lead-acid	1,623.5	811.7	7,360.9
	LFP	901,9	811.7	27,124.0
	NCA	2286,3	2,057.5	154,013.1
	NMC/LMO	2286,3	2,057.5	119,197.1

Table 6.4: Main results using the 2030 energy storage characteristics

Table 6.4 shows that NaS is the technology that gives the highest cost reductions, followed by NaNiCl in all scenarios except *Cargo port - Scenario 1*. In the City port scenarios, all the energy storage technologies have similar optimal capacities and power ratings with ”energy to power”-ratios of roughly 2.0. This means that the batteries can discharge for roughly two hours at rated power. This is also the case in Scenario 1 for the Cargo port, but in Scenario 2, the ”energy to power”-ratios vary between 1.1 and 2.0. Although all the load and battery combinations presented in Table 6.4 give cost reductions, there are major differences between the NaS-systems and the other systems for all the scenarios and ports. In the subsections below, the operation of the NaS storage systems for the city and cargo loads are studied in further detail.

6.4.1 City port

The main results of using a 379.4 kWh / 189.7 kW NaS battery system in *City port, Scenario 1* and a 1040.2 kWh / 520.1 kW NaS battery system in *City port, Scenario 2* are given in Tables 6.5 and 6.6.

City port, Scenario 1	With NaS system	Diff. from initial
Energy cost [NOK/yr]	1,404,007.7	-2,462.6
Peak power cost [NOK/yr]	1,632,952.2	-108,496.8
Battery-system cost [NOK/yr]	82,340.4	+82,340.4
Imported energy [kWh]	3,396,251.7	+14,665
Exported energy [kWh]	1,868	+1,868
Avg. spot price [NOK/kWh]	0.3745	-0.0022

Table 6.5: Optimal battery capacity, rated power and annual savings of NaS battery system for *Cargo port - Scenario 2*.

City port, Scenario 2	With NaS system	Diff. from initial
Energy cost [NOK/yr]	3,398,294.9	-2,960.7
Peak power cost [NOK/yr]	2,675,835.5	-300,776
Battery-system cost [NOK/yr]	225,745.3	-225,745.2
Imported energy [kWh]	8,014,087.7	+48,952.2
Exported energy [kWh]	4601.8	+4601.8
Avg. spot price [NOK/kWh]	0.3853	-0.0027

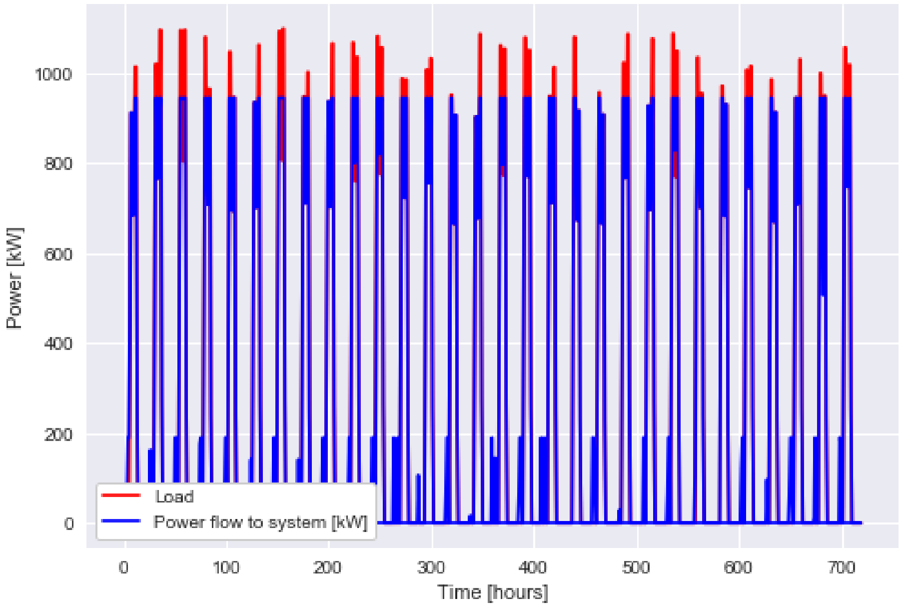
Table 6.6: Optimal battery capacity, rated power and annual savings of NaS battery system for *City port - Scenario 2*.

Similar to the main results of *Cargo port, Scenario 2* using the 2016 battery parameters, the main cost savings in the City port origin from the reduction of peak power grid tariff. In Scenario 1, the peak power costs are reduced by 6.23%, while the energy costs are reduced by only 0.18%. The percentage reduction of peak power costs are increased in Scenario 2, to 10.11%, but the reduction in energy costs are lowered to 0.09%.

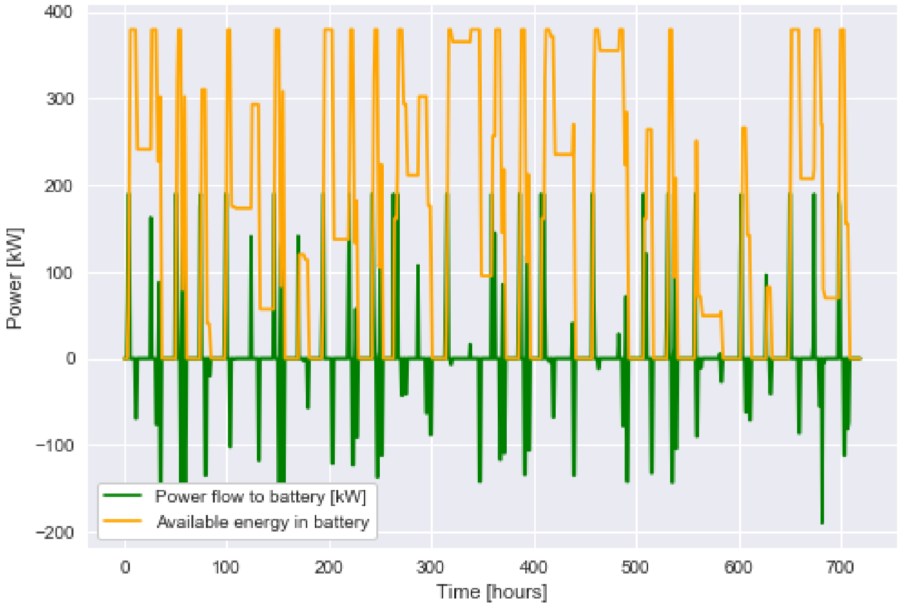
As a result of utilizing the ESSs, the annual imported and exported energy for the systems with NaS batteries is higher than the initial systems. In Scenario 1, the increase in imported energy is 14,665 kWh, while the exported energy is 1,868 kWh. This means that the energy loss is 12,797 kWh due to inefficiency and self-discharge. Similarly, the energy loss in Scenario 2 is 44,350.4 kWh. The difference in average spot-price is bigger in Scenario 2, with 0.0027 NOK/kWh compared to 0.0022 NOK/kWh. This indicates that the bigger ESS can better utilize the variations in electricity prices.

To study the operation of the ESSs closer, the power flow and available energy in the system are presented in Figures 8.2 and 8.3 in the Appendix. In both figures, the peak shaving effects of the ESSs are observable. The monthly peak loads from the sporadic cruise loads are reduced, but the effect is even more visible outside the cruise season, at the start and the end of the year. Here, the daily loads from the ro-ro ferry ”Kystruta” are shaved and the power flow to the system looks ”flat”. An interesting effect of the monthly peak tariff scheme is that the peak shaving of the load from ”Kystruta” ends abruptly. This shows that the peak-shaving of the load from ”Kystruta” is not profitable in the months where there are higher peaks from cruise traffic.

The peak-shaving activity is also visible in the lower two plots, where the power flow to/from the battery and the available energy capacity in the battery is presented. The charging and discharging is most frequent in the beginning and end of the year, where the daily peaks from ”Kystruta” are shaved. In Figures 6.4 and 6.5, the behaviour of the systems for Scenario 1 and Scenario 2 are presented for an arbitrary month. Figure 6.4 shows the peak shaving of the varying daily loads from ”Kystruta” in January and the resulting charging/discharging pattern of the battery system. In Figure 6.5, the daily loads from ”Kystruta” are not leveled, as the cruise traffic in month six gives higher peaks and only these peaks are profitable to level.

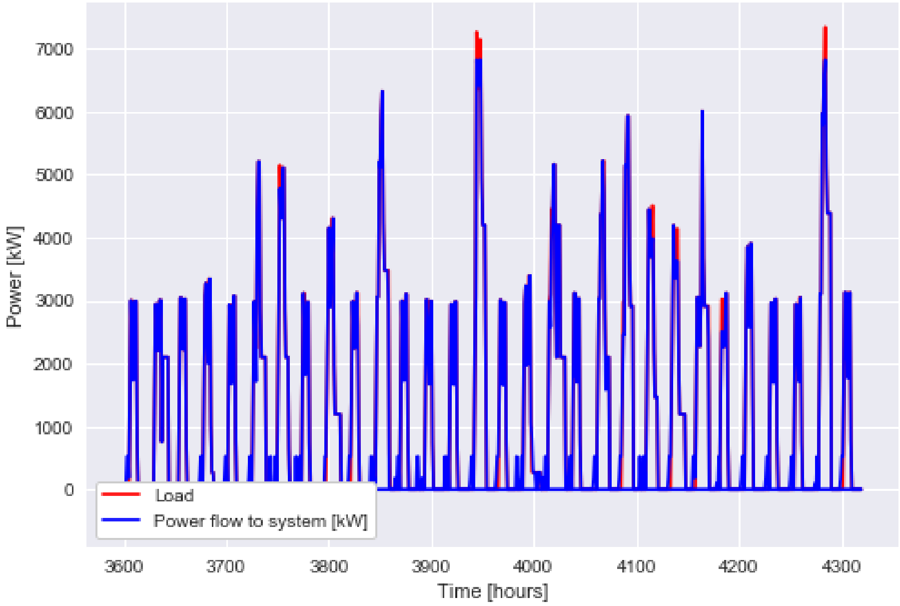


(a) System load and power to/from system for month one (January)

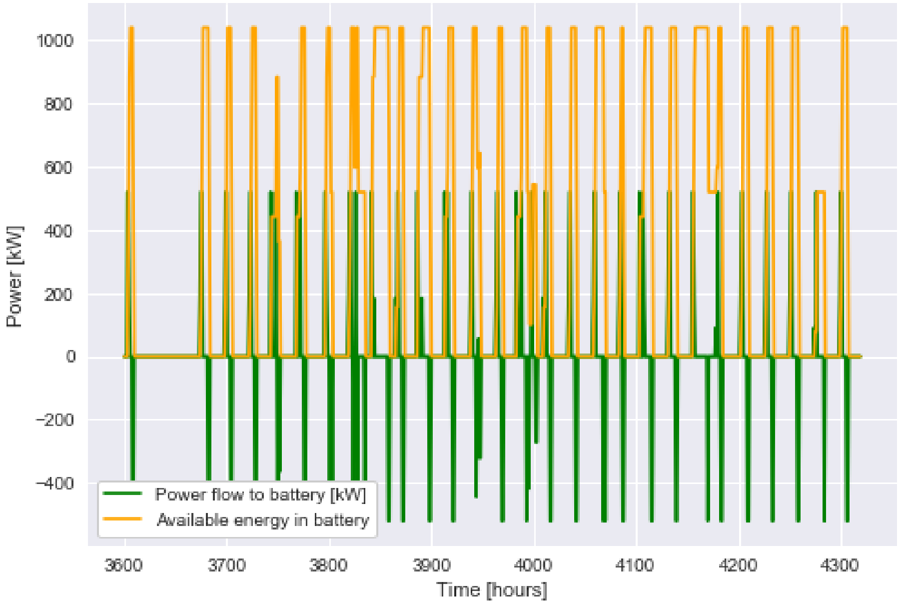


(b) Power to/from ESS and available energy for month one (January)

Figure 6.4: Monthly power flow in system supplying Scenario 1 for the City port using optimally sized NaS storage system



(a) System load and power to/from system for month six (June)



(b) Power to/from ESS and available energy for month six (June)

Figure 6.5: Monthly power flow in system supplying Scenario 2 for the City port using optimally sized NaS storage system

6.4.2 Cargo port

The main results of using a 88.5 kWh / 44.3 kW NaS battery system in *Cargo port, Scenario 1* and a 4,333.7 kWh / 3,566.7 kW NaS battery system in *Cargo port, Scenario 2* are given in Tables 6.7 and 6.8.

Scenario 1	With NaS	Diff.
Energy cost [NOK/yr]	702,744.8	-730.2
Peak power cost [NOK/yr]	547,106.4	-18,765.6
Battery-system cost [NOK/yr]	19,215.1	+19,215.1
Imported energy [kWh]	1,720,936.8	+2,736.2
Exported energy [kWh]	648.5	+648.5
Avg. spot price [NOK/kWh]	0.3692	-0.0009

Table 6.7: Optimal battery capacity, rated power and annual savings of NaS battery system for *Cargo port - Scenario 1*.

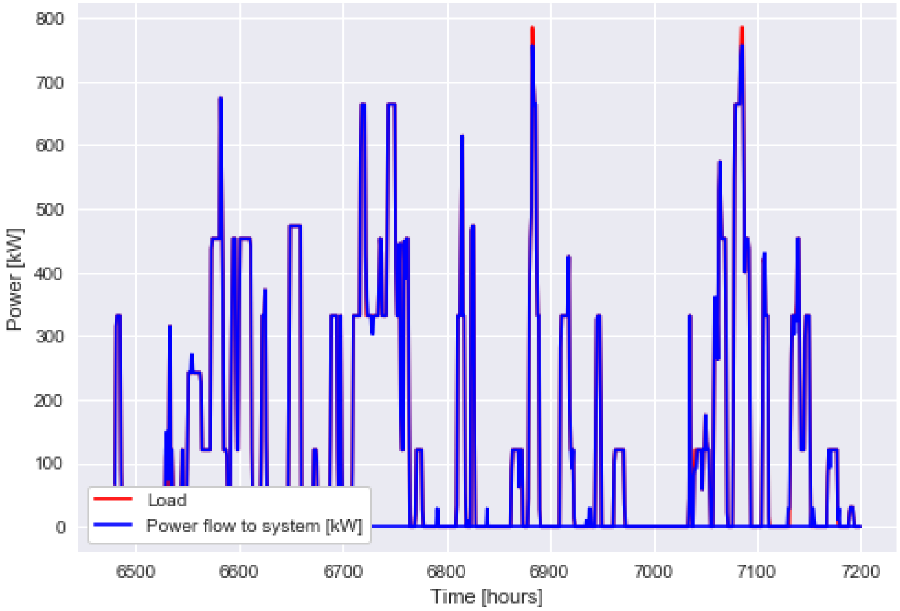
Scenario 2	With NaS	Diff.
Energy cost [NOK/yr]	991,498.6	-21,344.4
Peak power cost [NOK/yr]	999,105.2	-1,892,496.7
Battery-system cost [NOK/yr]	1,286,410.5	+1,286,410.5
Imported energy [kWh]	2,644,543.0	+179,921.6
Exported energy [kWh]	98,623.2	+98,623.2
Avg. spot price [NOK/kWh]	0.3531	-0.0185

Table 6.8: Optimal battery capacity, rated power and annual savings of NaS battery system for *Cargo port - Scenario 2*.

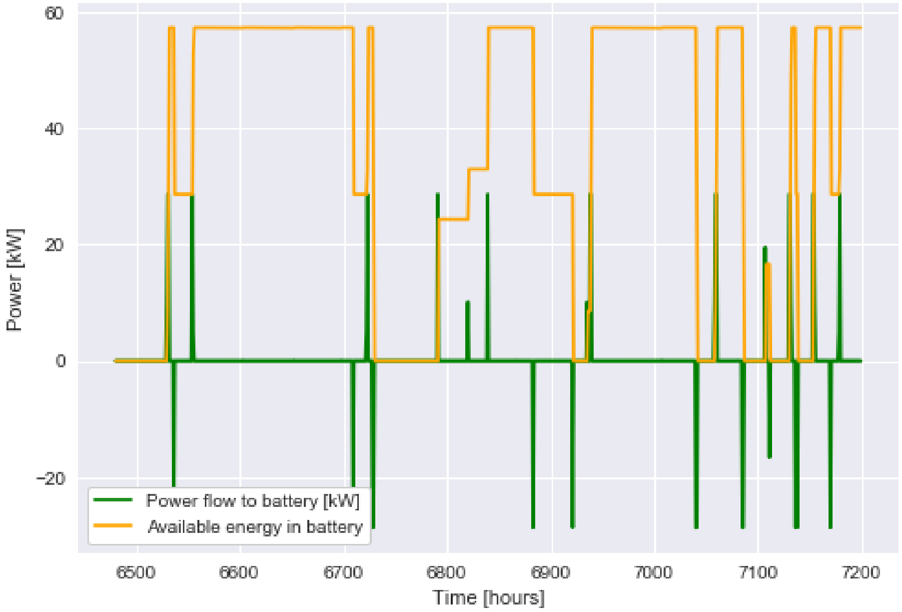
Also for the Cargo port, the greatest impact of the ESS is the reduction of the peak power costs. The optimal NaS battery system for Scenario 1 is small, so the reduction of cost is correspondingly small, but for Scenario 2, the battery system reduced the peak power cost by more than 65%. This system also reduced the energy costs by 2.11%, although increasing the imported energy by 179,921.6 kWh. Of the extra imported energy, 98,623.2 kWh is sold to the grid, which indicates that 81,298.4 kWh is lost due to inefficiency and self-discharge. This is however less than 50% of the additionally imported energy, which is way less than in the other cases so far. The system in Scenario 2 has also leveraged an average spot price of 0.3531 NOK/kWh, which is 0.0185 NOK/kWh lower than in the initial analysis. This is also the highest reduction in spot price for all cases.

The yearly operation of the systems are presented in Figures 8.4 and 8.5 in the Appendix. As expected, in Figure 8.4, the system load and power flow to the system look very similar. This is due to the small dimensions of the ESS in Scenario 1, which leads to a smaller peak-shaving effect. The activity in the lower two plots does however prove that the ESS is charging and discharging to reduce the peaks. Figure 8.5 shows a much clearer impact of the ESS in Scenario 2. The monthly peaks are shaved significantly, and an interesting result of the monthly peak tariff scheme is visible: the power flow to the system is shaved to the same peaks in monthly segments. The size of each segment corresponds to the cost-optimal peak power for each month. Further, the system has a much clearer export of power to the grid, with multiple ”negative” bars in the plot showing the power flow to/from the system. The power flow to/from the ESS is less hectic than what was seen in the City port, which is due to the more infrequent cargo ship traffic.

To better study the operation of the systems, the system power flow for arbitrary months are studied. In Figure 6.6, the power flows for the system in Scenario 1 in month six is presented, and in 6.7, the power flows for the system in Scenario 2 in month five is presented. In Figure 6.6, the peak-shaving effect of the ESS is visible - the monthly peak of the power flow to the system is reduced, but this is also the only peak reduction. The rest of the activity in the ESS origins in energy arbitrage. The load-leveling is much clearer in Scenario 2 in Figure 6.7. Here, the ESSs reduces the high loads and increases many of the low loads. The monthly peak is reduced by roughly 3500 kW, and power is exported to the grid multiple times.

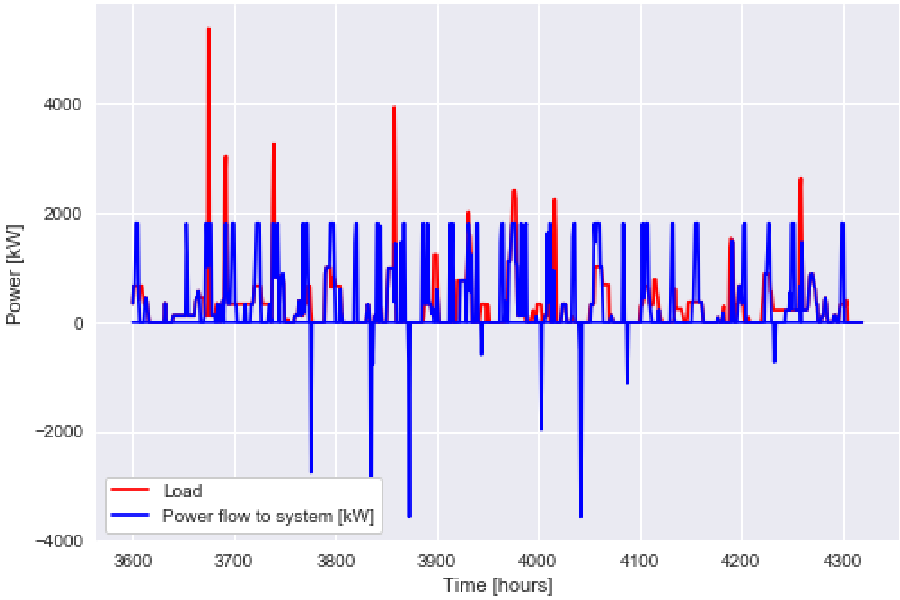


(a) System load and power to/from system for month six (June)

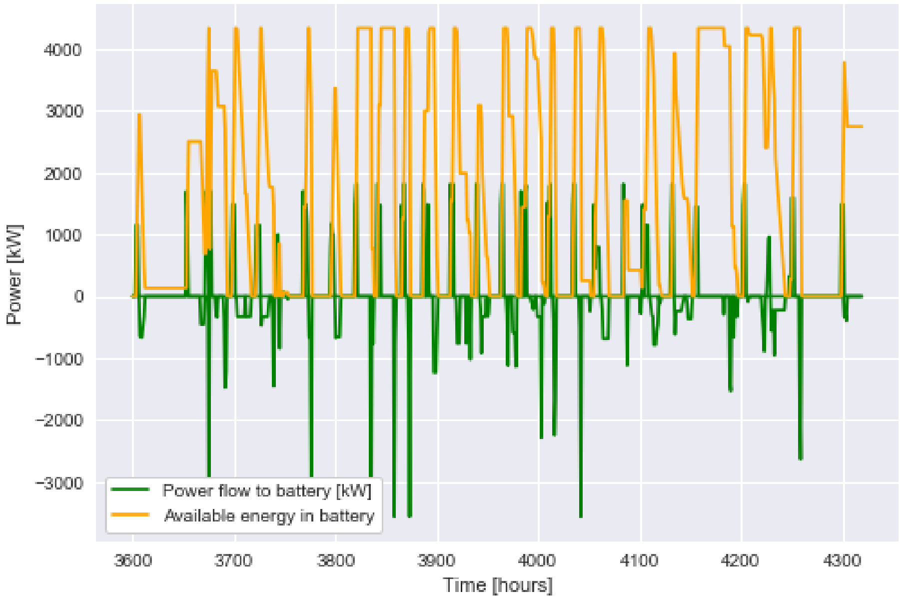


(b) Power to/from ESS and available energy for month six (June)

Figure 6.6: Monthly power flow in system supplying Scenario 1 for the Cargo port using optimally sized NaS storage system



(a) System load and power to/from system for month six (June)



(b) Power to/from ESS and available energy for month six (June)

Figure 6.7: Monthly power flow in system supplying Scenario 2 for the Cargo port using optimally sized NaS storage system

6.4.3 Constrained grid power capacity

In many ports around the world, there are limitations to how much power capacity is available in the electricity grid supplying the port. In the following tests, the maximum power capacity of the grid is limited to 90%, 80%, and 70% of the yearly peak load. The resulting annual costs using the 2016 and 2030 energy storage characteristics are presented in Appendix 8.4 and 8.5. The main results are however presented below in Tables 6.9 and 6.10. In the tables, the optimal energy capacities, power ratings, and annual cost increases for NaS, compared to the initial cases, are given.

The annual costs of nearly all cases are increased by constraining the grid capacity. As expected, the annual costs of using the 2016 energy storage characteristics are significantly higher than using the 2030 energy storage characteristics. Further, the cost increase is lowest for the Cargo port, followed by the City port. This is a direct result of the type of load in the different ports - the portcalls in the Offshore port are in general much longer, which means that more energy capacity is required. Additionally, the peak consumption in the Offshore port is much closer to the average consumption. This is also clear from the ”energy-to-power” ratios of the different cases, with the ratios of the ESSs in the offshore port being much higher.

In all cases except for *Cargo port, Scenario 2*, the optimal capacities and power ratings are similar when using the 2016 and 2030 characteristics. Implicitly, this means that the sizing of an ESS is only dependent on the capacity and power required to reduce the peak below the given threshold. As a bonus, the application of the ESS contributes to lowering the costs by reducing grid tariffs and performing energy arbitrage. Here, the contribution of the 2030 characteristics will in general be larger. With increasing size of ESSs, the potential savings of energy arbitrage and peak shaving increase, but not enough to make up for the cost increases of a reduction in grid power capacity.

With the 2030 energy storage characteristics for *Cargo port, Scenario 2*, the optimal solution of the unconstrained case reduces the peak below the given threshold. This means that 90%, 80%, and 7 0% grid capacity constraints have no impact at all. This is also the case for *Cargo port, Scenario 1* with a 90% constraint in grid power capacity. With an 80% grid power capacity constraint, the optimal ESS is still profitable, but the required capacity and power rating is larger than in the optimal case, which reduces the profit.

Case		City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
90 %	Cap. [kWh]	2,006.9	1,444.7	611.2	811.7	4,511.1	264.3
	Pow. [kW]	533.0	734.6	152.8	811.7	213.3	264.3
	Cost inc. [NOK/yr]	393,080.2	240,778.4	126,850.2	-13,518.1	1,157,383.6	113,413.9
80 %	Cap. [kWh]	5,012.6	5,046.2	1,222.5	1,288.4	13,566.1	1,261.3
	Pow. [kW]	1,058.0	1,469.2	305.6	1,288.3	426.6	528.7
	Cost inc. [NOK/yr]	1,077,421.3	1,004,404.3	269,744.7	-4,834.6	3,522,394.4	378,310.5
70 %	Cap. [kWh]	9,692.2	8719.3	4,292.6	1,932.5	42,381.5	6,938.0
	Pow. [kW]	1,584.7	2,203.7	458.4	1,932.5	639.9	793.0
	Cost inc. [NOK/yr]	2,240,735.3	1,829,443.3	1,029,258.9	7,403.3	11,184,864.9	1,849,934.5

Table 6.9: Optimal energy storage capacities, power ratings and resulting cost increase - 2016 characteristics

Case		City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
90 %	Cap. [kWh]	2,006.9	1,729.5	611.2	4,333.7	4,511.1	298.8
	Pow. [kW]	536.7	734.6	157.6	3,566.7	213.3	264.3
	Cost inc. [NOK/yr]	9,093.4	-62,502.5	11,611.2	-627,430.6	363,055.0	52,431.5
80 %	Cap. [kWh]	5,012.6	5,046.2	1,222.5	4,333.7	13,330.4	1,261.3
	Pow. [kW]	1,073.6	1,469.2	305.6	3,566.7	426.6	528.7
	Cost inc. [NOK/yr]	133,902.2	28,559.2	39,549.0	-627,430.6	1,125,993.4	128,667.8
70 %	Cap. [kWh]	9,692.2	8,719.3	4,169.0	4,333.7	40,961.5	6,938.0
	Pow. [kW]	1,593.5	2,203.7	458.4	3,566.7	639.9	793.0
	Cost inc. [NOK/yr]	452,196.7	156,808.7	246,104.8	-627,430.6	3,682,807.7	600,605.3

Table 6.10: Optimal energy storage capacities, power ratings and resulting cost increase - 2030 characteristics

6.5 Sensitivity analysis

To study how variations in model specifications impact the feasibility of implementing battery systems in ports, a sensitivity analysis is conducted. The purpose of the sensitivity analysis is to determine how variations in key model parameters impact the feasibility of energy storage in ports. In the sensitivity analysis, the initial model specifications are used while one target value is altered in each analysis. The battery-parameters of 2030 are used in all the analyses. Further, the results of NaS are specifically studied in cases where this is representative. The sensitivities of grid tariffs, end-of-life return values, and electricity spot prices are studied.

6.5.1 Grid tariff

In the initial analysis, the grid tariff was found to be a decisive parameter for the economic feasibility of ESSs in ports. To study the sensitivity of the grid tariff in the optimization model, in the following analysis, the grid tariff is altered by 50%, 75%, 90%, 110%, 125%, and 150%. The corresponding annual costs are presented in Tables 8.9-8.14. In Table 3.1, the optimal capacity and power rating, and the corresponding reduction in annual costs are presented. The reductions in annual costs are calculated based on the annual costs of supplying the loads with the given grid tariff without ESSs.

Case	Parameter	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
50 %	Cap. [kWh]	0.0	0.0	0.0	0.0	0.0	0.0
	Pow. [kW]	0.0	0.0	0.0	0.0	0.0	0.0
	Cost diff. [NOK/yr]	0.0	0.0	0.0	0.0	0.0	0.0
75 %	Cap. [kWh]	281.2	789.9	0.0	3,041.1	0.0	0.0
	Pow. [kW]	147.6	395.0	0.0	2,578.8	0.0	0.0
	Cost diff. [NOK/yr]	3,872.8	7,253.4	0.0	182,502.9	0.0	0.0
90 %	Cap. [kWh]	333.0	1,015.6	0.0	4,115.7	0.0	0.0
	Pow. [kW]	174.7	507.8	0.0	3,512.2	0.0	0.0
	Cost diff. [NOK/yr]	18,071.4	48,343.7	0.0	440,806.2	0.0	0.0
110 %	Cap. [kWh]	437.7	1,103.1	190.7	4,333.7	0.0	0.0
	Pow. [kW]	218.9	551.5	95.3	3,943.8	0.0	0.0
	Cost diff. [NOK/yr]	40,158.1	108,915.3	3,193.7	822,036.9	0.0	0.0
125 %	Cap. [kWh]	2,633.6	4,329.7	318.6	5,316.4	0.0	0,0
	Pow. [kW]	668.2	1,224.8	121.0	4,103.7	0.0	0.0
	Cost red. [NOK/yr]	66,148.1	175,698.0	10,514.1	1,129,938.0	0.0	0.0
150 %	Cap. [kWh]	3,761.8	9,643.3	1,121.7	5,351.2	0.0	48.4
	Pow. [kW]	880.1	2,250.2	280.4	4,113.4	0.0	16.1
	Cost diff. [NOK/yr]	174,064.7	433,295.0	32,439.3	1,653,890.4	0.0	569.1

Table 6.11: Optimal ESS capacities, power ratings and corresponding cost reduction for a selection of grid tariffs

The annual costs of energy in all cases increase with the increase in grid tariffs. The cost increases between the ports vary significantly, as this is a direct result of the type of load. The case that has the highest cost increase when the grid tariff increases is *Cargo port, Scenario 2*, followed by *City port, Scenario 2*, *City port, Scenario 1*, *Offshore port, Scenario 2*, *Offshore port, Scenario 1* and *Cargo port, Scenario 1*. The cost increases are as expected, but the Offshore port is in more impacted by an increase in grid tariff than *Cargo port, Scenario 1*.

Table 3.1 proves the significance of the grid tariff for the feasibility of implementing ESS into Norwegian ports. If the grid tariff is reduced to 50% of the values used in the initial analysis, implementing ESSs is not economically viable. With reductions to 75% and 90%, ESSs are viable in both the City port scenarios and Scenario 2 of the Cargo port. With an increase to 150%, a small energy storage system is viable in *Offshore port, Scenario 2*, but the corresponding savings are minor. As expected, the capacity and rated power of the ESSs increase with the grid tariff. This is because, with higher grid tariffs, a larger effort is made to lower the peaks.

6.5.2 Electricity spot price

The energy cost savings from the systems in the initial analysis were minor, but this may not be the case if the electricity spot price was different. The potential profits of energy arbitrage and energy shifting is highly dependent on the variations in spot price, and this can also impact what ESS dimensions are optimal. To test this, the electricity system spot prices of Germany, Austria, Slovenia, and Switzerland are used as input in the sensitivity analysis. The resulting annual costs are given in Appendix 8.7. The main results are given in Table 6.12.

Case		City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
Norway	Cap. [kWh]	379.4	1,040.2	57.2	4,333.7	0.0	0.0
	Pow. [kW]	189.7	520.1	28.6	3,566.7	0.0	0.0
	Cost red. [NOK]	28,619.1	77,991.4	277.9	627,430.6	0.0	0.0
Germany	Cap. [kWh]	2,796.2	6,802.8	734.3	4,851.0	0.0	56.3
	Pow. [kW]	700.8	1,706.9	183.6	3,696.0	0.0	16.3
	Cost red. [NOK]	92,112.5	223,044.0	17,586.3	842,944.9	0.0	681.9
Austria	Cap. [kWh]	2,681.1	5,952.7	389.6	4,592.4	0.0	45.3
	Pow. [kW]	671.6	1,536.9	129.9	3,631.4	0.0	15.1
	Cost red. [NOK]	69,983.1	174,371.5	11,358.9	791,017.3	0.0	51.0
Slovenia	Cap. [kWh]	3,346.0	8,558.8	985.0	5,123.9	97.5	349.1
	Pow. [kW]	810.7	2,071.2	246.2	3,724.8	32.5	102.7
	Cost red. [NOK]	143,711.2	360,030.2	30,872.3	936,742.8	221.4	3,013.0
Switzerland	Cap. [kWh]	842.0	2,414.6	279.9	4,333.7	0.0	0.0
	Pow. [kW]	303.5	828.5	108.1	3,566.7	0.0	0.0
	Cost red. [NOK]	40,481.2	110,375.0	4,876.0	709,400.1	0.0	0.0

Table 6.12: Optimal ESS capacities, power ratings and corresponding cost reduction using a selection of electricity spot prices

As expected, the electricity spot price has a severe impact on the feasibility of the port ESSs. The spot prices in Norway are known to be less fluctuating than spot prices in other countries, which weakens the potential profits from energy arbitrage and energy shifting. From Table 6.12, it's clear that the utilization of energy storage gives higher savings with all the other system spot prices. In Germany, and Austria, it's profitable to implement ESSs into the Offshore port for Scenario 2, and in Slovenia, it's profitable for both scenarios.

Further, the optimal ESS dimensions are in general larger with the other spot prices, which is especially evident in the City port and Scenario 1 of the Cargo port. An exception is with the spot price of Switzerland, which results in higher energy capacities and lower power ratings. The optimal "energy-to-power" ratios of the systems are also generally higher, which indicates that it is more profitable to charge and discharge the ESSs over longer durations. This could either be a result of increased energy arbitrage, or a result of increased peak-shaving.

6.5.3 End-of-life return value

With an increased focus on recycling and possible scarcity of materials used for battery production, new markets for end-of-life batteries may evolve. If these markets succeed in driving up the price of end-of-life batteries, the return value on battery systems can be increased and the business case can be greatly improved. In the following analysis, the end-of-life percentage of investment cost return value is varied from 10% to 50%. The annual costs for all technologies are presented in Appendix 8.8. In Table 6.13, the optimal capacities, power ratings, and the resulting reduction in annual costs (compared to the initial analysis) for NaS are given.

Case		City, S1	City, S2	Cargo, S1	Cargo, S2
10 %	Cap. [kWh]	423.2	1,096.9	88.7	4,333.7
	Pow. [kW]	211.6	548.4	44.4	3,742.9
	Cost red. [NOK/yr]	31,784.6	86,417,0	972.5	673,262.8
20 %	Cap. [kWh]	423.2	1,103.1	190.7	4,333.7
	Pow. [kW]	211.6	551.5	95.3	3,943.8
	Cost red. [NOK/yr]	35,101.9	95,037.9	2,290.9	721.905.7
30 %	Cap. [kWh]	437.7	1,103.1	202.0	4,649.5
	Pow. [kW]	218.9	551.5	97.0	3,996.4
	Cost red. [NOK/yr]	38,488.1	103,684.2	3,808.5	770,895.5
40 %	Cap. [kWh]	745.5	2,406.8	302.1	5,002.0
	Pow. [kW]	283.5	840.0	115.5	4,055.2
	Cost red. [NOK/yr]	42,446.2	115,206.7	5,712.7	822,435.9
50 %	Cap. [kWh]	2,326.6	4,050.3	318.6	5,270.4
	Pow. [kW]	600.7	1,168.9	121.0	4,099.9
	Cost red. [NOK/yr]	50,126.5	134,751.5	7,887.4	875,706.7

Table 6.13: Optimal ESS capacities, power ratings and resulting cost reductions for a selection of end-of-life percentage values.

Surprisingly, the increase of end-of-life return value to 50% does not make it profitable to implement ESSs into the offshore port. These results are for this reason left out. For the City and Cargo port, as expected, the potential cost reductions increase with the end-of-life return value. In general, the optimal capacities and rated powers increase with each step-wise increase in the end-of-life return value. Further, based on the results in Appendix 8.8, it's clear that the increase in end-of-life return value makes more energy storage technologies feasible. As the development in end-of-life return value is likely to vary between technologies, this parameter can be decisive and should be studied further.

Chapter 7

Discussion

In this section, the main discoveries from the results in Chapter 6 and the basis of these results are discussed.

7.1 Optimization model

The mathematical model works well in highlighting the feasibility of using energy storage for different system parameters, loads, and storage technologies, but it shouldn't be used directly for dimensioning of ESSs or for real scheduling of battery dispatch. The port loads are assumed to be known and perfectly forecasted, which is highly unlikely in a real scenario. The AMP and charging loads can however be forecasted more precisely than many other loads, as the schedules for vessel traffic are often planned far ahead. Advanced monitoring of shipping traffic is ordinary, so this real-time information can be used as input into models that optimize the operation of energy storage as well. This is an interesting methodology that should be examined.

The use of constant round-trip efficiency and power conversion unit efficiency of 100% is not realistic but hold for the intended use of the mathematical model. The round-trip efficiency will be dependent on various system and local parameters, and it will degrade over time. The inclusion of these effects would greatly complexify the model, which would not be expedient. Including the efficiency of the power conversion unit would not complicate the model significantly and this can be done in further works. The impact on the studies of feasibility is however likely to be small.

The simplifications used in the optimization model have various results. The reduction of the number of days to 360 has minimal impact, as the results are used for comparison purposes. In practice, this only results in minor errors in the capitalization, annuity, and discounting factors, as well as the total annual costs. The timestep of one hour was chosen to reduce the computational time of the optimization model, and this has a quite significant impact on the model. In the case studies, the original loads have timesteps of one minute and the loads are averaged over hours. This results in an undesirable leveling of loads, something that undermines the potential benefits of using energy storage.

The economic lifetime of each energy storage technology is chosen as the given calendar life in Tables 2.1 and 2.2. The calendar life of an ESS is defined based on specified conditions, and these conditions are unlikely to be fulfilled by the port ESSs. This indicates that the economic lifetimes used in the analysis are likely to be exaggerated. The cycle life could have been used, but this would greatly increase the complexity of the model and not necessarily increase the accuracy. The last simplification that should be discussed is the ignoring of battery degradation. The performance of a battery is degraded during its lifetime, with reduced energy capacity, power, and efficiency. Battery degradation will hence impact the operation of a battery, and in turn, the potential returns and cost savings. Not including the battery degradation weakens the precision of the model, but for the intended use, this precision is not necessary.

7.2 Estimation of case study port loads

The estimation of case study port loads is based on the ports' schedules for vessel traffic. These schedules should be representative of the typical traffic of the relevant port type, but there may be consequential variations. In the estimation of the port loads, the power need of each ship has been assumed to start at the ship's arrival time and end at the ship's departure time. However, when estimating power consumption from AMP, a typical procedure is to subtract 60 minutes from the duration of a portcall to make up for the time to connect and disconnect AMP-equipment. This procedure has however been denounced by several ship operators and AMP-equipment suppliers, as new technology has lowered the connection and disconnection time drastically ([7], page 11-12). This supports the methodology that is used in this report, but the neglecting of connection and disconnection time undoubtedly results in a slight overestimation of port loads.

A counter-measure to the neglecting of AMP connection and disconnection time is the utilization of Enova's coefficients for port power consumption. These coefficients are in some cases extremely modest, and the allocation of ship power consumption according to the given sizes is imprecise. In ([7], page 12), the use of Enova's coefficients was found to give shiploads that were on average one-third of other estimation methods. There is however a lack of proper tools and methodologies to estimate a ship's power consumption in port, which is why Enova's coefficients were used.

The two scenarios are based on the goal of having zero-emission ports in 2030 ([38], page 7) and the analyses conducted in [40]. Scenario 1 assumes a 100% utilization of AMP, but this isn't realistic in 2030, as that would mean the whole fleet must be exchanged or equipped with AMP-equipment in just ten years. A high percentage is achievable, but as ([38], page 7) states that the emission cut is only for feasible ports, it's uncertain whether this holds for the chosen cases. The shares for plug-in hybridization and the size of batteries in Scenario 2 are based on the analyses in [40], but the selection is quite arbitrary as there are no common guidelines for this. The selection is however made based on what the potential of reducing the emissions of each vessel type is, and this is relevant because this is the main goal of the electrification-process.

The assumption that the power consumption of ships in ports is constant is obviously inaccurate. Many of the vessels, especially in the cargo and offshore ports, have equipment and processes that sporadically require power when in port. However, for cruise ships, this assumption is more valid, as the peak and mean consumption of cruise ships AMP-need are quite similar ([7], page 38). Another issue with the assumption of constant port load is that it interferes with one of the major advantages of AMP and plug-in hybridization; the flexibility. As the ships have backup-systems, the AMP- and charging-need is extremely flexible, which means that the power from shore can be regulated according to electricity price fluctuations and capacity constraints. The fluctuations in load and the potential of leveraging consumption flexibility should be studied in further works.

The rigid procedure of estimating AMP- and charging-demands in the analyses is also one of the reasons the peak powers are extremely high in *Cargo port, Scenario 2*. As the charging load is determined based on the duration of portcall, the vessels with short portcalls will give high loads - in practice, the vessels could stay for longer durations or only charge a share of the on-board batteries. Correspondingly, as the duration of the portcalls in the Offshore port are in general much longer, the charging-loads are in most cases very small. In practice, the vessels' batteries are unlikely to be charged over the whole course of the portcall.

7.3 Initial analysis

In the initial analysis, the three case ports were studied for two different scenarios and energy storage parameters that represent 2016 and 2030 conditions. One of the most important results from the initial analysis is that the feasibility of ESSs in Norwegian ports is highly dependent on the potential reduction of the monthly peak power related grid tariff. The cost savings and profits from energy arbitrage are small, which was expected as the Norwegian system price has relatively small daily variations. In practice, this means that a port ESS in Norway does not necessarily profit much from being able to export energy to the grid - this can ease the regulative barrier of investing in these storage systems, as a trading license is not necessarily required.

With the monthly peak power consumption acting as the main cost driver, ports with high loads that are spread throughout the year are more suitable for the implementation of energy storage. Further, ports with shorter portcalls are more suitable, as the resulting loads require less energy to level/peak shave. These arguments are strengthened by the results of the analysis, as the cargo port, with the shortest and most frequent portcalls, have the highest cost savings of implementing ESSs, and the offshore port, with long portcalls, have no cost savings.

With increasing dimensions of energy storage, the profit of energy arbitrage increases. This is justified by the fact that the difference in imported and exported energy is larger in the cases with larger ESSs. Another justification is that the systems with larger ESSs import energy at a lower spot price, relative to the same loads without the utilization of ESSs. In all the optimal solutions, the ”energy-to-power” ratios of the ESSs are relatively small. In both scenarios in the City port and Scenario 1 of the Cargo port, the ratios of the optimal ESSs are roughly 2.0. In Scenario 2 of the Cargo port, the ratio of the optimal capacities is in the range 1.1-2.0. This indicates that it is not profitable for the ports to have large capacities, which is often normal for systems that perform energy shifting and energy arbitrage.

With the 2016 energy storage parameters, only one of the port loads and only one of the storage technologies give cost savings. This indicates that without a positive development in energy storage technologies, it will not be profitable to use energy storage in most ports with the given system parameters and scenarios. It may however be profitable in some cargo ports, but this will require an aggressive implementation of AMP and plug-in hybridization of a significant share of vessels. In ports with more frequent traffic, bigger ships, or a combination of these, energy storage may be feasible with the 2016 characteristics. With the 2030 energy storage parameters, both scenarios in the City port and Scenario 2 in the cargo port give cost savings for a range of energy storage technologies. Additionally, Scenario 1 in the cargo port gives cost savings if using a NaS battery system. This emphasizes the correlation between development in energy storage technologies and feasibility of port ESSs.

Ignoring scenario 1 for the cargo port, the four energy storage technologies that give the highest savings are VRFB, NaNiCl, NaS, and Li-ion NCA for all the loads. NaS, followed by NaNiCl, give the highest savings in all cases, but the ranking of VRFB and Li-ion NCA are different for the City port and the Cargo port. For the City port scenarios, Li-ion NCA has significantly higher savings, while for the cargo port, VRFB has slightly higher savings. This is likely caused by the fact that VRFB has a lower energy installation cost and higher power installation cost, which makes it more suited for high energy and low power loads. This is also reflected in the optimal ”energy-to-power” ratios of the ESSs using the two technologies in *Cargo port, Scenario 2*: VRFB has a ratio of roughly 1.3, while Li-ion NCA has a ratio of roughly 1.1.

Potential barriers to implementing the different energy storage technologies are not studied in this report, but there may be significant challenges related to the maturity, safety, operation, and supply of the technologies. NaS and NaNiCl, which are the technologies that give the most promising results have high operating temperatures, something that can give added complications related to safety, but also something that can be conflicting with the relatively cold Norwegian climate. According to ([12], page 290), NaS and NaNiCl have a technological maturity level of 4 out of 5, which is equal to Lithium-ion, but this of course depends on the type of Lithium-ion technology. VRFB on the other hand, which also gives significant savings in the case studies, is a relatively ”new” technology which is given a maturity level of 3 out of 5. This is also indicated by the development of characteristics and cost between 2016 and 2030: the least mature technologies have the most promising developments. The potential supply or availability of each technology will be case-to-case specific and is hence not studied further.

With the limitations in grid power capacity, the optimization model is forced to include ESSs to supply the caseloads. The grid capacity varies between ports, but also during the year. In some of the cases, the optimal dimensions of the ESSs are not impacted by the inclusion of limited grid capacity, as the grid constraints are not breached with optimal operation. For the other cases, the optimal power rating and especially energy capacity is greatly increased. In turn, this increased the annual costs, but it is not known whether the cost increases are higher or lower than comparable costs of upgrading grid capacities. These costs will also vary significantly from port to port, but should be studied in further works. The inclusion of ESSs in ports is more suitable for the ports with short portcalls than the ports with long portcalls, as long portcalls require much higher energy capacities and hence result in higher investment costs.

7.4 Sensitivity analysis

In the sensitivity analysis, the sensitivities of grid tariffs, end-of-life return value, and electricity spot prices are studied. Several more parameters could have been studied, but these were regarded as the most impactful ones and an extended sensitivity analysis is out of the scope for this report.

The sensitivity analyses prove that the grid tariff is essential for the feasibility of ESSs in ports. It is however important to remember that with the increase in grid tariffs, the annual costs of supplying the load increase. This impacts the competitiveness of AMP- and plug-in hybridization, which means that the feasibility of an ESS in a port is not necessarily a good sign for the electrification of the maritime industry. As the grid tariffs vary from DSO to DSO, the sensitivity analysis can be used as an indication of the feasibility of implementing ESSs in ports with different charges.

The electricity spot price in another parameter that has an extensive impact on the feasibility and sizing of ESSs in ports. In the sensitivity analysis, the use of electricity prices from other countries is shown to greatly affect the optimal capacities, rated powers, and annual cost reductions. As the Norwegian electricity price is quite stable due to the vast implementation of hydropower, the potential savings and profits of using ESSs are in general much lower in Norway than in other countries. This means that the business case for ESSs in Norwegian ports should be worse, but conflictingly the business case of AMP- and plug-in hybridization is likely to be better than in many of the other countries, as Norway has strong ambitions. The reason for the higher savings and profits with other electricity prices is the daily fluctuation in spot prices, which means that if the Norwegian electricity price experiences increased fluctuations in the future, the feasibility of implementing ESS into ports is improved.

The sensitivity of the end-of-life return value is interesting because this is a parameter with an unknown future. The analysis clearly shows the impact of an increase in the end-of-life return value, first of all through increased savings, but also through larger ESSs. An important aspect of this analysis is that the end-of-life return values of the different technologies are not separated. The potential returns will vary between technologies, as this is related to the recyclability and the value of the materials used. Some of the technologies have purchase prices that are more correlated to the cost of materials than others, and this will help increase the end-of-life return value. This is typically technologies that use scarce minerals, like nickel, copper, and lithium [55], and these are more likely to experience increasing end-of-life return values.

Chapter 8

Conclusion

In this report, the potential of utilizing ESSs in ports are analyzed. The objective is to study whether electrical energy storage can be leveraged to cut costs of supplying the future electrified marine traffic by cutting energy costs or by acting as an alternative to grid investments.

Ten chemical energy storage technologies are studied, as these are considered most relevant for port use. The performance of all the technologies is expected to be improved towards 2030. This includes technical characteristics as well as the development of costs. Of the ten technologies that are found to be potential candidates for port use, the molten-salt batteries, NaS and NaNiCl, the Vanadium redox flow battery (VRFB), and the Lithium-ion NCA-battery technologies stand out as most promising. The safety, maturity, and supply of the technologies are however not taken into consideration. The Levelized cost of storage (LCOS) is introduced, but as this cost model has weaknesses related to its maturity and lack of possibilities to combine several applications, a new cost model that excludes energy costs is derived.

With the current Norwegian regulations, the participation in the day-ahead, intraday, and reserve markets for the trading of power is achievable for ESSs, but this is still uncommon. ESSs can perform several grid applications, but many of these applications are difficult to quantify. This also makes analysis of a combination of grid applications and behind-the-meter applications unsuitable. It's unclear what grid tariffs will be used for ESSs in the future, but the grid tariff of commercial customers can currently be used. The main driver of costs using this grid tariff is the monthly peak power charge, which greatly facilitates the implementation of ESSs.

The Norwegian government has ambitious plans regarding maritime electrification, first of all through a goal of emission-free ports where feasible by 2030, and further by facilitating hybridization and total-electrification [38]. With the planned development, the ports are challenged in terms of high energy costs and high power demands. This, combined with the current Norwegian regulations, establishes a promising foundation for the utilization of ESSs that combine load leveling and energy arbitrage in ports. Following the regulations, the ESS should be owned by the port or a third party.

The optimization model that is used in the case studies, shows promising results and due to its flexibility and choice of timestep, numerous inputs and outputs can be analyzed quickly. As the model optimizes both energy capacity and power rating, the optimal combination of these can be studied for each of the loads. This makes the interpretation of the model results effortless, and the impact of modifying system parameters becomes clear. A weakness of the model is the exclusion of the battery degradation, the variable OPEX, and the efficiency of the PCU but this can be included in future analysis.

Three types of ports are analyzed: a City port dominated by passenger traffic, a Cargo port, and an Offshore/subsea base. Further, a scenario that represents an aggressive implementation of AMP and a scenario that represents an aggressive implementation of AMP combined with plug-in hybridization of part of the fleet, are modeled. The loads are modeled for one year in timesteps of one minute and are based on the vessel traffic schedules of each port. With a lack of proper methodologies to estimate AMP- and charging-needs, each ship's load is estimated based on modest coefficients from Enova and assumptions of battery size. To be applied to the optimization model, the minutely loads are averaged over one hour, hence involuntarily leveling some of the peaks slightly.

With energy storage characteristics and costs that represent the 2016-level, utilization of ESS is only feasible in the Cargo port for the most aggressive Scenario, indicating that an investment in port ESS is in general not profitable. With energy storage characteristics and costs predicted for 2030, the utilization of ESS in the City and Cargo ports are profitable for both Scenarios. The energy storage technology that provides the largest cost savings is NaS, followed by NaNiCl, Lithium-ion NCA, and VRFB. The offshore/subsea port is unsuitable for the implementation of ESS, as the monthly peaks are costly to shave and the yearly load is in general quite leveled. The majority of cost savings come from the reduction of monthly power peak related grid tariffs. The reduction in energy costs is close to negligible, and the system's ability to sell energy to the grid is in most cases trivial. An interesting discovery is that the optimal ESS capacities and power ratings are determined only by the system's ability to reduce the monthly peak powers. This indicates that profit from energy arbitrage in the Norwegian electricity grid is minor. The ESSs do however sell power to the grid on some occasions, but the frequency and volumes are heavily dependent on the size of the ESS.

With power capacity constraints of 70%, 80%, and 90% of the annual peak consumption, the annual costs of supplying the caseloads are in general increased. To supply the loads, the optimization model chooses power ratings and energy capacities that exactly reduce the annual peak to the given threshold. In some of the cases, the grid constraint does not interfere with the optimal operation of the system, hence not increasing the costs. Also here, the most aggressive scenario in the Cargo port gives the most promising results. The Offshore/subsea port has the highest cost increases by introducing grid capacities by far, hence strengthening the already mentioned deficit in terms of ESS feasibility. As the upgrading of port grid capacity will vary on a case-to-case basis, no comparisons between these solutions are conducted.

A sensitivity analysis is conducted for three key parameters; the grid tariff, the electricity price, and the end-of-life return value. As expected, the grid tariff is proven to be significant in the sizing of the ESSs and the direct correlation between grid tariff and annual cost reduction is clear. Further, conducting case studies with electricity spot prices that represent a selection of European system prices shows that energy arbitrage is much less profitable in Norway than in other countries. The optimal capacities and power ratings are larger using these spot prices than using the Norwegian spot price, indicating that the dimensions are not solely based on the monthly peak demands when using other electricity spot prices. The development in the end-of-life return value also has the potential of being decisive for the utilization of ESS in many ports. An increase in end-of-life return value reduces the lifetime cost, increases the size, and hence reduces the annual costs of the port systems.

8.1 Suggestions for further work

Below, the main suggestions for further work are summarized.

- More robust methods for estimation of vessels' AMP- and charging-needs should be derived and the variation in consumption during a portcall should be studied.
- The impact of including PCU efficiency, battery degradation and variable OPEX into the model should be tested.
- The timestep of the optimization model should be reduced to enhance accuracy.
- Sensitivity analyses of more parameters can be conducted.
- Further analysis of the maturity and supply of the different energy storage technologies.
- The costs of grid power capacity upgrades should be studied and compared to the costs of including ESSs.
- In a future scenario, where a significant share of the ships portcalling in Norwegian ports use AMP, are plug-in hybrid or totally electric, major economic benefits can be realized by leveraging consumption flexibility. This requires a market for flexibility, but the potential should be analyzed.

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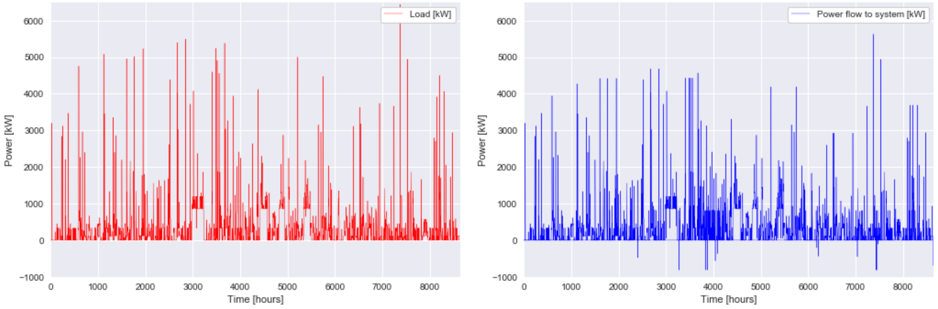
Appendix

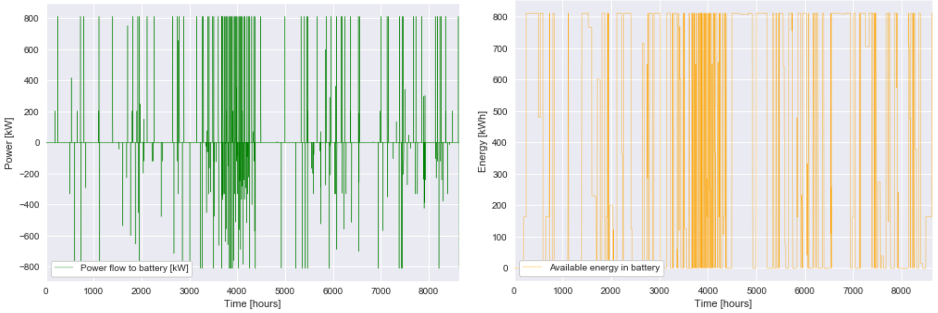
8.2 Plots

8.2.1 Cargo port with 2016 ESS characteristics



(a) System load

(b) Power flow to/from system

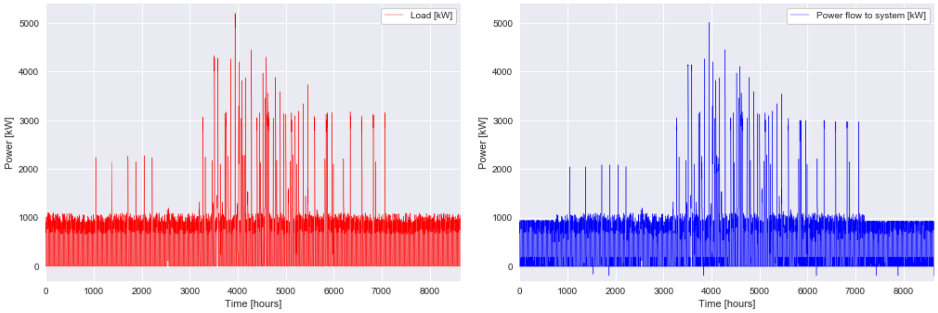


(c) Power flow to/from battery

(d) Available energy capacity in battery

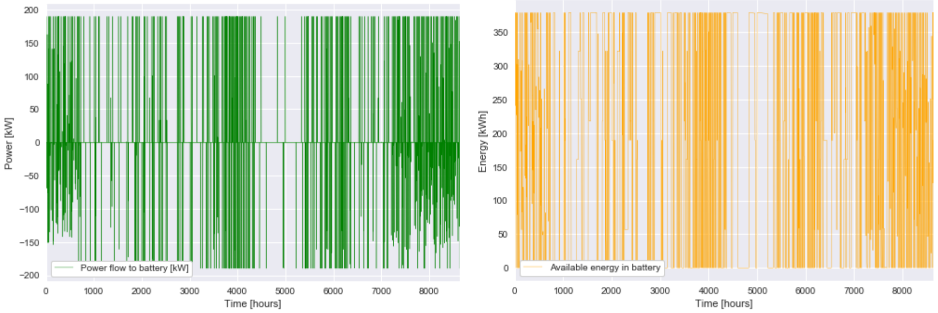
Figure 8.1: Yearly power flow in system supplying Scenario 2 for the Cargo port using optimally sized NaS ESS

8.2.2 City port with 2030 ESS characteristics



(a) System load

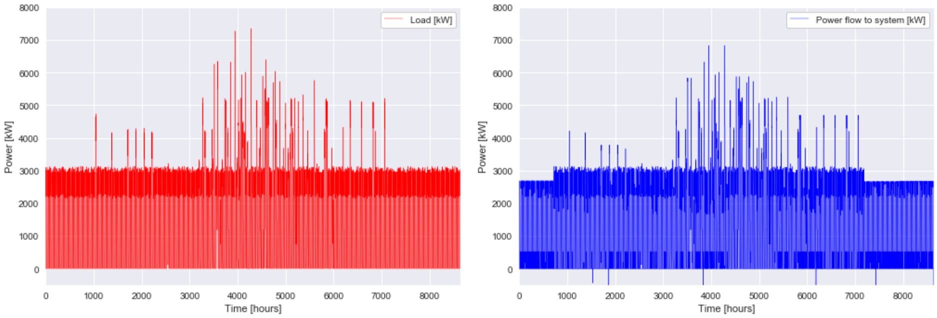
(b) Power flow to/from system



(c) Power flow to/from ESS

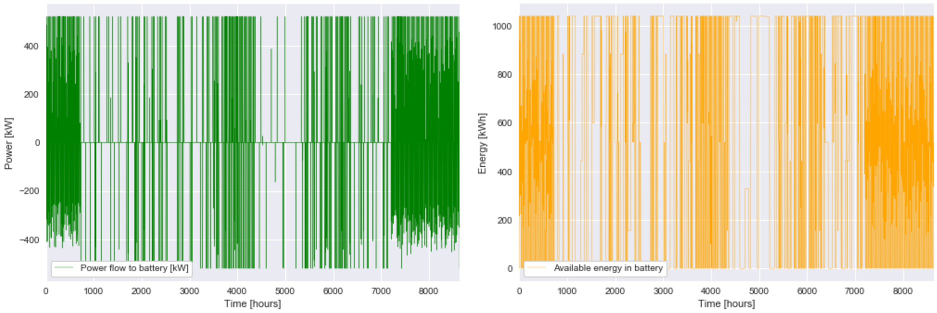
(d) Available energy in energy storage unit

Figure 8.2: Yearly power flow in *City port, Scenario 1* with optimal NaS ESS



(a) System load

(b) Power flow to/from system

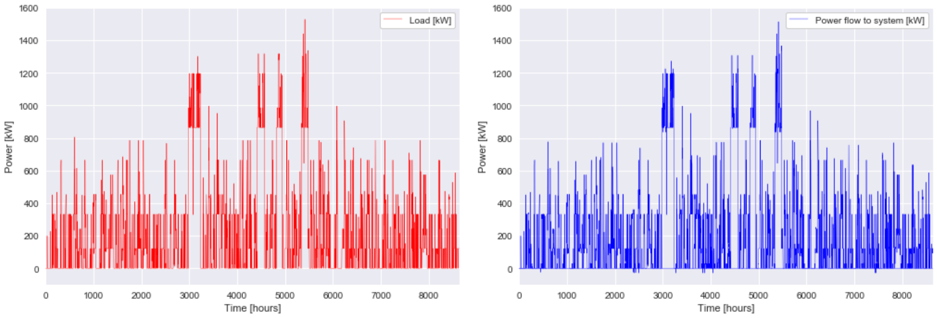


(c) Power flow to/from ESS

(d) Available energy in energy storage unit

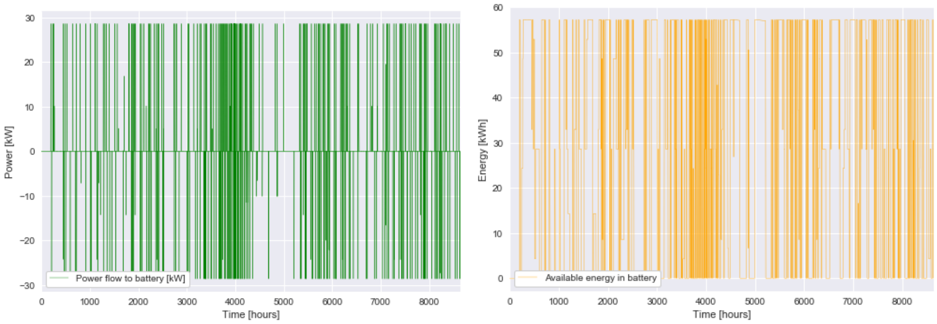
Figure 8.3: Yearly power flow in *City port, Scenario 2* with optimal NaS ESS

8.2.3 Cargo port with 2030 ESS characteristics



(a) System load

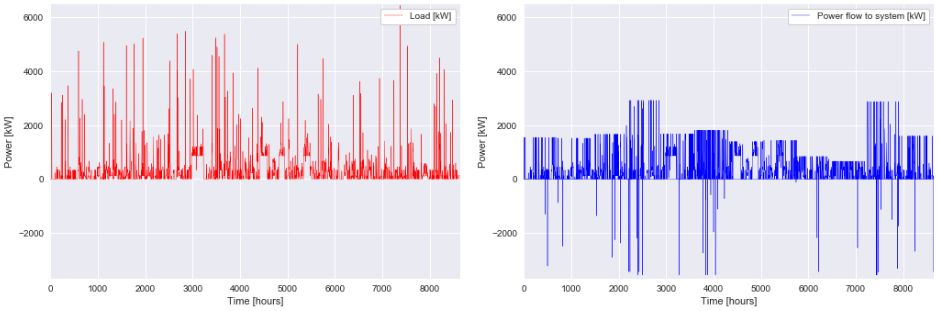
(b) Power flow to/from system



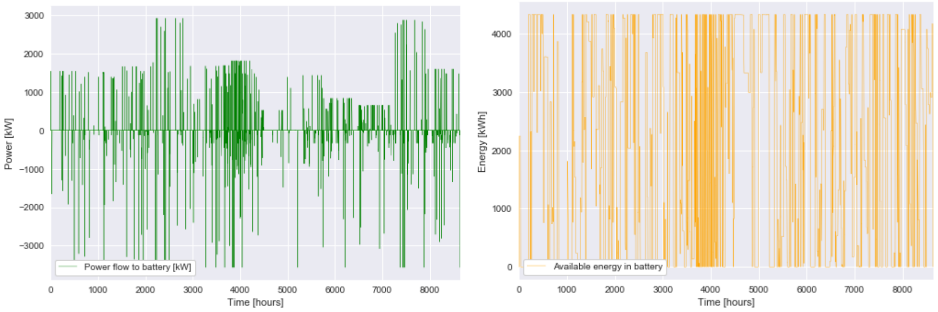
(c) Power flow to/from ESS

(d) Available energy in energy storage unit

Figure 8.4: Yearly power flow in *Cargo port, Scenario 1* with optimal NaS ESS



(a) System load **(b)** Power flow to/from system



(c) Power flow to/from ESS **(d)** Available energy in energy storage unit

Figure 8.5: Yearly power flow in *Cargo port, Scenario 2* with optimal NaS ESS

8.3 Annual costs in Initial analysis

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3147919	6377867	1257582	3904445	3493382	3580974
ZBFB	3147919	6377867	1257582	3904445	3493382	3580974
NaNiCl	3147919	6377867	1257582	3904445	3493382	3580974
NaS	3147919	6377867	1257582	3890927	3493382	3580974
F. Lead-acid	3147919	6377867	1257582	3904445	3493382	3580974
VRLA	3147919	6377867	1257582	3904445	3493382	3580974
LFP	3147919	6377867	1257582	3904445	3493382	3580974
LTO	3147919	6377867	1257582	3904445	3493382	3580974
NCA	3147919	6377867	1257582	3904445	3493382	3580974
NMC/LMO	3147919	6377867	1257582	3904445	3493382	3580974

Table 8.1: Annual costs with 2016 energy storage characteristics

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3144639	6372978	1257582	3746949	3493382	3580974
ZBFB	3147919	6377867	1257582	3904445	3493382	3580974
NaNiCl	3135517	6345225	1257582	3581168	3493382	3580974
NaS	3119300	6299876	1257305	3277014	3493382	3580974
F. Lead-acid	3147919	6377867	1257582	3897084	3493382	3580974
VRLA	3147919	6377867	1257582	3904445	3493382	3580974
LFP	3147919	6377867	1257582	3877321	3493382	3580974
LTO	3147919	6377867	1257582	3904445	3493382	3580974
NCA	3143793	6366946	1257582	3750432	3493382	3580974
NMC/LMO	3147919	6377867	1257582	3785248	3493382	3580974

Table 8.2: Annual costs with 2016 energy storage characteristics

8.4 Constrained grid capacity - 2016 characteristics

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3801423	6909453	1459298	4088367	4976146	3774968
ZBFB	5146326	7898852	1866256	4503738	8266428	3945836
NaNiCl	3708773	6779271	1435618	4007052	4941688	3741485
NaS	3541000	6618646	1384433	3890927	4650766	3694388
F. Lead-acid	3852463	6943524	1478227	4130554	5082077	3792074
VRLA	4406933	7345990	1646539	4308037	6323379	3864949
LFP	4297548	7205850	1616484	4233084	6198476	3833706
LTO	4797969	7516342	1769886	4360942	7405077	3885867
NCA	3817174	6865654	1470682	4078994	5131617	3770259
NMC/LMO	3959169	6964071	1513923	4124582	5450155	3788963

Table 8.3: Annual costs with grid capacity constrained to 90% of yearly peak

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	4810498	8084343	1677579	4291497	8108921	4165996
ZBFB	8180476	11467335	2492903	5122407	28261004	5069395
NaNiCl	4614941	7822470	1629995	4129101	8581461	4098066
NaS	4225341	7382271	1527327	3899610	7015777	3959285
F. Lead-acid	4929894	8210542	1714899	4376024	8249125	4214490
VRLA	6314411	9606154	2051547	4730910	12038375	4562240
LFP	6067111	9310170	1991905	4581781	11310999	4478936
LTO	7336747	10556551	2299234	4837975	14632864	4779334
NCA	4868939	8101732	1700676	4273932	8201550	4177187
NMC/LMO	5223523	8458764	1787154	4365107	9095666	4266288

Table 8.4: Annual costs with grid capacity constrained to 80% of yearly peak

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	6394467	9352466	2760811	4499828	18381131	6047769
ZBFB	12965079	15208463	6912003	5746812	-1	11384445
NaNiCl	6093381	8923299	2617030	4256234	22058964	5940049
NaS	5388655	8207310	2286841	3911848	14678247	5430909
F. Lead-acid	6623305	9539794	2755179	4626494	18276494	6227631
VRLA	9296584	11953350	3956195	5158801	30240057	8137608
LFP	8889205	11461870	3630434	4935791	27767598	7897736
LTO	11391902	13637092	4593109	5320578	38593764	9717390
NCA	6584913	9372720	2658684	4474357	18292476	6254019
NMC/LMO	7270444	9989618	2934655	4611119	21098220	6743893

Table 8.5: Annual costs with grid capacity constrained to 70% of yearly peak

8.5 Constrained grid capacity - 2030 characteristics

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3226520	6424422	1287476	3746949	3834515	3673303
ZBFB	3536163	6646427	1380928	3924823	4615920	3708218
NaNiCl	3208464	6382405	1284698	3581168	3899720	3657204
NaS	3157013	6315365	1269194	3277014	3856437	3633406
F. Lead-acid	3336366	6519482	1322601	3897084	4066940	3696238
VRLA	3545010	6670288	1385644	3963845	4530166	3723639
LFP	3371526	6514890	1335441	3877321	4233992	3689275
LTO	3585883	6640714	1401364	3926849	4778293	3707557
NCA	3240766	6419880	1295974	3750432	3952728	3671764
NMC/LMO	3274744	6444755	1306312	3785248	4028834	3676235

Table 8.6: Annual costs with grid capacity constrained to 90% of yearly peak

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3412377	6610183	1333473	3746949	4548203	3782561
ZBFB	4197761	7387520	1521509	3964496	9268133	3983392
NaNiCl	3389882	6546873	1328208	3581168	4956979	3760840
NaS	3281821	6406426	1297131	3277014	4619376	3709642
F. Lead-acid	3678460	6887641	1403666	3909553	5211842	3862318
VRLA	4199156	7413630	1529732	4042655	6610363	3992748
LFP	3784867	6962878	1430056	3878717	5649938	3873903
LTO	4333900	7493498	1562535	3970124	7167310	3998031
NCA	3459653	6633707	1351575	3750432	4840625	3791375
NMC/LMO	3544456	6719140	1372247	3785248	5051734	3812686

Table 8.7: Annual costs with grid capacity constrained to 80% of yearly peak

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3762509	6839928	1543052	3746949	6917204	4226871
ZBFB	5300725	8200287	2440455	4009529	-1	5480463
NaNiCl	3772231	6748930	1578338	3581168	8880396	4291700
NaS	3600116	6534676	1503687	3277014	7176190	4181580
F. Lead-acid	4274401	7299214	1751373	3926892	8875125	4598463
VRLA	5276794	8209710	2192327	4126463	13244669	5311883
LFP	4535844	7443475	1850164	3881411	10375278	4821437
LTO	5637478	8375284	2283488	4019177	15326815	5631406
NCA	3920274	6873730	1595962	3750432	7914898	4385556
NMC/LMO	4084219	7021320	1661012	3785248	8582239	4502564

Table 8.8: Annual costs with grid capacity constrained to 70% of yearly peak

8.6 Sensitivity of grid tariff

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	2210912	4734275	941391,1	2410223	2958864	3019131
ZBFB	2210912	4734275	941391,1	2410223	2958864	3019131
NaNiCl	2210912	4734275	941391,1	2410223	2958864	3019131
NaS	2210912	4734275	941391,1	2410223	2958864	3019131
F. Lead-acid	2210912	4734275	941391,1	2410223	2958864	3019131
VRLA	2210912	4734275	941391,1	2410223	2958864	3019131
LFP	2210912	4734275	941391,1	2410223	2958864	3019131
LTO	2210912	4734275	941391,1	2410223	2958864	3019131
NCA	2210912	4734275	941391,1	2410223	2958864	3019131
NMC/LMO	2210912	4734275	941391,1	2410223	2958864	3019131

Table 8.9: Annual costs with grid tariff 50% of initial.

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	2679416	5556071	1099487	3157334	3226123	3300053
ZBFB	2679416	5556071	1099487	3157334	3226123	3300053
NaNiCl	2679416	5556071	1099487	3146871	3226123	3300053
NaS	2675543	5548818	1099487	2974831	3226123	3300053
F. Lead-acid	2679416	5556071	1099487	3157334	3226123	3300053
VRLA	2679416	5556071	1099487	3157334	3226123	3300053
LFP	2679416	5556071	1099487	3157334	3226123	3300053
LTO	2679416	5556071	1099487	3157334	3226123	3300053
NCA	2679416	5556071	1099487	3157334	3226123	3300053
NMC/LMO	2679416	5556071	1099487	3157334	3226123	3300053

Table 8.10: Annual costs with grid tariff 75% of initial.

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	2960518	6049149	1194344	3571390	3386479	3468606
ZBFB	2960518	6049149	1194344	3605601	3386479	3468606
NaNiCl	2957065	6042031	1194344	3440114	3386479	3468606
NaS	2942446	6000805	1194344	3164794	3386479	3468606
F. Lead-acid	2960518	6049149	1194344	3605601	3386479	3468606
VRLA	2960518	6049149	1194344	3605601	3386479	3468606
LFP	2960518	6049149	1194344	3605601	3386479	3468606
LTO	2960518	6049149	1194344	3605601	3386479	3468606
NCA	2960518	6049149	1194344	3564431	3386479	3468606
NMC/LMO	2960518	6049149	1194344	3586004	3386479	3468606

Table 8.11: Annual costs with grid tariff 90% of initial.

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3323357	6677881	1320821	3884167	3600286	3693343
ZBFB	3335321	6706585	1320821	4183795	3600286	3693343
NaNiCl	3312801	6644728	1320821	3706388	3600286	3693343
NaS	3295163	6597670	1317627	3381252	3600286	3693343
F. Lead-acid	3335321	6706585	1320821	4116289	3600286	3693343
VRLA	3335321	6706585	1320821	4203289	3600286	3693343
LFP	3335321	6706585	1320821	4068303	3600286	3693343
LTO	3335321	6706585	1320821	4186724	3600286	3693343
NCA	3322141	6669206	1320821	3901186	3600286	3693343
NMC/LMO	3327309	6684871	1320821	3960263	3600286	3693343

Table 8.12: Annual costs with grid tariff 110% of initial.

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3589603	7128795	1415678	4071861	3760641	3861896
ZBFB	3616423	7199663	1415678	4481935	3760641	3861896
NaNiCl	3577838	7092958	1414845	3876324	3760641	3861896
NaS	3550275	7023965	1405164	3521618	3760641	3861896
F. Lead-acid	3609539	7183630	1415678	4378256	3760641	3861896
VRLA	3616423	7199663	1415678	4604079	3760641	3861896
LFP	3609368	7182194	1415678	4330135	3760641	3861896
LTO	3616423	7199663	1415678	4492353	3760641	3861896
NCA	3587329	7116755	1415678	4092464	3760641	3861896
NMC/LMO	3593611	7134630	1415678	4162638	3760641	3861896

Table 8.13: Annual costs with grid tariff 125% of initial.

	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	4014171	7842078	1563869	4341758	4027901	4142818
ZBFB	4078135	8013810	1573774	4884985	4027901	4142818
NaNiCl	3989930	7783956	1561003	4120973	4027901	4142818
NaS	3910862	7588164	1541334	3744777	4027901	4142249
F. Lead-acid	4054069	7936296	1573774	4700898	4027901	4142818
VRLA	4084349	8021459	1573774	5060298	4027901	4142818
LFP	4053390	7932716	1573774	4648081	4027901	4142818
LTO	4080755	8017717	1573774	4902940	4027901	4142818
NCA	4027031	7859051	1568759	4373960	4027901	4142818
NMC/LMO	4034450	7878677	1572426	4449736	4027901	4142818

Table 8.14: Annual costs with grid tariff 150% of initial.

8.7 Sensitivity of electricity prices

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3022523	6042560	1210202	3461058	3184776	3265524
ZBFB	3042831	6095306	1210202	3787498	3184776	3265524
NaNiCl	3004466	5992308	1205937	3259757	3184776	3265524
NaS	2950719	5872262	1192523	2959836	3183422	3264842
F. Lead-acid	3040042	6091056	1210202	3699674	3184776	3265524
VRLA	3042831	6095306	1210202	3802781	3184776	3265524
LFP	3038131	6084469	1210202	3634907	3184776	3265524
LTO	3042831	6095306	1210202	3770231	3184776	3265524
NCA	3014688	6016975	1209479	3405356	3184776	3265524
NMC/LMO	3021095	6035002	1210202	3475316	3184776	3265524

Table 8.15: Annual costs with system spot price of Germany

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3102796	6251975	1234643	3563427	3340788	3423155
ZBFB	3118513	6292132	1234643	3845803	3340788	3423155
NaNiCl	3088354	6209842	1233637	3357352	3340788	3423155
NaS	3048530	6117760	1223228	3060430	3340328	3423104
F. Lead-acid	3118429	6291964	1234643	3777234	3340788	3423155
VRLA	3118513	6292132	1234643	3851448	3340788	3423155
LFP	3117207	6290452	1234643	3708314	3340788	3423155
LTO	3118513	6292132	1234643	3827993	3340788	3423155
NCA	3094619	6225327	1234643	3498513	3340788	3423155
NMC/LMO	3100912	6243181	1234643	3565696	3340788	3423155

Table 8.16: Annual costs with system spot price of Austria

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3447516	6996441	1387059	3670652	3784930	3875560
ZBFB	3479538	7081732	1389711	4056030	3784930	3875560
NaNiCl	3404687	6895404	1377597	3447771	3784568	3875446
NaS	3335827	6721701	1358807	3147842	3781971	3872547
F. Lead-acid	3470901	7061528	1389711	3913554	3784930	3875560
VRLA	3479538	7081732	1389711	4080507	3784930	3875560
LFP	3466372	7046829	1389711	3826837	3784930	3875560
LTO	3479538	7081732	1389711	3979104	3784930	3875560
NCA	3414695	6923427	1379551	3559084	3784730	3875490
NMC/LMO	3444516	6986660	1386482	3632494	3784930	3875560

Table 8.17: Annual costs with system spot price of Slovenia

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3103551	6279180	1234020	3643059	3429451	3512614
ZBFB	3112912	6301231	1234020	3858811	3429451	3512614
NaNiCl	3090926	6241313	1234020	3450315	3429451	3512614
NaS	3072430	6190856	1229110	3150166	3429451	3512614
F. Lead-acid	3112912	6301231	1234020	3829850	3429451	3512614
VRLA	3112912	6301231	1234020	3859567	3429451	3512614
LFP	3112912	6301231	1234020	3770887	3429451	3512614
LTO	3112912	6301231	1234020	3854187	3429451	3512614
NCA	3098182	6260199	1234020	3600517	3429451	3512614
NMC/LMO	3103710	6276444	1234020	3658358	3429451	3512614

Table 8.18: Annual costs with system spot price of Switzerland

8.8 Sensitivity of end-of-life return value

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3141316	6364287	1257582	3688282	3493382	3580974
ZBFB	3147919	6377867	1257582	3900661	3493382	3580974
NaNiCl	3132242	6335552	1257582	3529655	3493382	3580974
NaS	3116135	6291450	1256610	3231182	3493382	3580974
F. Lead-acid	3147919	6377867	1257582	3863022	3493382	3580974
VRLA	3147919	6377867	1257582	3904445	3493382	3580974
LFP	3147919	6377867	1257582	3832342	3493382	3580974
LTO	3147919	6377867	1257582	3902713	3493382	3580974
NCA	3139692	6355249	1257582	3693436	3493382	3580974
NMC/LMO	3144544	6369033	1257582	3738782	3493382	3580974

Table 8.19: Annual costs with end-of-life percentage return value of 10%

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3137780	6354372	1257582	3627842	3493382	3580974
ZBFB	3147919	6377867	1257582	3881884	3493382	3580974
NaNiCl	3128834	6325812	1257582	3477353	3493382	3580974
NaS	3112817	6282829	1255291	3182539	3493382	3580974
F. Lead-acid	3147919	6377867	1257582	3796639	3493382	3580974
VRLA	3147919	6377867	1257582	3903528	3493382	3580974
LFP	3147919	6377867	1257582	3781940	3493382	3580974
LTO	3147919	6377867	1257582	3896638	3493382	3580974
NCA	3135509	6342656	1257582	3628791	3493382	3580974
NMC/LMO	3140184	6356777	1257582	3682622	3493382	3580974

Table 8.20: Annual costs with end-of-life percentage return value of 20%

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3133885	6343292	1257582	3563494	3493382	3580974
ZBFB	3147919	6377867	1257582	3830202	3493382	3580974
NaNiCl	3125345	6315966	1257582	3424189	3493382	3580974
NaS	3109431	6274183	1253774	3133549	3493382	3580974
F. Lead-acid	3144821	6372192	1257582	3726511	3493382	3580974
VRLA	3147919	6377867	1257582	3886011	3493382	3580974
LFP	3147817	6377867	1257582	3730741	3493382	3580974
LTO	3147919	6377867	1257582	3877638	3493382	3580974
NCA	3130569	6328541	1257582	3558168	3493382	3580974
NMC/LMO	3135659	6343416	1257582	3615720	3493382	3580974

Table 8.21: Annual costs with end-of-life percentage return value of 30%

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3129862	6331877	1257582	3498312	3493382	3580974
ZBFB	3147919	6377867	1257582	3767497	3493382	3580974
NaNiCl	3121772	6306005	1257582	3368323	3493382	3580974
NaS	3105473	6262660	1251870	3082009	3493382	3580974
F. Lead-acid	3138831	6355316	1257582	3631356	3493382	3580974
VRLA	3147919	6377867	1257582	3823249	3493382	3580974
LFP	3143357	6366922	1257582	3676578	3493382	3580974
LTO	3147919	6377867	1257582	3837110	3493382	3580974
NCA	3125520	6314211	1257582	3485556	3493382	3580974
NMC/LMO	3130554	6328515	1257582	3541586	3493382	3580974

Table 8.22: Annual costs with end-of-life percentage return value of 40%

Tech.	City, S1	City, S2	Cargo, S1	Cargo, S2	Offsh., S1	Offsh., S2
VRFB	3125767	6320348	1257582	3433130	3493382	3580974
ZBFB	3147676	6377867	1257582	3703498	3493382	3580974
NaNiCl	3118099	6295925	1257136	3310460	3493382	3580974
NaS	3097793	6243116	1249695	3028738	3493382	3580974
F. Lead-acid	3132215	6336024	1257582	3523599	3493382	3580974
VRLA	3147919	6377867	1257582	3743004	3493382	3580974
LFP	3138284	6352518	1257582	3604563	3493382	3580974
LTO	3147919	6377867	1257582	3789552	3493382	3580974
NCA	3120366	6299699	1257582	3410194	3493382	3580974
NMC/LMO	3125196	6313292	1257582	3464403	3493382	3580974

Table 8.23: Annual costs with end-of-life percentage return value of 50%

8.9 Code

8.9.1 Optimization model in Python

```
"""
This code shows creates, updates and solves the
optimization problem.
Author: Tobias Grande Hansen
"""
import pyomo.environ as pyo
import numpy as np
import pandas as pd
from pyomo.opt import SolverStatus, TerminationCondition


def create_model(system, grid_specs):
    """
    This function creates an empty model
    """
    ### Creating Sets
    model=pyo.ConcreteModel()
    model.m=pyo.Set(initialize=pyo.RangeSet(12))
    #12 months a year (0,1,2,...,12)
    model.d=pyo.Set(initialize=pyo.RangeSet(30))
    #365 days(1,2,...,365)
    model.h=pyo.Set(initialize=range(24))
    #24 hours every day(0,1,2,...,23)

    ### Creating Variables

    ## Power flow
```

```
# Power from grid to system
model.P_in=pyo.Var(model.m,model.d,model.h,\
                   within=pyo.NonNegativeReals)
# Power from system to grid
model.P_out=pyo.Var(model.m,model.d,model.h,\
                    within=pyo.NonNegativeReals)
# Power to battery
model.P_charge=pyo.Var(model.m,model.d,model.h,\
                       within=pyo.NonNegativeReals)
# Power from battery
model.P_discharge=pyo.Var(model.m,model.d,model.h,\
                          within=pyo.NonNegativeReals)

## Cost elements
# Grid tariff
#model.G_ec=pyo.Var()
#model.G_pt=pyo.Var()
# Monthly peak power
model.P_m_peak=pyo.Var(model.m,within=pyo.NonNegativeReals)


## Battery variables
# Stored energy in battery (in kWh)
model.B_soc=pyo.Var(model.m,model.d,model.h,\
                    within=pyo.NonNegativeReals)
# Installed capacity of battery
model.B_cap=pyo.Var(within=pyo.NonNegativeReals)
# Rated power
model.B_ratedP=pyo.Var(within=pyo.NonNegativeReals)


### Constant system-parameters

## Electricity price
# Electricity spot price
model.spot_price=pyo.Param(model.m,model.d,model.h,\
                           initialize=system.spot_price,\
                               mutable=False)
# Grid capacity
model.Pgrid_max=pyo.Param(initialize=system.Pgrid_max,\
                          mutable=False)

# End of life percentage return value
model.B_eof=pyo.Param(initialize=system.eof/100,\
                      mutable=False)
```

```
## Cost related parameters
model.rent=pyo.Param(initialize=system.rent ,mutable=False)

## Grid related parameters
# Grid tariff energy cost [NOK/kWh]
G_ec={}
G_pt={}
for month in range(1,13):
    if month<3 and month<10:
        G_ec[month]=grid_specs.ec_s
        G_pt[month]=grid_specs.pt_s
    else:
        G_ec[month]=grid_specs.ec_w
        G_pt[month]=grid_specs.pt_w

model.G_ec=pyo.Param(model.m,initialize=G_ec,\
                     mutable=False)
# Grid tariff power tariff [NOK/kW]
model.G_pt=pyo.Param(model.m,initialize=G_pt,\
                     mutable=False)
# Grid tariff feed-in tariff [NOK/kWh]
model.G_ft=pyo.Param(initialize=grid_specs.ft,\
                     mutable=False)


### Mutable Parameters
## Load
model.P_load=pyo.Param(model.m,model.d,model.h,\
                       mutable=True)
## Battery parameters
# Round-trip efficiency
model.B_rt_eff=pyo.Param(mutable=True)
# Depth of discharge
model.B_dod=pyo.Param(mutable=True)
# Self discharge rate of battery in rate per minute
model.B_sdr=pyo.Param(mutable=True)
# OPEX
model.B_OPEX=pyo.Param(mutable=True)
# Power installation cost of power conversion unit
model.B_pic=pyo.Param(mutable=True)
# Energy installation cost of energy storage unit
model.B_eic=pyo.Param(mutable=True)
# Calender life
model.B_life=pyo.Param(mutable=True)
return model
```

```
def update_model(model, battery ,load):
    """
    This function updates an empty model with
    given battery, system and load parameters.
    """
    ### Updating Mutable Parameters
    ## Load
    for m in range(1,13):
        for d in range(1,31):
            for h in range(24):
                model.P_load[m,d,h]=load[m,d,h]
    ## Battery parameters
    # Round-trip efficiency
    model.B_rt_eff=battery.rt_eff
    # Depth of discharge
    model.B_dod=battery.DoD
    # Self discharge rate of battery in rate per minute
    model.B_sdr=battery.self_dch_rate
    # OPEX
    model.B_OPEX=battery.OPEX
    # Power installation cost of power conversion unit
    model.B_pic=battery.pic
    # Energy installation cost of energy storage unit
    model.B_eic=battery.el_install_cost
    # Calender life
    model.B_life=battery.cal_life

    ### Adding constraints

    ### Adding constraints to model
    model.c1=pyo.Constraint(model.m,model.d,model.h,  rule=c1)
    model.c2=pyo.Constraint(model.m,model.d,model.h,  rule=c2)
    model.c3=pyo.Constraint(model.m,model.d,model.h,  rule=c3)
    model.c4=pyo.Constraint(model.m,model.d,model.h,  rule=c4)
    model.c5=pyo.Constraint(model.m,model.d,model.h,  rule=c5)
    model.c6=pyo.Constraint(model.m,model.d,model.h,  rule=c6)
    model.c7=pyo.Constraint(model.m,model.d,model.h,rule=c7)
    model.c8=pyo.Constraint(model.m,model.d,model.h,rule=c8)
    model.c9=pyo.Constraint(model.m,model.d,model.h,rule=c9)
    model.c10=pyo.Constraint(model.m,model.d,model.h,rule=c10)
    model.obj=pyo.Objective(rule=obj_rule ,sense=pyo.minimize)

    return model
```

```
def run_model(model):
    """
    This function runs the model and returns the model.
    """
    ### Choosing solver gurobi
    opt=pyo.SolverFactory("gurobi",solver_io='python')

    results=opt.solve(model, load_solutions = True)

    if (results.solver.status == SolverStatus.ok) and \
        (results.solver.termination_condition == \
         TerminationCondition.optimal):
            return model
    elif (results.solver.termination_condition == \
          TerminationCondition.infeasible):
        print('Model infeasible')
        return -1
    else:
        # Something else is wrong
        print ("Solver Status: ", results.solver.status)
        return -1


## Defining objective function
def obj_rule(model):

    Energy_cost=sum((model.spot_price[m,d,h]+model.G_ec[m])*\
                    model.P_in[m,d,h]-\
                        (model.spot_price[m,d,h]-model.G_ft)*\
                        model.P_out[m,d,h] \
                            for h in model.h for d in model.d \
                                for m in model.m)

    # Annualization factor
    epsilon=model.rent/(1-(1+model.rent)**(-model.B_life))
    # Discount factor
    alpha=(1+model.rent)**(-model.B_life)

    Ann_Battery_cost=((model.B_eic*model.B_cap+model.B_pic*\
            model.B_ratedP)*(epsilon*(1-alpha*model.B_eof))+\
            model.B_OPEX*model.B_ratedP)


    Gridtariff_cost=sum(model.P_m_peak[m]*model.G_pt[m]\
```

```
                                    for m in model.m)

    return Energy_cost+Ann_Battery_cost+Gridtariff_cost


### Defining constraints

## Load flow rule
def c1(model,m,d,h):
    return model.P_in[m,d,h]-model.P_out[m,d,h]\
        ==model.P_load[m,d,h]+model.P_charge[m,d,h]\
            -model.P_discharge[m,d,h]

## Battery restrictions rule
def c2(model,m,d,h):
    return 0<=model.B_soc[m,d,h]#(1-model.B_dod)*model.B_cap

def c3(model,m,d,h):
    return model.B_soc[m,d,h]<=model.B_cap*model.B_dod

## Charging of battery rule
def c4(model,m,d,h):
    if h>0:
        return model.B_soc[m,d,h]==(1-model.B_sdr)\
            *model.B_soc[m,d,h-1]+\
            (model.B_rt_eff*model.P_charge[m,d,h-1]\
                -model.P_discharge[m,d,h-1])
    elif d>1 and h==0:
        return model.B_soc[m,d,h]==(1-model.B_sdr)*\
            model.B_soc[m,d-1,23]+\
            (model.B_rt_eff*model.P_charge[m,d-1,23]\
                -model.P_discharge[m,d-1,23])
    elif m>1 and d==1 and h==0:
        return model.B_soc[m,d,h]==(1-model.B_sdr)*\
            model.B_soc[m-1,30,23]+\
            (model.B_rt_eff*model.P_charge[m-1,30,23]\
                -model.P_discharge[m-1,30,23])
    elif m==1 and d==1 and h==0:
        return model.B_soc[m,d,h]==0

## Energy balance rule
def c5(model,m,d,h):
    if h>0:
        return model.P_discharge[m,d,h]<=\
            (1-model.B_sdr)*model.B_soc[m,d,h-1]
```

```
    elif d>1 and h==0:
        return model.P_discharge[m,d,h]<=\
            (1-model.B_sdr)*model.B_soc[m,d-1,23]
    elif m>1 and d==1 and h==0:
        return model.P_discharge[m,d,h]<=\
            (1-model.B_sdr)*model.B_soc[m-1,30,23]
    elif m==1 and d==1 and h==0:
        return model.P_discharge[m,d,h]==0

## Big M for P_charge
def c6(model,m,d,h):
    return model.P_charge[m,d,h]<=model.B_ratedP

def c7(model,m,d,h):
    return model.P_discharge[m,d,h]<=model.B_ratedP

## Big M for P_out
def c8(model,m,d,h):
    return model.P_in[m,d,h]<=model.Pgrid_max

def c9(model,m,d,h):
    return model.P_out[m,d,h]<=model.Pgrid_max


#Monthly peak power
def c10(model,m,d,h):
    return model.P_m_peak[m]>=model.P_in[m,d,h]


def c11(model,m):
    if m>3 and m<10:
        return model.G_ec==model.G_ec_s
    else:
        return model.G_ec==model.G_ec_w

def c12(model,m):
     if m>3 and m<10:
         return model.G_pt==model.G_pt_s
     else:
         return model.G_pt==model.G_pt_w

def c13(model):
    return model.B_cap<=0
```

8.9.2 Derivations of scenarios in Python

```
"""
Derivation of Scenarios
Author: Tobias Grande Hansen
"""
import random
import numpy as np
import matplotlib.pyplot as plt

"""
Required functions for derivation of scenarios
"""
def list_to_dict(data,type_of_data):
    d={}
    if type_of_data=='dayhour':
        for day in range(1,366):
            for hour in range(0,24):
                d[day,hour]=data[(day-1)*24+hour]
    elif type_of_data=='dayhourminute':
        for day in range(1,366):
            for hour in range(0,24):
                for minute in range(0,60):
                    d[day,hour,minute]=data[((day-1)\
                        *24+hour)*60+minute]
def to_hourly(minutely):
    #makes a yearly minutely load to hourly
    d=[]
    for h in range(24):
        avg=0
        for m in range(60):
            avg=avg+minutely[h*60+m]
        avg=avg/60
        d.append(avg)
    return d

def minute_in_year(timestamp):
    #finds minute in year from timestamp
    day_of_year=timestamp.dayofyear
    hour_of_day=timestamp.hour
    minute_of_hour=timestamp.minute
    return ((day_of_year-1)*24+hour_of_day)\
        *60+minute_of_hour

def enova_table(ship_type,BT):
    ##returning coefficient from enova table
    #returns are Enova's estimated power
```

```
#consumption in port in kW
if ship_type=='cruise':
    if BT<=999:
        return 20
    elif BT>999 and BT<=4999:
        return 119
    elif BT>4999 and BT<=9999:
        return 272
    elif BT>9999 and BT<=29999:
        return 570
    elif BT>29999 and BT<=49999:
        return 1194
    elif BT>49999 and BT<=99999:
        return 2100
    elif BT>99999:
        return 2912
elif ship_type=='container':
    if BT<=999:
        return 31
    elif BT>999 and BT<=4999:
        return 121
    elif BT>4999 and BT<=9999:
        return 332
    elif BT>9999 and BT<=24999:
        return 473
    elif BT>24999 and BT<=49999:
        return 864
    elif BT>49999 and BT<=99999:
        return 1535
    elif BT>99999:
        return 2295
elif ship_type=='offshore':
    if BT<=999:
        return 45
    elif BT>999 and BT<=4999:
        return 144
    elif BT>4999 and BT<=9999:
        return 345
    elif BT>9999 and BT<=24999:
        return 553
    elif BT>24999 and BT<=49999:
        return 912
    elif BT>49999 and BT<=99999:
        return 1144
    elif BT>99999:
```

```
            return 1248

def minute_shipload(anlops_liste,plot_choice):
    #finding minutely load from portcall schedules
    time=[]
    ships=[]
    load=[]
    for m in range(60*24*365):
        time.append(m)
        load.append(0)
        ships.append(0)
    for i in range(len(anlops_liste)):
        arrival_minute=minute_in_year(anlops_liste[i].arrival)
        departure_minute=minute_in_year(anlops_liste[i].departure)
        if departure_minute-arrival_minute>=60:
            for j in range(arrival_minute,departure_minute):
                load[j]=load[j]+anlops_liste[i].boat.power
                ships[j]=ships[j]+1
    if plot_choice==True:
        ##Plotting
        plt.subplot(211)
        plt.plot(time,ships,label='Number␣of␣ships␣in␣port')
        plt.ylabel('Number␣of␣ships')
        plt.subplot(212)
        plt.plot(time,load,label='Power␣need␣in␣port')
        plt.ylabel('Power␣need␣[kW]')
        plt.xlabel('Time␣[minutes]')
        plt.show()
    return np.array(([time,ships,load]))

def kystruta(scenario):
    #calculating daily load from kystruta
    n_chr_st=10*60+15
    n_chr_end=13*60+15
    #south-going
    s_chr_st=6*60+30
    s_chr_end=9*60+45
    tp_kystruta=[]
    time=[]
    if scenario==1:
        n_amp=random.randrange(900,1100)
        s_amp=random.randrange(900,1100)
        for i in range(0,24*60):
            time.append(i)
            if i<(n_chr_end) and i>(n_chr_st):
```

```
                tp_kystruta.append(n_amp)
            elif i<(s_chr_end) and i>(s_chr_st):
                tp_kystruta.append(s_amp)
            else:
                tp_kystruta.append(0)
    elif scenario==2:
        Battery_capacity=6100 #kWh
        Ch_power=Battery_capacity/\
            ((n_chr_end-n_chr_st)/60)#kWh/h
        n_amp=random.randrange(900,1100)
        s_amp=random.randrange(900,1100)
        for i in range(0,24*60):
            time.append(i)
            if i<(n_chr_end) and i>(n_chr_st):
                tp_kystruta.append(n_amp+Ch_power)
            elif i<(s_chr_end) and i>(s_chr_st):
                tp_kystruta.append(s_amp+Ch_power)
            else:
                tp_kystruta.append(0)
    return tp_kystruta

”””
Trondheim (City) port
”””
import trondheim_cruiseanlop19 #portcall schedule

### Scenario 1
tp_cruise19=minute_shipload\
    (trondheim_cruiseanlop19,False)[2]
tp_scenario1={}
tp_scenario1_list=[]
random.seed(2000)
for m in range(1,13):
    for d in range(1,31):
        daily_kystruta=to_hourly(kystruta(1))
        for h in range(24):
            hourly_cruise=0
            for minute in range(60):
                hourly_cruise=hourly_cruise+\
                    tp_cruise19[(((m-1)*30+(d-1))\
                                *24+h)*60+minute]
            tp_scenario1[m,d,h]=hourly_cruise/60+\
                    daily_kystruta[h]
```

```
tp_scenario1_minutely=[]
random.seed(2000)
for days in range(1,366):
    daily_kystruta=kystruta(1)
    for minute in range(24*60):
        tp_scenario1_minutely.append(\
                    tp_cruise19[(days-1)*24*60+minute]\
                        +daily_kystruta[minute])

### Scenario 2
tp_scenario2={}

## Kystruta
random.seed(9002)

tp_scenario2_kystruta=[]
for days in range(365):
    tp_scenario2_kystruta.extend(kystruta(2))

## Cruise yearly load
hybrid_share=20#%
time=[]
ships=[]
tp_scenario2_cruise=[]
hybrid_count2=0
Ch_powers2=[]
for m in range(60*24*365):
    time.append(m)
    tp_scenario2_cruise.append(0)

for i in range(len(trondheim_cruiseanlop19)):
    arrival_minute=minute_in_year\
        (trondheim_cruiseanlop19[i].arrival)
    departure_minute=minute_in_year\
        (trondheim_cruiseanlop19[i].departure)
    if departure_minute-arrival_minute>60:
        if random.randint(1,100)<=hybrid_share:
            hybrid_count2=hybrid_count2+1
            Bat_cap_factor=random.randint(10,18) #GT per kWh
            Bat_cap=trondheim_cruiseanlop19[i].boat.BT\
                /Bat_cap_factor
            Ch_powers2.append(Bat_cap/((departure_minute\
                                -arrival_minute)/60))
        else:
            Ch_powers2.append(0)
```

```
        for j in range(arrival_minute,departure_minute):
            tp_scenario2_cruise[j]=tp_scenario2_cruise[j]\
                +trondheim_cruiseanlop19[i].boat.power\
                    +Ch_powers2[i]
    else:
        Ch_powers2.append(0)


##
tp_minutely_load_2=[]
for days in range(1,366):
    for m in range(24*60):
        tp_minutely_load_2.append(tp_scenario2_cruise\
            [(days-1)*24*60+m]+tp_scenario2_kystruta\
                [(days-1)*24*60+m])

tp_hourly_load_2=[]
for days in range(1,366):
    for hour in range(24):
        hourly_load=0
        for minute in range(60):
            hourly_load=hourly_load+\
                tp_minutely_load_2[((days-1)*24+hour)\
                    *60+minute]
        tp_hourly_load_2.append(hourly_load/60)

for month in range(1,13):
    for days in range(1,31):
        for hour in range(24):
            tp_scenario2[month,days,hour]=\
                tp_hourly_load_2[((month-1)*30+(days-1))\
                        *24+hour]


"""
Hus y (Cargo) port
"""
import h19_anlop

random.seed(25)
## Scenario 1

h19_load_list=minute_shipload(h19_anlop,False)[2]
h19_load=list_to_dict(h19_load_list,'dayhourminute')
```

```
h19_scenario1_hourly=[]
for day in range(1,366):
    for hour in range(24):
        hourly_load=0
        for minute in range(60):
            hourly_load=hourly_load+h19_load[day,hour,minute]
        h19_scenario1_hourly.append(hourly_load/60)
h_scenario1={}
for month in range(1,13):
    for day in range(1,31):
        for hour in range(24):
            h_scenario1[month,day,hour]=h19_scenario1_hourly\
                [((month-1)*30+day-1)*24+hour]


## Scenario 2

## Minutely load
sizes=[999,4999,9999,24999,5000000]
hybrid_shares=[40,40,30,25,15] #%
battery_caps=[1000,2000,3000,4000,5000] #kWh
time=[]
ships=[]
h_scenario2_list=[]
hybrid_count=0
Ch_power=[]
for m in range(60*24*365):
    time.append(m)
    h_scenario2_list.append(0)
for i in range(len(h19_anlop)):
    for j in range(len(sizes)):
        if h19_anlop[i].boat.BT<sizes[j]:
            hybrid_share=hybrid_shares[j]
            bat_cap=battery_caps[j]

    arrival_minute=minute_in_year(h19_anlop[i].arrival)
    departure_minute=minute_in_year(h19_anlop[i].departure)
    if (departure_minute-arrival_minute)>30:
        if random.randint(1,100)<=hybrid_share:
            Ch_power.append(bat_cap/\
                ((departure_minute-arrival_minute)/60))
            hybrid_count=hybrid_count+1
        else:
            Ch_power.append(0)
```

```
        for j in range(arrival_minute ,departure_minute):
            h_scenario2_list[j]=h_scenario2_list[j]\
                +h19_anlop[i].boat.power+Ch_power[i]
    else:
        Ch_power.append(0)

## Hourly load
h_scenario2_hourly=[]
for day in range(1,366):
    for hour in range(24):
        hourly_load=0
        for minute in range(60):
            hourly_load=hourly_load+\
                h_scenario2_list[((day-1)*24+hour)*60+minute]
        h_scenario2_hourly.append(hourly_load/60)

## Dict
h_scenario2={}
for month in range(1,13):
    for day in range(1,31):
        for hour in range(24):
            h_scenario2[month,day,hour]=\
                h_scenario2_hourly[((month-1)*30+(day-1))*24+hour]

"""
Killingoy (Offshore) port
"""
import k19_anlop

## Scenario 1
random.seed(9003)
k19_load_list=minute_shipload(k19_anlop,False)[2]
k19_load=list_to_dict(k19_load_list,'dayhourminute')

k19_scenario1_hourly=[]
for day in range(1,366):
    for hour in range(24):
        hourly_load=0
        for minute in range(60):
            hourly_load=hourly_load+k19_load[day,hour,minute]
        k19_scenario1_hourly.append(hourly_load/60)
k_scenario1={}
for month in range(1,13):
    for day in range(1,31):
        for hour in range(24):
```

```
            k_scenario1[month,day,hour]=\
                k19_scenario1_hourly[((month-1)*30+day-1)*24+hour]
k_scenario1_minutely={}
for month in range(1,13):
    for day in range(1,31):
        for hour in range(24):
            for minute in range(60):
                k_scenario1_minutely[month,day,hour,minute]\
                    =k19_load[(month-1)*30+day,hour,minute]
## Scenario 2

hybrid_share=50#%
time=[]
k_scenario2_list=[]
hybrid_count=0
Ch_power=[]
Bat_cap=[]
for m in range(60*24*365):
    time.append(m)
    k_scenario2_list.append(0)
for i in range(len(k19_anlop)):
    arrival_minute=minute_in_year(k19_anlop[i].arrival)
    departure_minute=minute_in_year(k19_anlop[i].departure)
    if departure_minute-arrival_minute>60:
        if random.randint(1,100)<=hybrid_share:
            hybrid_count=hybrid_count+1
            Bat_cap_factor=random.randint(7,9) #GT per kWh
            Bat_cap.append(k19_anlop[i].boat.BT/Bat_cap_factor)
            Ch_power.append((k19_anlop[i].boat.BT/Bat_cap_factor)\
                /((departure_minute-arrival_minute)/60))
        else:
            Ch_power.append(0)
            Bat_cap.append(0)
        for j in range(arrival_minute,departure_minute):
            k_scenario2_list[j]=k_scenario2_list[j]\
                +k19_anlop[i].boat.power+Ch_power[i]
    else:
        Ch_power.append(0)
        Bat_cap.append(0)

k_scenario2_hourly=[]
for days in range(1,366):
        for hour in range(24):
            hourly_load=0
            for minute in range(60):
```

```
                hourly_load=hourly_load+\
                    k_scenario2_list[((days-1)*24+hour)*60+minute]
            #print(hourly_load)
            k_scenario2_hourly.append(hourly_load/60)

k_scenario2={}
for month in range(1,13):
    for day in range(1,31):
        for hour in range(24):
            k_scenario2[month,day,hour]=k_scenario2_hourly\
                [((month-1)*30+(day-1))*24+hour]
```

Tobias Grande Hansen

Utilization of energy storage systems in ports

NTNU
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Science and Technology