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Using Energy Storage Systems to Provide Grid Support for Ferry Charging

Bachelor's thesis in Engineering, Renewable Energy
May 2022

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NTNU
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Preface

This bachelor thesis is the final part of the study program ”Bachelor of Engineering, Renewable Energy” at the Norwegian University of Science and Technology (NTNU).

The thesis has been done in collaboration with the battery technology company Beyonder. The thesis aims to find out if Beyonder’s LIC technology could be a good fit in the market of ferry charging.

We want to thank our internal supervisor, Professor Steven Boles, for his guidance and assistance throughout the project. We also want to thank Beyonder for their help and feedback during this period.

In addition, we want to thank all the people that have taken the time to answer our questions to make the paper complete: Manager of the Planning Section Olav Hårstad from Tensio TS, CEO Tor Åge Ingvaldsen from Kraftmontasjen AS, Project- and Development Manager Joachim Ness from FosenNamsos Sjø and Sales Manager Martin Aasheim from Norwegian Electric Systems.

Abstract

The Norwegian government aims to make all public transport fossil-free by 2025, including the Norwegian ferry fleet. For many ferry routes, electrification will be the best solution. In order to realize this electrification, the distribution grid connected to the quays must be able to deliver enough power to charge the ferries, which is not always the case today. In many cases, it would be possible to use a Battery Energy Storage System (BESS) to assist the grid when charging the ferries. This thesis focuses on Beyonder's Lithium-Ion Capacitor (LIC) technology and investigates if it could be a good fit in the ferry charging market.

Two case studies have been conducted to see how LIC compares to the most commonly used battery technology, Lithium-Ion Battery (LIB). Case study 2 also compares a grid upgrade to the BESS solutions. LIC has a high power density but limited energy density, while LIB has a high energy density and limited power density. Combining both technologies into a Hybrid Energy Storage System (HESS) is a way to incorporate both technologies' strengths.

After conducting the case studies, a more general analysis of the technical-, economic- and environmental aspects is done. The results from the technical analysis found that many quays require higher grid power than what is available. However, integrating a BESS can minimize the grid upgrade and reduce overall cost. How long the ferry charges will affect whether LIC or LIB is the better solution. LIC was found to have a smaller surface area than LIB when the charging time is 6 minutes or less. Even though LIC is more expensive per energy unit, the results per power unit were the opposite. If the ferry is charged for 5 minutes, the price of Beyonder's LIC was calculated to be 151 USD/kW, while the price of the chosen LIB was calculated to be 496 USD/kW.

In the economic analysis, part of the main findings is that there is no correlation between the price of the upgrade and the power the grid capacity is upgraded to. Each case will be unique due to the different infrastructure at each location. Using higher power has an added cost, and including a BESS is a great way to reduce this cost and reduce the strain on the grid, no matter the application. The environmental analysis shows that LIC has lower emissions than LIB. In case study 1, the LIB production emits 6.3 times more CO_2 than the LIC production. LIC will store less energy than LIB in high-power applications. As a result, LIC is the most environmental-friendly alternative when calculating emissions per kWh.

Finally, based on the analysis conducted in this thesis, Beyonder's LIC seems to be a good fit in the market for ferry charging under the right circumstances, such as; high power requirement, short charging time, and limited available grid power. LIBs will still be a tough competitor in this market, as the technology is more established, and the market may be skeptical of new technologies.

Sammendrag

Den norske staten har som mål å få en fossilfri kollektivtrafikk innen 2025, dette inkluderer fergeflåten. For mange fergestrekk vil elektrifisering være den beste løsningen. For å kunne gjennomføre dette må distribusjonsnettet i området kunne levere høy nok effekt til å lade de kommende fergene. Mange kaier har i dag ikke nok tilgjengelig effekt til dette formålet. En mulig løsning på dette problemet er å installere batteribaserte energilagringssystemer (BESS) som støtter opp distribusjonsnettet under fergeladning. Denne oppgaven fokuserer på Beyonders LIC teknologi og vil undersøke om den passer inn i fergeladningsemarkedet.

To case-studier er utført for å se hvordan en Litium- Ion kondensator (LIC) sammenligner seg med den mest brukte batteriteknologien, Litium-Ion Batteri (LIB). Case-studie 2 sammenligner også en nettoppgradering med BESS-løsningene. LIC har høy effekttetthet, men begrenset energitetthet, mens LIB har høy energitetthet og begrenset effekttetthet. I applikasjoner som krever høy effekt, slik som fergelading, vil LIB i stor grad måtte overdimensjoneres for å levere ønsket effekt, mens LIC ikke vil ha dette problemet. En måte å utnytte styrkene til begge teknologiene på er å kombinere dem i et hybrid energilagringssystem (HESS).

Etter gjennomføring av casestudiene, gjøres en mer generell analyse av de tekniske, økonomiske og miljømessige aspektene. Resultatene fra den tekniske analysen viste at mange kaier krever høyere effekt enn det som er tilgjengelig. Å inkludere et BESS kan imidlertid minimere den nødvendige nettoppgraderingen og redusere de totale kostnadene. Hvor lenge fergen lader vil påvirke om LIC eller LIB er den beste løsningen. Når ladetiden er under 6 minutter, vil LIC ha et mindre overflateareal enn LIB. Selv om LIC er dyrere per energienhet, var prisen per effektenhet lavere for LIC enn LIB. Dersom fergen lades i 5 minutter, er prisen på Beyonders LIC beregnet til 151 USD/kW, mens prisen på det valgte LIB er 496 USD/kW.

I den økonomiske analysen er en del av hovedfunnene at det ikke er noen sammenheng mellom prisen på en nettoppgradering og manglende effekt. Hvert tilfelle vil være unikt på grunn av varierende infrastruktur ved fergekaiene. Å bruke høyere effekt har en ekstra kostnad knyttet til seg, og å inkludere et BESS er en god måte å redusere denne kostnaden på, samtidig som belastningen på nettet reduseres. Miljøanalysen viser at LIC har lavere utslipp enn LIB. I Casestudie 1 har produksjon av LIB et 6,3 ganger høyere CO_2 utslipp enn produksjon av LIC. Ettersom LIC lagrer mindre energi enn LIB i høyeffektapplikasjoner, vil LIC være det mest miljøvennlige alternativet når man beregner utslipp fra kWh.

Avslutningsvis ser Beyonders LIC ut til å passe godt inn i markedet for fergeladning, ut ifra analysene gjort i denne oppgaven. LIC vil særlig egne seg for bruk i fergeladning under disse omstendighetene: høyt effektbehov, kort ladetid og begrenset tilgjengelig effekt i nettet. LIB vil fortsatt være en tøff konkurrent i dette markedet, ettersom teknologien er mer etablert, og markedet kan være skeptisk til nye teknologier.

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List of Abbreviations

	Elaboration
AC	Alternating Current
AMS	Advanced Metering System
BESS	Battery Energy Storage System (LIC and LIB)
BMS	Battery Management System
DC	Direct Current
DOD	Depth Of Discharge
EDLC	Electric Double-Layer Capacitor
EMS	Energy Management System
EOL	End Of Life
EV	Electric Vehicle
ESS	Energy Storage System
GHG	GreenHouse Gas
HESS	Hybrid Energy Storage System
LCA	Life Cycle Assesment
LFP	Lithium Iron Phosphate
LIB	Litium-Ion battery
LIC	Lithium-Ion Capacitor
LTO	Lithium Titanate Oxide
NMC	Nickel Manganese Cobalt
OCV	Open Cell Voltage
PE	Power Electronics
SEI	Solid Electrolyte Interface
SOC	State Of Charge
SOH	State Of Health
TMS	Thermal Management System
UC	UltraCapacitor

List of symbols

Symbol	**Unit**	**Elaboration**
η	%	Efficiency
Cr	1/h	C-rate related to charge
Cp	1/h	C-rate related to power
E	kWh	Energy
I	A	Current
L	%	Losses
P	kW	Power
Q	Ah	Charge
RTE	%	Round Trip Efficiency
t	minutes	Time
U	V	Voltage

1 Introduction

The power demand is increasing, and the Norwegian distribution grid will be facing several supply challenges in the coming years. The grid must be upgraded to provide enough power for the electrification of the transport sector, including ferries. One solution would be to upgrade the existing grid, but this would come at a significant expense. Another possible solution is implementing Battery Energy Storage Systems (BESS) as a grid asset. This solution will be examined in more detail in this thesis.

1.1 Background and Motivation

The Norwegian government has high ambitions to implement zero-emission technology in the transport sector. Fossil-free public transport is essential to achieving Norway's emissions plans by 2030. Therefore, the government has set a target of achieving fossil-free public transport by 2025. To reach this goal, electrification of passenger ferries is vital. Ferry charging requires a large amount of power over a short period of time. However, the distribution network may not be able to deliver enough power, especially with the electrification of other sectors happening simultaneously. Implementing energy storage systems could function as a buffer between the grid and consumers to relieve the stress on the grid.

Beyonder produces Lithium-Ion Capacitors (LIC), a hybrid technology between Lithium-Ion Batteries (LIB) and supercapacitors. This technology can deliver high power, provide fast response time, and has a long service life. The safety is also deemed to be higher than traditional lithium-ion batteries. LIC does not have as good energy storage capacity as LIB, and will often be used in combination with LIB in cases where energy- and power capacity is important. Therefore, typical application areas for LIC will be areas in the industry where there is a high power demand.

The thesis aims to find out if there is a market for Beyonder's LIC in the ferry charging industry, and investigates whether it can be a solution to grid challenges related to electric ferry charging. Implementing a BESS will lead to a more flexible grid by reducing the stress on the grid when charging. It will also contribute to peak shavings which will be crucial for electrification in the coming years. For the purpose of this thesis, BESS includes both LIC and LIB. The LIC will be compared to a LIB to get a good idea of its advantages and disadvantages.

1.2 Objective

The project's overall purpose is to gain knowledge about the topic and contribute to finding out if ferry charging could be a suitable area of application for Beyonder's LIC technology. The main objective of the bachelor thesis is to explore how energy storage systems could be used to provide grid support when charging ferries.

The objectives of this thesis include:

- Give an introduction of relevant theory regarding energy storage systems, lithium-ion battery, and lithium-ion capacitor.
- Investigate the advantages and disadvantages of different energy storage technologies: LIBs and LICs related to grid applications.
- Find optimal BESS size for different case studies, along with a description of the system solution.
- Draw conclusions that are less dependent on the specific case studies, to form a general opinion on different solutions for ferry charging.
- Conduct technical-, economic- and environmental analysis of the solutions.

1.3 Limitations

Limitations regarding the scope of the thesis have been made. The purpose of this is to keep the study within reasonable boundaries. The study does not dive deeply into how the distribution network is operated and the technology behind it. However, a brief explanation will be given. The battery systems on board existing electric ferries will not be the focus area of this thesis, but some aspects will need to be considered. Creating a proper Hybrid Energy Storage System (HESS) solution is time-consuming and complicated, and only a simplified solution will be created.

1.4 Structure of the Report

This bachelor thesis is structured in the following way:

- Section 1, *Introduction*, aims to give an introduction to the thesis with background, motivation, objective and limitations of the work.
- Section 2, *Theory*, aims to provide the necessary theory that underlies the work.
- Section 3, *Methodology*, describes the chosen method used for this study. Data collection and assumption are presented.
- Section 4, *Case Study*, introduces the chosen case studies, with different scenarios. The results are compared and will be a basis for further analysis.

- Section 5, *Analysis*, contains, technical, economic and environmental analysis. The results are analyzed, and a general understanding of the different solutions are presented.
- Section 6, *Discussion*, the main findings are discussed.
- Section 7, *Conclusion*, summarizes and concludes the main aspects of the study, along with suggestions for further work.

2 Theory

This chapter defines relevant theory for the coming analysis. Firstly, information about the Norwegian distribution network is given before going into the market for electric ferries and potential challenges there. Further, this section will explain the theory of energy storage systems, specifically LIBs and LICs.

2.1 The Norwegian Electricity Grid

The electricity grid provides electrical power from the producers to the consumers. It also connects Norway's power system to other nations. Norway has the largest share of electricity produced from renewable energy in Europe, where hydropower is the main source of energy. [1]

The Norwegian electricity grid is made up of three levels: the transmission grid, the regional grid and the distribution network. The transmission grid contains inter-connectors with other nation-wide systems, and connects producers with consumers. The transmission grid is used for high-voltage electricity transportation, usually 300 to 420 kV. Statnett is the Norwegian transmission system operator. The regional grid is the connection between the transmission- and distribution-grid. The distribution network contains the local electricity grids that supply low voltage electricity transportation, up to 22 kV. [2]

A steady supply of electricity is essential, and almost all businesses, industries and households are depended on a reliable distribution network. If no storage is utilized, electric power needs to be consumed as it is being produced. This requires the producers to know how much power is needed at all times. [3] The increasing power demand causes a huge strain on the distribution network, and it will be necessary to develop a grid capable of meeting this demand. The desired solution is to develop a smart grid, which enables two-way electricity- and data flow. [4]

2.1.1 The Energy situation in Norway

The overall electricity consumption is expected to be more power-intensive in the future due to increased electrification in many sectors. This will affect the transmission system operators and lead to capacity challenges in local distribution networks. [4] In Norway the industry- and transport sectors have the highest energy consumption. The distribution network must be upgraded to supply enough power for electric cars, buses and ferries, among other things. [5]

The Norwegian water resources and energy directorate (NVE) estimated in 2018 that during the next decade (2018-2027), Norway would have to invest 135 billion NOK in upgrading the distribution network. [6] In a report by DNV, the estimated investment in the distribution network was just over 900 million NOK to ensure the electrification of 52 of Norway's passenger ferries. The power sector needs to be able to supply the necessary capacity for electrification of the ferry sector. [7] Electric ferries require a lot of energy and could cause a problem for the grid in the area. Most electrical ferries have to be charged every time they dock even when the power demand in other sectors are high. In some cases, the distribution network needs to be upgraded regardless, to account for other consumers increasing their consumption. In other cases, it is only the power peaks that causes problems for the grid, and it would be beneficial to install a BESS to practice peak shaving. [7]

2.1.2 Laws and Regulations

The Norwegian distribution and transmission network is regulated by the state and it is a monopoly. [1] Each area has one transmission system operator, but customers can choose a power supplier freely. Grid operators have to ensure voltage quality and a reliable power supply for the customers. NVE is the regulator authority and oversees the distribution network and grants licenses for transmission and production of energy. Quality of supply tells the customers how often they have access to electricity, while voltage quality is about the usability of the electricity, so it does not damage electrical equipment. [8] There are no specified restrictions associated with the regulations of the reliability of power supply. [9].

By law, the distribution system operators and transmission system operators are obligated to give all customers a grid connection. All consumers have to pay a grid rental fee. The grid rental fees are the costs for the connected grid level. The tariff is based on load and consumption at a high voltage local distribution level. The grid tariffs vary for each distribution system operator. [1] The tariff cost is intended to contribute to smarter power use and distribute the load more evenly throughout the day. Commercial customers must pay for the power link in addition to the fixed costs. This price is usually a fee for each kW pulled from the grid and is decided based on the highest monthly power consumption. For high power applications that tend to have high continuous load demand and peak power, a large portion of the total electricity cost will be from using high power. In some cases, reducing the power demand or shifting the load to off-peak hours is not an option. A solution would be to implement a BESS, where energy is bought and stored during off-peak hours. This is called peak shaving and would relieve the stress on the grid. [10]

2.1.3 The value of a Battery Energy Storage Systems as a Grid Asset

BESS used as a grid asset is predicted to be a good alternative to other grid investments in the distribution network. Large industrial applications often run their devices over relativity short time intervals during the day. This will lead to high peak demands. Peak shaving is leveling out the peak power consumption by commercial and industrial consumers. Peak shaving is vital for grid stability and has an impact on the power procurement costs. [11]

Peak shaving is not a new concept and has been practiced for years using on-site diesel-generators or gas turbines. In the case of BESS, the concept involves charging the batteries during off-peak hours and using the batteries during peak hours to avoid high prices and straining the grid. Installing BESS where the grid cannot manage peak loads alone may delay the need for grid upgrades, or may even make a grid upgrade redundant. Peak shavings are about temporary reduction of power usage. This can be accomplished by reducing the production or using a BESS. On the other hand, load shifting is a short-term reduction in electricity consumption, followed by increasing production when the grid demand is lower. The concept of peak shaving is demonstrated graphically in Figure 2.1. [11]

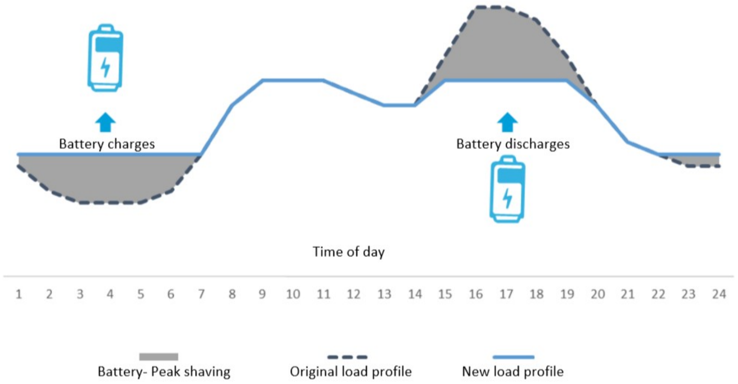


Figure 2.1: Peak shaving in the distribution network. *(Modified from [12])*

The technical components of the grid are sized based on the predicted maximum load. Grid congestion (bottlenecks) can occur if the network's dimensioned transmission capacity is less than the power demand. This problem can occur when electric transportation systems, like electric ferries and cars are charged simultaneously. The traditional way to solve the stress problem is to perform costly grid upgrades. [4] Therefore, it is desirable to find suitable alternatives for the cases where a grid upgrade is not necessary right away. A battery installation can be a good technical- and economical solution for many locations. [3]

2.2 The Market for Electric Ferries in Norway

The world's first electric passenger ferry, *Ampere*, went into operation in Norway in 2015 (Figure 2.2). [13] This laid the foundation for further electrification of the Norwegian ferry fleet. Currently (April 2022), 53 of Norway's approximately 135 ferry routes are electrified, with 20 more planned later in 2022. [14] The Norwegian government's goal to have fossil-free public transportation by 2025 means that the shift from fossil fuel needs to happen quickly. Norwegian ferries also operate on 10-year contracts, and new tenders for ferries do require low or zero-emission solutions. [15] This means that many ferry routes are in need of a new solution in the coming years. However, switching from using fossil fuel comes with its own set of problems. In addition to upgrading ferries with electric systems on board, the ferry quays must be rebuilt to store the ferry charging equipment. In certain cases, the grid can provide the required power; in others, new infrastructure must be installed. Ferries require high power when charging to transfer enough energy while the ferry is docked which can cause high power peaks.

Figure 2.2: The worlds first electric passenger ferry, *Ampere*. [13]

Upgrading to electric ferries is most relevant for shorter distances, while ammonia and hydrogen solutions may be better for longer ferry routes and the shipping industry. [16] Several research has shown that ammonia has multiple key properties fitting for the shipping industry. Ammonia can be almost double the energy of liquid hydrogen, and is a flexible fuel. [17] Regarding installing a BESS for ferry applications, there are currently two leading suppliers in Norway, Siemens energy and Corvus energy. Both these suppliers use LIBs in their BESSs. These suppliers delivers BESSs for both onshore and onboard usage. [18] [19]

2.3 Electrochemical Energy Storage

Energy storage systems store a form of energy and then convert it to electric energy for consumption. Renewable energy has grown rapidly in popularity in recent years, partly due to the decreasing cost of renewable energy systems and the rapid technological development. Power generated by renewable energy systems fluctuates significantly. This results in a lack of stability, if the supplied energy is used in real time. A solution to this problem is to store the energy electrochemically. [20] As a result, there is a greater demand for energy storage systems, and much research has gone into this field. Thermal, mechanical, and electrochemical energy storage are only a few examples of energy storage systems. Electrochemical energy storage technologies will be the topic of this thesis.

Within electrochemical energy storage systems, there are several technologies. The most commonly used type of electrochemical energy storage is batteries, an umbrella term for a wide range of different chemistries. Capacitors are also a form of electrochemical energy storage, some examples are Lithium-Ion Capacitors (LIC) and Electric Double-Layer Capacitors (EDLC). [21] For the purpose of this thesis, LIC is classified as a battery, and is included in the term BESS.

Different types of ESSs have different properties, which make them suitable for different applications. When comparing different energy storage systems, a Ragone plot is often used. A Ragone plot has power density on one axis and energy density on the other. The axes are scaled logarithmic, meaning that the technologies can be compared. Figure 2.3 shows the energy density and the power density for LIB, LIC, EDLC and capacitors. Energy density is a measure of how much energy a cell contains in relation to its mass or volume and is measured in kWh/kg or kWh/L. In the same way, power density is the relation between the power and the cell's mass or volume and is measured in kW/kg or kW/L. [22]

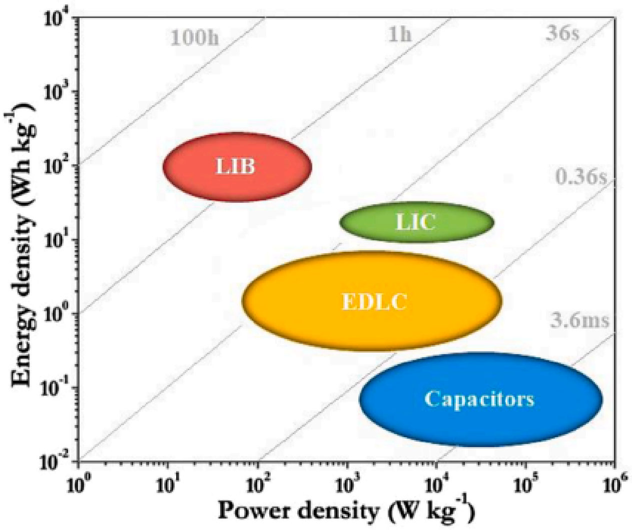


Figure 2.3: Ragone plot of different electrochemical energy storage systems. [23]

The figure demonstrates that LIBs have high energy density but lower power density, while capacitors have a much higher power density but a very low energy density. LIC can be seen as a combination of these technologies, with fairly high power density and higher energy density compared to capacitors. Some of the most common BESS battery types are Lithium-Ion Batteries (LIB), Lead-acid Batteries (PbA), Nickel-Cadmium Batteries (Ni-Cd) and Sodium-Sulfur batteries (Na-S). Some of the attributes of LIBs are high energy density and low self-discharge rate. PbA batteries are highly recyclable, have high specific power and easy maintenance but have low cycle lifetime. Ni-Cd batteries are inexpensive and highly resistant to low temperatures but is behind the other technologies when it comes to energy density and self-discharge rate. [24] Lithium is often the preferred material to use in battery technology since it is non-toxic and long-lasting. The standard reduction potential makes it clear that lithium is the most electropositive metal and will get a higher voltage, which is beneficial for a BESS. [25] Flow batteries have also been researched and developed in recent years. The storage capacity can be scaled independently of the power, and it is possible to replace parts to extend the service life. [26]

Electrochemical capacitors, also called supercapacitors, store energy in the form of electrical charges. When a capacitor is connected to a power source, it will collect energy that can be released when disconnected from the charging source, like a battery. The difference between a battery and a capacitor is that a battery works through electrochemical processes, while a capacitor stores charge. Since chemical processes take time to process, capacitors can release energy at a higher rate. There are two types of electrochemical capacitors, symmetric and asymmetric. A symmetrically designed capacitor has a positive and negative electrode made of the same carbon. An asymmetric design uses different materials for the two electrodes. [27]

2.3.1 Terminology

In order to understand the workings of an electrochemical energy storage system, a few terms needs to be established and explained. These are listed below.

- Efficiency is the ratio between the output and input power. For electrochemical energy storage, chemical energy is transformed into electric energy through a redox reaction when discharging, and reversed while charging. The total efficiency is therefore often called Round-Trip Efficiency (RTE), and is related to how well the energy put into the system can be utilized.
- C-rate is the rate at which the battery is charged and discharged at. A C-rate of 1 equals a full charge (0% to 100%) in one hour, while a C-rate of 2 means a charge time of 30 minutes. During discharging, the C-rate is negative. C-rate is the relation between the charge and current in the battery, displayed in Equation (1). Cr is the C-rate, I is the current (A) and Q the charge (Ah).

  $$Cr = \frac{I}{Q} \tag{1}$$

  A continuous C-rate is the rate at which the BESS can operate throughout its lifetime. The max C-rate is often also given and is higher than the continuous C-rate. However, the BESS can only operate at this C-rate for a very short period of time, often a few seconds, to prevent faster degradation. Cp-rate is also sometimes used and is the relation between the power (kW) and energy (kWh) in the system, shown in Equation (2). [28]

  $$Cp = \frac{P}{E} \tag{2}$$

- State Of Charge, SOC, is the available capacity, relative to the nominal capacity, which is the maximum possible charge. A fully charged battery will have a SOC of 100%.
- Depth Of Discharge, DOD, directly relates to SOC, and is how much the battery discharges in percent. This value will often have limitations as discharging too much each time will

lead to quicker degradation. When the cell starts aging, the maximum state of charge will decrease. [29]

- The State Of Health, or SOH, of a battery relates to how much charge (in coulombs) is available for usage at a certain C-rate, compared to a new battery. A new battery will have a higher SOH at a higher C-rate than an old battery.
- Self discharge is the loss of capacity due to internal reactions in the battery cell. Different BESS have different self-discharge rates. BESS used for short-term storage will not be greatly affected by this. [29]
- End Of Life, EOL, is when the battery cannot operate at sufficient capacity. The SOH is typically about 80 %(LIB) at the end of life. After this point, the battery will start degrading rapidly and safety issues will occur more frequently. To ensure that the required energy is available throughout the battery's whole lifetime, EOL needs to be taken into account. Equation (3) shows how much larger the battery needs to be for it to fulfill its purpose. [29]

$$Scaling\,factor = \frac{1}{DOD \cdot EOL} \tag{3}$$

2.3.2 Stationary Energy Storage

Stationary storage systems are fixed installations, while portable energy storage systems are used for mobile applications and are not usually connected to the grid. The portable energy storage market has risen significantly over the last decade, while the market for stationary energy storage has not grown as rapidly. However, it is expected that the growth will increase significantly over the coming years. [30]

The charge/discharge pattern differs notably between stationary and portable energy storage systems. The stationary applications will often have a higher number of charging cycles, making them more expensive. In comparison, electric vehicles (EVs) may have one complete charge cycles during one week, depending on the driving pattern. Weight and volume are less relevant in stationary applications since a bigger area is generally accessible, implying that energy and power density is less important. However, this is not always the case, and an assessment needs to be made. As the need for stationary energy storage increase, the gap between the two sectors is projected to widen. [31]

2.4 Lithium-Ion Battery

Lithium-ion battery is a secondary battery and is the most popular battery technology today, especially for portable electronics. LIBs are preferred over other battery technologies due to having high efficiency, high open-circuit voltage, and high energy density. Lithium is a highly reactive material but is stable when part of an oxide. LIBs have close to no memory effect, something other battery chemistries have. Memory effects reduce cell capacity due to incomplete charging and discharging. [32]

2.4.1 Structure

Lithium-ion battery's main components are the anode, cathode, current collectors, electrolyte, and separator. The structure of a LIB is shown in Figure 2.4. To stay consistent and avoid confusion, a battery is when the cell is discharging. [29]

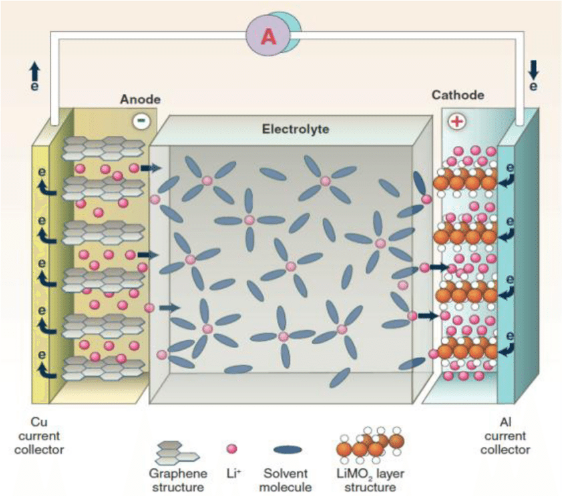


Figure 2.4: The structure of a lithium-ion battery. [33]

The battery anode is the negative electrode where oxidation occurs and consists of lithium ions inside a carbon structure. Graphite is the most common anode material as it is safe and non-toxic, however, the specific capacity is low. A lot of research has been done with different anode materials to improve this. Using another anode material like lithium-titanate oxide (LTO) provides high power densities, but at the expense of decreasing the energy density. [34][35]

The cathode is the positive electrode and consists of lithium metal oxides. Lighter metals with few electrons in the outer shell are often preferred due to being more flexible. [25] Different metal oxides give different characteristics and different areas of usage. Some of the most used cathode materials are Lithium Cobalt Oxide (LCO), Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt (NMC) and Lithium Manganese Oxide (LMO). Table 2.1 demonstrates some characteristics of different cathode materials. Each cathode material will have advantages and disadvantages. NMC and LFP are some of the most commonly used cathode materials for battery production. NMC has a high specific capacity and cycle life. In contrast, LFP has a higher standard of safety. [36] One of the advantages of using an NMC battery is that the ratio between nickel, manganese and cobalt can be changed to get desired properties.

Table 2.1: Different types of lithium-ion batteries. [29][37]

	Acronym	Electrode material	Specific energy [Wh/kg]	Nominal voltage [V]
Lithium Cobalt Oxide	LCO	$LiCoO_2$	190	3.6
Lithium Iron Phosphate	LFP	$LiFePO_4$	120	3.3
Lithium Nickle Cobalt Manganese	NMC	$LiNiMnCoCO_2$	220	4.2
Lithium Manganese Oxide	LMO	$LiMn_2O_4$	150	3.7

The extraction of minerals used in batteries, such as cobalt, requires large amounts of water and energy and is also linked to unethical mining practices. [38] LIBs require lithium, and the lithium supply is expanding due to the rapidly growing demand for portable electronic devices and batteries for vehicles. Lithium mining depletes water resources and destroys the soil structure. LIBs can be recycled, but this is not yet a universally established method. It is therefore looked at a replacement for lithium, since there is no guarantee for finding enough raw material to follow up the demand. [39]

Typically, the anode current collector is made of copper, and the cathode current collector is made of aluminum. The current collectors are connected through the battery terminal and this is where the electrons travel during charging and discharging. The cathode is shaped and pasted on to the aluminum using a solvent and a binder. Similarly, the anode is pasted on the copper current collector. [29]

The electrolyte is an organic liquid and a mixture of lithium salts and other solvents and additives. The lithium salt used is often $LiPF_6$, while the solvents/additives can be Ethylene Carbonate (EC), Dimethyl Carbonate (DMC) Etc. The electrolyte acts as a catalyst by increasing the conductivity and mobility of lithium-ions. Transporting lithium-ion without transporting electrons is crucial. The electrolyte is very important since it is in contact with both the cathode and anode. [40] During the first cycles, a passivation layer is created on the electrodes. This is called the solid electrolyte interface (SEI), and protects the electrodes from further reacting with the electrolyte. The SEI will allow lithium-ions through but hinder electrons, preventing decomposition of the electrolyte. [41]

A separator is placed between the anode and cathode to create a mechanical barrier and prevent electrical contact. [42] Still, the separator has to allow for a high level of ionic conductivity. The separator is made from a porous material and can be organic, polymeric, or fiber glass material. The separator is also in place as a safety measure, and will stop the cell from overheating and short circuiting. [29] During high temperatures, a liquid electrolyte can dry up, and having a separator is therefore an important part of the LIB.

2.4.2 Applications

LIBs are the most common batteries in portable electronics and the leading technology in EVs. More recently, it has become increasingly popular in stationary energy storage. The popularity and demand for LIBs are expected to increase in the coming years due to the transition into more renewable energy sources. [25] The cost of lithium-ion batteries was reduced by 85% between 2010 and 2018. This was mostly a result of large technological developments and economies of scale. [31]

2.4.3 Safety

The safety of a battery is mainly determined by battery chemistry, operation conditions and its abuse tolerance. Heat is generated during charging and discharging and needs to be dissipated to ensure that the battery does not over-heat. Abuse conditions can be electrical like over-charging/discharging and external short-circuiting, thermal abuse by external heating, or mechanical abuse by physical damage and penetration of the battery. [43] Rising temperatures inside the battery can cause other unstable exothermic reactions and short-circuiting, which can lead to thermal runaway. Thermal runaway is when the heating rate exceeds the dissipation rate. This can cause smoke and gas venting of the battery and can cause a fire in the worst case. [44] A cooling system is in place to prevent the LIB from overheating during usage. This is all controlled by the Battery Management System, BMS. Liquid electrolytes are also highly flammable and have poor thermal stability. Adding additives or researching solid-state electrolytes would therefore increase safety. Regulations and safety standards are in place to ensure that LIBs and their components are safe and meet specific criteria. Different standards are set for different intended purposes. [45]

2.4.4 Aging

There are two main forms of aging in LIBs; cycle aging and calendar aging. Calendar aging is irreversible loss when the battery is not used. Operating temperatures will have a great impact here, where a high temperature can lead to corrosion. Cycle aging occurs when the battery is charged and discharged. A higher SOC window will lead to faster aging due to the positive electrode degrading, and SEI develops at high charge/discharge rates. [46]

2.5 Lithium-Ion Capacitor

The Lithium-ion capacitor is a hybrid energy storage device that combines the advantages of lithium-ion batteries and supercapacitors. A LIC combines the energy storage mechanisms of a LIB anode with the double-layer mechanism of the cathode of an Electric Double-Layer Capacitor

(EDLC). This will combine some of the best properties of both technologies. Today, secondary batteries and supercapacitors are the main technologies for storing electrochemical energy. As previously stated, the LIB is the most popular for portable electronics due to the high specific energy and low self-discharge rate but lacks some abilities related to power and cycle life. In comparison, EDLCs have a greater specific power, longer cycle life and fast charge-discharge capability. On the other side, it has a limited charge storage capacity. LIBs and EDLCs merged will deliver a high power density with longer cycle life. [47] [48]

The LIC was first introduced in 2001 by Amatucci *et al.* [49] LICs are considered one of the most effective energy storing devices. Another BESS that often gets compared to LIC is Sodium-ion (SIC) and Potassiumion capacitors (KIC) since they also combine ion battery technology with a traditional capacitor. [48]

2.5.1 Market

The demand for supercapacitors in automotive applications is a major drive for market growth. The market is predicted to rise due to the demand for renewable energy systems and favorable government policies. Governments have set several regulations to promote environmentally friendly and fuel-efficient transportation. However, the market growth is expected to be hampered by high material prices and low technology awareness. In the solar and wind energy sector, there will be a need for a new storage solution, and this will provide attractive opportunities for the supercapacitor market. [50]

To meet rigorous pollution standards worldwide, a LIC is anticipated to fit all sorts of vehicle types, including conventional, hybrid, and electric automobiles. Rising demand for capacitors in the industry and adoption in the power sector will incite market growth. In 2021 the global lithium-ion capacitor market size was projected to grow from USD 24.7 million to USD 35.6 million by 2028. This is an expected grow of 5.4% at a compound annual growth rate (CAGR). There will be a growing demand for LIC for industrial applications worldwide. [51]

2.5.2 Structure

A LIC uses a high capacity battery-type electrode and high rate capacitor-type electrode with a suitable electrolyte. During charge-discharge, charges are concurrently and asymmetrically stored in the LIC. The charges get stored by surface ion adsorption/desorption on the capacitor-type electrode, while Li^+ gets intercalated/de-intercalated in the battery-type electrode. This is illustrated in Figure 2.5, where graphite is used for the negative electrode and activated carbon for the positive electrode. The capacitor-type electrode can be served as either the cathode or the anode, while the battery-type electrode acts as the counter electrode. The different electrode types will perform in different potential windows, increasing the operating voltage range and cause higher energy density. [52]

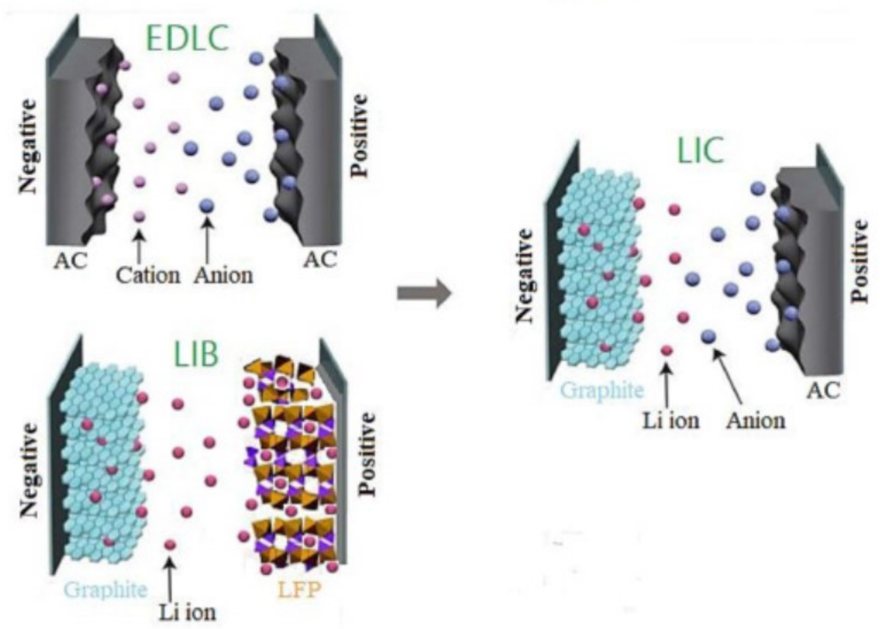


Figure 2.5: The structure of a LIC, based on EDLC and LIB. [53]

On the cathode, activated carbon is typically used, and the anode consists of pre-lithiated graphite. [54] Pre-lithiation is a method used to decrease the electrode's potential to increase the overall voltage. The amount of pre-lithiation has an impact on cycle stability and cell capacitance. [55] aqThe electrochemical performance of the LIC depends on the design of electrode materials used, the pre-lithiation process and the electrode configuration. Various different electrode materials, such as metal compounds, have been utilized in the battery-like electrode due to their high specific gravimetric capacity. On the downside, the low conductivity and large volume variation limit further development. Carbon materials were often incorporated since they had a large specific surface area, high conductivity, and electrolyte accessibility and could be used as the active material directly because of the active Li^+ intercalation/de-intercalation area. Various porous carbon materials, like activated carbon, are the most suitable for the capacitor-type electrode. Their capacitance depends highly on the ion adsorption/desorption on the carbon-based electrode surface. To further advance the LIC technology, the development of carbon materials plays a big role. [52]

In LICs, like other electrochemical energy storage systems, the electrolyte transfers charges inside the cell. [47] Both electrodes are placed in an organic electrolyte that consists of lithium salt. The electrolyte pairs the LIC electrodes and influences energy capacity, power efficiency, and cycling stability. A separator is placed between the electrodes to isolate the association electronically while the ions can penetrate. The same electrolyte configuration is usually used in LIBs. [48]

Graphite will guarantee a secure charge-discharge level at the negative electrode of the LIC (anode). On the other hand, graphite suffers from a low-rate capability and needs to undergo several processes to increase its capacity. [47] High operating voltage is also required in the LIC technology and can be obtained by specific cathode materials. The cathode materials include carbon-, Li^+-intercalation- and composite materials. Porous carbon material is commonly used in the cathode, characterized by high specific surface area, good electron conductivity, and electrolyte accessibility. Activated carbon, graphene, and carbon nanotube are examples of carbonous cathodes widely used. [47]

2.5.3 Application

LIC technology has a wide range of applications in various fields. They are suitable for high-power applications, for which LIB are not currently advisable. LIBs are often oversized to yield the desired power, while LIC needs to be oversized to yield the energy density. Because of the different performances compared to EDLCs, there is no need for additional electrical storage, which will reduce the overall cost. In recent years, EDLCs have been applied to high power applications, but several stacks in parallel have been needed due to low energy density. LIC is a good fit for high power transportation applications and charging systems. [56]

2.5.4 Safety

One of the challenges with LIC is increasing the energy- and power density altogether while improving safety. The safety of LIC has been researched under different abuse tests, and the high specific surface area, and the electrodes are believed to enhance the chemical- and thermal stability with reduced thermal runaway. The LIC provides several safety benefits since it is less flammable than other BESS, making it a great option for safe applications in portable electronics. Since LIC does not contain oxygen or oxide, it is not prone to thermal runaway conditions. [57]

2.5.5 Beyonder's Technology

Beyonder is a battery technology company conducting research and development on high-power battery cells for industrial applications and market segments. Beyonder aims to meet the demand of the global battery market by developing sustainable batteries in the absence of minerals like cobalt and nickel. [58]

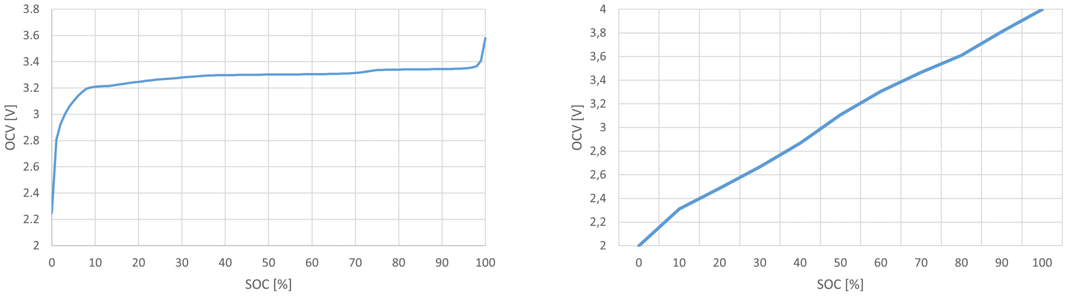
Beyonder states that they have created a next-generation solution of an eco-friendly and energy-effective battery, using renewable energy and sawdust in their battery production. Therefore, their patent battery technology can be seen as a better alternative to the conventional LIB and solve several challenges related to high-power applications. Beyonder's patented activation process transforms sawdust from pine and spruce into super-activated carbon. Using sawdust from Norwegian forestry will not contribute to deforestation and will replace hazardous heavy metals like cobalt. Wood-derived carbon on the cathode allows the LIC to operate at higher specific power than other batteries. [58]

By combining this battery with other existing technologies, there will be a possibility of producing solutions for many different applications related to grid stability, ferries, and other high-power charging solutions.

Since the product has not yet been manufactured, specifications are taken from a preliminary datasheet from Beyonder. According to the datasheet (Appendix A), the LIC cells will be fully charged and discharged within two minutes, recharged up to 100 000 times, and have a C-rate up to 30. Their LIC is non-flammable and is designed for fast charging. The LIC cells have a significantly lower internal resistance than conventional lithium-ion batteries and will need less cooling and resulting in higher full cycle efficiency. [58]

2.6 Applications of LIB and LIC

From the previous sections, it is clear that LIBs and LICs have several similarities and differences. They can be used for many of the same applications, but while LIBs are known for having a high energy density, LICs are known for having a high power density. LICs have a much higher cycle life and C-rate than LIB. This means that there may be different markets for the two technologies.



(a) OCV as a function of SOC for a NMC lithium -ion battery *(Based on data from [59, p.78-80]).*

(b) OCV as a function of SOC for a lithium-ion capacitor. *(Based on testing data from Beyonder generation 1.5).*

Figure 2.6: OCV as a function of SOC for LIB and LIC.

The voltage profile for LIB as a function of SOC is presented in figure 2.6a. The voltage stays at a rather constant level when the SOC is between 10-90%, unlike other battery chemistries. [59] As a comparison, the voltage profile for LIC as a function of SOC is presented in Figure 2.6b. This plot shows a relatively linear correlation between OCV and SOC throughout the whole cycle.

2.6.1 Economical Development

LIB is a more mature technology than LIC. Since its debut on the market over a decade ago, it has decreased a lot in price as shown graphically in Figure 2.7. In 2021, the price was 132 USD/KWh, according to research by BloombergNEF. They also state that the average price for battery packs will drop to under 100 USD/kWh by 2024. [60]

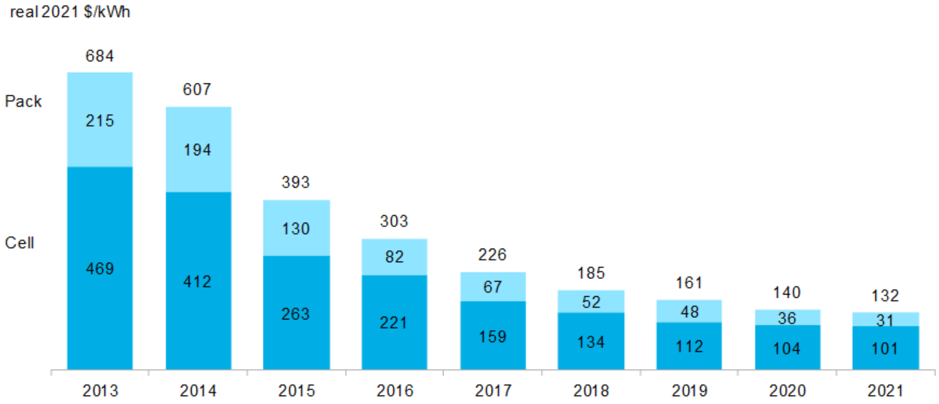


Figure 2.7: Volume weighted pack and cell price for LIB. [60]

New technologies are often costly when they arrive on the market. A preliminary suggestion for the price of Beyonder's LIC was estimated to be around 1300 USD/kWh. This is about the same as the LIB cost in 2010. [60]

2.7 Battery Energy Storage System

Several components need to be in place to ensure proper operation and safety when using LIBs or LICs in an application. Including all the components, the whole system is called BESS.

2.7.1 Primary Components of a BESS

BESS is ideally positioned to assist and supplement the functioning of the energy supply system. It is therefore important to understand the physical components of a BESS and know how they interoperate with one another. The stored energy and voltage are two important output factors when creating the energy storage system. Creating the system starts with individual cells. Each cell is connected in series and/or parallel to create a module. Several modules are then placed together to create a battery pack with the desired voltage output. This type of configuration is shown in Figure 2.8. Several packs can then be connected in parallel to get the desired stored energy. The finished battery or capacitor system will have the final size of the system and contain the management and cooling systems as well as the housing. [61]

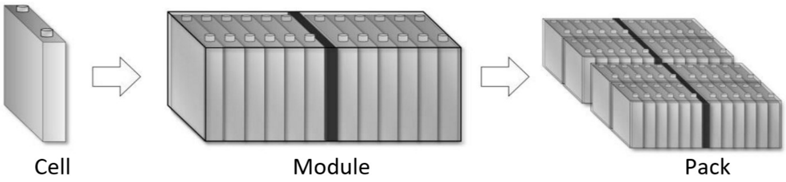


Figure 2.8: Battery pack configuration. *(Modified from [62])*

The main components of a typical stationary BESS are:

1. Battery system:
    - Cell
    - Module
    - Pack
2. Power electronics
    - DC/DC converters
    - AC/DC converters
3. Monitoring and control systems
    - Battery Management System (BMS)
    - Energy Management System (EMS)
    - Thermal Management System (TMS)
    - Power Management System (PMS)

The schematic diagram of a typical stationary BESS is shown in Figure 2.9, the greyed-out subcomponents in the figure are beyond the scope of this work. The cells are connected together to form packs. The next component is the power electronics (PE), where a DC/DC converter will be used to transform the DC terminal voltage of the pack before it connects to the AC/DC converter interfacing the grid. This transformation can happen directly or with a transformer, depending on the voltage. The DC/DC converter is optional, but when it is utilized, it allows the BESS to be operated over a larger range of its voltage curve since lower terminal voltages can be stepped up to satisfy the AC/DC converter requirements. The wider user application range comes at the expense of efficiency losses across the DC/DC converter. [63]

The monitoring and control systems include energy management, battery management, and thermal management systems. These systems are responsible for controlling and assuring the safe operation of the BESS. Energy management systems are automation systems that accumulate energy measurement data. The control system gives input to the BMS if the battery should charge or discharge and is also a part of the EMS. The battery management system ensures the safety and

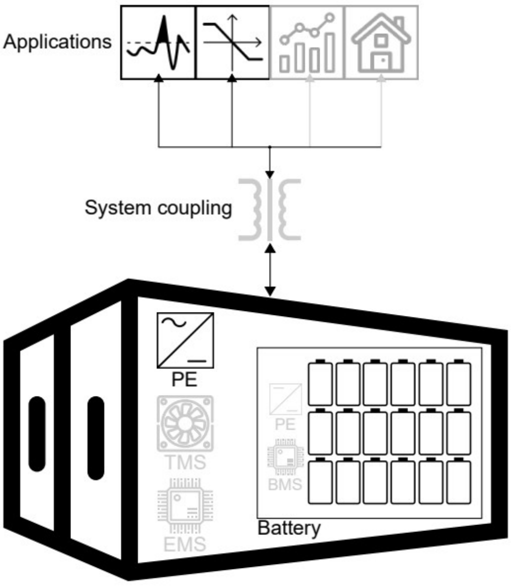


Figure 2.9: Schematic diagram of a stationary BESS. [63]

maximum performance and prevents the cells from overcharging. For controlling the temperature of the BESS, the thermal management system is utilized based on thermodynamics and heat transfer technology. [64] Conversion losses account for a major share of the losses in the energy- and battery management systems. The system losses include the remaining losses, such as standby losses and consumption by other components. The sub-components' size and layout play an important role in deciding the overall efficiency. [63]

2.8 Hybrid Energy Storage System

A Hybrid Energy Storage System (HESS) combines two or more types of energy storage technologies to utilize the best properties of each technology. In this section, a HESS topology with a ultracapacitor (UC), also called supercapacitor, and a battery will be explained. LIC is here used for the UC, and LIB for the battery. A HESS will lead to better overall performance since ultracapacitors have a high power sensitivity and batteries have a higher energy density. [65]

Research done on HESS systems has proven that the lifespan of the LIB could be improved by 16% by implementing it in a HESS. This is because LIB is protected against damage due to the high-power rates during charging and discharging. [66] [67]

2.8.1 Topology

There are several configurations of HESS designs. HESS can be separated into two types based on the presence of a power electronic converter: passive or active. The active configuration uses one or multiple full-size DC/DC converters to interface the energy storage device to the DC link.

The most commonly used HESS design is where the battery pack is directly connected to the DC link, and a half-bridge converter is between the LIC bank and the DC link. In order to utilize the power from the LIC, the half-bridge converter has to be at the same power level. The operating principles of batteries and LICs are different, resulting in different properties.

One of the most widely used HESS topologies is the battery/capacitor configuration, shown in Figure 2.10. In Figure 2.10 a), the bidirectional DC/DC converter is used to interface the UC. The converter needs to be larger to handle the UC power. The DC-link cannot be varied since the battery is directly connected. In Figure 2.10 b), the positions of the battery and UC are switched. In this configuration, the battery voltage can be varied, and the UC is connected to the DC-link directly. This typology's control method allows the DC-link voltage to vary within a range, allowing the UC energy to be more efficiently. The DC-DC converter must endure high power levels in the system when power is supplied or absorbed by the UC bank, which is one of the downsides of this design. [67]

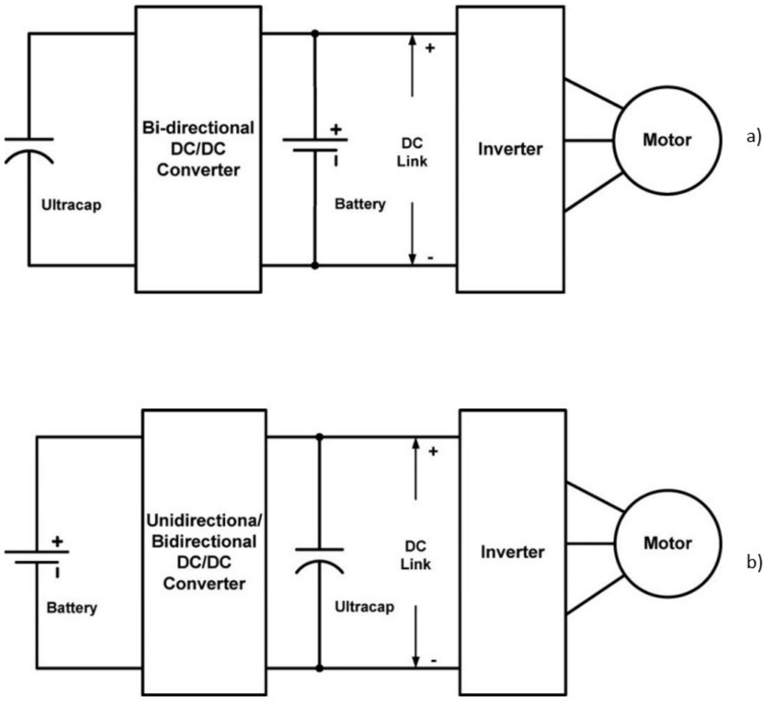


Figure 2.10: HESS configurations. [67]

2.8.2 Application

Several researchers have proposed and investigated HESS technology in renewable energy and electrification of transport. Despite numerous research on improved BESS capability, it is unlikely to find a perfect BESS technology for all applications in the near future. Single BESS often lack the combination of energy and power rating that most systems require. A HESS can, in general, be used in all the applications of an energy storage unit and can make up for the lacks to a single BESS technology. It can improve the performance of many applications and is particularly suitable as an energy source device in the transport sector and for grid support. [68]

Electrification of the transport sector is expected to play a vital part in achieving a decarbonized transportation sector. While batteries have undergone and continue to undergo significant advancements in cost reduction, energy increase and lifetime, the charging infrastructure has remained relatively the same. The long charging time is a significant barrier to the electric transport adoption for a broader market. HESS implementation can enable widespread fast charging of EVs without major investment in upgrading the grid to support the high power demand. [69]

Unique for HESS, compared to a single BESS technology, is that every HESS needs to be custom designed for the intended application. The power and energy required for the application must be considered and one would have to combine the technologies in a way that makes them compliment each other in a good way. When this is done right, HESS can be a superior alternative compared to single BESS technologies in applications that requires high energy and power, such as ferry charging.

3 Methodology

In this section, the methodology is described. Firstly, data collection and analysis tools are presented. Then the assumptions and limitations of the thesis are defined, followed by the methodology for optimal sizing of an energy storage system. Lastly, the method for conducting economic and environmental analysis is presented.

3.1 Data Collection

Data collection is an important part of doing research. The most critical objective of data collection is to ensure that the information is reliable. To carry out the case studies and perform analysis, it is necessary to collect data and specifications for the various ferry routes.

The report "Elektrifisering av bilferger i Norge – kartlegging av investeringsbehov i strømnettet" was conducted by DNV in 2015 for Energi Norge. DNV is an international classification company specializing in assurance and risk management. They are the world's top classification society and a well-known marine industry advisor. [70] The report provides key parameters on power and energy needs for the electrification of 52 ferry routes in Norway. It aims to provide an initial cost estimate of the grid updates necessary to have the charging infrastructure to replace existing ferries with electric ferries. It concludes that 900 MNOK will have to be invested in the distribution grid. The report also mentions that investing in a BESS could reduce some of the upgrades to the grid. The report does not include very long or complex ferry routes with harsh weather, as these are not very suited nor qualified for electrification. [7] The report provides many of the essential parameters about the ferry routes that will be examined in this study. Appendix E includes a table from the report with information about the ferry routes. The key parameters gathered from the report are listed below:

- Distance of crossing
- Number of crossings per day
- Power needed for charging in 5 minutes
- Energy needed per crossing
- Available power at the quay today
- Available power if upgrading the grid, and price estimate of this

Beyonder has shared properties for their 3. generation lithium-ion capacitor and spesifications can be found in Appendix A. Characteristics and specifications about the lithium-ion battery used for calculations are based on Corvus' Orca Energy battery and are shown in Appendix B.

The group has contacted several companies within the energy and ferry sector for more up-to-date information. Information and theory linked to this report has been gathered from various scientific articles and textbooks.

3.2 Analysis Tools

The optimal sizing model is developed using MATLAB. The MATLAB code is used to do the calculations for the different case studies. The method used for sizing the BESS is presented in Section 3.5 *Optimal Sizing of Energy Storage Systems.* By changing the main parameters, such as time available for charging, the number of crossings per day and the amount of power distributed between the grid and the BESS, the code can be used for different ferry routes. MATLAB was also used to visualize some of the results graphically. Excel have been used to visualize the results graphically and to organize the data from the DNV report.

3.3 Assumptions and Limitations

Before calculations can be done, some assumptions are made to set a clear framework. An overview of assumptions and properties for the battery-, capacitor- and system characteristics is presented. The assumptions for the economic and environmental analysis is also presented.

3.3.1 LIB and LIC Characteristics

The LIC used in this thesis is Beyonder's 3. generation LIC. This technology is still in the development phase and is yet to be produced. The datasheet for Beyonder's 3. generation LIC is found in Appendix A. It is worth mentioning that the properties in the datasheet may differ from reality as the 3. generation LIC has not yet been tested.

The LIB used in this system is Corvus Energy's battery; "Orca Energy". The battery is a lithium-ion NMC battery, and the specifics are attached in Appendix B. This chemistry is the most commonly used type for stationary energy storage systems. [71] "Orca Energy" is made for applications that are in need of both energy and high power. The battery is installed on 250+ vessels around the world, and is used both on board ferries and for onshore charging. [72] Many ferry routes today uses the same supplier for their onshore and onboard batteries. Using the same supplier ensures easier communication between the ferry chargers and the ferry.

An overview of properties used for calculations can be found in Table 3.1.

In the LIB specifications, the C-rate is set to be up to 3C continuously. However, for the batteries to withstand a lifetime of 10 years, a lower C-rate is used. The C-rate is, therefore, set to be 2C.

When ferries are charged with high voltage, the LIBs are charged and discharged with SOC in the range of 30-70%. This is to prolong the lifetime and to ensure the batteries can withstand the number of cycles needed for this application. (T. Ingvaldsen, Kraftmontasjen AS, personal communication, 17.02.2022)

The method used for sizing a LIB calculates EOL based on SOH (EOL=80% of SOH) instead of the degradation rate. The degradation rate of an LIB is not standardized and requires a thorough analysis to define. The end of life is therefore set to 80% for a LIB used over a span of 10 years.

In technical specifications for the LIB and LIC used in calculations, the volumetric energy density for LIB was given per pack, while it was given per cell for LIC. The battery pack contains several components and will give a better estimate of the needed area. In order to more accurately compare the two technologies, LIC and LIB, the volumetric energy density of LIC is changed. Beyonder estimates that a volume of 1.4 m^3 can store about 24.7 kWh. This gives an estimated volumetric energy density of 17.6 Wh/L for a LIC pack.

Table 3.1: Properties for LIB and LIC. Gathered from Appendix B and Appendix A

	LIB	LIC
Volumetric Energy density (cell)	-	160 Wh/L
Volumetric Energy density (pack)	88 Wh/L	17.6 Wh/L
C-rate	Up to 3 (continuous)	Up to 30 (continuous)
Projected cycle stability (cycles)	10 000 [73]	100 000
Projected life span (storage time)	10 years	15 years
DOD	40%	90%
EOL	80%	80%
η	95%	95%
Degradation rate	-	0.0002/cycle

3.3.2 System Characteristics

The following assumptions are made about the system characteristics to simplify the problem when creating a system:

- All efficiencies remain constant throughout the lifetime.
- The analysis period is set equal to the service life of the battery solution on board, which is set at 10 years. Ferries also operate on a 10 year contract.
- The energy needed for each ferry route is based on the characteristics of a 120 person car ferry with a speed of 12 knots, a conservative estimate. [7]

- When calculating the surface area of the BESS, 2.5 m is used as the height of the system.
- The same BESS solution, for the specific route, will be integrated on both quays.
- The ferry operates 365 days a year, with the same amount of crossings each day.
- The volume and area of a proposed BESS is the size of the BESS packs alone. It does not include the additional needed space for the charger, temperature management and room to do necessary maintenance.
- The system loss is set to be 8%.

3.3.3 Economics

The following assumptions are made to simplify the economical analysis:

- 1 USD = 9.05 NOK (25.04.2022). This is used for currency conversion.
- The total system costs for LIC is set to 1300 USD/kWh. This is an includes the price of EMS, BMS, racks, packaging and residing auxilliaries. These are preliminary price suggestions for the sake of this report, provided by Beyonder.
- The total cost of the LIB system is set to 700 USD/kWh. The price is provided by Corvus's sales department. This price is higher than the average cost of LIB, due to the complexity of this application.
- For a LIB system with a lower C-rate of 0.5-1C, the price will be lower, here estimated to be 420 USD/kWh. [74]
- The HESS proposed in the case studies uses the same LIB as the stand-alone solution.
- The price for upgrading the grid is collected from the DNV report. Here, the price estimate is done for upgrading the grid to fully be able to charge the ferry within 5 minutes. Estimating a price for partially upgrading the grid has not been possible.
- Net cost tariff NM3-1 for high power applications from the power company Tensio is assumed to be a valid estimate for all ferry operators. [75]

3.3.4 Environmental Analysis

The CO_2 footprint of any battery value chain is complex, and accurately calculating the climate impact is therefore challenging. The following assumptions are made about the climate impact regarding the production of the different technologies:

- 70 kg CO_2e per kWh for LIC. These are preliminary suggestions provided by Beyonder for the sake of this report and not verified with regards to the real production line.
- 73 kg CO_2e per kWh for LIB (NMC111 battery pack). Taken from Argonne National Laboratory Greet 2018. [76]

3.4 System Description

A simplified single-line diagram of the proposed battery system can be found in Figure 3.1. This system contains the electrical grid, a transformer, the battery bank, a power conversion system, and a plug connection to the ferry.

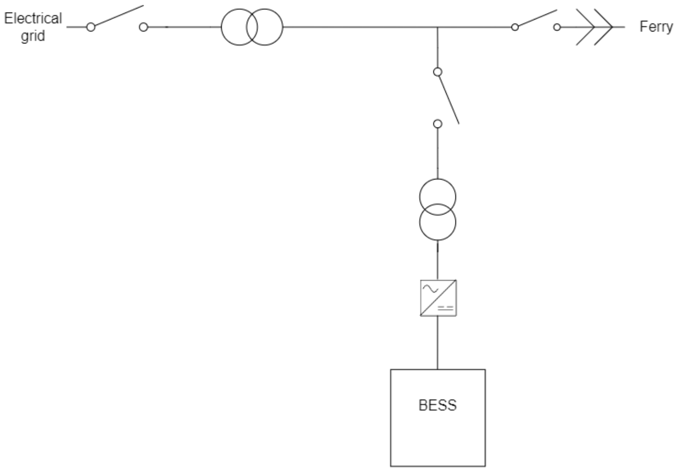


Figure 3.1: Simplified single-line diagram of a BESS.

3.5 Optimal Sizing of Battery Energy Storage Systems

Proper sizing of a BESS depends on many conditions such as weather conditions, operating strategy, maintenance and operating costs. The main objective of the proposed method is to find a suitable and reasonable size of the BESS that will maximize the annual benefits for ferry charging and the related problems with the electrical grid.

The most important step when sizing a battery system is to determine the required or desired amount of energy and power the BESS should provide. The size of the storage system is crucial for the application. The size will vary for the different intended purposes. The amount of power that can be extracted from the grid and power needed from the onshore battery is decided by several parameters. Several research papers have studied the optimal operation of batteries, and a variety of different optimization models have been carried out.

For the optimization model presented in this report, the system is designed based on energy and power calculations. These results are the basis for calculating the size and price of the battery system. For BESS modeling, a logical-numerical technique is used. The finished MATLAB code can be found in Appendix C and Appendix D. The case study analyzes different ferry routes. Several scenarios for each ferry route are set, where specific solutions are suggested. The different scenarios are; all available power is utilized, drawing less power from the grid and more from the BESS, and a grid upgrade.

3.5.1 Optimal Sizing of Lithium-ion Battery

When sizing a LIB, it is important to assure that the battery pack can provide enough power to support the system. The equations used to calculate the needed stored energy are shown in Equation (4) - Equation (6) where I is current in Ampere, P is power in Watt, U is voltage in Volt, Q is charge in Ah, Cr is C-rate and E is energy in Wh. The equations are then simplified into Equation (7). The total stored energy is adjusted to account for EOL, losses (L), and the efficiency (η) of the device in Equation (8).

$$I = \frac{P}{U} \tag{4}$$

$$Q = \frac{I}{Cr} \tag{5}$$

$$E = Q \cdot U \tag{6}$$

$$E = \frac{P}{Cr} \tag{7}$$

$$E_{tot} = \frac{E}{EOL \cdot (1 - L) \cdot \eta} \tag{8}$$

As stated earlier, the sizing of the LIB uses a EOL of 80% of SOH. A problem with this assumption is that a LIB used for charging ferries often will have a higher C-rate than a commonly used LIB. It will also not take the number of cycles into account, which will make the results less accurate. It is crucial to ensure that the load demand is met at all times and the power balance is obtained.

When using a C-rate of 2, this method is only valid for a charging time below 12 minutes in order to keep the DOD to 40%. If the ferry is charged for more than 12 minutes, a lower operational C-rate needs to be determined if one wants to keep the DOD under 40%.

3.5.2 Optimal Sizing of Lithium-ion Capacitor

When determining the size of the LIC system, the same method is used as for the LIB. The main difference is that while LIB is limited by power, LIC will be limited by energy. This shifts the focus area when deciding if the LIC meets the system's needs. The slightly different approach is due to having information about the degradation rate per cycle for the LIC.

Beyonder provided the degradation rate for their LIC and made this method feasible. Beyonder's LICs have a lifetime of 100 000 cycles and a degradation rate of 0.0002/cycle. This correlation can be used to determine how much the LIC will degrade. To do this Equation (9) and Equation (10) is used. Number of crossings per day is sensitive to each ferry route and will vary. This also means that EOL will vary in each case, unlike the EOL for LIB, which is a set number. To find the number of cycles, the number of crossings is multiplied with the DOD.

$$Cycles = N\,crossings/days \cdot 365\,days/year \cdot 10\,years \cdot DOD \tag{9}$$

$$EOL = Cycles \cdot 0.0002/cycle \tag{10}$$

LICs can charge and discharge with a C-rate up to 30. For the intended application, however, a lower C-rate is required. Since the charge time for each ferry route may vary, the optimal C-rate is calculated for each ferry route. The system on board the ferry limits the rate of the charging. This means that even though the LIC is able to provide a higher power, the C-rate must be adapted to fit the application. Equation (11) shows how C-rate is calculated, where t is time in minutes and the DOD is set to be 90%.

$$Cr = \frac{60}{t/DOD} \tag{11}$$

By using this C-rate the stored energy needed in the LIC system is calculated using Equation (7) and Equation (8) from Section 3.5.1 *Optimal Sizing of Lithium-ion Battery.*

3.5.3 Volume of a BESS

It is necessary to know how big the installed BESS will be when planning on placing a charging solution on a ferry quay. A quay has limited space, and can be a limiting factor in some cases. To calculate out how big the installed battery pack will be, in m^3, Equation (12) is used. Stored energy is measured in Wh and volumetric energy density in Wh/L. Specifications used for the calculations are shown in Table 3.1, where the volumetric energy densities for the LIB/LIC packs are given.

$$Total\ volume\ of LIB/LIC = \frac{Stored\ energy}{Energy\ density} \cdot 10^{-3} \tag{12}$$

3.6 Sizing Hybrid Energy Storage Systems

When sizing the HESS, the goal is to find the optimal combination between LIC and LIB to get the case-desired properties. This is a complex and time-consuming process. Because of the time limitations of this thesis, it was necessary to simplify the process. The solution for this project is to dimension the LIB and LIC using the same method as in Section 3.5.1 *Optimal Sizing of Lithium-ion Battery* and Section 3.5.2 *Optimal Sizing of Lithium-ion Capacitor*, dividing the total power needed between LIC and LIB and doing calculations based on this. The complete method is shown in Appendix C, written in MATLAB. Equation (13) shows how the power used to calculate the stored energy is calculated. The percentages were drawn from a vector, starting at opposite ends, meaning that if the system has 10% LIC, it would have 90% LIB.

$$\begin{aligned} P_{LIC} &= P_{tot} \cdot \%LIC \\ P_{LIB} &= P_{tot} \cdot (1 - \%LIC) \end{aligned} \tag{13}$$

After doing the calculations, the results are presented in a plot going from 100% LIB to 100% LIC to get an overall presentation of the different combinations. The factors that are presented in the different plots are price and volume.

3.7 Technical Challenges

It is necessary to look at the calculations from a technical standpoint to see if the optimal solution is doable and realistic. Both LIB and LIC can perform a number of cycles before they no longer operate at a sufficient capacity. This is when the BESS reaches end of life, EOL. Equation (14) shows how to calculate how many times the BESS can be charged each day. In this equation it is assumed that the BESS will be charged the same number of times each day for 10 years.

$$Ncharges/day = \frac{LIB/LIC\; cycle\, life}{3650\, days \cdot DOD} \tag{14}$$

If the number of crossings exceeds this calculated value, the BESS needs to discharge with a lower DOD value. This is done to decrease the number of cycles. The new DOD will then be calculated using Equation (15).

$$DOD_{new} = \frac{LIB/LIC\; cycle\, life}{Ncharges/day \cdot 3650 days} \tag{15}$$

3.8 Economics

An economic analysis is important to get an overview of which technical solution is the most economically beneficial. The least expensive option will not always be chosen since other things may be more important. However it is a big influencing factor. The economic analysis will compare the cost of LIB and LIC as well as upgrading the grid vs installing a BESS.

After determining the stored energy (kWh) required in a possible LIC and LIB system, the price of the system can be calculated. The determined stored energy for each of the technologies is then multiplied with the price (USD/kWh) for the given technology. This makes it possible to compare the two solutions and determine which one is the most inexpensive.

According to the grid rental fees, ferry operators are obligated to pay for consumed energy. Charging ferries use high power, and the energy price reflects this. Tensio, Trøndelag's power company, uses the tariff NM3-1 for high power-consuming business clients. The added cost of using high power is found in Table 3.2 and lay the foundation for calculating the cost of using a higher power for charging. Since almost all ferries charge at a power of over 1000 kW, the price points in the bottom row will be most relevant for calculations. (O. Hårstad, Tensio TS, personal communication, 07.04.2022)

Table 3.2: Cost for power peaks. [75]

Power consumption	Price during winter (Nov-Apr):	Price during summer (May-Oct):
0-499 kW	34 NOK/kW/month	26 NOK/kW/month
500-999 kW	32 NOK/kW/month	24 NOK/kW/month
1000+ kW	29 NOK/kW/month	20 NOK/kW/month

Reducing the peak power consumption from the grid will allow ferry operators to reduce costs. To do this, a BESS can be installed, however, there is also a cost of installing this. It is therefore possible to calculate if this will be beneficial. Since the BESS has a lifespan of 10 years, the reduced cost of using less power is calculated over a 10 year time period. Equation (16) shows how these calculations are done. Since the same amount of energy is always drawn from the grid even when using a BESS, the fixed cost, energy price and consumption tax are not included in the calculations. The price difference can then be calculated, as shown in Equation (17), and further be compared with the price of installing a BESS.

$$\begin{aligned} PowerPrice = P \cdot 10years \cdot (&29NOK/kW/months \cdot 6months \\ &+20NOK/kW/month \cdot 6months) \end{aligned} \tag{16}$$

$$Pricedifference = PowerPrice(P_{noEES}) - PowerPrice(P_{ESS}) \tag{17}$$

3.9 Environmental aspect

Although batteries play an important role in decarbonization, they still cause a climate impact from the manufacturing and recycling process. The environmental analysis will examine how the different solutions compare in climate impact. The emissions from a grid upgrade has not been included in this analysis as it was not possible to obtain any information about this.

The two technologies will be compared based on CO_2 emissions per kWh for the battery cell production. The carbon footprint linked to mining and conversion of the active materials of the LIB will be compared to the LICs in regards of the exclusion of hazardous heavy metals.

The difference in the geographical production area of the technology will also be looked at based on the different energy mixes used for electricity in the production. There will be some limitations due to a lack of information about the production area for the LIC components. Due to the lack of emission data, a complete analysis of the climate impact linked to grid upgrading will not be done.

In order for the variables to be useful and comparable, they must be combined with so-called functional units. The chosen unit depends on the purpose with the analysis. Some common functional units for LIC and LIB are the following: cumulative energy demand (CED) to produce the battery's capacity, in MJ/kWh, and kg CO_2 equivalents/kWh which is the amount of CO_2 and other green house gass emissions (GHGs) converted into CO_2 equivalents. It will be looked at kg CO_2e/kWh. [77]

4 Case study

Two different ferry routes have been examined in greater detail. This will provide a deeper understanding of potential challenges and which factors come into play when finding the best solution. The case studies will form a basis for further analyzes. The two ferry routes that will be analyzed are Flakk-Rørvik and Bognes-Skarberget. The different scenarios are chosen in a way that will give a broad perspective of the benefits for various solutions. The numbers selected for power from the grid and BESS are stated to give an example of possible solutions.

4.1 Case study 1: Flakk-Rørvik

The ferry connection Flakk-Rørvik is operated by FosenNamsos Sjø, and is located between Flakk in Trondheim and Rørvik in Indre Fosen, as shown in Figure 4.1. The route has two hybrid electric ferries, MF Munken and MF Lagatun. The ferries charges using power from the distribution network and onshore batteries between each crossing. Technical information about the ferry connection is presented in Table 4.1. [78]

Distance	7,5 km
Crossing time	25 min
Charge time	5 min
Crossings pr day	30
Charge power	4.5 MW
Energy needed pr trip	375 kWh
Charging voltage	11 kV

Table 4.1: Specifics for Flakk-Rørvik. [78]

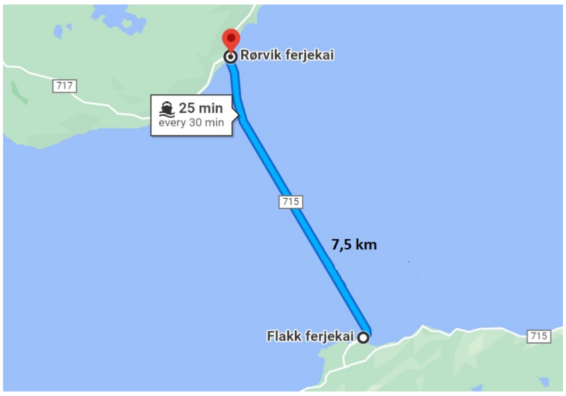


Figure 4.1: Case study 1: Ferry crossing Flakk-Rørvik including distance and travel time.

More accurate information about the ferry route was provided by Joachim Ness from FosenNamsos Sjø via email communication (01.02.22). The ferry is, on average, charged for 5 minutes with a power of 4.5 MW. The onboard batteries need 300-400 kWh of energy per charge, and usually store closer to 400 kWh. The energy stored per charging will vary as it takes some time for the chargers to be connected and disconnected to/from the ferry. As a simplification, 375 kWh of energy and a charge time of 5 minutes are used in further calculations.

Firstly, the existing solution today is examined further. In scenario 1, the available grid power is the same as it is today, but a new BESS is designed with both LIB and LIC to compare the two solutions. In scenario 2, less power is drawn from the grid to reduce the peak load. This means that more power needs to come from the BESS. Here it will also be looked at which BESS solution is the most suitable in terms of price and size.

4.1.1 Today's Solution

Flakk-Rørvik is already electrified, and a charging solution has been established. A BESS with LIBs has been installed for charging the ferries as the grid cannot supply the required amount of power alone. Table 4.2 shows the power drawn from the grid, the on-shore battery pack as well as the energy capacity of the LIBs on board.

Table 4.2: Today's solution, Case study 1.

Power from grid	2.5 MW
Power from batteries	2 MW
Energy capacity shore batteries	1782 kWh

After a conversation with the power company Kraftmontasjen, it was established that 2,5 MW is the definite maximum power that can be drawn from the grid. The grid was upgraded recently and will unlikely be upgraded further in the near future. (T. Ingvaldsen, Kraftmontasjen AS, personal communication, 17.02.2022) As shown in table 4.2, the power drawn from the grid is 2.5 MW when charging the ferry. Drawing this amount of power from the grid will cause high peak charges. It can also pose a challenge during times of high power demand among households and other power consumers.

As mentioned, the ferry is charged with 375 kWh per charge. 44% of this comes from the LIB, which is equivalent to 166 kWh each charge. The existing battery system has an energy storage of 1782 kWh, as shown in 4.2. [78] The reason for the battery system to be oversized to such an extent is to be able to deliver power at high rates.

Even if the current solution works well, it has room for improvement. The battery pack has been oversized to provide the necessary power, resulting in higher costs and environmental impact. The strain on the grid results in high peak charges, which could be an issue at times of high peak demand. Further, two scenarios will be presented in an attempt to replace the current approach with one that addresses these issues.

4.1.2 Scenario 1

The basis of this scenario is to still draw 2.5 MW from the grid but look at LIC as a possible replacement for LIB. When the grid delivers 2.5 MW, the BESS will have to deliver 2 MW. Using only LIB, the existing battery pack of 1.8 MWh is sufficient. The method for calculations is described in Section 3.5.1 *Optimal Sizing of Lithium-ion Battery* and Section 3.5.2 *Optimal Sizing of Lithium-ion Capacitor*. The results, using this method, suggests that the LIBs will have to store

1.4 MWh and have a volume of 16.1 m^3, less energy than the LIB in place today. A likely cause of why the calculated value differs from the actual value could be that the end of life is set to 80 % in the calculations. This is typically the end of life for lithium-ion batteries; however, because the C-rate in the calculations is set to 2, degradation may occur quicker, and the end of life will be at a greater percentage, requiring a larger battery.

Delivering 2 MW with only LIC would require the LIC to store 233 kWh, which corresponds to a volume of 13.2 m^3. This is slightly lower compared to the LIB, as shown in Figure 4.2. This solution will require less space on the dock as the capacitor will be smaller than the LIB. Even though LIC costs 1300 USD/kWh for the whole system and LIB 700 USD/kWh, the cheapest alternative would be the LIC since it has less stored energy than the LIB. The results are shown in Table 4.3. The table shows that LIC costs 689 000 USD less than LIB, which is a price reduction of 70 %. These results are also shown graphically in Section 4.1.4 *Comparing the Scenarios* in Figure 4.5.

	LIB	LIC
Stored energy (kWh)	1418	233
Volume (m^3)	16.1	13.2
Surface area (m^2)	6.4	5.3
Price (USD)	992 000	303 000

Table 4.3: Results from calculations for Case study 1, scenario 1.

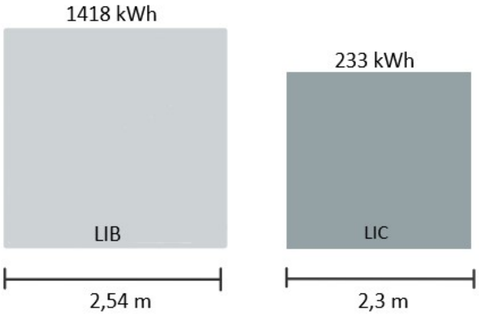


Figure 4.2: Case study 1, scenario 1, Visual size comparison.

4.1.3 Scenario 2

In this scenario, only 1.5 MW is drawn from the grid. This is to ease the strain on the grid by reducing the peaks. Then, as in scenario 1, it is determined which BESS is best suited when drawing this amount of power from the grid.

When the grid delivers 1.5 MW, the energy storage system must deliver 3 MW. Doing the calculations with these values, a system containing only LIBs will have an energy storage of 2.1 MWh and a volume of 24.1 m^3. As shown in scenario 1, the calculations may not be entirely accurate so it is reasonable to assume that the battery will have to be even larger. A LIC for this solution will have to store 349 kWh, which corresponds to a volume of 19.8 m^3. This is 18 % smaller compared to the LIB, as shown in Figure 4.3. This could make it possible to draw less power from the grid when charging the ferries, reducing the power peaks. Table 4.4 summarizes the results from this scenario, including the price of the two solutions. In this scenario, LIC is also the cheaper solution, by 1 034 000 USD.

	LIB	LIC
Stored energy (kWh)	2126	349
Volume (m^3)	24.1	19.8
Surface area (m^2)	9.6	7.9
Price (USD)	1 488 000	454 000

Table 4.4: Results from calculations for Case study 1, scenario 2

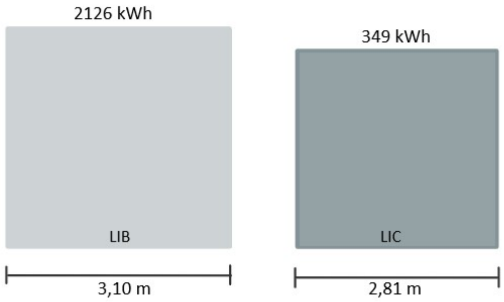


Figure 4.3: Case study 1, scenario 2, visual size comparison.

4.1.4 Comparing the Scenarios

When comparing the existing system to the described scenarios, it is clear that LIC may be a better alternative in this case. Presenting LIC as a possible ferry charging solution also allows for a reduction in the amount of power pulled from the grid. Peak shaving will be aided due to this, and the price related to power peaks will be reduced. This is shown in Figure 4.4. In addition to reduced costs, the load is shifted, which reduces the strain on the grid.

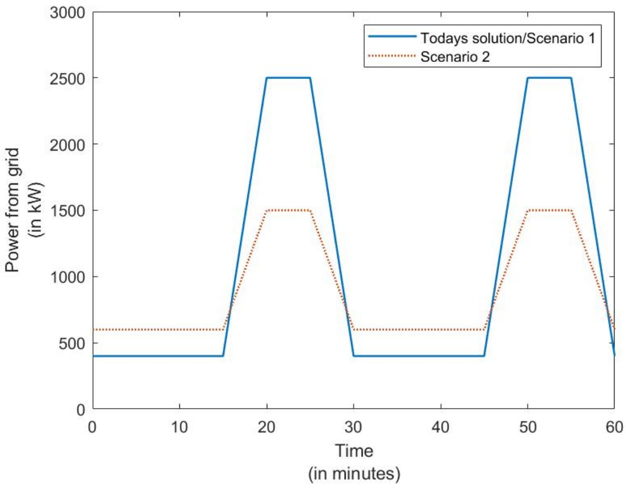
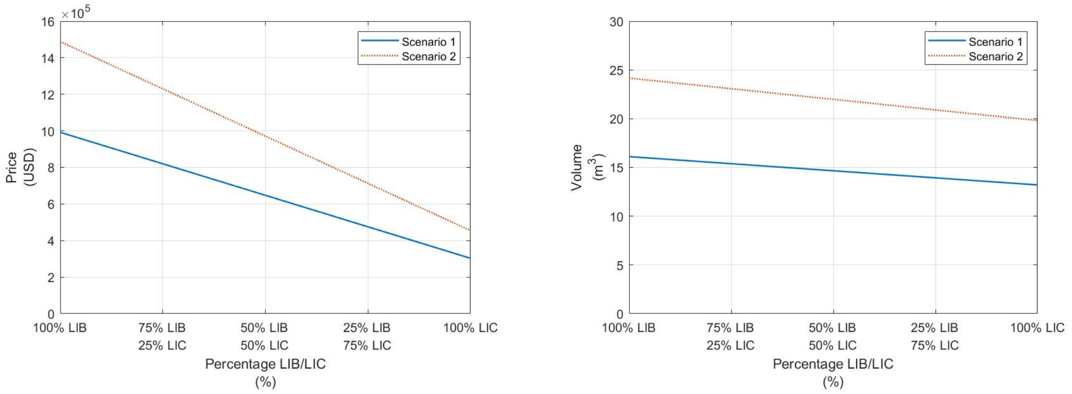


Figure 4.4: Power peaks Case study 1, scenario 1 and 2.

In Figure 4.5, different combinations of LIC and LIB are displayed in regard to costs (a) and volume (b). This is an attempt to show how a HESS would perform. However, it is important to mention that this analysis does not consider how the technologies would complement each other in a well-designed HESS. A thorough analysis of a HESS solution would give different results and could make a HESS a better option than the graph suggests. From the graph, it is clear that the volume and price is lower for scenario 1 since it draws more power from the grid and less from the BESS. Using only LIC is the best option in both scenarios regarding price and volume.



(a) Price

(b) Volume

Figure 4.5: Case study 1, price and volume results.

There will be greater costs associated with higher power peaks. The price is decided from the highest drawn power. In scenario 1, 2.5 MW is drawn as the maximum power from the grid. This equals a cost of 7.35 million NOK over 10 years. For scenario 2, drawing 1.5 MW from the grid will result in a price of 4.41 million NOK over 10 years. A comparison between the price of the BESSs and the power price is shown in Figure 4.6. The price differences between the two scenarios are not significant, when looking at the technologies separately. Still, the fact that the prices for both scenarios are similar could be used as an argument to reduce the power drawn from the grid, as this could lead to more available power in the distribution network.

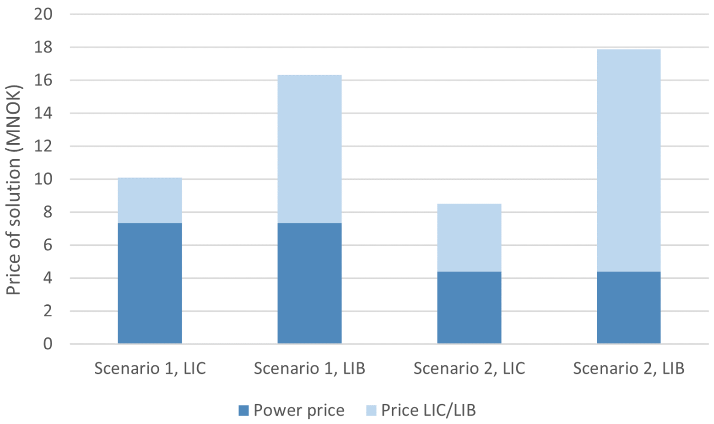


Figure 4.6: Case study 1, scenario 1 and 2, power prices and price for battery packs.

4.2 Case study 2: Bognes-Skarberget

Bognes-Skarberget is a ferry route operated by Fjord 1. The route crosses Tysfjorden, located in Hamarøy municipality in Nordland county, as shown in Figure 4.7. This ferry route is not yet made electric, however, electrification is planned and will be in place by the end of 2022. Technical information about the ferry connection is shown in Table 4.5.

Table 4.5: Specifics for Bognes-Skarberget.

Distance	8 km
Crossing time	25 min
Charge time	10-15 min
Crossing pr day	48
Charge power	2350 MW (10min)
Energy needed pr trip	393 kWh

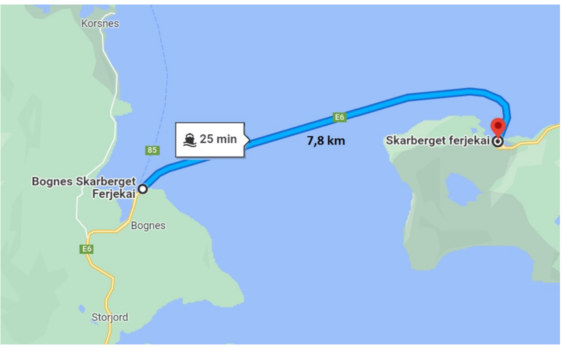


Figure 4.7: Case study 2: Ferry crossing Bognes-Skarberget including distance and travel time.

This ferry route shares several similarities with Flakk-Rørvik when it comes to crossing distance and energy consumption, but it has the opportunity to charge for a longer amount of time. Since Bognes-Skarberget does not yet have a solution in place, other challenges will be in focus. The grid on both quays must be upgraded to enable the electric ferries. The grid can be improved to support the ferries on their own, or it can upgraded to a level so that it requires a BESS. Currently, the available power on Bognes is 1 MW and Skarberget has 0.5 MW available. [7]

Kystnett AS filed a concession to build a 66 kV power line in order to be able to provide the needed power to operate the ferries. The concession was approved by NVE. Before the concession was approved, an analysis was done, discussing the different options regarding charging the coming electric ferries. The options that will be analyzed in this case study are building the 66 kV line, and including a BESS. [79]

4.2.1 Scenario 1

This scenario will analyze the chosen solution using a 66kV line that gives a transmission capacity of 18.8 MW distributed between both quays. This solution will not require a battery pack as the grid capacity will be more than sufficient for charging the ferries using the grid alone. The costs for this solution are 94 million NOK. [79]

When the grid has such a high capacity, the ferry could charge in a shorter time. Figure 4.8 shows the grid's power peaks when charging the ferry for 5 and 10 minutes. Charging for the full 10 minutes would probably be the preferred option as it reduces the peak costs. Having the opportunity to provide high power from the grid also makes the system more reliable.

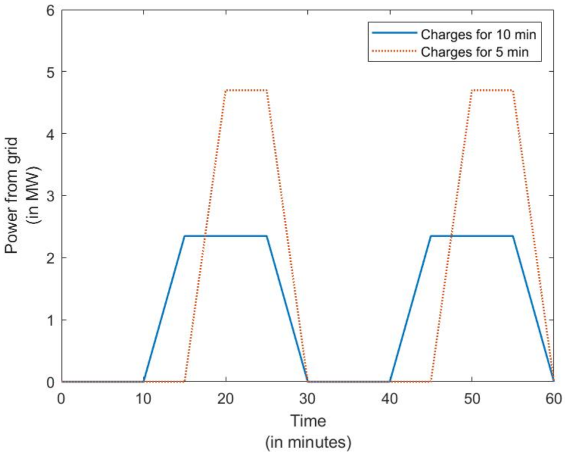


Figure 4.8: Case study 2, scenario 1, power peaks when charging for 5 and 10 minutes.

4.2.2 Scenario 2

The other proposed solution was to upgrade to a 22 kV power line. This would give the grid a capacity of 3.9 MW combined, which corresponds to 1.95 MW on each quay. A BESS is required in addition to the grid in order to deliver the required power during charging. This solution has a grid investment cost of 71 million NOK. The investment cost does not include the costs of the battery pack. [79] Bognes-Skarberget has a charging time of 10 minutes. It is however also looked at a solution where the ferry is only charged for 5 minutes. Assuming the grid provides 1 MW for both solutions, the battery pack would have to deliver 1,35 MW if the ferry charges for 10 minutes, and 2.7 MW if it charges for 5 minutes. The LICs stored energy, volume and price will be the same, regardless if the ferry is charged for 5 or 10 minutes. The LIBs characteristic will vary, as it is limited by power, and has to be scaled up when the required power is higher. The calculation results for this scenario for the LIB and LIC solution are shown in Table 4.6.

	LIC (1.35/2.7 MW)	LIB (2.7 MW)	LIB (1.35 MW)
Stored energy (kWh)	337	1913	956
Volume (m^3)	19.1	21.8	10.8
Surface area (m^2)	7.6	8.7	4.3
Price (USD)	438 000	1 340 000	670 000
Price (MNOK)	3.96	12.13	6.06

Table 4.6: Results from calculations for Case study 2, scenario 2.

If charging for 5 minutes, the LIC comes out as the best option considering all aspects. When charging for 10 minutes, the LIB will have the smallest surface area, but it will still be more expensive than LIC. If there was a limited available space on the quay the LIB might be the preferable option as it is smaller if with a charging time of 10 minutes.

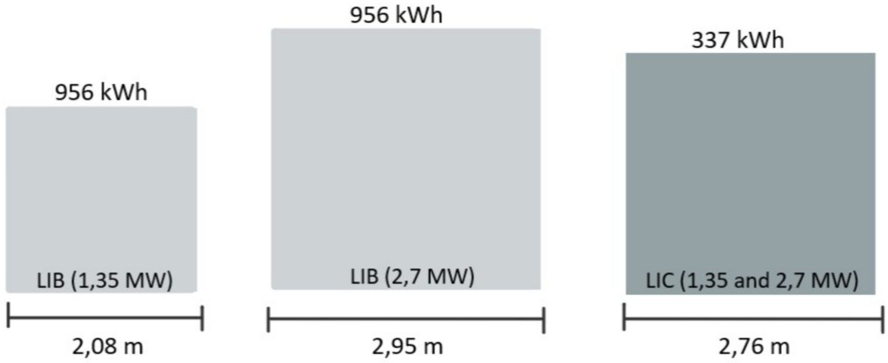
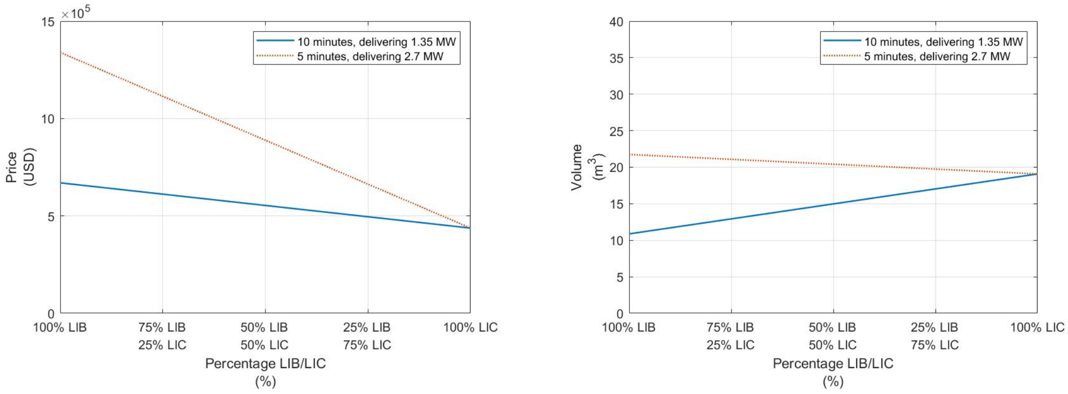


Figure 4.9: Case study 2, scenario 2, visual size comparison.

A size comparison of the two technologies is shown in Figure 4.9. A graphical comparison of the volume and price, charging for 5 and 10 minutes, is shown in Figure 4.10. It is worth mentioning that this solution with drawing 1MW from the grid is doable with the current available grid capacity on Bognes, but not on Skarberget.



(a) Price (b) Volume

Figure 4.10: Case study 2, price and volume results.

4.2.3 Comparing the Scenarios

The investment costs for the two scenarios, when including the BESS, is quite similar as shown in Figure 4.11. The cheapest alternative is scenario 2 when using LIC. However, since the BESS only has a lifespan of 10 years, the investment cost for the system has to be reinvested every decade. It is difficult to give a precise estimate of the lifespan of the grid, but it is safe to say that it is higher than 10 years. Considering this, the first scenario might be the cheapest in the long run. It will also give a far greater transmission capacity of 18.8 MW compared to 3.9 MW which will prevent the need for further upgrades in the nearest future.

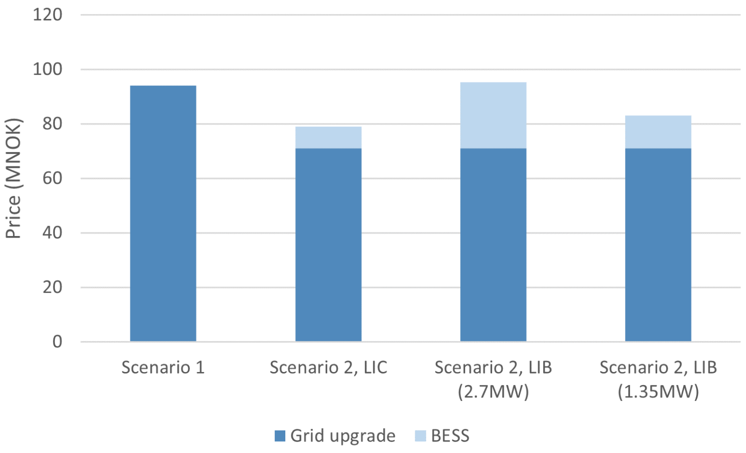


Figure 4.11: Price for grid upgrade and BESS, Scenario 1 and 2, Case study 2.

The cost of using different peak power for the different scenarios are presented in table Table 4.7. In Scenario 1 the ferry could be charged with a power of 2.35-4.7 MW, most likely 2.35 MW, depending on how long the ferry is charged.

Table 4.7: The power peak costs over a 10-year period for Case study 2.

Power drawn from the grid (MW)	Cost of power peak (MNOK)
1	2.94
2.35	6.9
4.7	13.8

5 Analysis

This section will try to give an overall understanding of how LIC compares to LIB regarding technical, economic and environmental aspects. The case studies from the previous section are used as examples and more general conclusions are drawn.

5.1 Technical Analysis

The most important factors were identified after conducting case studies and considering various parameters. This section will highlight these factors and attempt to demonstrate how they influence choosing the optimal solution from a technical standpoint.

5.1.1 Available Power on Ferry Quays

Figure 5.1 displays the available power on several different ferry quays and the difference between the available and the required power to use the distribution grid for ferry charging. [7] The ferry ports with an available grid power of over 1200 kWh are not included since this only applies to a small portion of the quays. From the plot, it is clear that many quays do not have any available grid power. These quays will have to upgrade the grid, as one would need some available power to charge a potential battery pack. According to the report conducted by DNV, almost 70% of the analyzed quays have less than 1000 kW of available power. [7] This means that some form of grid upgrade is needed. However, how much power a grid upgrade needs to provide is not given, as it is a possibility to only upgrade the grid partly and include a BESS for additional support.

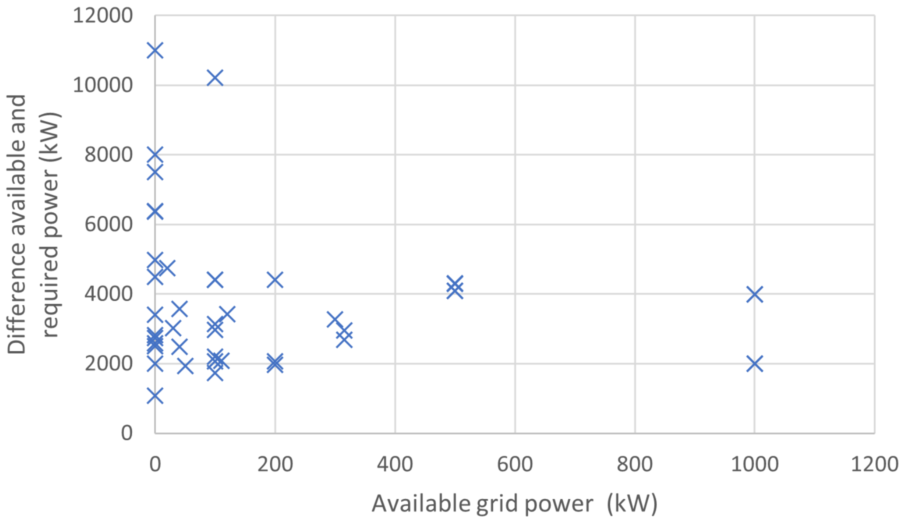


Figure 5.1: The available grid power on multiple ferry quays, and how much more power is required for use in ferry charging. *(Modified from [7])*

In Case study 1, Flakk-Rørvik, the grid was upgraded to 2.5 MW even though a higher power was required to charge the ferries. A likely cause to this, is that the general power demand in the area may be low, and will stay that way in the immediate future. This is likely the case for many of the ferry quays included in the plot. If the ferry operators do not get a concession to upgrade the grid to the desired power on the quay, including a BESS is a great way to achieve the required power to charge the ferries. Figure 5.1 is based on the DNV report, which assumes a charge time of 5 minutes. This affects how much power is needed at the quay. If a ferry has more available time to charge, the power required will be lower than what is presented in this graph.

5.1.2 How different C-rates Affect the Results

The C-rate for LIC will vary depending on how much time is available for ferry charging. How quickly the ferry can be charged, and at what power, will be limited by the batteries on board the ferry, and the electrical equipment used for ferry charging. This means that even though the LIC is able to deliver higher power, and can charge the ferry faster by utilizing a higher C-rate, it is not able to do so in many cases. When the ferry charges for a longer time, the C-rate for LIC will decrease to deliver power throughout the charging time. This is demonstrated in Table 5.1.

Table 5.1: Operational C-rates for LIC with different charging times.

Charging time (min)	C-rate
5	10.8
10	5.4
12	4.5

The C-rate for LIB used in the case studies is 2C. This is a higher C-rate than most LIBs in use today but may be necessary when used in a high-power application. Corvus's "Orca Energy" has a continuous C-rate up to 3C, but using such high C-rate may shorten the lifetime of the battery. Since weight is less important in stationary storage systems, higher C-rates than 3C can also be obtained by changing the anode material from the traditional graphite to other materials such as LTO. LIBs with higher C-rates tend to be more expensive. While the price of the LIB used in the case studies is set to be 700 USD/kWh, a LIB with a C-rate of 0.5-1.5C is expected to have a price closer to 420 USD/kWh. [74]

For high power applications, such as ferry charging, it could be more interesting to look at the price per power unit instead of per energy unit. Table 5.2 shows an overview of the price per power unit for LIBs and LIC with a charging time of 5 minutes. The price is calculated for LIBs with different C-rates to demonstrate how Beyonder's LIC compares to LIBs with different characteristics. The price per energy unit also differs between LIBs with different C-rates. This is also accounted for in the table. The table clearly demonstrates that LIC is the cheapest option from a power perspective. Comparing LIC with a C-rate of 10.8 and LIB with a C-rate of 2, the LIC is 85% more expensive than the LIB.

Table 5.2: Price per power unit for LIC and LIB with different C-rates, charging for 5 minutes.

Technology used	C-rate	Price (USD/kWh)	Price (USD/kW)
LIC	10.8	1300	151.4
LIB (standard)	0.5	420	1190.7
LIB (standard)	1	420	595.5
LIB (Corvus)	2	700	496.1
LIB (Corvus)	3	700	330.8

This point is also demonstrated graphically in Figure 5.2. The graph clearly shows that LIC is a less expensive solution with today's C-rates for LIB. As more power is required from the system, the price difference between using LIC and LIB increases. The plot uses values from Table 5.2.

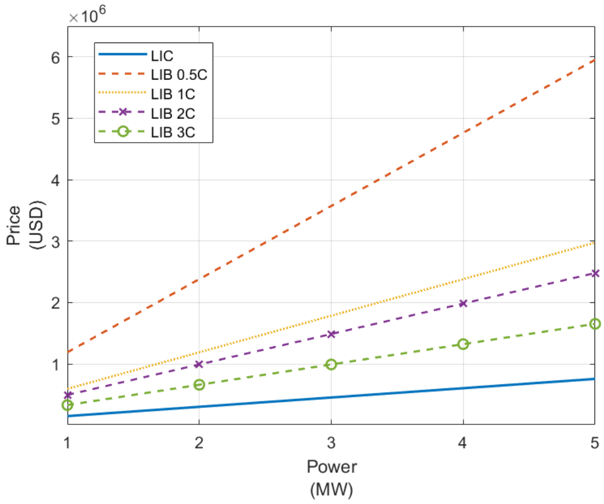


Figure 5.2: The price as a function of power for LIC, and LIB with different C-rates. Calculated with a charging time of 5 minutes.

5.1.3 Number of Crossings per day

The number of charges each day is an important factor in making sure that the battery can withstand a lifetime of 10 years. The cycle life of a LIC is estimated to be 100 000 cycles. With a DOD of 90%, the battery can not have more than 30 charges each day, as shown in Equation (18). If the LIC system on each quay have 30 charges per day, the ferry route can have up to 60 crossings per day. 16 of the 52 ferry routes analyzed in the report from DNV have more than 60 crossings per day.

$$\frac{100\,000\ cycles}{365\ days \cdot 0.9} = 30\ charges/day \tag{18}$$

For ferry routes with more than 60 crossings per day, the DOD has to be lowered, resulting in a larger LIC with higher stored energy. Whereas the LIB can not withstand as many cycles as the LIC, the LIB is oversized to a great extent, resulting in a low DOD. The cycle lifetime for LIB lies between 2000-20000 cycles. In the calculations, a cycle life of 10 000 cycles is used. [73] This is only valid when the DOD is low, in this case, set to be under 40%. This makes it possible for the LIB to manage a high amount of charges. Since the DOD will differ for the different applications when looking at LIBs, the number of charges it can withstand will vary.

Assuming this DOD level, and cycle life, the maximum number of charges per day can be calculated. This is done in Equation (19), with a result of 68 charges per day. This means that the LIB used for calculations can be used for ferry routes with up to 136 crossings per day. None of the ferry routes in the report from DNV had more crossings than this per day.

$$\frac{10\,000\, cycles}{365\, days \cdot 0.4} = 68\, charges/day \tag{19}$$

5.1.4 Time Available for Charging

The available time a ferry has to charge, varies for different ferry routes, depending on how often they depart. Whereas the report from DNV used 5 minutes as a basis for charging time, case study 2 allowed for a charging time of 10 minutes. Case study 2 shows that LIB is a better fit for ferry routes with a longer charging time than ferry routes with shorter charging times.

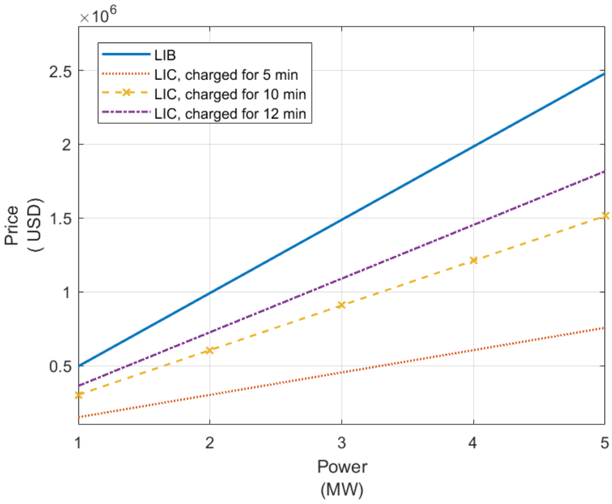


Figure 5.3: The cost of a LIB and LIC system as a function of power, charging for 5, 10 and 12 minutes.

Figure 5.3 shows how the price for a BESS solution will vary as a function of power when the charging time is changed. Since the LIB has to be oversized to deliver enough power, the size and, therefore, the price will be the same when the charging time changes. This is only valid with a charging time of up til 12 minutes. However, for the LIC, how long the ferry is charged will affect the C-rate, and how much energy the LIC system has to store. This plot is not based on a fixed amount of energy, the amount of energy is the product of the required power and the time. This is also why the LIC solution varies when looking at different charging times, as stored energy limits the LIC. From the graph, it is clear that the price of LIC will increase when the ferry's charging time increases. However, LIB will be the most expensive solution despite the different charging time.

5.1.5 Available Space on the Ferry Quay

Another aspect to consider is the available space on the quay. In Figure 5.4 the surface area of a LIB and LIC system is shown for different power rates. The graph reveals that the most space-efficient option, when charging for 5 minutes, is LIC, while LIB has a smaller surface area when charging for 10 minutes. If a charging time of less than 6 minutes is required, LIC is the most space-efficient alternative.

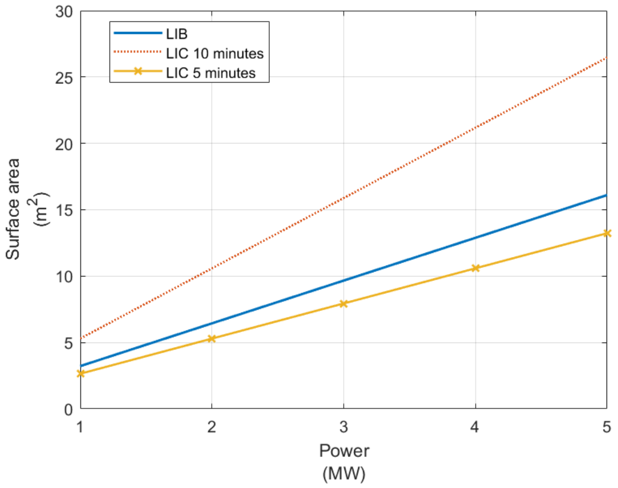


Figure 5.4: The surface area of a BESS for different required power.

The graph shows that the maximum size of a LIC is 26.5 m^2 when providing 5 MW for 10 minutes and 13.2 m^2 providing the same power for 5 minutes. The area for a LIB, when delivering this amount of power is 16.1 m^2.

Figure 5.4 only calculates the surface area of the LIB and LIC pack. The battery pack will, in reality, be placed in a structure that includes a thermal management system as well as the charger. In addition to this, there must be sufficient air between the components to ensure proper ventilation and safety, and enough empty space to be able to do maintenance to the system. An estimate of how much extra space this requires is not given in this report as it is outside the scope of this thesis.

As the required power and charging time increase, the size of the BESS increases as well, and the thermal system will have to increase accordingly to ensure proper temperature control. This system can become very large and costly and is also something to consider when determining the size of the overall system. Having LIBs with increasing C-rates also generates more heat and needs a larger thermal management system. These factors will increase the total required space on the quay.

5.2 Economical Analysis

The economic analysis will go deeper into the economic aspects of the different ferry charging options.

5.2.1 Grid Related Costs

Figure 5.5 shows a plot created using data from the DNV report of how much more power is required from the grid and the cost of upgrading the grid to this level. [7] The points are different ferry quays. The ferry quays that already have enough available power are not included in the plot. As one can see, there is no clear correlation between the cost of a grid upgrade and the power needed. The reason for this is likely the differences in existing infrastructure at each location. Therefore, it is difficult to make a general conclusion from this, and each case will have to be analyzed separately. It is also important to mention that these costs are only estimations and could differ from the actual cost.

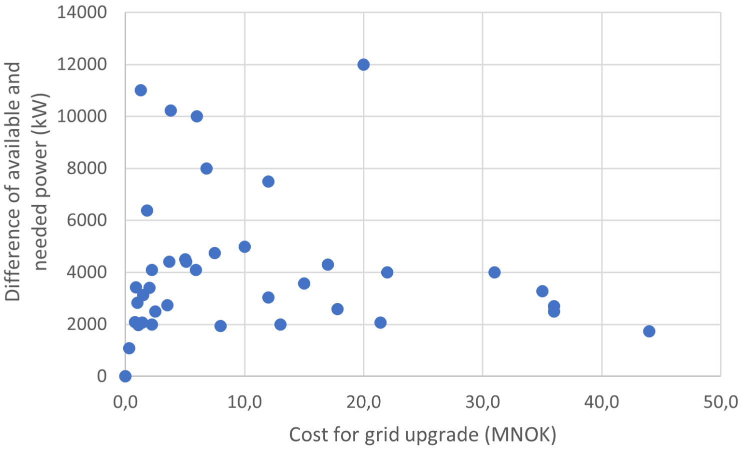


Figure 5.5: Price for a grid upgrade on different ferry quays to obtain required power. *(Modified from [7])*

There is a higher cost related to using a higher peak power. Using grid tariffs from Tensio, Table 5.3 is created to show how the price rises when the peak power increases. This correlation is linear. As an example, if a ferry quay needed 6 MW delivered during a charging time of 5 minutes, the cost of power peaks would be 17.6 MNOK. If a BESS with LIC were installed in addition to the grid, delivering 3 MW during charging, the cost of the power peaks would be reduced to 8.8 MNOK, while the price of the LIC system is estimated to have a cost of around 4.4 MNOK. This means that in addition to contributing to peak shavings, the system's price would be 4.4 MNOK less. The price for LIC is only calculated for the BESS, not maintenance and installations, Etc., meaning that the actual price of utilizing the BESS may be larger. This does however demonstrate how LIC can contribute to reduce costs in grid applications.

Table 5.3: Cost of different power peak over a 10 year period. [75]

Power (MW)	Cost of power peaks (MNOK)
1.5	4.4
3.0	8.8
4.5	13.2
6.0	17.6

5.2.2 System Costs

In addition to the expense of the LIB or the LIC itself, there are also additional costs for the surrounding systems. Personal communication with Martin Aasheim from Norwegian Electric systems led to an estimated cost for the ferry charging system. For the transformer and AC/DC converter, the estimated price was over 2,3 MNOK which is close to 250 000 USD. This does not include the cost of installation, but does give a pointer of the added costs of installing a BESS. These price estimations were given with a basis of a proposed LIB and LIC system from Case study 1.

5.2.3 Changes in the Price of LIB

As stated in the Theory in Section 2.6.1, the price for LIB has decreased a lot in the last decade and will continue to decrease in the coming years. The average price for LIB packs today is set to be 132 USD/kWh. This is, however, not an accurate price for the LIB used in the case studies, since prices for larger, more complex battery systems are higher. The LIBs used for ferry charging will have to be custom-designed to fit the criteria of the application. Therefore, the prices will vary greatly, and it is not easy to know exactly how much it will cost. Nevertheless, the trend of decreasing prices is still valid. Since LIC is a newer technology, the price is not expected to decrease at the same rate at this time. It is, however, also predicted to decrease in the future as the technology develops further. Beyonder's LIC is yet to be commercialized, and mass production will help decrease the price. The price for Beyonder's LIC technology is estimated to be 1300 USD/kWh including the surrounding system. Using this information, it is possible to see how LIC will compare to LIB if the price for LIB decreases.

Case study 1, scenario 2, is used as an example to visualize this. In this scenario, 3 MW is provided from the BESS for 5 minutes. Figure 5.6 shows the price for the BESS using LIC with the current price and the cost of using LIB when the price per kWh changes. The price for LIB used in calculations in this thesis is 700 USD/kWh, and the plot clearly shows that LIB is more expensive at that price. In order for the LIB solution to cost the same as the LIC solution, the LIB price will have to decrease to about 160 USD/kWh. Even with decreasing prices, it is not reasonable that the price will decrease to that extent any time soon for LIBs used for this purpose. LIC is therefor expected to be the most cost-efficient for ferry charging in the coming years, based on these numbers.

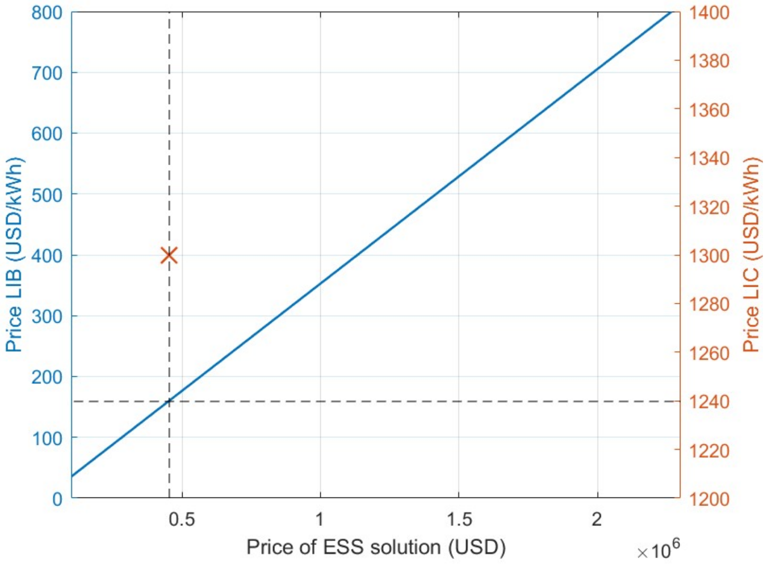


Figure 5.6: Price of a BESS providing 3 MW for 5 minutes, with a changing LIB price and constant LIC.

5.3 Environmental Aspects

Electrical transport is known for being emission-free, at least when they are powered by renewable energy. There are still emissions associated with battery production. This section will look at the environmental impact of battery cell production, recycling, shipping and differences in where the production site is located.

5.3.1 Cell Production

A LIB can be divided into three main components: the cells with active materials, the BMS and the mounting structure. These components are part of the battery supply chain. The production starts with material extraction, conversion and ends with the production of the battery cells and packs. The biggest impact of battery technology production will come from cell production. The BMS and the pack structure consist of materials such as aluminum, steel and plastics. These materials are not exclusive to the LIB value chain and often originate from different material databases. [77]

The first step of energy consumption from LIB is found in the mining and conversion step of the active materials: nickel, manganese, cobalt and lithium. The amount of environmental emission depends on the cathode chemistry. The mining process has significant environmental impacts, including habitat destruction, water and air pollution. [80] Around 40% of the total climate impact of the battery is from the mining, conversion and refining step of the cathode powder. For an NMC battery, this will correspond to around 28.8 kg CO_2e/kWh. The geographical area for the raw materials for the cathode and anode is set where the production is concentrated, e.g. Chile, China, Finland, and Australia. [77]

Beyonder's LIC cell production is based on sustainable forestry residue that replaces hazardous heavy metals such as cobalt and nickel. LICs will have a better environmental standpoint from cell production and can be seen as an environmentally better alternative than the conventional LIB.

The total NMC battery production's emissions were calculated to be 73 kg CO_2e/kWh by Argonne national laboratory Greet 2018. Argonne's study has a "cradle-to-gate" boundary, where it covers material production and manufacturing. The boundary does not cover when the battery is used or the recycling process. [77] Beyonder's LIC technology is assumed to have 70 kg CO_2e/kWh. The BESS solutions with LIC will have a lower impact on the environment than LIB since it has a slightly lower greenhouse gas emission and stores less energy. In Figure 5.7 the calculated emissions are shown graphically of the different scenarios for Case studies 1 and 2. For case study 1, the LIB has around 6.3 times the amount of emissions compared to the LIC application. In Case study 2, it is only 2.9 times greater for a LIB with 1.35 MW. In a case with higher power, 2.7 MW, the LIB will be 5.9 times bigger.

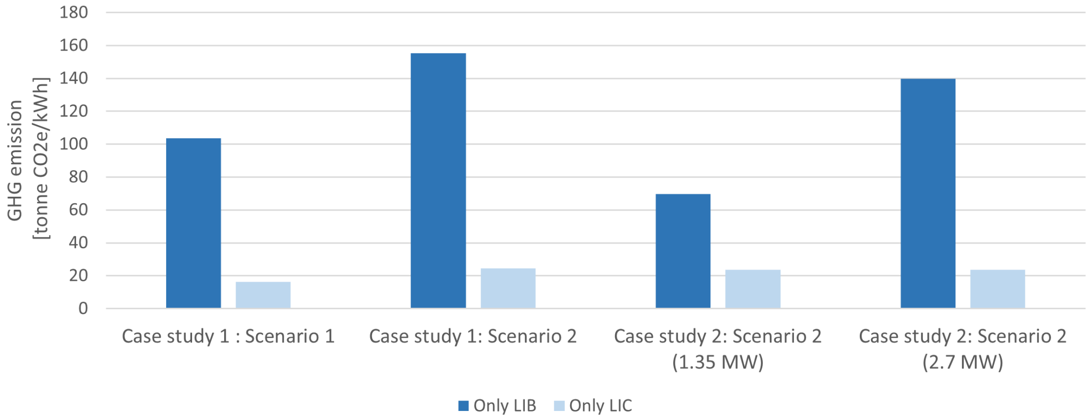


Figure 5.7: GHG emissions from the battey cell production for the different case studies.

The overall sustainability of future batteries is dependent on recycling. Recycling LIB has the potential to reduce energy consumption and greenhouse gas emissions. This will avoid new extractions and processes of raw materials, and conserve natural resources. It has been shown that recycling LIBs will result in 51.3% natural resource savings compared to landfills. However, it is not possible to have a recycling process without having any environmental impacts. [81] Relatively few lithium-ion batteries end up being recycled, since the battery industry is limited by various factors, including complexity, lack of monetization of recycling benefit and recycling regulations. Instead, the battery development is going towards using cheaper materials, increasing the battery longevity and charge capacity. [82] Recycling plays therefore an important role, and should be considered when developing a battery system. Beyonder's LIC technology is still in the development phase and has the opportunity to set a clear plan for recycling before the full-scale battery production begins.

5.3.2 Geographical Production Area and Transportation

The geographical production area of the battery technology does also affect the emissions. Today, the battery value chain is global, where production is located on populated continents. The energy source will therefore vary from where the material is produced. To do a complete emission analysis, the production would need to be tracked to individual production sites. The same goes for the specific energy mix used for electricity in production. In the study done by Argonne National Laboratory, it is assumed that the NMC battery is produced in the United States with electricity from the national grid mix. Aluminum is assumed to be sourced from the US, and the cathode and anode raw materials are from different countries. If the same battery was produced in Europe, the environmental impact would likely be lower. This is because Europe's energy mix contains a higher share of renewable energy and nuclear power. If the production was placed in china, the total CO_2 emissions would likely be higher since coal is a major part of the energy mix. Beyonder states that their LIC cells will be produced using ecological materials such as Norwegian sawdust and using renewable energy. [58]

Emissions from transportation are another aspect that contributes to the total emissions. This factor depends on the production site, where the battery is being transported to at the end, and the mode of transportation. In a life cycle assessment (LCA) study done by Kim *et al*, the battery cells are produced in South Korea and packs manufactured in the United States. The additional greenhouse gas emission from the transportation of these cells was calculated to be 4.1 kg CO_2e/kWh. [77] [83] This shows that the transportation emissions of the battery cells do not account for as big of a part as the emissions linked to the production. Since greenhouse gas emissions are sensitive to the electricity mix and fuel used, this value may not be representative of LIB production and shipping from other parts of the world.

6 Discussion

This section aims to further discuss the main findings from Section 4 *Case Study* and Section 5 *Analysis*. The results from the case studies are analyzed and compared in Section 5, and will be discussed in a broader perspective. Lastly, the uncertainties associated with the assumptions and methodology is reviewed.

6.1 How LIC Compares to LIB

A visual representation of how LIB compares to LIC is shown in Figure 6.1. Here the comparison is made regarding three factors; surface area, price and GHG emissions. This comparison is made based on a charging time of 5 minutes, and LIC is set to have a value of 1. This way, one can see how many times larger the LIBs quantities are than LIC.

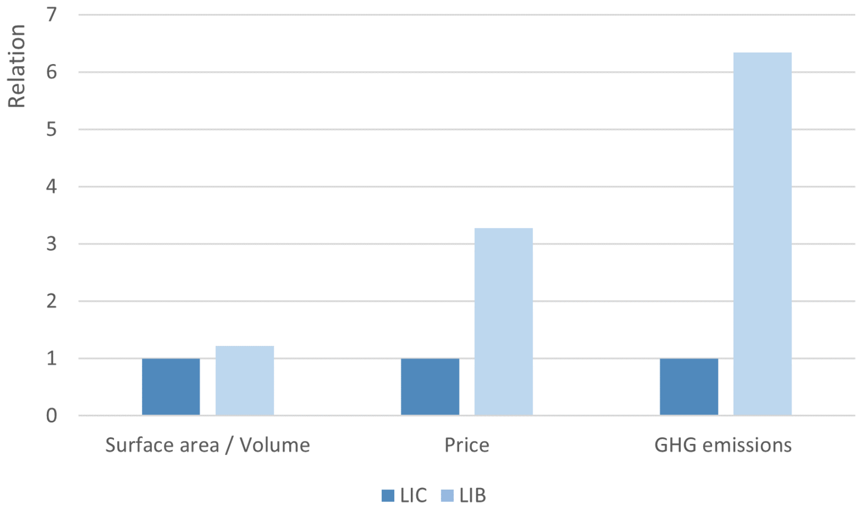


Figure 6.1: Comparison of LIB and LIC in regards of surface area, price and GHG emissions. Based on a charging time of 5minutes.

Based on the findings in the previous sections, it is clear that LIC can be a good contender to the more typical LIB solution regarding ferry charging. If a charging time of less than 6 minutes is required, LIC is the most space-efficient alternative. All solutions proposed in the case studies will fit into a space with a surface area of less than 10 m^2. The conducted analysis also determined that the maximum surface for a LIC, charging for 5 minutes with a power of 5 MW, is 13.2 m^2, while the LIB will be 16.1 m^2. If the ferry is only charged for 5 minutes, it is clear that the size will not be the determinant for which solution is overall best. However, when the ferry is charged for 10 minutes at 5 MW, the size of the LIC was 1.6 times larger than the size of the LIB. In this case, choosing LIB could be a better option if the space on the quay is limited. This shows that LIC is the best fit for charging solutions when there is a limited charging time.

The calculated surface areas only include the size of the battery pack and do not reflect how much space on the quay is actually needed. The design must consider the added space for temperature management, chargers, and open-air between the components. How much larger the finished structure will be compared to the size of the battery packs is hard to say and will be case-specific. This must, however, be done for both LIB and LIC. It is reasonable to assume that the extra needed space will be similar for both technologies. Even though the calculated values do not provide the total size of an actual system, it portrays the relationship between the size of the two technologies. If the BESS becomes larger, the size of the thermal management system will also have to increase to dissipate the extra heat.

From an economic standpoint, it has been a big difference between using LIB and LIC. The conducted analysis showed that using a BESS with LIC is the cheaper option regarding ferry charging. The LIB has a lower price per energy unit, but LIC has the lowest price when looking at the price per power unit. Since ferry charging is a high-power application, the price per power unit may be a more relevant way to look at the price of the technology.

Many ferry routes only have between 5-10 minutes to charge, depending on how many crossings they have each day. Today LIC would be the cheapest option for this purpose. However, the price of LIB is predicted to continue to decrease in the coming years. As LIC is a newer technology, the price is not expected to decrease at the same rate as LIB. As shown in an example in Figure 5.6 in Section 5.2.3 *Changes in the Price of LIB*, the price of the LIB would have to be around 160 USD/kWh to have the same price as the LIC. On the one hand, this is reasonable since the average price of a LIB pack is set to be 132 USD/kWh. On the other hand, the price of the LIB packs used for the analysis was 700 USD/kWh, meaning a price reduction of 77% would be necessary. This is most likely not a reasonable price reduction over a short period of time and is also a prerequisite that the price of the LIC does not decrease.

In the analysis, it was looked at two LIBs with different C-rates and estimated prices. The LIB with a C-rate of 2-3C had an estimated price of 700 USD/kWh, while the LIB with a C-rate of 0.5-1C had an estimated price of 420 USD/kWh. Even though the LIB with a lower C-rate was the cheaper option per energy unit, the cost per power unit was less for the LIB with the highest C-rate. This shows that for high-power applications like ferry charging, using a LIB with a higher C-rate is beneficial to keep the cost down. The LIC is still much cheaper per power unit due to having such a high power density. If LIC and LIB were to be used in a HESS, however, a LIB with a lower C-rate is preferred. A HESS plays on the strength of each technology, meaning that the LIB would not have to deliver high energy. This would also help to keep the cost down. Since the case studies used the same battery for the stand-alone LIB solution and the HESS, the price of the proposed HESS solution differs from the actual cost.

Due to the onboard batteries determining how much power can be delivered by the grid/BESS, the LIC must adapt accordingly. This means that the LIC is not able to fully utilize its potential by not being able to charge and discharge at high C-rates. Beyonder's LIC has the potential to charge with C-rates up to 30C; if the ferry is charged for 5 minutes, a C-rate of 10.8C is used. To remove this limitation, Beyonder could consider making a HESS solution with their LIC to have on board the ferries. Even though the LIC is using lower C-rates than what is possible, the C-rates are still much higher than for LIB. This means that the LIC does not have to be oversized in the way the LIB has to.

Production of Beyonder's LIC has not started yet, and it is unclear where the production will take place. This means that there are many uncertainties regarding emissions. Assumptions made for climate impact in terms of production of the technologies did not vary much for LIB and LIC. One can question how accurate these values are since they are calculated per energy unit, and the energy density for the two technologies is very different. Even though the technologies have had a similar volume in the case studies, the LIC comes out as the clear winner regarding CO_2 emissions when using this method for calculation.

Regardless of which solution is deemed the best in terms of surface area or price, it is still up to the ferry operator to decide which solution to use. For a ferry operator, a more important factor may be the solution's reliability and how well it cooperates with the ferry chargers and the batteries on board the ferry. LIB is a more mature technology and has been used as onshore batteries for charging several ferries. Ferry operators may also be more critical of new technology, like LIC, as it has not been used for this purpose yet. In the previous electrification of ferry routes, it has been common for the onboard BESS supplier to install the onshore BESS as well. This will ensure easier communication between the systems, and can be more convenient for the ferry operators. These factors can preponderate over price and volume and make LIBs the preferred option for ferry operators. This can be one of the biggest challenges for Beyonder in order to use their LIC for this purpose.

6.2 Challenges Related to the Grid

According to the technical research, many of the grids connected to ferry quays will need to be upgraded to support electric ferries. Even though an upgrade has to be done, there is still uncertainty around the extent of the upgrade. The question is if the grid should be upgraded to fully support ferry charging, or if the grid should be upgraded partly and be supported by a BESS. A general answer to this question can not be given as the case studies have shown that many factors come into play when making this decision. It strongly depends on the existing infrastructure and surrounding conditions. Each case has to be examined separately to find the best solution.

Since the grid is facing major upgrading all over the country in the coming years, it is worth mentioning that a BESS can be used as a temporary solution where it is needed. It is not possible to do all the upgrades simultaneously. In some places with some available capacity in the grid, a

BESS could be installed in the wait for a new upgrade, giving the transmission system operators more time.

When comparing a grid upgrade with a grid upgrade plus a BESS, the lifetime of the grid is not considered. The reason for this is that it is difficult to obtain an estimate of the lifetime of the grid. As mentioned, the BESS in this paper was set to have a lifetime of 10 years. It is reasonable to assume that the grid has a longer lifetime than a BESS. Ideally, the lifetimes would be included in the calculations, making an accurate price comparison possible to conduct.

The prices for grid upgrades on the various ferry quays vary a lot and are case-specific. As mentioned, this is because it depends on the existing infrastructure and the surrounding conditions. Reducing the upgrade by installing a BESS could affect the price, as shown in Case study 2. But the price will not necessarily be the most important factor when making this decision.

Another aspect not included in this thesis is the emissions from upgrading the grid. The transmission system operators that were contacted in an attempt to obtain this information did not have any numbers on emissions related to a grid upgrade. However, it was said that this area of research will be getting more attention going forward, and a life cycle assessments of their carbon footprint will be conducted.

A concession has to be filed with NVE to do any upgrades to the grid. An evaluation of whether the concession filed is reasonable will then be conducted and may be approved. Precisely which factors are in focus when deciding this is difficult to know as many aspects have to be accounted for. One important factor is to acknowledge the future power needs in the area so that the upgrade will support that for a reasonable amount of time. Equivalently, if the power needs at the location are deemed to remain low in the future, and the ferry charging is the sole reason for an upgrade, it would be more responsible to upgrade the grid to a lower capacity and be supported by a BESS. This was the case at Flakk-Rørvik, the filed concession was for a higher grid capacity than what was approved, and the solution was to incorporate a BESS to charge the ferries. However, in Case study 2, the concession for the desired grid capacity was approved even though it was higher than what was needed to charge the ferries. This illustrates that it is not given that grids connected to the ferry quays will get a sufficient upgrade to support the ferries alone. An additional power supply would be needed in these cases, and a BESS is a great option for this purpose. Having a high grid capacity will, however, make the ferry charging more reliable than with a BESS. There is still much uncertainty around using BESSs, as it has not been used for ferry charging until recently.

6.3 Assumptions and Method

There are numerous ways of conducting research. The method used for optimal sizing of the BESS for each scenario has several weaknesses and limitations. The assumptions made for the system characteristics were made to simplify the optimal sizing method. The analysis done for the case studies is based on a simple battery model, where all efficiencies remain constant throughout the lifetime. It has only been looked at a solution taking the maximum charging power, storage capacity and efficiency of the BESS into account. This will not be the case for a real system. A simple battery model will assume that the available storage capacity is the same throughout the whole lifetime of the battery. However, during an actual battery operation, loss of available capacity will decrease the stored surplus energy.

The recommended charging area used for the chosen LIB is with SOC in the range of 30-70%. This is to prolong the lifetime and ensure that the LIB will last a lifetime of 10 years. This will lead to at least 60% of the battery capacity never being utilized, and, therefore, the BESS has to be oversized to meet the capacity requirements. With a wider charging range, it would have not been necessary to oversize the applications to such an extent, resulting in a lower investment cost for the amount of technology needed for the project. The chosen sizing method for LIB using a C-rate of 2, is only valid for a charging time below 12 minutes. This is in order to keep the DOD to 40%. If there is a case where the charging time is greater than 12 minutes, the C-rate would have to be lower to keep the same DOD. A small DOD is significant to prolong the lifetime of the battery.

HESS application involves complicated sizing and power management problems, which is a challenging and time-consuming process. The chosen method used for sizing the HESS solution is a simplified method and will not reflect the proper way to do it for a real-life system. The calculated values for the HESS solution are only to estimate what it might look like and give an idea of how a HESS can work. No existing HESS solution for ferry charging is available for reference, and each scenario needs to have a custom method for HESS modeling. Another battery, with a higher energy density, would probably be a better fit in a HESS solution, compared to the LIB used in this thesis.

Beyonder's technology is new and still in the development phase. This means that there are some uncertainties regarding the specifications of the LIC cell. The specifications provided by Beyonder are mostly estimates of a possible LIC. The specifications for a finalized LIC may be different. The estimations can be both over- and underestimations. The cost and emissions related to the LIC calculations in this report are preliminary suggestions, meaning it is possibly different in reality. However, the suggestions are assumed to be in a reasonable range.

7 Conclusion

In this thesis, utilizing energy storage charge systems as a grid asset has been studied. The objective was to investigate if BESS with Beyonder's LIC can be a solution to grid problems related to electric ferries, and if it is a better option than using a BESS with LIB. BESS is used for peak shaving and could be vital for grid stability. A case study has been carried out by looking at various scenarios for two different ferry routes. The optimization size tool presented in this thesis has been developed in MATLAB. A technical-, economic- and environmental analysis has been performed for the solutions and then compared. The most important conclusions from the case study and the analysis are drawn below.

After conducting case studies on specific ferry routes and analyzing different aspects, Beyonder's LIC seems to be a suitable technology for ferry charging. Especially for ferry routes that have the following characteristics:

- Charging time between 5-10 minutes
- Requires high power
- Limited available grid power

If the ferry has a charging time of 5 minutes the price for Beyonder's LIC is determined to be 151.4 USD/kW, while the price for the LIB used in the case studies is 496.1 USD/kW. This clearly demonstrates that LIC is a better fit for applications where high power is important, from an economic point of view. LIC has been the cheapest option in all conducted analysis. LIC will have a smaller surface area than LIB when the charging time is less than 6 minutes. LIC will require less stored energy than LIB in high-power applications, which results in lower emissions when using the method of calculation used in this thesis. LIC will be the superior option if reducing carbon footprint is a high priority.

LIB is more established in the market today, and will likely be the preferable option when the price difference between two suggested systems (with LIB and LIC) are low. LIB is more suited for ferries with longer charging times that does not require very high power.

This study has not been able to provide a proper HESS solution, with both LIC and LIB, for ferry charging. However, it is reasonable to assume that a HESS solution could be used for this purpose, and may be a good option. The HESS solution would likely have used a more conventional LIB, with a lower C-rate and higher energy density.

It has also been established that some ferry routes will require some sort of ESS, like a BESS, when switching to electric ferries to provide grid stability/support. In conclusion, it is safe to say that there is a market for Beyonder's LIC in the ferry charging industry.

7.1 Further work

Topics that could be investigated further are listed below.

- Use a more detailed model of the LIC and LIB to size the system, and include more factors into the calculations.
- Do simulations on how the proposed systems would work.
- Design a complete HESS system to see how the LIB and LIC would compliment each other.
- Investigate the use of other forms of energy storage systems for ferry charging, e.g. flow batteries, HESS with different technologies and other capacitor technologies.
- Conduct an LCA study for the emissions of upgrading the grid and production of Beyonder's LIC technology.
- Consider how much space the LIBs/LICs requires on the quay including the thermal management system, the charger converter and transformer, and open air between the components.

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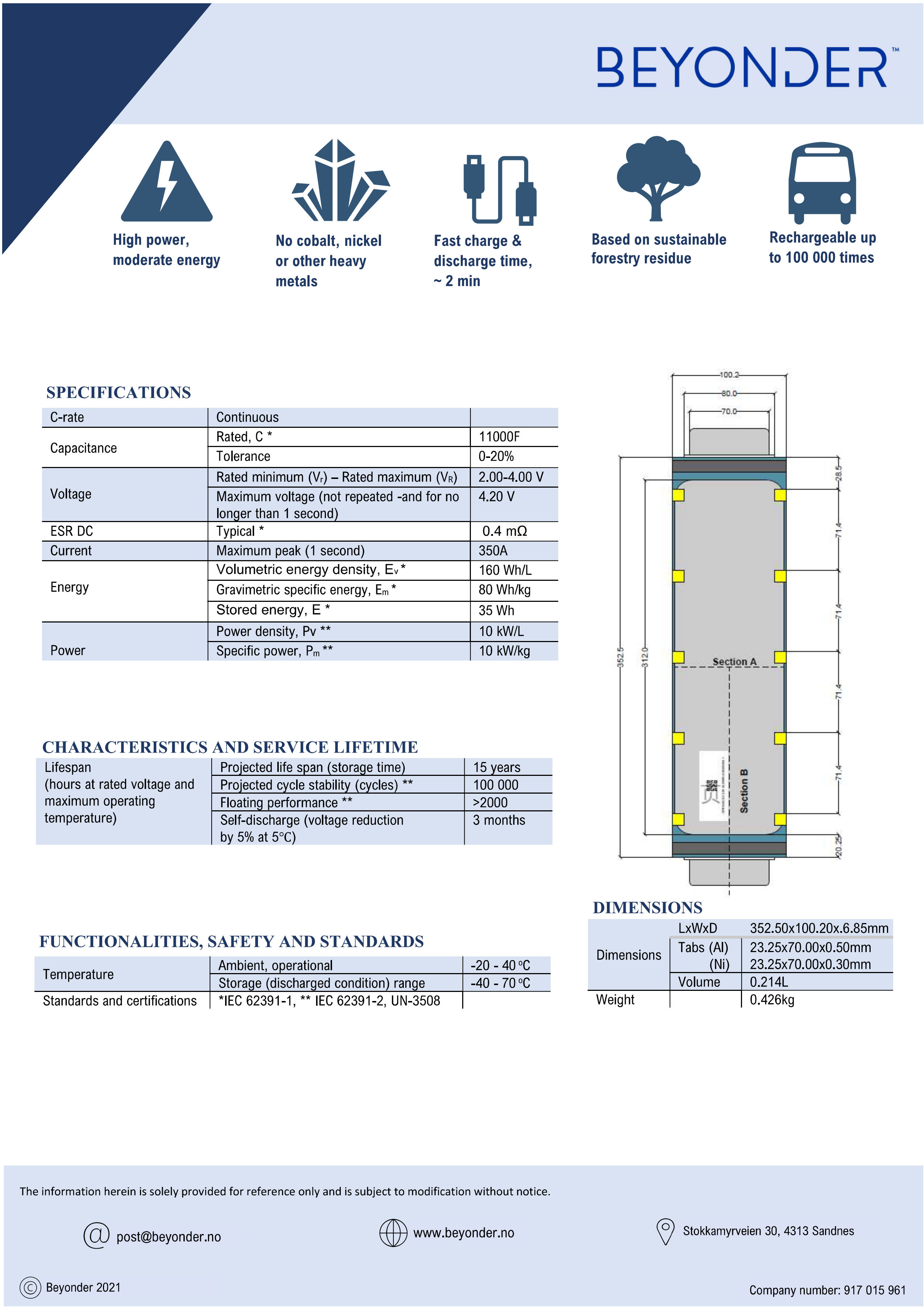
Appendix

A Datasheet for Beyonder’s 3.gen LIC



High power, moderate energy

No cobalt, nickel or other heavy metals

Fast charge & discharge time, ~ 2 min

Based on sustainable forestry residue

Rechargeable up to 100 000 times

SPECIFICATIONS

C-rate	Continuous	
Capacitance	Rated, C *	11000F
	Tolerance	0-20%
Voltage	Rated minimum (V_r) – Rated maximum (V_R)	2.00-4.00 V
	Maximum voltage (not repeated -and for no longer than 1 second)	4.20 V
ESR DC	Typical *	0.4 mΩ
Current	Maximum peak (1 second)	350A
Energy	Volumetric energy density, E_v *	160 Wh/L
	Gravimetric specific energy, E_m *	80 Wh/kg
	Stored energy, E *	35 Wh
Power	Power density, Pv **	10 kW/L
	Specific power, P_m **	10 kW/kg

CHARACTERISTICS AND SERVICE LIFETIME

Lifespan (hours at rated voltage and maximum operating temperature)	Projected life span (storage time)	15 years
	Projected cycle stability (cycles) **	100 000
	Floating performance **	>2000
	Self-discharge (voltage reduction by 5% at 5°C)	3 months

DIMENSIONS

Dimensions	LxWxD	352.50x100.20x.6.85mm
	Tabs (Al) (Ni)	23.25x70.00x0.50mm 23.25x70.00x0.30mm
	Volume	0.214L
Weight		0.426kg

FUNCTIONALITIES, SAFETY AND STANDARDS

Temperature	Ambient, operational	-20 - 40 °C
	Storage (discharged condition) range	-40 - 70 °C
Standards and certifications	*IEC 62391-1, ** IEC 62391-2, UN-3508	

The information herein is solely provided for reference only and is subject to modification without notice.

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Company number: 917 015 961

B Datasheet for Corvus Orca Energy

Corvus Energy

Technical Specifications | Corvus Orca Energy

Performance Specifications

C-Rate - Peak (Discharge / Charge)	Project Specific Values
C-Rate - Continuous (Discharge / Charge)	Up to 3C / Up to 3C

System Specifications

Single Module Size / Increments	5,6 kWh / 50 VDC
Single Pack Range	38-136 kWh / 350-1200 VDC
Max Gravimetric Density - **Pack**	77 Wh/kg | 13 kg/kWh
Max Volumetric Density - **Pack**	88 Wh/l

Example Packs

Energy	124 kWh (249 kWh for Tall Pack)
Voltage	Max: 1100 VDC | Nom: 980 VDC | Min: 800 VDC
Dimensions - Vertical Pack - 124 kWh	Height: 2241 mm | Width: 865 mm | Depth: 738 mm | 1628 kg
Dimensions - Horizontal Pack - 124 kWh	Height: 1260 mm | Width: 1730 mm | Depth: 738 mm | 1726 kg
Dimensions - Tall Pack - 249 kWh	Height: 3000 mm | Width: 1345 mm | Depth: 738 mm | 3375 kg

Example System - 8 Vertical Packs

Energy	992 kWh
Voltage	Max: 1100 VDC | Nom: 980 VDC | Min: 800 VDC
Dimensions - 8 x 124 kWh	Height: 2241 mm | Width: 6920 mm | Depth: 738 mm | 13 024 Kg

Safety Specifications

Thermal Runaway Anti-Propagation	Passive cell-level thermal runaway isolation with exhaust gas system
Fire Suppression	Per SOLAS, class and Corvus recommendation
Disconnect Circuit	Hardware-based fail-safe-for over-temperature and over-voltage
Short Circuit Protection	Fuses included on pack level
Emergency Stop Circuit	Hard-wired
Ground fault Detection	Integrated
Disconnect switchgear rating	Full load

General Specifications

Class Compliance	DNV GL, Lloyds Register, Bureau Veritas, ABS, RINA
Type Approval	DNV GL, Bureau Veritas, ABS, RINA
Ingress Protection	System: IP44
Cooling	Forced air
Vibration and Shock	UNT38.3, DNV 2.4, IEC 60068-2-6
EMC	IEC 61000-4, IEC 60945-9, CISPR16-2-1

2021-06-30

C Matlab code used for sizing

```matlab
format longG

%Properties, The values are from Flakk-Rørvik scenario 1

numberOfChargings = 15;                                                     %per day

requiredEnergy = 375;                                                       %kWh

minutesChargingFerry = 5;                                                   %minutes

minutesChargingBattery = 25;                                                %minutes

requiredPower = requiredEnergy/(minutesChargingFerry/60);                   %kW

%gridPower = 2500;                                                          %kW

essPower = 2000;                                                            %kW

energyESS = (essPower/requiredPower)*requiredEnergy;                        %kWh

nominalVoltage = 950;                                                       %V


%Dimensioning LIC

DODLIC = 0.9;

degredationRate = 0.0002;                                                   %per cycle

systemLosses = 0.08;

efficiency = 0.95;

numberOfCycles = numberOfChargings*365*10*DODLIC;

%Checks if the number of cycles exceeds 100 000,
%if it does it adjust the DOD so that it has 100 000 cycles
if numberOfCycles>100000
    DODLIC = (100000)/(numberOfChargings*365*10);
    numberOfCycles = numberOfChargings*365*10*DODLIC;
end

cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);

endOfLifeLIC = 1-(degredationRate*numberOfCycles*1/100);

energyLIC = energyESS;

storedEnergyLIC =((essPower/cRateLIC)/endOfLifeLIC)*(1+systemLosses)...     %kWh
    *(1-efficiency+1)

%numberOfCells = (storedEnergyLIC*10^3)/(35*0.45)

volumeLIC1 = (storedEnergyLIC*10^(-3)/(17.64))*10^(3)                       %m^3

%weightLIC = numberOfCells*0.426;                                           %kg

%How much the grid has to charge the battery between each docking
gridCharging = energyLIC/(minutesChargingBattery/60);                       %kW
```

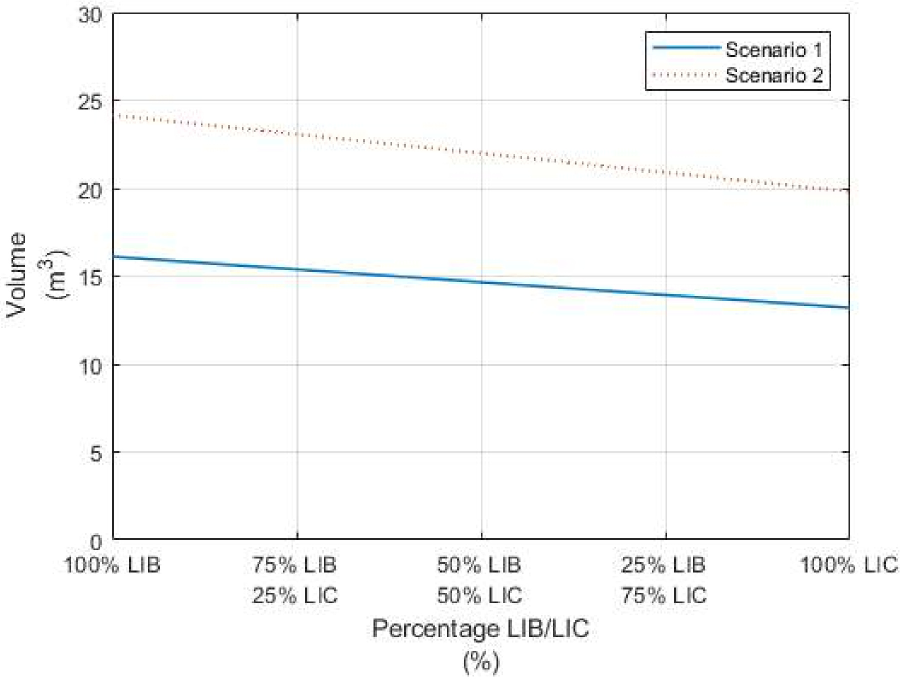
```
priceLIC1 = 1300*storedEnergyLIC                                            %USD($)


%Dimensioning LIB

cRateLIB = 2;

endOfLifeLIB = 0.8;

storedEnergyLIB = ((essPower/cRateLIB)/endOfLifeLIB)*(1+systemLosses)...    %kWh
    *(1-efficiency+1)

DODLIB = energyESS/storedEnergyLIB;

numberOfCyclesLIB = numberOfChargings*365*10*DODLIB;

%Checks if the number of cycles is in an accesptable range
if numberOfCyclesLIB < 10000
    fprintf('Number of cycles does not exceed the cycle lifetime.')
end

volumeLIB1 = (storedEnergyLIB*10^(-3)/88)*10^(3)                            %m^3

priceLIB1 = 700*storedEnergyLIB                                             %USD($)


%HESS

%percentage of HESS solution that is LIC/LIB
HESSPercentage = [0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1];

HESSPowerLIC = essPower.*HESSPercentage;                                    %kW

HESSPowerLIB = flip(HESSPowerLIC);                                          %kW

HESSenergyLIC =((HESSPowerLIC./cRateLIC)./endOfLifeLIC)...                  %kWh
    .*(1+systemLosses).*(1-efficiency+1);

HESSenergyLIB = ((HESSPowerLIB./cRateLIB)./endOfLifeLIB)...                 %kWh
    .*(1+systemLosses).*(1-efficiency+1);

priceLIC = HESSenergyLIC.*1300;                                             %USD($)

priceLIB = HESSenergyLIB.*700;                                              %USD($)

priceHESS = priceLIC+priceLIB;                                              %USD($)

volumeLIC = ((HESSenergyLIC.*10^(-3))./(17.64)).*10^(3);                 %m^3

volumeLIB = (HESSenergyLIB.*10^(-3)./88).*10^(3);                           %m^3

volumeHESS = volumeLIC+volumeLIB;                                           %m^3


%Graph volume
figure
x = HESSPercentage;
y = volumeHESS;
plot(x,y, 'Linewidth', 1.2)
grid on
```

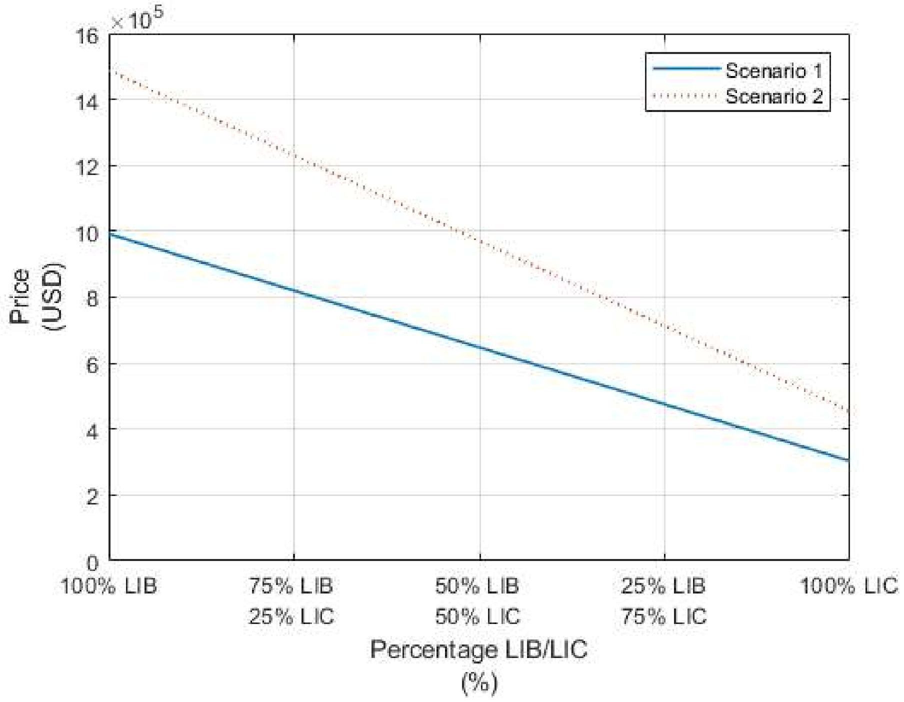
```
row1 = {'100% LIB' '75% LIB' '50% LIB' '25% LIB' '100% LIC'};
row2 = {'' '25% LIC' '50% LIC' '75% LIC' ''};
labelArray = [row1; row2];
tickLabels = strtrim(sprintf('%s\\newline%s\n', labelArray{:}));

ax = gca();
ax.XTick = 1:5;
ax.XLim = [0,1];
ax.XTickLabel = tickLabels;

xticks([0 0.25 0.50 0.75 1])
ylim([0 40])
xlabel({'Percentage LIB/LIC', '(%)'})
ylabel({'Volume','(m^3)'})

hold on

minutesChargingFerry = 5;

requiredPower = requiredEnergy/(minutesChargingFerry/60);

essPower = 3000;

energyESS = (essPower/requiredPower)*requiredEnergy;

HESSPowerLIC = essPower.*HESSPercentage;

HESSPowerLIB = flip(HESSPowerLIC);

cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);

HESSenergyLIC =((HESSPowerLIC./cRateLIC)./endOfLifeLIC)...
    .*(1+systemLosses).*(1-efficiency+1);

HESSenergyLIB = ((HESSPowerLIB./cRateLIB)./endOfLifeLIB)...
    .*(1+systemLosses).*(1-efficiency+1);

volumeLIC = ((HESSenergyLIC.*10^(-3))./17.64).*10^(3);

volumeLIB = ((HESSenergyLIB.*10^(-3))./88).*10^(3);

volumeHESS = volumeLIC+volumeLIB;

x = HESSPercentage;
y = volumeHESS;
plot(x,y, ':', 'Linewidth', 1.2)

row1 = {'100% LIB' '75% LIB' '50% LIB' '25% LIB' '100% LIC'};
row2 = {'' '25% LIC' '50% LIC' '75% LIC' ''};
labelArray = [row1; row2];
tickLabels = strtrim(sprintf('%s\\newline%s\n', labelArray{:}));

ax = gca();
ax.XTick = 1:5;
ax.XLim = [0,1];
ax.XTickLabel = tickLabels;

xticks([0 0.25 0.50 0.75 1])
ylim([0 30])
xlabel({'Percentage LIB/LIC', '(%)'})
```

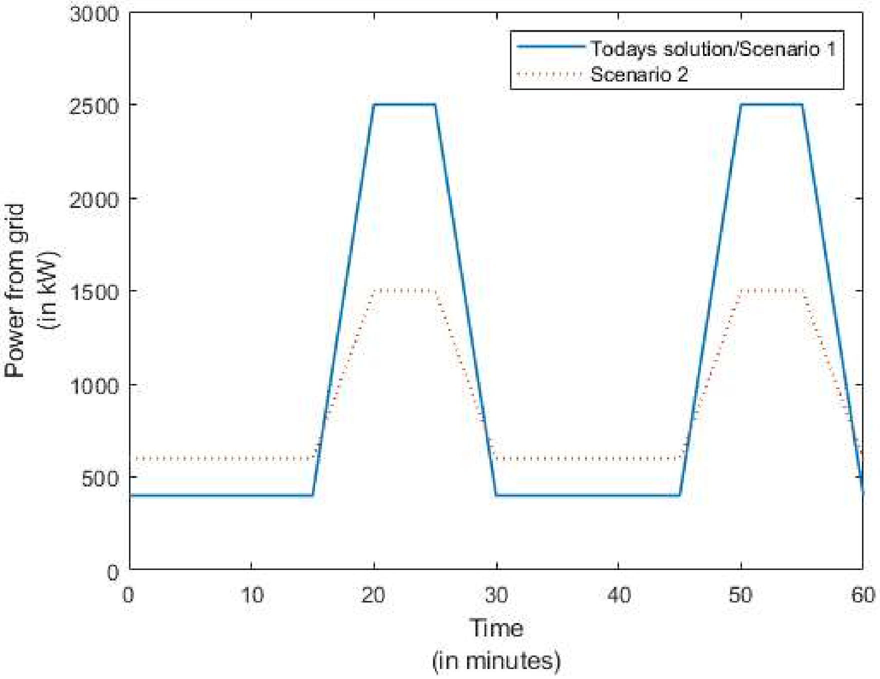
```
ylabel({'Volume','(m^3)'})
legend('Scenario 1', 'Scenario 2')

hold off



%Graph price
figure
x = HESSPercentage;
y = priceHESS;
plot(x,y, 'Linewidth', 1.2)
grid on

row1 = {'100% LIB' '75% LIB' '50% LIB' '25% LIB' '100% LIC'};
row2 = {'' '25% LIC' '50% LIC' '75% LIC' ''};
labelArray = [row1; row2];
tickLabels = strtrim(sprintf('%s\\newline%s\n', labelArray{:}));

ax = gca();
ax.XTick = 1:5;
ax.XLim = [0,1];
ax.XTickLabel = tickLabels;

xticks([0 0.25 0.50 0.75 1])
ylim([0 800000])
xlabel({'Percentage LIB/LIC','(%)'})
ylabel({'Price','(USD)'})

hold on

minutesChargingFerry = 5;

minutesChargingBattery = 25;

requiredPower = requiredEnergy/(minutesChargingFerry/60);

essPower = 3000;

energyESS = (essPower/requiredPower)*requiredEnergy;

HESSPowerLIC = essPower.*HESSPercentage;

HESSPowerLIB = flip(HESSPowerLIC);

HESSenergyLIC =((HESSPowerLIC./cRateLIC)./endOfLifeLIC)...
    .*(1+systemLosses).*(1-efficiency+1);

HESSenergyLIB = ((HESSPowerLIB./cRateLIB)./endOfLifeLIB)...
    .*(1+systemLosses).*(1-efficiency+1);

priceLIC = HESSenergyLIC.*1300;

priceLIB = HESSenergyLIB.*700;

priceHESS = priceLIC+priceLIB;

x = HESSPercentage;
y = priceHESS;
plot(x,y,':', 'Linewidth', 1.2)
```

```
row1 = {'100% LIB' '75% LIB' '50% LIB' '25% LIB' '100% LIC'};
row2 = {'' '25% LIC' '50% LIC' '75% LIC' ''};
labelArray = [row1; row2];
tickLabels = strtrim(sprintf('%s\\newline%s\n', labelArray{:}));

ax = gca();
ax.XTick = 1:5;
ax.XLim = [0,1];
ax.XTickLabel = tickLabels;

xticks([0 0.25 0.50 0.75 1])
ylim([0 1600000])
xlabel({'Percentage LIB/LIC','(%)'})
ylabel({'Price','(USD)'})
legend('Scenario 1', 'Scenario 2')
hold off


%Load profile
figure
xData = [0,5,10,15,20,25,30,35,40,45,50,55,60];
yData = [400,400,400,400,2500,2500,400,400,400,400,2500,2500,400];
plot(xData,yData,'Linewidth', 1.2)

hold on
yData2 = [600,600,600,600,1500,1500,600,600,600,600,1500,1500,600];
plot(xData,yData2, ':', 'Linewidth', 1.2)
ylim([0,3000])
xlabel({'Time','(in minutes)'})
ylabel({'Power from grid','(in kW)'})
legend('Todays solution/Scenario 1', 'Scenario 2')
hold off
```

```
storedEnergyLIC =

          232.95801209163


volumeLIC1 =

          13.206236513131


priceLIC1 =

         302845.415719119


storedEnergyLIB =

                   1417.5

Number of cycles does not exceed the cycle lifetime.
volumeLIB1 =

         16.1079545454545


priceLIB1 =
```


Volume
(m^3)
30
25
20
15
10
5
0
Scenario 1
Scenario 2
100% LIB
75% LIB
25% LIC
50% LIB
50% LIC
25% LIB
75% LIC
100% LIC
Percentage LIB/LIC
(%)


$\times 10^5$
Price
(USD)
16
14
12
10
8
6
4
2
0
Scenario 1
Scenario 2
100% LIB
75% LIB
25% LIC
50% LIB
50% LIC
25% LIB
75% LIC
100% LIC
Percentage LIB/LIC
(%)



Published with MATLAB® R2019b

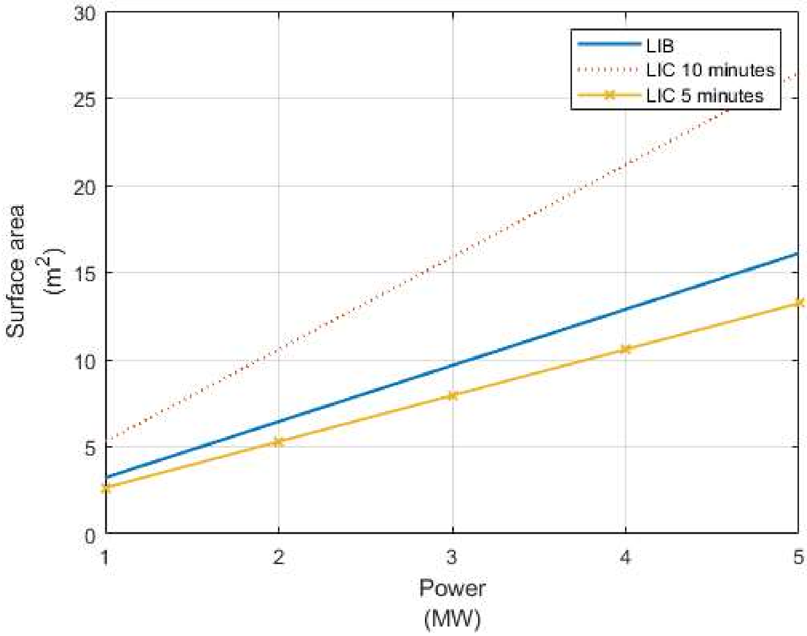
D Matlab code used for analysis plots

```
%Plot, how different charging times affect the price of the solution
%charging for 5minutes

numberOfChargings = 15;                                                     %per day
minutesChargingFerry = 5;                                                   %minutes
minutesChargingBattery = 25;                                                %minutes

requiredPower = [1000 2000 3000 4000 5000 6000];                            %kW
essPower = requiredPower;                                                   %kW


%Dimensioning LIC

DODLIC = 0.9;

degredationRate = 0.0002;                                                   %per cycle

systemLosses = 0.08;

efficiency = 0.95;

cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);

numberOfCycles = numberOfChargings*365*10*DODLIC;

endOfLifeLIC = 1-(degredationRate*numberOfCycles*1/100);

storedEnergyLIC =((essPower./cRateLIC)./endOfLifeLIC).*(1+systemLosses)...  %kWh
    .*(1-efficiency+1);

priceLIC1 = 1300.*storedEnergyLIC;                                          %USD($)


%Dimensioning LIB

cRateLIB = 2;

endOfLifeLIB = 0.8;

storedEnergyLIB = ((essPower./cRateLIB)./endOfLifeLIB).*(1+systemLosses)... %kWh
    .*(1-efficiency+1);

priceLIB = 420.*storedEnergyLIB;                                            %USD($)

figure
plot(requiredPower,priceLIB,'LineWidth',1.5)
grid on

hold on
plot(requiredPower,priceLIC1,':', 'Linewidth', 1.3)
ylim([0.1e6 2.8e6])
xlabel({'Power', '(kW)'})
ylabel({'Price','(USD)'})

hold on

%Charging in 10 minutes
minutesChargingFerry = 10;                                                  %minutes

%Dimensioning LIC

cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);
numberOfCycles = numberOfChargings*365*10*DODLIC;
```

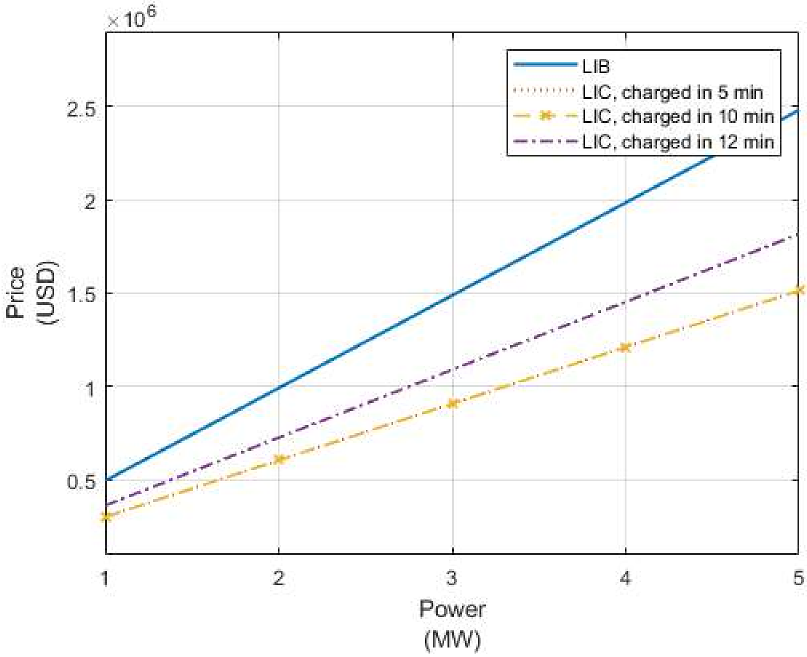
```
volumeLIC = (storedEnergyLIC*10^(-3)/(17.6))*(10^(3));                      %m^3
areaLIC = volumeLIC./2.5 ;                                                  %m^2



plot(requiredPower,areaLIC,'-x', 'Linewidth', 1.3)
grid on
xticks([1000 2000 3000 4000 5000])
xticklabels({'1','2','3','4','5'})
xlabel({'Power', '(MW)'})
ylabel({'Surface area','(m^2)'})
legend('LIB', 'LIC 10 minutes', 'LIC 5 minutes')


hold off

%Plot, how different charging times affect price
%Charging in 5 minutes
minutesChargingFerry = 10;                                                  %minutes

%Dimensioning LIC
cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);

numberOfCycles = numberOfChargings*365*10*DODLIC;

endOfLifeLIC = 1-(degredationRate*numberOfCycles*1/100);

storedEnergyLIC =((essPower./cRateLIC)./endOfLifeLIC).*(1+systemLosses)...  %kWh
    .*(1-efficiency+1);

priceLIC1 = 1300.*storedEnergyLIC;                                          %USD($)


%Dimensioning LIB
cRateLIB = 2;

storedEnergyLIB = ((essPower./cRateLIB)./endOfLifeLIB).*(1+systemLosses)... %kWh
    .*(1-efficiency+1);

priceLIB = 700.*storedEnergyLIB;                                            %USD($)

figure
plot(requiredPower,priceLIB,'LineWidth',1.5)
grid on

hold on
plot(requiredPower,priceLIC1,':', 'Linewidth', 1.3)

%Charging in 10 minutes
minutesChargingFerry = 10;                                                  %minutes

%Dimensioning LIC

cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);

storedEnergyLIC =((essPower./cRateLIC)./endOfLifeLIC).*(1+systemLosses)...  %kWh
    .*(1-efficiency+1);

priceLIC1 = 1300.*storedEnergyLIC;                                          %USD($)

plot(requiredPower,priceLIC1,'--x' , 'Linewidth', 1.2)
hold on
```

```
%Charging for 12minutes
minutesChargingFerry = 12;                                              %minutes


%Dimensioning LIC
cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);

energyLIC = energyESS;

storedEnergyLIC =((essPower./cRateLIC)./endOfLifeLIC).*(1+systemLosses)...  %kWh
    .*(1-efficiency+1);

priceLIC1 = 1300.*storedEnergyLIC;                                      %USD($)

plot(requiredPower,priceLIC1,'-.', 'Linewidth', 1.3)
ylim([0.1e6 2.9e6])
xticks([1000 2000 3000 4000 5000])
xticklabels({'1','2','3','4','5'})
xlabel({'Power', '(MW)'})
ylabel({'Price','(USD)'})
legend('LIB', 'LIC, charged in 5 min', 'LIC, charged in 10 min'...
    , 'LIC, charged in 12 min')

hold off




%Plot, how different C-rates for LIB affects the price compared to LIC
numberOfChargings = 15; %per day
minutesChargingFerry = 5; %minutes


requiredPower = [1000 2000 3000 4000 5000];                             %kW

essPower = requiredPower;                                               %kW



%Dimensioning LIC

cRateLIC = 1/((minutesChargingFerry/60)/DODLIC);

numberOfCycles = numberOfChargings*365*10*DODLIC;

endOfLifeLIC = 1-(degredationRate*numberOfCycles*1/100);


storedEnergyLIC =((essPower./cRateLIC)./endOfLifeLIC).*(1+systemLosses)...
    .*(1-efficiency+1);                                                 %kWh


priceLIC1 = 1300.*storedEnergyLIC;                                      %USD($)

%0.5C
%Dimensioning LIB

cRateLIB = 0.5;

endOfLifeLIB = 0.8;

storedEnergyLIB = ((essPower./cRateLIB)./endOfLifeLIB).*(1+systemLosses)...
    .*(1-efficiency+1);                                                 %kWh
```

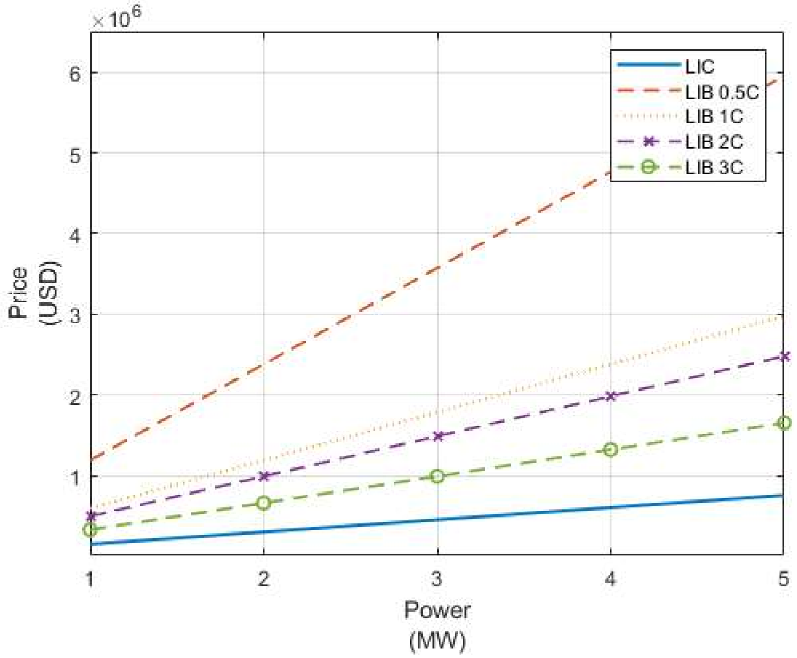
```
priceLIB = 420.*storedEnergyLIB;                                            %USD($)

figure
plot(requiredPower,priceLIC1,'LineWidth',1.5)
grid on

hold on
plot(requiredPower,priceLIB,'--', 'Linewidth', 1.3)


hold on
%1C
cRateLIB = 1;

storedEnergyLIB = ((essPower./cRateLIB)./endOfLifeLIB).*(1+systemLosses)...
    .*(1-efficiency+1);                                                     %kWh

priceLIB = 420.*storedEnergyLIB;                                            %USD($)

plot(requiredPower,priceLIB,':', 'Linewidth', 1.3)

hold on

%2C
%Dimensioning LIB

cRateLIB = 2;

storedEnergyLIB = ((essPower./cRateLIB)./endOfLifeLIB).*(1+systemLosses)...
    .*(1-efficiency+1);                                                      %kWh


priceLIB = 700.*storedEnergyLIB;                                            %USD($)

plot(requiredPower,priceLIB,'--x' , 'Linewidth', 1.2)


hold on

%3C
%Dimensioning LIB

cRateLIB = 3;

storedEnergyLIB = ((essPower./cRateLIB)./endOfLifeLIB).*(1+systemLosses)...
    .*(1-efficiency+1);                                                     %kWh


priceLIB = 700.*storedEnergyLIB;
plot(requiredPower,priceLIB,'--o', 'Linewidth', 1.3)
xticks([1000 2000 3000 4000 5000])
xticklabels({'1','2','3','4','5'})
xlabel({'Power', '(MW)'})
ylabel({'Price','(USD)'})
ylim([0.01e6 6.5e6])
legend('LIC', 'LIB 0.5C','LIB 1C', 'LIB 2C', 'LIB 3C')

hold off
```



30
25
20
15
10
5
0
Surface area
(m^2)
1
2
3
4
5
Power
(MW)
LIB
LIC 10 minutes
LIC 5 minutes

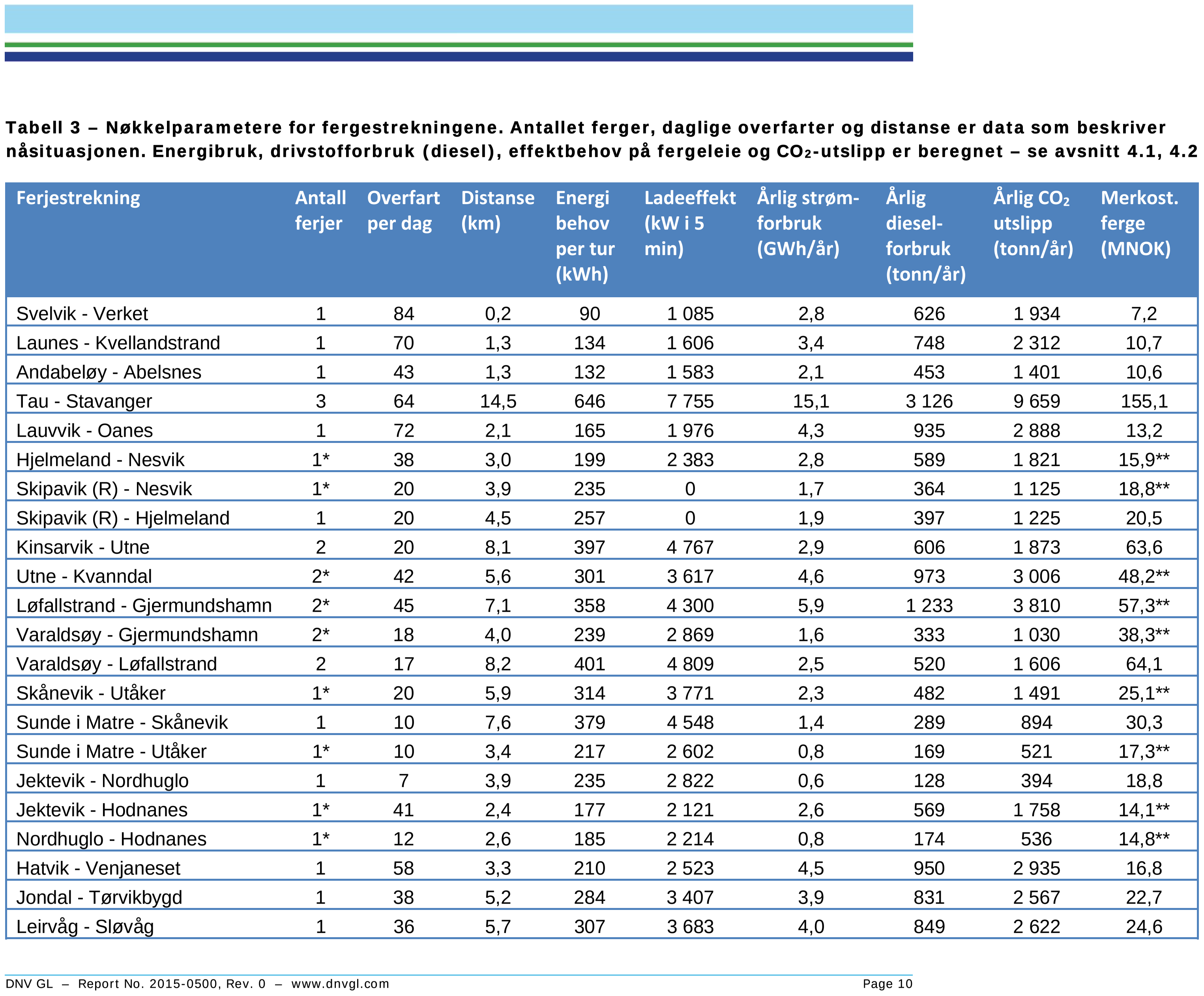


×10^6
2.5
2
1.5
1
0.5
Price
(USD)
1
2
3
4
5
Power
(MW)
LIB
LIC, charged in 5 min
LIC, charged in 10 min
LIC, charged in 12 min



Published with MATLAB® R2022a

E Table 3 from the report ”Elektrifisering av bilferger i Norge – kartlegging av investeringsbehov i strømnettet”



Tabell 3 – Nøkkelparametere for fergestrekningene. Antallet ferger, daglige overfarter og distanse er data som beskriver nåsituasjonen. Energibruk, drivstofforbruk (diesel), effektbehov på fergeleie og CO_2-utslipp er beregnet – se avsnitt 4.1, 4.2 og 4.3.

Ferjestrekning	Antall ferjer	Overfart per dag	Distanse (km)	Energi behov per tur (kWh)	Ladeeffekt (kW i 5 min)	Årlig strøm-forbruk (GWh/år)	Årlig diesel-forbruk (tonn/år)	Årlig CO_2 utslipp (tonn/år)	Merkost. ferge (MNOK)
Svelvik - Verket	1	84	0,2	90	1 085	2,8	626	1 934	7,2
Launes - Kvellandstrand	1	70	1,3	134	1 606	3,4	748	2 312	10,7
Andabeløy - Abelsnes	1	43	1,3	132	1 583	2,1	453	1 401	10,6
Tau - Stavanger	3	64	14,5	646	7 755	15,1	3 126	9 659	155,1
Lauvvik - Oanes	1	72	2,1	165	1 976	4,3	935	2 888	13,2
Hjelmeland - Nesvik	1*	38	3,0	199	2 383	2,8	589	1 821	15,9**
Skipavik (R) - Nesvik	1*	20	3,9	235	0	1,7	364	1 125	18,8**
Skipavik (R) - Hjelmeland	1	20	4,5	257	0	1,9	397	1 225	20,5
Kinsarvik - Utne	2	20	8,1	397	4 767	2,9	606	1 873	63,6
Utne - Kvanndal	2*	42	5,6	301	3 617	4,6	973	3 006	48,2**
Løfallstrand - Gjermundshamn	2*	45	7,1	358	4 300	5,9	1 233	3 810	57,3**
Varaldsøy - Gjermundshamn	2*	18	4,0	239	2 869	1,6	333	1 030	38,3**
Varaldsøy - Løfallstrand	2	17	8,2	401	4 809	2,5	520	1 606	64,1
Skånevik - Utåker	1*	20	5,9	314	3 771	2,3	482	1 491	25,1**
Sunde i Matre - Skånevik	1	10	7,6	379	4 548	1,4	289	894	30,3
Sunde i Matre - Utåker	1*	10	3,4	217	2 602	0,8	169	521	17,3**
Jektevik - Nordhuglo	1	7	3,9	235	2 822	0,6	128	394	18,8
Jektevik - Hodnanes	1*	41	2,4	177	2 121	2,6	569	1 758	14,1**
Nordhuglo - Hodnanes	1*	12	2,6	185	2 214	0,8	174	536	14,8**
Hatvik - Venjaneset	1	58	3,3	210	2 523	4,5	950	2 935	16,8
Jondal - Tørvikbygd	1	38	5,2	284	3 407	3,9	831	2 567	22,7
Leirvåg - Sløvåg	1	36	5,7	307	3 683	4,0	849	2 622	24,6

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Ferjestrekning	Antall ferjer	Overfart per dag	Distanse (km)	Energi behov per tur (kWh)	Ladeeffekt (kW i 5 min)	Årlig strøm-forbruk (GWh/år)	Årlig diesel-forbruk (tonn/år)	Årlig CO_2 utslipp (tonn/år)	Merkost. ferge (MNOK)
Breistein - Valestrandfossen	1	66	2,5	181	2 167	4,4	935	2 890	14,4
Hella - Dragsvik	3*	48	1,8	153	1 840	2,7	583	1 801	36,8**
Vangsnes - Hella	3*	46	4,3	251	3 009	4,2	892	2 757	60,2**
Vangsnes - Dragsvik	3	46	4,9	272	3 266	4,6	965	2 983	65,3
Lote - Anda	1	74	2,1	165	1 980	4,5	963	2 975	13,2
Fodnes - Mannheller	2	108	3,3	211	2 532	8,3	1 775	5 484	33,8
Isane - Stårheim	1	40	4,4	255	3 056	3,7	787	2 433	20,4
Årvik - Koparneset	2	68	2,5	181	2 167	4,5	964	2 977	28,9
Hareid - Sulesund	2	72	7,7	385	4 618	10,1	2 115	6 535	61,6
Volda - Folkestad	1	64	3,3	212	2 546	5,0	1 057	3 267	17,0
Volda - Lauvstad	2	32	7,5	376	4 510	4,4	919	2 839	60,1
Festøya - Hundeidvika	1	30	4,8	269	3 234	3,0	624	1 927	21,6
Festøya - Solavågen	2	84	4,4	256	3 075	7,9	1 663	5 139	41,0
Sykkylven - Magerholm	2	112	3,7	228	2 733	9,3	1 980	6 119	36,4
Stranda - Liabygda	3	60	2,8	192	2 308	4,2	902	2 789	46,2
Eidsdal - Linge	3	58	2,7	188	2 261	4,0	856	2 644	45,2
Geiranger - Hellesylt	2	16	19,9	860	10 322	5,0	1 036	3 202	137,6
Molde - Vestnes	3	74	11,5	532	6 385	14,4	2 985	9 225	127,7
Molde - Sekken	1	18	11,5	531	6 376	3,5	725	2 241	42,5
Sølsnes - Åfarnes	1	73	3,4	216	2 588	5,7	1 225	3 785	17,3
Kvanne - Rykkjem	1	68	2,5	179	2 144	4,4	954	2 947	14,3
Halsa - Kanestraum	2	78	5,4	295	3 538	8,4	1 768	5 464	47,2
Flakk - Rørvik	3	30	7,4	372	4 468	4,1	853	2 637	89,4
Levang - Nesna	1	32	8,5	414	4 973	4,8	1 011	3 123	33,2

Ferjestrekning	Antall ferjer	Overfart per dag	Distanse (km)	Energi behov per tur (kWh)	Ladeeffekt (kW i 5 min)	Årlig strøm-forbruk (GWh/år)	Årlig diesel-forbruk (tonn/år)	Årlig CO_2 utslipp (tonn/år)	Merkost. ferge (MNOK)
Bognes - Skarberget	2	48	8,0	393	4 721	6,9	1 441	4 451	62,9
Kjøpsvik - Drag	1	22	13,6	613	7 358	4,9	1 020	3 153	49,1
Forøy - Ågskardet	2	48	2,6	184	2 210	3,2	693	2 140	29,5
Refsnes - Flesnes	1	36	5,5	298	3 570	3,9	823	2 545	23,8
Svensby - Breivikeidet	1	38	6,2	325	3 898	4,5	946	2 924	26,0
Lyngseidet - Olderdalen	1	32	12,6	574	6 890	6,7	1 391	4 299	45,9
TOTAL for strekningene	**65***	**2 406**	**N/A**	**N/A**	**N/A**	**238**	**50 195**	**155 102**	**1710****

*Kun unike fartøy summert, jf. at en og samme ferge kan betjene flere fergestrekninger i flerstrekningssamband. Strekning merket * er utelatt i summering.

**Kun kostnadene for unike fartøy summert, jf. at en og samme ferge kan betjene flere fergestrekninger i flerstrekningssamband. Strekning merket ** er utelatt i summering.

Holmen, Hopland, Høyland

Bachelor's thesis

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