Bachelor's thesis

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

Sjur Andersson Brovold, Carl Fredrik Haug Rath, Felix Aanensen Karlsen, Thomas Frostad Stephensen

Electrification of Ferries Utilizing Battery Technology

Bachelor's thesis in Fornybar Energi
Supervisor: Steven Tylor Boles
May 2024

NTNU
Norwegian University of Science and Technology

Sjur Andersson Brovold, Carl Fredrik Haug Rath, Felix Aanensen Karlsen, Thomas Frostad Stephensen

Electrification of Ferries Utilizing Battery Technology

Bachelor’s thesis in Fornybar Energi
Supervisor: Steven Tylor Boles
May 2024

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

NTNU
Norwegian University of
Science and Technology

NTNU

Institutt for energi- og prosessteknikk

Bacheloroppgave

Oppgavens tittel: Elektrifisering av ferger ved bruk av batteri teknologi **Project title (ENG):** Electrification of Ferries Utilizing Battery Technology	**Gitt dato:** 20.11.2023 **Innleveringsdato:** 22.05.2024 **Antall sider rapport / sider vedlagt:** 86/6
Gruppedeltakere: Sjur Andersson Brovold, Carl Fredrik Haug Rath, Felix Aanensen Karlsen, Thomas Frostad Stephensen	**Veileder:** Steven Tyler Boles **Prosjektnummer:** 23
Oppdragsgiver: NTNU	**Kontaktperson hos oppdragsgiver:**

Fritt tilgjengelig: ☒

Tilgjengelig etter avtale med oppdragsgiver: ☐

Rapporten frigitt etter:

Gruppedeltakere signaturer:

Thomas Frostad Stephensen, Felix Aanensen Karlsen,

Sjur Andersson Brovold. Carl Fredrik Haug Rath

Preface

This is the bachelor's thesis of four students from the study program Renewable Energy (FENT2900) at the Faculty of Engineering at the Norwegian University of Science and Technology (NTNU). The thesis is written in the 6th and final semester, spring of 2024.

The group chose the assignment from a list of projects provided by the student coordinator, Prof. Jacob Lamb. The projects are weighted with 20 credits and are typically completed in groups of 3-4 students. The chosen tasks should be relevant to the student's study program. Being able to write about an innovative technology with the potential to improve an important sector of transportation has been both exciting and challenging. The work process has been educational and engaging, while also enhancing collaboration skills. As a group, we are pleased with the result and our cooperation.

The group would like to thank the project supervisor Prof. Steven Tyler Boles for help throughout the semester. Additionally, the group would like to thank Ask Ibsen Lindal (CEO of Bryte Batteries), Synne Aa. Sandvik (Master's Student in Energy and Environmental Engineering, NTNU), and Arne Brynlund from Boreal for their contribution to the thesis through information and guidance.

Abstract

The main contribution of this thesis is to evaluate flow battery technologies for ferry electrification. Norway is pursuing a political goal to mandate that all ferries operate as zero-emission vessels, aiming to decrease greenhouse gas emissions in the transport sector. This initiative is a crucial component of the nation's strategy to meet the objectives of the Paris Agreement, specifically the target to limit global warming to 2 °C. This thesis investigates whether Vanadium Redox Flow Batteries (VRFB) and Zinc Bromine Flow Batteries (ZBFB) can replace Lithium-Ion batteries (LIB) as the primary energy source on Norwegian ferries or serve as buffer batteries on docks to relieve the power grid.

The thesis begins with essential battery theory, focusing on flow and lithium-ion batteries. Their advantages, challenges, and economic impacts will be addressed. Attention is also given to safety concerns and the importance of health, safety, and environmental (HSE) practices in electrical ferries. The thesis then examines ferry applications, investigating potential solutions for ferry electrification, energy requirements, and challenges in areas with weak power grids.

Two case studies explore the use of flow batteries for ferry lines. The Valset-Brekstad case assesses the use of flow batteries on the ferries MF Austrått and MF Vestrått on a 5.7 km route. The Forvik case studies the use of a flow battery as a buffer battery at Forvik dock to relieve the weak power grid.

For the Valset-Brekstad route, both ferries currently use a LIB of 1.0 MWh capacity. The study shows that potential flow batteries would weigh three times more with the application of a VRFB instead. The ZBFB shows promising results where the weight of the battery would be almost identical to the LIB if the depth of discharge were considered.

At the Forvik dock in Nordland, a LIB is installed as a buffer battery onshore. The study evaluates using flow batteries such as VRFB or ZBFB instead and how it would perform compared to LIB in terms of energy and effect. The analysis shows that flow batteries can give advantages in durability and environmental impact, but offer challenges in requiring unnecessary energy scaling to meet the high power requirements.

Sammendrag

Hovedbidraget til denne avhandlingen er å evaluere flytbatteriteknologier for bruk i elektrifisering av ferjer. Norge har som mål at alle ferjer skal være nullutslippsfartøy for å redusere klimagassutslipp i transportsektoren, og dette er en del av strategien for å oppfylle Parisavtalens mål om å begrense global oppvarming til 2 °C. I avhandlingen undersøkes om flytbatterier kan bidra til at Norge når dette målet. Avhandlingen ser nærmere på om dagens mest undersøkte flytbatterityper, Vanadium Redox flytbatteri (VRFB) og Sink-Brom flytbatteri (ZBFB), kan brukes i stedet for litium-ion-batteri (LIB) som primær energikilde på en norsk ferje, eller som bufferbatteri på en ferjekai for å avlaste strømnettet.

Avhandlingen begynner med batteriteori, med fokus på generelle prinsipper og spesifikke detaljer om flytbatterier og litium-ion-batterier, samt deres fordeler og utfordringer. Deretter undersøkes hvordan elektriske ferjer opererer, ladeteknologier som brukes, og eksempler på batterier i bruk. Sikkerhetsproblemer og HMS-praksis i elektriske ferjer diskuteres også. Potensielle løsninger for ferjelektrifisering, energibehov og utfordringer med svake strømnett undersøkes.

To casestudier ble gjennomført for å sette teorien ut i praksis. Case Valset-Brekstad vurderte bruk av flytbatteri på ferjene MF Austrått og MF Vestrått som opererer den 5,7 km lange ferjestrekningen mellom Valset og Brekstad. Case Forvik vurderte bruk av flytbatteri som bufferbatteri på Forvik ferjekai for å avlaste det svake strømnettet ved å lade ferjene ved kaien.

For ferjestrekningen Valset-Brekstad er begge ferjene utstyrt med litium-ion-batteri på 1,0 MWh. Studien viser at potensielle flytbatterier vil veie tre ganger mer ved bruk av VRFB i stedet. ZBFB viser lovende resultater der vekten av batteriet vil være nesten identisk med LIB hvis utladningsdybden blir tatt i betraktning.

På Forvik ferjekai brukes et litium-ion-batterisystem for å løse utfordringer knyttet det svake strømnettet. Studien evaluerer å erstatte dette batterisystemet med flytbatterier som VRFB eller ZBFB for å forbedre energilagring og effektivitet. Analysen viser at flytbatterier kan gi fordeler når det gjelder holdbarhet og miljøpåvirkning, men byr på utfordringer ved at de krever unødvendig oppskalering av energi for å møte de høye effektkravene.

Contents

List of abbreviation

Abbreviation	Definition
AC	Alternating Current
ACH	Air Changes per Hour
BMS	Battery Management System
BoL	Beginning of Life
CC-CV	Constant-Current/Constant-Voltage
DNV	Det Norske Veritas
DC	Direct Current
DoD	Depth of Discharge
EV	Electric Vehicle
ESS	Energy Storage System
HFB	Hybrid Flow Batteries
ICE	Internal Combustion Engine
IEM	Ion-Exchange Membrane
IRENA	International Renewable Energy Agency
LIB	Lithium-Ion Battery
LCA	Life Cycle Assessment
LRES	Li-ion Renewable Energy System
NASA	National Aeronautics and Space Administration
NMC	Nickel Manganese Cobalt
NTNU	Norwegian University of Science and Technology
NVE	Norwegian Water Resources and Energy Directorate
PBE	Personal Vehicle Equivalent
RFB	Redox Flow Battery
SoC	State of Charge
SoH	State of Health
TR	Thermal Runaway
VRFB	Vanadium Redox Flow Battery
VRES	Vanadium Renewable Energy System
ZBFB	Zinc/Bromine Flow Battery

List of Figures

List of Tables

1 Introduction

Ever since the Industrial Revolution at the start of the 18th century climate gas emitting fossil fuels have been humanity's main source of energy. In December 2015 the UN reached an agreement named the Paris Agreement. The purpose of this agreement is to limit the global temperature rise by less than 2 °C compared to pre-industrial levels. To reach this goal fossil fuels have to be replaced by renewable energy. Renewable energy does not produce any climate gases, but it is not as reliable as fossil fuels. When the sun does not shine, or the wind does not blow it is necessary to have extra energy in store. This causes a demand for energy storage technology, both for storing energy in the grid and as the energy source for vehicles that run on electric energy. [1]

There are many ways to store energy. One of the most common is through batteries. Batteries are found in all sorts of applications both large and small, from electric vehicles to smartphones. In the last few years, the Lithium-ion Battery (LIB) has become the most prominent battery technology. It is a thoroughly researched and developed technology with many advantages. Some concerns with LIBs are that there are safety risks and environmental challenges connected to them. Therefore the search for new energy storage opportunities continues. Flow battery is a technology that has gained attention as a promising battery energy storage technology. The concept of flow batteries is an old proposition and dates back to the late 1800s when John Doyle, a lesser-known scientist, presented the first known flow battery chemistry based on Zinc and Bromine through his patent [2]. However, there was no further use of the technology until 1973 when NASA (National Aeronautics and Space Administration) considered the technology as energy storage in a potential moon base. In 1984 the most promising flow battery to date, the vanadium flow battery, was patented by Maria Skyllas-Kazacos and her colleagues at the University of New South Wales. Today research and development of the flow battery is conducted to find out whether it could be the energy storage technology that is needed to support the renewable energy of the future [3]. A potential application for flow batteries is in the electrification of ferries, where they can contribute to a more sustainable transportation sector. This thesis will explore this potential by examining the possibilities of using flow batteries as the primary energy source for ferries and as buffer batteries at ferry docks.

2 Background

Norway is a country with an extensive coastline, characterized by numerous nooks and crannies. It is necessary to have ferries to transport humans and vehicles efficiently throughout the country. In Norway, there are a total of 231 ferry connections transporting both passengers and cars. As of May 2024, 96 electric ferries and boats are in operation, distributed across 59 connections, corresponding to electrification of 25.5 % of the total connections. Norway is obligated to reduce climate gas emissions by 55 % within 2030 through the Paris Agreement. Additionally, through an agreement with the EU, Norway will reduce non-ETS(Emissions Trading System) emissions by 40 percent by 2030 compared to 2005. Non-ETS emissions cover sectors not included in the EU ETS. These sectors are transportation (excluding aviation), agriculture, waste, and industrial emissions. In Norway, the total emissions of the transportation sector in the year 2019 were 16.3 million tonnes CO_2-equivalents. Coastal transportation was responsible for 2.9 million tonnes CO_2-equivalents. Electrifying the ferry industry is part of the solution to decrease emissions of climate gasses. [4], [5]

2.1 Potential Developments

According to the Norwegian Water Resources and Energy Directorate's (NVE) report about the national power grid from 2017, two-thirds of ferry connections in Norway are expected to be electric by 2030. As the ferry sector becomes electrified, it is likely that the electrification of cars and buses will also increase. This will result in a significant strain on the current power grid, thus necessitating smart solutions to alleviate the electrical load on the grid. [6]

Figure 2.1 illustrates the existing data along with a potential percentile increase. This projection is based on the annual growth rate observed from 2019 to 2023, estimated at 5 % per year. This will be the same as electrifying 12 ferry connections every year. According to the manager of energy and environmental matters in Fjord1, Jan Hovden Eide, their company currently has 39 electric ferries, which is approaching a 50 % electrification of their fleet. Fjord1's goal is for all their ferries in normal operation to be electric by 2035.

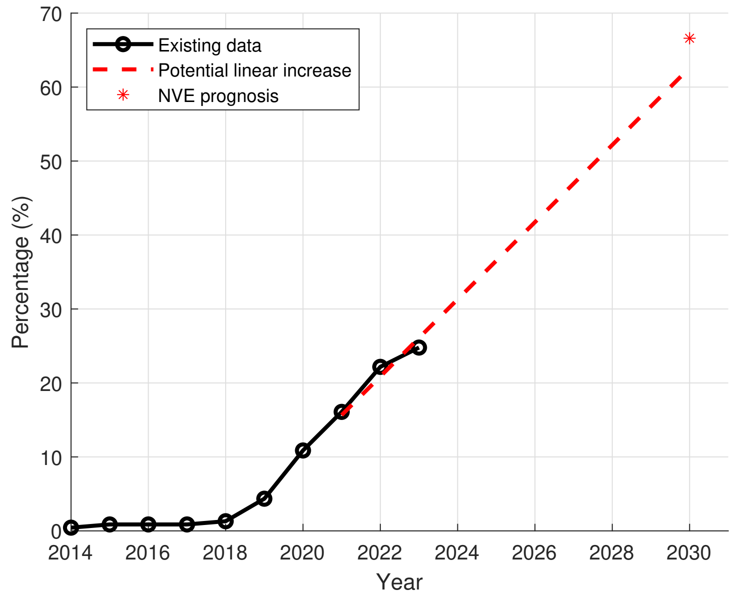
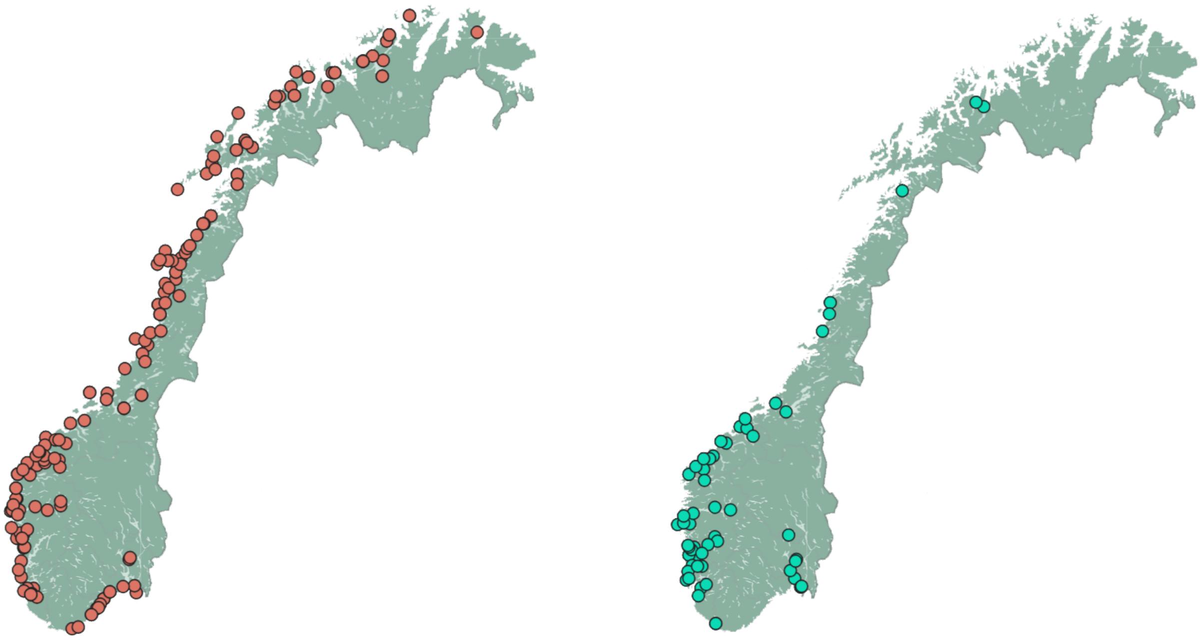


Figure 2.1: Electrification of ferries (2013 - 2030).

Figure 2.2 presents the location of fossil and electric vessels in Norway. Most vessels in the northern parts of Norway still operate with fossil fuel, mainly diesel. Electrification of these vessels is more complicated due to a weaker power grid, frequently linked to the geographical constraints of islands. The constraints caused by the weak grid can be solved using battery banks on shore. Some ferry operators are starting to utilize this method.



(a) Locations for fossil vessel connections

(b) Locations for electric vessel connections

Figure 2.2: Fossil-fuel ferry and electric vessel locations in Norway [4].

Torghatten Nord has signed a contract for three ferry connections in the southern part of Troms. Two of these connections will be fully electric and charged with onshore batteries by February 2025 [7]. Further details of the connections are presented in Table 2.1 below. The table suggests that the distance and size of the vessels, indicated by the carrying capacity expressed as personal vehicle equivalent (PBE), is the reason the latter connection is not electric. The specifications of the grid at the locations are however unknown.

Table 2.1: Details of the three connections in south Troms.

Ferry connection and vessel	Distance [Km]	Type	Average daily crossings	PAX	PBE
Stornes – Bjørnerå MF ≪Lyngen≫	3.3	Electric	12 – 20	250	75
Flesnes – Refsnes MF ≪Hålogaland≫	5.5	Electric	12 - 16	229	75
Stangnes – Sørrollnes MF ≪Selbjørnsfjord≫	13.9	Diesel	9	290	120

In collaboration with municipalities and port authorities, the government endeavors for Norwegian ports to achieve emission-free status by 2030, at all ports feasible. Being able to provide onshore power, charging facilities, and adequate bunkering services for sustainable fuels such as hydrogen and biogas are the main developments necessary in order to achieve emission-free ports. [8]

State-owned Enova has supported onshore power projects since 2016. To this date, 131 onshore electricity projects have been deemed eligible for support, where 86 projects have been completed. Enova is currently preparing a new support program for charging infrastructure for maritime transport [9]. Allowing electric trucks and buses to use the ferries' onshore power systems between departures is considered essential for increasing the electrification of road transportation. By 2030, 50 % of new transport trucks are expected to be electric. A lack of dedicated charging infrastructure is the main reason this goal may be postponed. Electric charging of vehicles can enable a new revenue stream for the ferry companies. [10]

3 Battery Technology

This part of the thesis presents the theoretical foundation of battery technology. Batteries are used as a way to store energy chemically and convert it to electrical energy when it is required. Some batteries are one-time use, usually referred to as primary batteries, while rechargeable batteries are called secondary batteries. This thesis will mainly focus on secondary batteries as they are the most relevant type to be utilized in the ferry industry.

A battery consists of two electrodes that are separated by an electrolyte. The electrodes are called anode and cathode. The anode is a negative electrode, electrons are released when the anode material reacts with the electrolyte. The cathode is a positive electrode, electrons are accepted at the cathode in a reduction reaction. When the electrodes are connected by a conductive material an electric current will flow. If the electrodes are connected to an external power source the reactions are reversed and the battery is charged. These two reactions in the electrodes, named half-cell reactions, both have an electric potential. The potential of all reduction reactions is given in reference to that of hydrogen. When the half-cell reactions are put together they create an electrical potential in a redox reaction. If this occurs during standard conditions the standard potential (E^0) of a redox reaction is given by equation 3.1 with voltage (V) as a unit.

$$E^0 = E^0_{cathode} - E^0_{anode} \tag{3.1}$$

If two electrodes of different half-cell potentials are combined, there will be an electrochemical cell potential. Therefore, the materials of the anode and cathode will be the main determining factors of the voltage of a battery. A material or compound that has a low half-cell potential will be more willing to let go of an electron, therefore the anode half-cell reaction is usually significantly lower than that of the cathode. [11]

3.1 Evaluation Parameters For Batteries

Capacity

Every battery has a rated voltage, which is determined by several factors such as cell chemistry and cell configuration. The battery capacity is the amount of charge the battery can deliver at rated voltage and is expressed as Ampere hours (Ah). A 50 Ah battery can deliver a current of

1 A for 50 hours if ideal conditions are assumed. Another way to assert the battery capacity is through Watt-hours (Wh). This describes the total amount of energy that can be drawn from the battery and is the product of the rated voltage multiplied by the capacity given in Ah. [12]

Density

Energy density is defined as the energy relative to the battery's weight (Wh/kg) or its volume (Wh/L). Energy density is one of the most important parameters within batteries and is a central part of this thesis. [13]

State of Charge (SoC)

The state of charge of a battery (SoC) is a measure of the currently available charge expressed as a percentage of the battery's rated capacity. If the SoC is 100 %, the battery is regarded as fully charged, whereas if the SoC is 0 % the battery is fully discharged. [13]

Depth of Discharge (DoD)

The depth of discharge (DoD) is how much of the battery capacity has been discharged from its rated capacity. The DoD and SoC are consequently complementary to each other. [13]

Cycle Lifetime

The capacity of many batteries degrades with use. The cycle lifetime is a parameter that is defined as the amount of charge and discharge cycles a battery is expected to perform before its capacity drops below a certain level. The cycle lifetime of a LIB is heavily affected by the depth of discharge of every cycle. [14]

C-rate

A C-rate is a measure of the rate at which the battery is discharged relative to an SoC of 100 %. It is useful to normalize the discharge current against battery capacity since it is very different between batteries. The C-rate can be calculated with the expression in equation 3.2.

$$C - rate = \frac{1}{Discharge\ time\ (h)} = \frac{Discharge\ current\ (A)}{Rated\ capacity\ (Ah)} \tag{3.2}$$

If a given discharge current fully discharges the battery within one hour, it is said to have a C-rate of one, or 1C. A C-rate of 6C will discharge the battery within 1/6 of an hour, while a C-rate of 0.5 C will discharge the battery within 2 hours. [14]

4 Flow Battery Technology

A flow battery (FB) is a type of electrochemical energy storage, where the energy is stored in liquid electrolytes. The concept of a flow battery technology has been studied for many decades but is considerably less researched and developed in comparison to other battery technologies like LIBs. [15]

4.1 Function And Structure

A flow battery, categorized as a secondary battery, can be recharged. This is possible because the cell reactions are reversible and can be restored to their original chemical conditions after discharge. The energy in a flow battery is stored within active chemical components dissolved into liquid electrolytes. Flow batteries can be classified into redox flow batteries (RFB), hybrid flow batteries (HFB), and membraneless flow batteries [16]. This thesis will mainly investigate redox flow batteries. Figure 4.1 shows the basic components of an RFB.

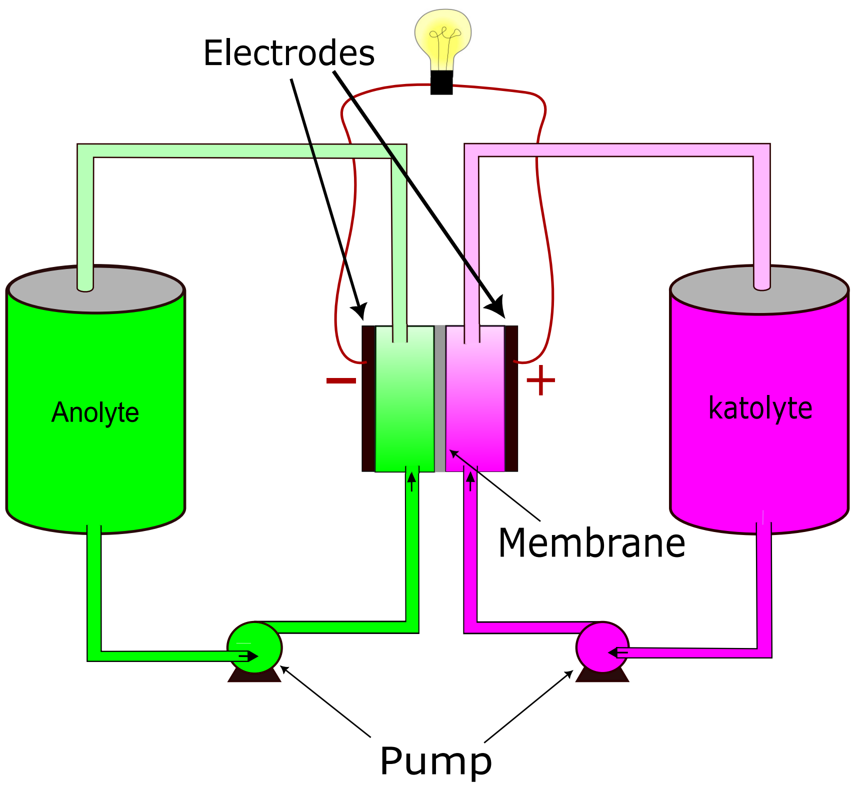


Figure 4.1: The main components of a flowbattery. Made with Inkscape.

In an RFB, the electrolyte is stored in two tanks where metal ions are the active components. The negative and positive electrolytes are called the anolyte and the catholyte respectively. During discharge, the electrolytes are pumped into an electrochemical cell which consists of two half-cells. The anolyte is pumped through one half-cell where an oxidation reaction occurs while the catholyte is pumped through the other half-cell and a reduction reaction occurs. The half cells are separated by an ion-selective membrane which allows specific ions to pass through. Electrons flow over the electrodes to produce electric power. The electrochemical cells can be connected in series or parallel to form a cell stack to determine the power potential of the RFB system. When the system is charged, an external power source is connected and the reverse reactions occur inside the cells. [17], [18]

The active metal ions stay dissolved in the electrolyte throughout charging and discharging. This makes it possible to store the electrolyte in external containers. This gives the RFB the unique characteristic of theoretically decoupled power and energy. This means that the cell stack determines the power while the energy is only limited to the size of the electrolyte containers. [19]

4.2 Different Types of Redox Flow Battery

There are many different types of RFBs with various electrolytes. Despite their differences, they share several common features, such as a minimum lifespan expectancy of 10 years. Some have theoretically high energy efficiency in the right conditions and a low self-discharge because the electrolyte is separated in two tanks. All RFBs tend to have carbon-based electrodes. [18]

RFBs are put in two different categories based on solvents used in the electrolytes. The two categories are an aqueous and a non-aqueous system. An aqueous system uses water as a solvent, which is cheap and safe to use, but has a lower energy density than the non-aqueous. The non-aqueous system can have a higher energy density but can be more expensive and less safe to use. [18]

4.2.1 Vanadium Redox Flow Battery

Vanadium Redox Flow battery (VRFB) is the most used and researched RFB. It was invented and patented by Skyllas-Kazacos at the University of New South Wales [20]. Vanadium is used as the active species in both electrolyte tanks. The electrolyte in the positive half cells contains VO^{2+} and VO_2^+ ions, while the electrolyte in the negative half cell contains V^{3+} and V^{2+} ions [21]. The half-cell reactions are shown in equations 4.1 and 4.2. The most common membrane material is perfluorinated sulfuric acid. An advantage the all-vanadium composition possesses is its resistance to crossover contamination between the two electrolytes. However, the toxicity of vanadium and the low energy density compared to LIBs makes commercialization difficult. [22], [18]

$$\mathrm{VO_2}^{+} + 2\,\mathrm{H}^{+} + \mathrm{e}^{-} \longleftrightarrow \mathrm{VO}^{2+} + \mathrm{H_2O}\ (1.00V) \tag{4.1}$$

$$\mathrm{V}^{2+} - \mathrm{e}^{-} \longleftrightarrow \mathrm{V}^{3+}\ (-0.26V) \tag{4.2}$$

There are other types of VRFBs that do not only use vanadium as an electrolyte. Examples of this are vanadium-bromine, vanadium-ion and vanadium-cerium flow batteries. For the most common type, the all-vanadium flow battery, the energy efficiency will typically be 75-85 %. The maximum vanadium ion concentration that can be used is 2 mol/L, this gives a specific energy of 25-35 Wh/kg. With a concentration of 2 mol/L, the battery can operate at temperatures up to 40 °C, and below 5 °C. To operate the battery at below 0 °C it is possible to reduce the concentration to downwards of 1 M. However, this will reduce the specific energy of the battery. [18], [23]

4.2.2 Zinc/Bromine Flow Battery

Zinc Bromine Flow battery (ZBFB) is a type of hybrid RFB that uses the chemical reaction between zinc and bromine to store chemical energy and produce electrical energy. The aqueous electrolyte consists of zinc-bromine salt dissolved in water where the half-cell reactions are displayed in equations 4.3 and 4.4. The specific energy in this type of RFB ranges between 60 and 85 Wh/kg and has a standard voltage of 1.82 V. Some benefits of ZBFB are that it has cheaper and more available materials, and has higher specific energy compared to VRFB. However, there are difficulties connected to the formation of dendrite on the anode that can cause short-circuiting. There are also safety concerns related to the use of bromine. [18]

$$\mathrm{Br_2} + 2\,\mathrm{e}^{-} \longleftrightarrow 2\,\mathrm{Br}^{-}\ (1.09V) \tag{4.3}$$

$$Zn - 2\,e^- \longleftrightarrow Zn^{2+}\ (-0.76) \tag{4.4}$$

4.2.3 Iron/Chromium Redox Flow Battery

Iron/chromium is considered the first RFB technology and was developed by the National Aeronautics and Space Administration (NASA) in the 1970s. In an iron chromium battery, the positive half-cell electrolyte solution is iron-based (Fe^{2+}/Fe^{3+}), while the negative half-cell electrolyte is chromium-based (Cr^{2+}/Cr^{3+}) shown in equations 4.5 and 4.6. This gives it a standard voltage of 1.18 V and the current density is 120 mA/cm^2. Iron and chromium are inexpensive and are not very harmful to the environment. The Inventions and Contribution Board in California has made a battery of this type with a capacity of 1 MWh and 250 kW. It has a high energy efficiency of 78,2 % and a current density of 120 mA/cm^2. However, the battery has a capacity reduction of 1.2 % per cycle which is undesirable and has halted the usage of this variety. [24], [25]

$$Fe^{3+} + e^- \longleftrightarrow Fe^{2+}\ (0.77V) \tag{4.5}$$

$$Cr^{2+} - e^- \longleftrightarrow Cr^{3+}\ (-0.41V) \tag{4.6}$$

4.2.4 Aqueous Organic Flow Batteries

Aqueous Organic Flow batteries are a type of flow battery that is in a very early stage of development and research. Instead of metal ions, an aqueous organic flow battery uses carbon-based molecules for its electrolytes. The electrolytes for this battery rely on redox reactions to charge and discharge. An organic flow battery is a flow battery that reversibly converts electrical energy to chemical energy through redox reactions of organic or metal-organic molecules. Examples of molecules used in this type of flow battery are carbon, hydrogen, and nitrogen, which are potentially low-cost raw materials. [26], [27]

4.2.5 Nanoelectrofuel Flow Batteries

Nanoelectrofuel flow batteries are a type of flow battery that is in the early stage of development and testing. In a Nanoelectrofuel flow battery, it is used nanoparticles dissolved in water to bind the active materials more closely in the electrolyte. NanoFlowcell is a nanoelectrofuel flow battery developed in Switzerland by the company NanoFlowcell Holdings plc. They are currently in the planning stages for the production of the world's first flow cell electric vehicle using their NanoFlowcell battery. The electrolyte used in NanoFlowcell has an energy density of 600 Wh/L, which is approximately 10 times larger than for a regular RFB cell. There is a lot of potential in the use and distribution of nanoelectrofuel flow batteries, but it is still in an early stage of development. [28], [29]

4.3 Advantages of Flow Batteries

One considerable advantage of RFBs compared to other battery types is their scalability. The energy capacity of RFBs can be scaled to the size needed by increasing the volume of the liquid electrolyte tanks. This is possible due to the separation of the tanks and the reactor in the design. The scalability of RFBs makes them especially suited for large-scale energy storage. [30], [31]

Flow batteries can use the full range of the capacity of the battery and have a DoD of 100 %. Using the full DoD will not cause any permanent harm or changes to the electrolyte. The only concern is overcharging which can cause hydrogen evolution. Hydrogen evolution is undesired as it creates an imbalance in the electrolyte and alters the pH. [32]

Another attribute RFBs have is their long cycle lifetime. An RFB can undergo thousands of charge and discharge cycles with minimal degradation. This long operational life reduces the need for frequent replacements and can lower the total cost over time compared to other battery types. RFBs have at least a lifetime of 10 years, and the best FBs on the market proclaim a lifetime of 20-30 years. One example of this is the INVITY Energy Systems vanadium flow battery which is designed to last 25 years [33]. [18], [31]

RFBs operate at low temperatures and are pretty safe to use. The most utilized types of electrolyte are non-flammable and aqueous solutions which have a lower risk of fire or explosion compared to other types of battery, like the LIB. In addition, many of the other materials used in a flow battery are less toxic and more eco-friendly as well. [30], [31]

Another benefit is the high efficiency in long-duration discharge. While flow batteries mainly have a smaller energy density compared to other batteries they are well suited for situations where energy needs to be discharged over several hours. This makes them very suitable for storing excess energy from wind turbines and solar panels. In the hours when there is little to no amount of sun or wind, the stored energy in the flow batteries can then be used to supply power to the grid. [31], [18], [30]

4.4 Challenges and Disadvantages With Flow Batteries

Flow batteries typically have a lower energy density in comparison to other types of battery technologies. This means they require more space or weigh more in order to store the same amount of energy. This makes the RFB not very suitable for applications requiring compact energy storage solutions, such as in electric vehicles or portable electronics. [18], [30]

Flow batteries typically have a limited efficiency compared to LIBs. While flow batteries offer the advantage of decoupling power and energy, allowing for independent scaling of power and capacity, they often have lower round-trip efficiency compared to other battery technologies. The efficiency of flow batteries can vary depending on factors such as electrolyte composition, flow rates, and temperature. According to a report by the International Renewable Energy Agency (IRENA) a VRFB can have up to 85 % energy efficiency, which is relatively high but still lower than a modern LIB. [18], [34], [30]

A quick response time can be achieved, but this will eliminate the advantage of negligible losses due to self-discharge. In order to have a fast response time, the electrolytes need to be stored in the stack. Self-discharge will occur when the electrolytes are kept stationary in the stack over a period of time [31]. Declan Bryan and his colleagues performed a test where a new electrolyte was cycled through the stack every 300 seconds for 48 hours. They found that 80 % of the charge was lost due to the self-discharge [32].

Another report carried out by Declan Bryan and colleagues looked at a 200 kW/ 400 kWh VRFB and found that the maximum efficiency obtainable was only 59 %. Efficiencies downwards of 48 % were also recorded as the energy efficiency of the VRFB at different power levels was tested. All values are displayed in Table 4.1. The reporter also suggests that the efficiency is heavily dependent on the temperature. Two charge/discharge cycles with a 100 kW cycle power were carried out, one at 44.8 °C and the other between the normal operating temperature of 10 °C to 40 °C. The one at 44.8 °C displayed an efficiency of only 47 % while the latter had an efficiency of 59 %. [32]

Table 4.1: Charge and discharge energies and system energy efficiencies at different charge/discharge powers. (a) Cycle initiated when electrolyte temperature exceeded upper-temperature limit; (b) cycle initiated within normal temperature range [32].*

Cycle Power (kW)	**Time Charging (min)**	**Charge Energy (kWh)**	**Charge level (%)**	**Time discharging (min)**	**Discharged Energy (kWh)**	**System Energy Efficiency (%)**
50	894	738	91.8	427	353	48
60	745	739	98.2	419	416	56
100(a)*	438	743	92.6	216	350	47
100(b)	443	727	100.0	272	435	59
150	293	730	95.8	172	397	54
200	192	638	91.6	125	365	57

Typically a flow battery is more expensive to manufacture and maintain compared to other batteries. One of the primary challenges of flow batteries is their cost. Flow batteries typically have higher upfront costs compared to traditional batteries, primarily due to the cost of the electrolyte and the membrane. In the same report from IRENA, it was found that flow batteries are generally more expensive than other battery types, such as LIBs, which have seen significant cost reductions in recent years [34]. [30]

Flow batteries are sensitive to cross-contamination. They can be harmed by impurities in their liquid electrolytes, which can affect their performance and how long they last. These impurities can be metal ions, organic compounds, or tiny particles. Metal ions can disturb redox reactions by competing with desired redox couples which leads to side reactions and a decreased efficiency. Organic compounds in the electrolyte can react with active species, stick onto the surface of the electrodes or membranes, and make blockages. This increases internal resistance and reduces the conversion energy. Tiny particles floating around in the electrolyte can block the battery's flow paths and get stuck on its surfaces. This will make it less efficient. To avoid cross-contamination and keep the flow batteries working well, it is important to clean the electrolyte, design the system carefully, and follow adequate practices when the battery is in use. [35], [36], [18]

Flow batteries generally have fewer safety concerns than other battery technologies like LIBs, but they still have certain risks that need to be managed. Some of the biggest safety concerns associated with flow batteries are electrolyte leakage, fire and explosion risks, and chemical hazards. Electrolyte leakage poses significant risks due to its potential environmental hazards, chemical exposure risks, and equipment damage. Although flow batteries are generally less prone to thermal runaway compared to LIBs, certain electrolyte chemistry used in flow batteries can still pose fire and explosion risks under specific conditions. The chemicals used in flow battery electrolytes can present significant hazards if mishandled or exposed to incompatible materials. Addressing these risks requires good risk assessment, effective safety protocols, and appropriate personnel training. [37], [30],[18]

4.5 Membrane

The membrane of a flow battery should ideally have high ionic conductivity and thermal resistance, in addition to being cheap. The most commonly used membrane for RFBs is the perfluorinated ion-exchange membrane (IEM) Nafion. Nafion is desirable because of its mechanical and chemical strength as well as its high proton conductivity. The Nafion membrane is produced and commercialized by the company DuPont and costs between $500 - $800 per square meter. This results in the membrane being about 40 % of the total stack cost. Porous membranes are also an alternative that is being considered for RFBs. The porous membranes are cheaper than the Nafion but have poor ion selectivity that reduces the energy efficiency. However, strategies to make the porous membrane more efficient are being researched. One solution that seems promising is to pair a poly(ether sulfone) porous membrane with an ultrathin ZSM-35 zeolite flake that will reduce the size of the pores. [25]

A problem that all the RFBs, except all-vanadium, face is cross-contamination of anolyte and catholyte which decreases the energy efficiency substantially. This also happens in the all-vanadium however, it is possible to perform a re-balancing procedure to recover the capacity. There are attempts at finding a solution to the cross-contamination problem, like using bipolar active material. Until a better solution is established to prevent cross-contamination the membrane remains an issue. [38]

4.6 Stack

The stack is the location in the RFB where the electrolytes interact with each other when it is in operation. The design of the stack determines the power of the RFB. The stack consists of current collectors, graphite plates, porous electrodes, and the membrane. An illustration of a stack is displayed in Figure 4.2. The electrolytes are pumped into the stack through channels in the graphite plate. The area of channels in the stack is called the flow field. The most common flow patterns in the flow field are the serpentine flow field and the interdigitated flow field. As power is dependent on current with the unit ampere (A) and voltage (V) as shown in equation 4.7, these are the two parameters that can be changed to determine the power of the battery.

$$Power\ (W) = Current\ (A) \cdot Voltage\ (V) \tag{4.7}$$

The voltage of the RFB is dependent on the composition of the electrolyte. The voltage is increased by placing multiple cell stacks in a series connection. The current capacity of the battery is dependent on the area of the electrode and the current density of the electrolyte. Large-scale RFBs that require high power usually consist of modules of cell stacks. The modules are connected in parallel to increase the power. [39]

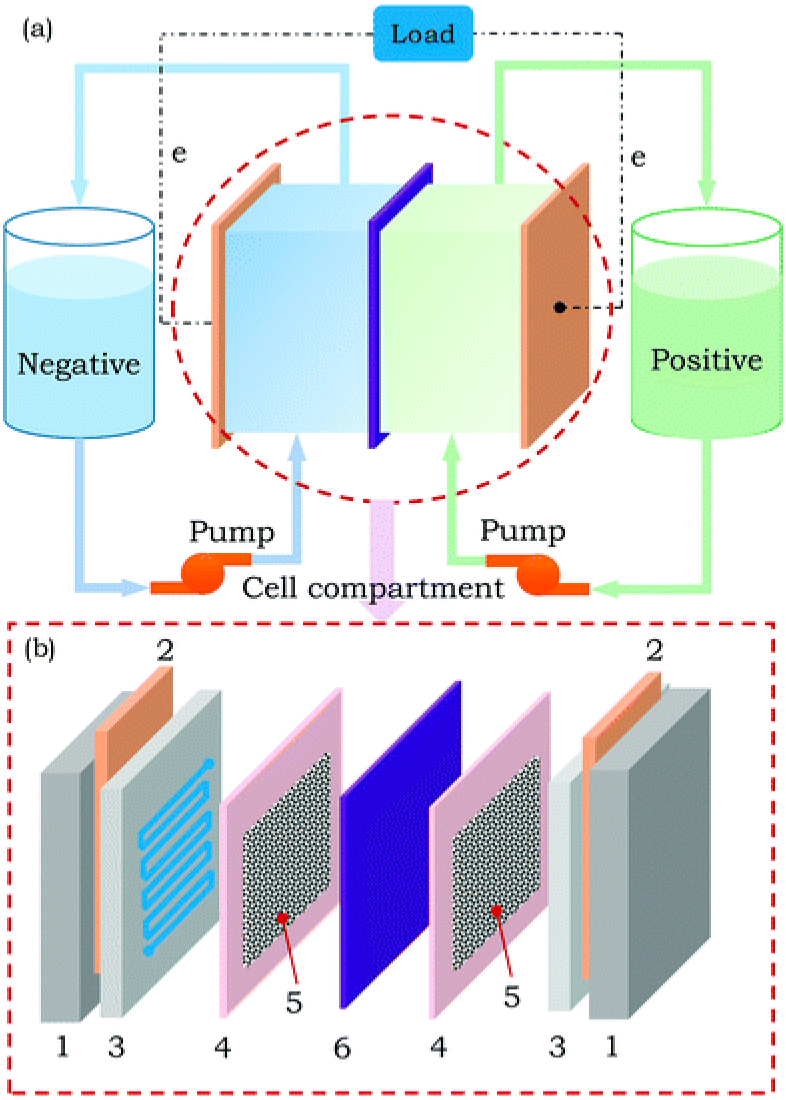


Figure 4.2: (a) Schematic of a typical flow battery and (b) a detailed diagram of cell compartment in flow batteries with a flow field design, main components include: 1-endplates, 2-current collectors, 3-graphite plates engraved with a serpentine flow field, 4-gaskets, 5-porous electrodes, and 6-ion exchange membrane. [39]

4.7 Note On C-rate For Flow Batteries

Indeed, a flow battery's power and energy capacities are essentially decoupled. This would imply that the C-rate has no significance for flow batteries. However, certain limitations arise if a flow battery design needs to deliver a high-power. If high power is required and a flow battery is to be designed accordingly, the volume of the electrolyte containers will also need to be bigger if the efficiency is to be maintained. The cause for this is made up of composite reasons.

As explained, the current density directly correlates to the power output in flow batteries. The current density depends on the concentration of active species within the electrolyte and at a high power output, the consumption of active species will increase. This necessitates a higher flow rate to maintain the concentration within the cell at acceptable limits. Insufficient electrolyte volume can lead to too rapid depletion of active species, resulting in voltage drops and reduced efficiency. [40], [41]

A higher flow rate also means the reactions will go faster, resulting in a temperature rise within the electrolyte. This becomes problematic since most electrolytes, especially vanadium-based ones, must operate within specific temperature ranges as explained in chapter 4.4. This sets a cap on the maximum flow rate that can be achieved at each cell. For a high power requirement, the battery system is usually distributed into several modules as this makes it easier to combine the power output, but in turn, sets a limit on how large the electrolyte container volume must be. According to Bryte batteries, flow batteries usually operate with a C-rate of 1/3C or lower. This thesis will not go any deeper into this matter, but the fact that a high power requirement prompts a C-rate will be important in the case studies performed later.

4.8 Grid-Scale Energy Storage

To make renewable energy sources more reliable it is crucial to be able to store the energy that is produced. Energy sources such as wind and solar are unpredictable as production depends on uncontrollable circumstances such as weather, season, and time of day. As the world aims to reduce its carbon footprint by cutting down on fossil fuel usage, the ability to deliver energy on demand will diminish because fossil fuels can be combusted whenever needed, granted they are available. The inability to generate energy on demand will lead to significant issues within the energy grid. It is not possible to consume more energy than the amount produced at a certain point. Therefore, renewable energy has to provide as much energy as is consumed from the grid at all times. Additionally, more electrical components such as electrical vehicles are causing new and unpredictable load patterns. The solution to this problem is to store the excess energy in low-demand periods and consume it during high-demand periods. However, the existing energy storage is currently not good enough to sustain a future carbon-free society. According to the EU, it is necessary to install 33 GWh of energy storage in Europe by 2030 to keep up with the estimated growth in renewable energy. In 2022 the capacity of energy storage in the EU was roughly 12 GWh. [42]

There are several rechargeable battery technologies as well as pumped storage hydropower and compressed air energy storage solutions available for grid-scale use. However, these require either existing reservoirs or substantial interventions in the environment to be available. This suggests that batteries are a key component in the future of energy storage and renewable energy. A long life cycle and low self-discharge rates are qualities of the flow battery that make it a great option for large-scale energy storage. Additionally, the power rating and the capacity of the flow battery are dependent on different properties of the battery. The power rating relates to the number of stacks in the battery, while the capacity is a function of the concentration of active species and the volume of the electrolyte. [25]

4.9 Commercial Products

RFB is still a relatively underdeveloped technology, and more research and improvements are needed before it can become fully competitive with other technologies. However, there are still companies that have commercialized the flow battery and taken it from the theoretical world to the real world. There is no production of flow batteries in Norway, but Bryte Batteries is a Norwegian company that sells and installs VRFBs produced by the Danish firm VisBlue. Bryte Batteries has installed three VRFBs at Skjetlein VGS. These batteries are shown in Figure 4.3. The purpose of this installation is for peak-shaving and use for further research. The batteries have a power of 10 kW and are scalable up to 100 kW. The DC round-trip efficiency is 87 % and the AC round-trip efficiency is 67 %. The AC voltage is 230 V in one-phase operation, and 400 V in three-phase operation at 50 Hz. The whole datasheet is found in Appendix A.

In 2022 the world's largest RFB was connected to the grid in Dalian in China. The Dalian Flow Battery Energy Storage Peak-Shaving Power Station is supposed to provide energy for 200 000 inhabitants. It has a capacity of 400 MWh and a power output of 100 MW. It is an energy storage system for solar and wind power and is used for peak shaving and valley filling. [43]

Figure 4.3: VRFB from Bryte Batteries.

5 Lithium-Ion Battery

Since the late 1970s when the first research and development was started, LIBs have become one of the most common battery technologies in the world. It is used in all types of applications, especially portable technologies. This is due to its high energy density which makes it well-suited for mobile use. This includes all types of electric vehicles such as cars and ferries. However, it is also possible to use it as an energy storage technology. By installing LIBs together with solar panels or wind farms, it is possible to store the energy to be consumed later when necessary rather than supplying the grid during low demand. Since 2010 the cost of LIBs has been reduced by 85 % [44]. The vast usage of LIBs motivates funding the technology for further developments, reducing the price, which in turn makes it more competitive. [45]

5.1 Function and Structure

The LIB is a type of rechargeable battery. It consists mainly of four different components, these are the anode, cathode, electrolyte, and separator. Figure 5.1 displays the principle of a LIB. When the battery is fully charged, the lithium ions are stored in the anode, which is usually made of graphite. During discharge lithium ions migrate through the separator to the cathode, while electrons flow in an external circuit. Since lithium is a highly reactive material, it has to be stored in the form of lithium oxide in the cathode. Other materials are also used to determine the characteristics of the battery. Therefore, there is no standard LIB, and manufacturers use different compounds in the cathode to make it specialized for their desired purpose. Materials that are commonly used in the cathode are cobalt, manganese, and phosphate. The compounds of the anode and cathode are called active materials. The active materials are coated onto a metal foil. The electrolyte is the medium that allows the lithium ions to move through the battery. However only the lithium ions move through the electrolyte, and it is therefore made out of highly ionic conductive materials. This includes salts, solvents, and additives. The separator acts as a physical barrier between the anode and the cathode. The main purpose of the separator is to only let ions pass through, and prevent electrons from passing. This keeps the battery from short-circuiting. The separator is usually made of synthetic resin. [46], [47], [48]

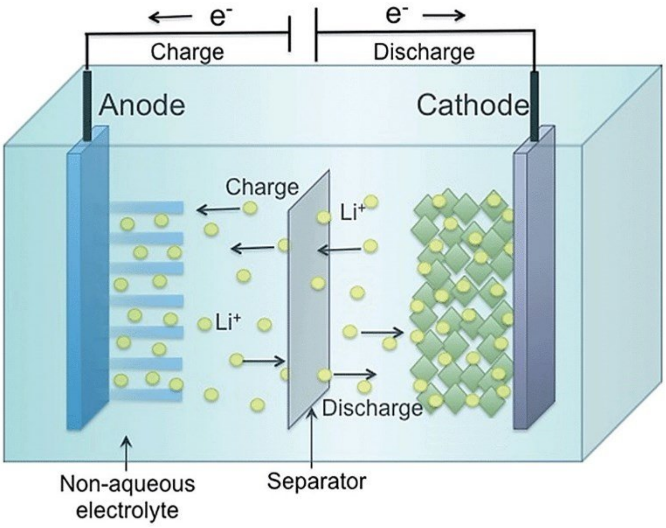


Figure 5.1: Illustration of a lithium-ion battery [49].

5.2 Advantages of Lithium-Ion Batteries

The LIB has a lot of advantages that make it a desirable technology. As mentioned it has a high energy density that makes it suitable for use in devices with weight restrictions. The theoretical energy density of LIBs is 300 Wh/kg. For comparison, nickel-cadmium batteries have an energy density of 75 Wh/kg, and many flow batteries have only 10 % of the energy density of LIBs. It also has a high standard cell potential of 3.6 V. This makes it a suitable option for use in applications that require high power. The self-discharge rate is 1-2 % per month. [50], [51]

5.3 Challenges With Lithium-Ion Battery

Although LIB technology is relatively well developed, it faces certain challenges. Overheating as well as physical damage are the main vulnerabilities concerning this technology. In rare cases, this might cause the battery to self-ignite or explode, which is a major safety concern. It is also necessary to have a battery management system (BMS) to prevent it from over and undercharging. This adds to the costs of the battery which is also a challenge. The compounds of the cathode are expensive and might fluctuate in price. They are typically 40 % more expensive to manufacture than other popular batteries like nickel-cadmium. The cycle lifetime of the LIB is only 1200 - 2000 charging cycles. When compared to RFBs with 10 000 or more charging cycles it will be more expensive on a long-term basis as the LIB has to be replaced. [52], [48], [53], [51]

5.4 Charging Strategy

The lifetime of batteries is dependent on how they are utilized and treated during their usage. Operational strategies are therefore important in order to maximize the value of the battery. One common charging strategy for LIBs is the constant-current/constant-voltage (CC-CV) method. When a battery that is fully discharged starts charging, the voltage will increase. During this time the battery is charged with constant current. When the battery reaches the upper voltage limit the charging strategy is changed to a constant voltage to prevent over-voltage. The charging cycle is displayed in Figure 5.2. The CC-CV algorithm is an easy and common charging strategy, but there is no battery feedback to optimize the battery's health. More advanced and efficient algorithms do exist. The Taguchi-based five-step method can increase the number of charging cycles by 57 % and reduce charging time by 11 %. [54], [55]

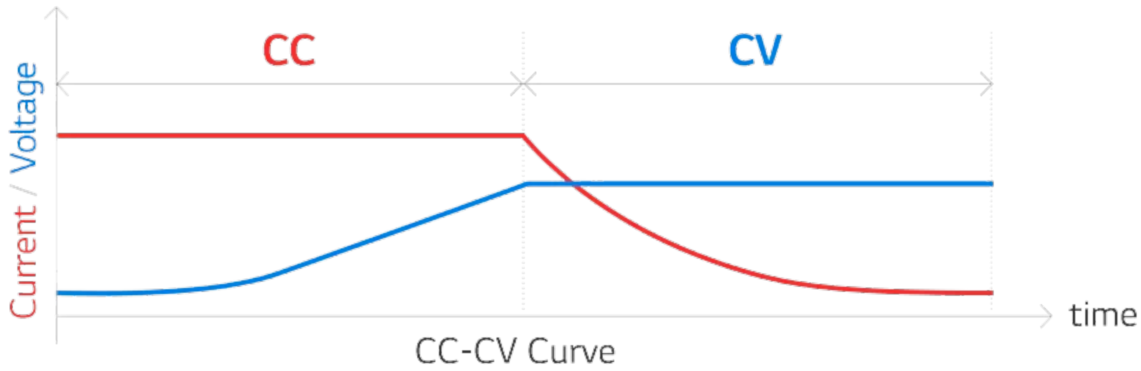


Figure 5.2: Display of a CC/CV charging cycle [55].

Due to the high energy density of LIBs, it is commonly used to power electric vehicles (EVs). The batteries in EVs usually consist of LIB cells arranged in modules that are connected in series and parallel to obtain the required power and energy. The batteries of EVs are reaching capacities upwards of 100 kWh which makes them a real competitor with the standard cars installed with an internal combustion engine (ICE). One drawback with the EVs is the charging time as they can not be charged as fast as the ICE refuels. How the battery is being charged affects the capacity and reduces the state of health (SoH). The best use of the LIB in EVs is to only charge it between 20 % and 80 % SoC. The use of the battery exceeding these limits is harmful to multiple parts of the battery. It can cause structural degradation and dissolution of active materials, shortening the lifespan of the battery. Figure 5.3 displays the effect of different depths of discharge on cycle lifetime. Overcharging might also cause the battery to burn or explode. Therefore, it is important to have a BMS to prevent both overcharging as well as over-discharging. [56], [57]

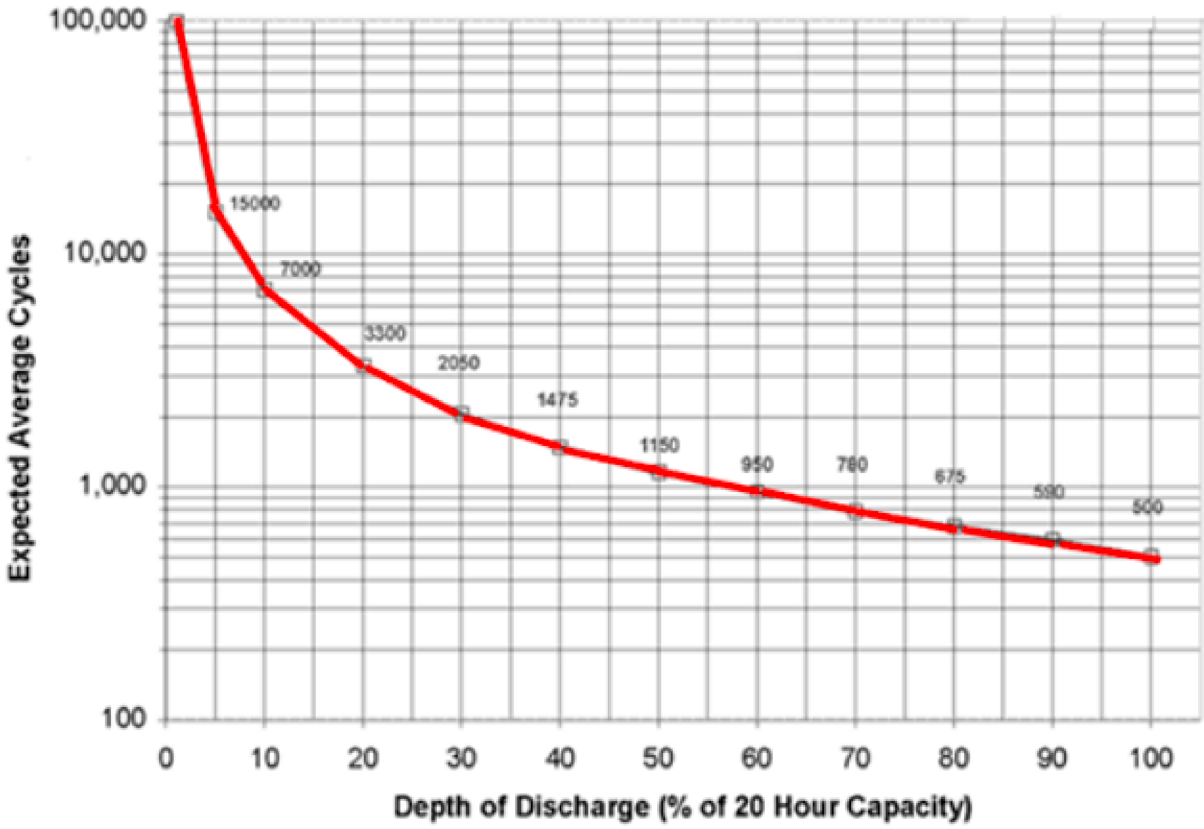


Figure 5.3: Depth of discharge effect on cycle lifetime [57].

6 Environmental Impact

There are several ways to electrify a ferry crossing with the application of batteries. Considering the environmental impact when evaluating the various possibilities is becoming more important. Numerous factors contribute to the total impact such as the product lifetime, materials used, and transportation routes. For simplicity, this part will only investigate and compare the environmental impact of flow batteries with Li-ion batteries based on materials and published Life cycle assessments (LCA).

Life Cycle Assessment

A life cycle assessment (LCA) can be based heavily upon assumptions and simplifications and may therefore be laborious to draw concrete conclusions from different studies. However, several LCAs have been published comparing the environmental impact of FBs and LIBs. In the following study, a LIB with a Nickel-Manganese-Cobalt based cathode with a ratio of 1:1:1 (NMC 111) has been compared with a VRFB [58]. The assembly of the batteries themselves was studied as the supply phase, while the total setup for a stationary energy storage system with additional components such as inverters and monitoring systems was accounted for during the use and end-of-life phase. The abbreviations LRES and VRES stand for Li-ion and Vanadium Renewable Energy Systems respectively.

Table 6.1: Overall scores per category for a VRFB and a LIB with NMC-based cathode with ratio 1:1:1 (NMC 111) [58].

		Supply phase		Life Cycle	
Impact category	**Unit**	Li-ion NMC 111	VRFB	LRES	VRES
Global warming	kg CO_2 eq.	56.3	57.0	95.0	100.8
Fine particulate matter formation	kg PM2.5 eq.	0.3	0.2	0.4	0.3
Terrestrial acidification	kg SO_2 eq.	1.0	0.6	1.2	0.8
Human toxicity	kg 1,4-DCB	162.4	120.9	218.2	173.8
Mineral resource scarcity	kg Cu eq.	5.0	4.8	5.9	5.9
Fossil resource scarcity	kg oil eq.	13.1	15.1	23.0	25.5
Cumulative energy demand	MJ	766.4	801.6	2734.1	3129.5

The results from the LCA shown in Table 6.1 present data for a 20-year period, assuming a 20-year lifetime for the VRFB and a 10-year lifetime for the LIB. The LIB is therefore replaced after 10 years. It is observed that the VRFB has a lower impact on all categories except for global warming, fossil resource scarcity, and cumulative energy demand. Another comparison was made within the same LCA, where the batteries described above were compared to a new scenario. In this case, the LRES has an NMC 811 cathode while the electrolyte used in the VRES is 50 % recycled. The results from this scenario are presented in Figure 6.1.

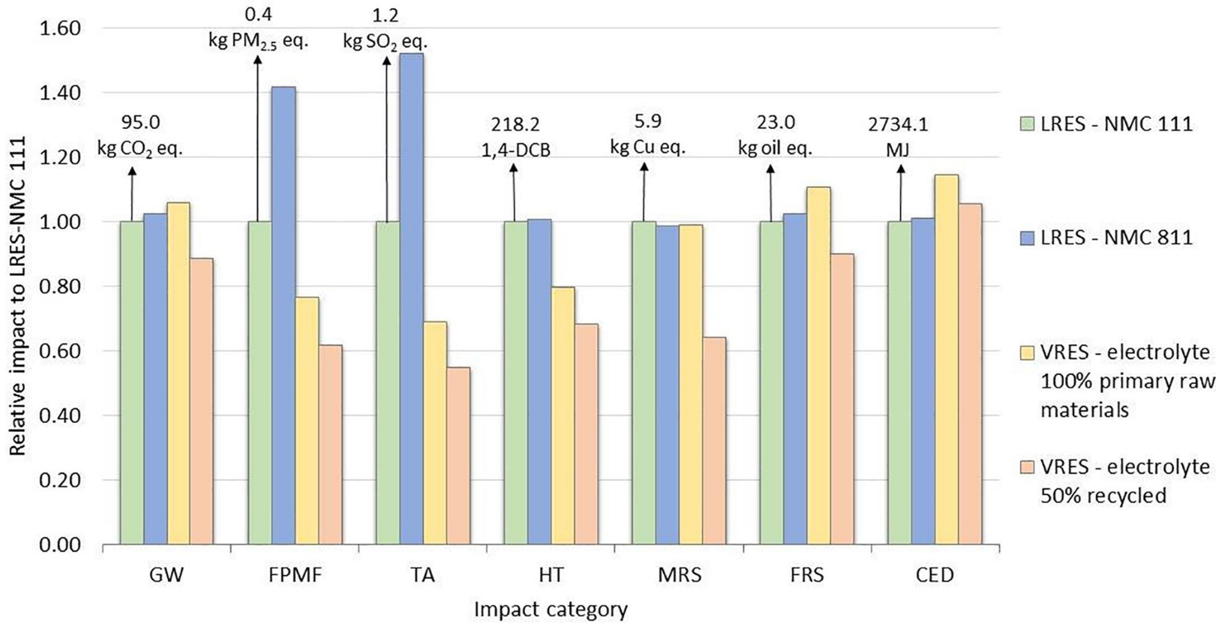


Figure 6.1: Impact per category for LRES with either NMC 111 or NMC811 and VRES with either 100 % fresh electrolyte or 50 % recycled electrolyte. The results are relative to the impact of the LRES with the NMC 111 cathode.

In the case of the partially recycled electrolyte, it is observed that all impacts are reduced in all categories to the point where it is the best option for every category except for cumulative energy demand. The LCA report states that the global warming potential is diminished by 11.1 % due to recycling 50 % of the electrolyte [58]. It has been reported by some VRFB suppliers that recycling of 97 % of the vanadium has been achieved [59]. In another report by Visblue, their VRFB product is compared with Li-ion batteries through an LCA which can be found as a brochure within their website [60]. Figure 6.2 shows the results from their LCA.

These results clearly illustrate that the life cycle of their VRFB battery is more environmentally friendly than LIBs with impacts generally being one-third in comparison. However, the report does not show a complete LCA. Any assumptions like an expected lifetime or whether the electrolyte or the Li-ion battery is recycled, are not clearly stated. However, the report states aside from the LCA that the CO_2-footprint of their VRFB is reduced by 77 % if the electrolyte is fully recycled. This is indicative that most of the footprint comes from manufacturing the electrolyte.

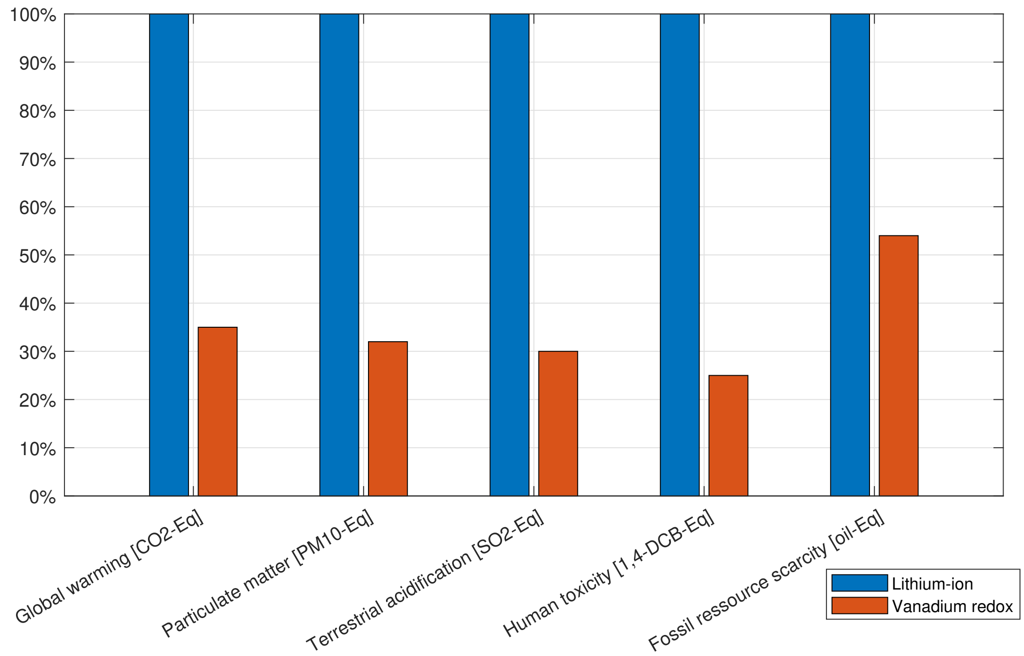


Figure 6.2: Comparison of impact per category between Visblue's VRFB product and a Li-ion battery [60].

6.1 Raw Materials

Vanadium

Manufacturing battery technology requires raw materials that are mined and produced in different parts of the world. Vanadium is normally used to create strong alloys for tools and construction equipment. Approximately 80 % of vanadium production is used in steel alloys. Because of this, the vanadium market is tightly linked to that of steel. Vanadium is not found in its metallic form in nature but in other minerals or fossil fuels. Vanadium is not usually mined as a primary product but as a byproduct of iron. Most of the world's vanadium resources are bound to a few countries, mainly China, Russia, and South Africa. This makes the supply of vanadium vulnerable. Chinese restrictions on the export of vanadium in 2018, and Russia's war in Ukraine have caused the price of vanadium to skyrocket and fluctuate. Due to vanadium's contribution to ESSs, the demand for vanadium is expected to double within 2030 to about 250 000 tonnes. There is currently no extraction of vanadium in Norway. However, big reservoirs containing vanadium may be accessible in the south and west parts of Norway. [61], [62], [63]

Lithium

As LIBs have become a dominant and sought-after battery technology the demand for lithium has increased and keeps rising. In 2021 there was a supply of 540 000 tonnes of lithium carbonate. The demand is predicted to grow by 250 000 tonnes per year. By 2030 it is predicted that the supply will lag the demand by upwards of 768 000 tonnes of lithium. About 90 % of lithium is mined from Australia, Chile, and China. Similarly to the case of vanadium, with few suppliers the prices of lithium are volatile. Other countries like Bolivia have large quantities of lithium available, however, the grade is too low to be economically sustainable. [64]

Cobalt

Cobalt is commonly used to enhance the cathode of LIBs. This has caused a substantial demand for cobalt. In 2022 the production of cobalt was 190 000 tonnes, compared with 140 000 tonnes in 2020. Approximately 70 % of cobalt is mined in the Democratic Republic of Congo. Unfortunately, the surge in cobalt demand has led to the establishment of both legal and illegal mining sites with sub-human working conditions. Congolese workers are subjects of human trafficking, child labor, and modern-day slavery and this is an ethical stain on the LIB industry. [65], [66]

Zinc

The raw materials zinc and bromine, which are important elements for a ZBFB are quite accessible worldwide. Zinc is the most available raw material of these two, and is the 23rd most abundant element in the earth's crust. The currently leading producer of zinc today is China, followed by Australia, India, Peru, and The United States. Zinc is relatively inexpensive due to its abundance and the efficiency of mining operations. [67], [68]

Bromine

Bromine is a less abundant raw material and is primarily extracted from brine pools, making it moderately available. The currently largest producers today of bromine are Israel, China, and the United States. Bromine is more expensive than zinc as for now due to the complexities involved in its extraction and processing. [69], [70]

7 Economy

Cost is an important factor when comparing batteries. The prices for LIBs for ferries and grid-scale stationary storage are somewhat reliable, but the estimated prices found for flow batteries are less trustworthy. This is because both VRFB and ZBFB are still in an early development stage and are not fully commercialized yet. This part will present a rudimentary comparison of the costs of LIBs, VRFBs, and ZBFBs. Table 7.1 shows the estimated price ranges for these different battery technologies.

Table 7.1: Comparison of battery prices.

Battery chemistry	Li-ion	VRFB	ZBFB
Estimated price ($/kWh)	350 - 400	264 - 713	428 - 478

7.1 Cost Lithium-ion Battery

Based on a 2023 article from Bloomberg the cost of a LIB is on average 139 $/kWh [71]. This was a reduction in price of 14 % from the year before, and experts estimate that the price will continue to be reduced in the years to come. The estimates are based on a continuation in manufacturing efficiencies and a decrease in the price of the important raw materials lithium, nickel, and cobalt [71]. The price of 139 $/kWh is nonetheless the cost for an average-size LIB. For a complete LIB built for grid-scale stationary storage, the costs are currently estimated to be between 350 to 400 $/kWh [72]. It is assumed that this price range is suitable as an estimate for a LIB on a ferry and as a buffer battery for a ferry on shore.

As the graph in Figure 7.1 shows, the cost of a LIB battery cell is expected to decrease in the years to come. Based on an analysis done by BloombergNEF the price of a LIB battery will be somewhere between 32 and 54 $/kWh in 2030. Based on this analysis it is assumed that the cost of LIB systems for grid-scale stationary storage will decrease substantially for the years to come. [73]

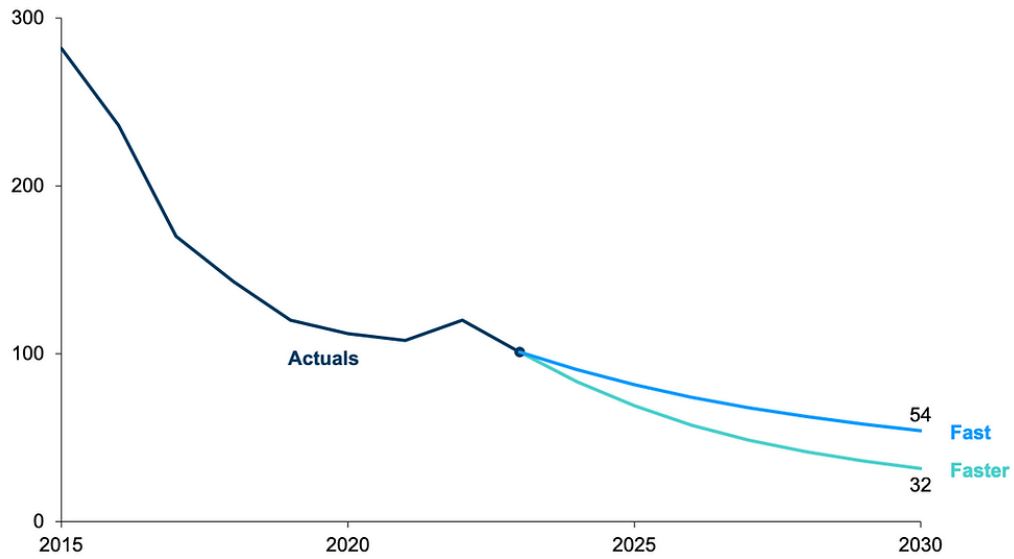


Figure 7.1: LIB battery cell cost outlook. Analysis based on historical learning rates and deployment outlook. Fast assumes a global demand of 5,5 TWh/y by 2030. Faster assumes a global demand of 8 TWh/y by 2030. [73].

7.2 Cost Vanadium Redox Flow Battery

The cost of a VRFB is estimated to be 500 $/kWh for grid-scale stationary storage [72]. Another source states that the price for a VRFB varies from 264 to 713 $/kWh [74]. As production volumes increase and as the technology is more researched and developed it is expected that the cost for VRFB will decrease significantly over time. It is assumed that the price range of 264 - 713 $/kWh is an estimate that will apply for both a VRFB used on a ferry and a VRFB used as a buffer battery at the dock.

As production volumes increase and as the technology is more researched and developed it is expected that the cost for VRFB will decrease significantly over time, and can potentially compete with LIBs on price in the future. In Figure 7.2 it is shown that the cell stack costs are about 31-40 % of the total cost, the balance of system equals 29-32 % and the electrolyte cost equals 31-37 %. It is expected that the costs of all these three categories may be reduced in the upcoming years. [74], [72]

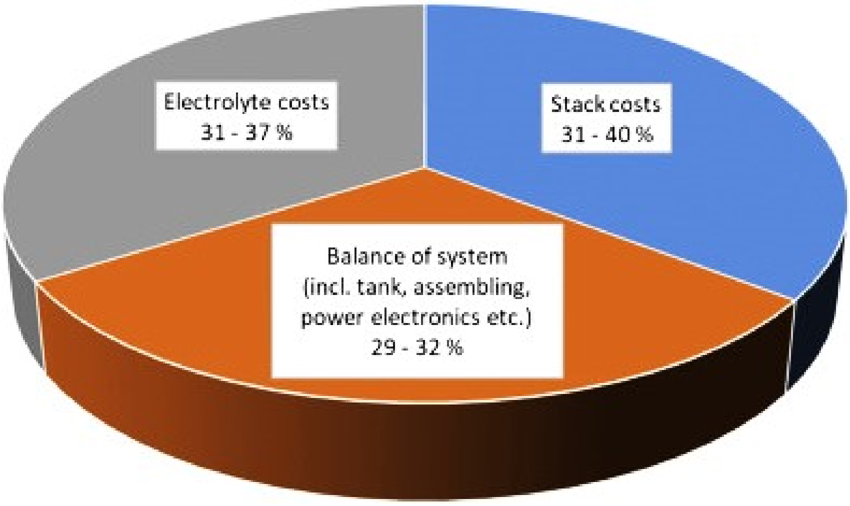


Figure 7.2: Cost breakdown for a VRFB [74].

7.3 Cost Zink Bromine Flow Battery

The cost of a Zinc-Bromine Flow battery is estimated to be around 153 $/kWh. The price is a substantially lower compared to VRFB because of the cheaper and more abundant materials, such as Zinc and Bromine which are highly available and low cost. It is assumed that the price for a ZBFB built for grid-scale stationary storage will be notably larger than the 153 $/kWh. A more accurate cost for ZBFB would be between 428 and 478 $/kWh. [74], [75]

8 Electrification of Ferries

Ferries are an important part of Norwegian infrastructure. A ferry is a vessel specially built to transport passengers and vehicles over short to medium distances. Ferries are mainly divided into two types which are passenger ferries and car ferries. Car ferries have a large deck and entry unit for loading and unloading. The examples and analysis later in the thesis will only encompass car ferries. The loading capacity of car ferries is usually stated as the number of personal vehicle equivalents (PBE). In Norwegian literature, the abbreviation PBE is short for 'person bil enheter' which is directly translated as 'personal car units'. In Norway, the ferry companies have to apply for a concession to be allowed to build and operate a ferry. This concession usually lasts for 10 years, and afterward, the company has to apply for a new concession period or stop their operation at that site. This part will explore different aspects and possibilities for electrifying a ferry. [76]

8.1 Energy and Power Requirement

A ferry must be able to provide reliable service and meet the needs of its route schedule. The energy reserve onboard, either fossil fuel or electricity, must be customized based on the route it will operate. The set energy capacity will depend on several factors, including the travel distance between each refill or charge, the buffer capacity requirements, and the weight, among others. Weather conditions will also affect the energy demand. Arne Brynlund from Boreal Sjø states that generally, a 10 % increase in energy use is expected due to bad weather compared to stable weather. Ferries powered with other fuels such as liquefied natural gas and hydrogen exist, but these types of ferries are beyond the scope of this project.

8.2 Weak Grid Challenges

A challenge with electrifying ferries is the high power consumption and the short time available for charging. A charging time limited to 5 minutes is not uncommon. Norway is an elongated country with many ferry crossings in remote places. Additionally, as the number of EVs on the road increases, the ability to charge while waiting for the ferry is desirable. These remote places usually lack the grid capacity necessary to handle these new dimensions of load. The main issue does not lie in the available energy, but the power that the grid can supply. Drawing too much power from the grid can affect the quality of the voltage for other users of the grid. To secure sufficient quality in the grid it is necessary to reinforce it. A study by DNV (Det Norske Veritas) asked grid providers how much it would cost to upgrade the grids with ferry connections to be able to supply the right demand. The results are displayed in Figure 8.1 [77]. The investments are substantial, as some are estimated to cost above 40 million NOK. An effective solution to solve this is to install an onshore battery energy storage system. This is tested at some ferry quays in Norway. With a battery on the dock, the energy can be drawn from the grid at a constant low power. This way the grid does not have to be built for the large power capacity needed for the spikes of power consumption by the ferry charging. This concept is also known as a virtual grid.

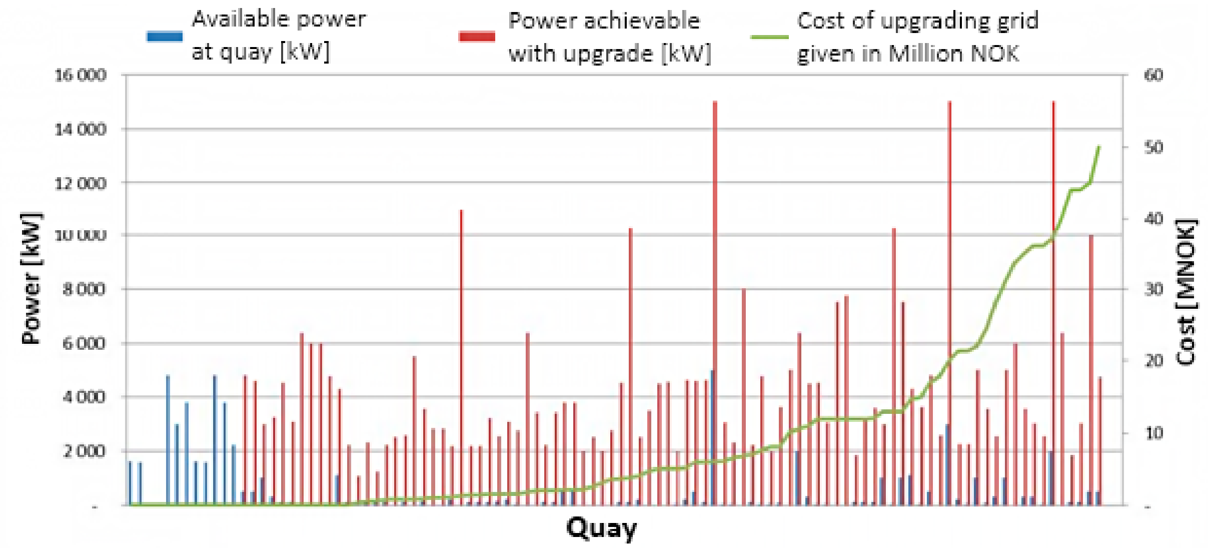


Figure 8.1: Cost of upgrading the grid at different quays achieving the necessary power [77].

8.3 Electric Charging

There are several ways one can charge an electric ferry. The charging can either be an alternating current (AC) or a direct current (DC). The transmission of energy can happen by physical contact using a plug or a pantograph, or wirelessly with induction. Induction will only be available with AC, while plug-in and pantograph charging works for both AC and DC. A 3-phase 400 V AC plug will suffice for the charging of most small electric fishery and leisure boats. This is also a standard system available in most industrial facilities. However, ferries require more energy and usually operate with a limited docking schedule, and a system this size may not deliver enough energy. Devoted infrastructure is often established, and some options dedicated to charging a ferry will be reviewed. [78]

8.3.1 Charging

Induction allows for transferring energy between two coils without physical contact. This is beneficial considering the brief time ferries usually spend at the dock. The ferry can begin the charging procedure as soon as it enters the dock, shortening the time it takes to begin the charging of the batteries. The ability to charge without direct contact helps reduce maintenance costs concerning wear and tear caused by physically connecting charging components. Induction charging also avoids exposure to saline weather conditions, further reducing maintenance and material costs. [79]

The efficiency of an induction charger is rarely less than 1 % of the efficiency of a plug-in charger, according to Frode Jenset at Wärtsilä. Economic losses will be in the ballpark of 40 kr each day, which can be neglected given the benefits of induction charging. However, with plug-in charging, it is possible to charge the ferry with DC, bypassing inverters and rectifiers needed for induction charging. This will reduce efficiency losses as well as infrastructural costs.

8.3.2 Efficiency

Jon Are Suul, an Adjunct Associate Professor in control of marine power conversion systems at the Department of Engineering Cybernetics at NTNU, had the following paraphrased response when asked about which system is better:

"A standardized solution for induction is not yet established, and there are several systems utilizing DC charging. Comparing the efficiency is therefore more complex. One can however assume a well-designed induction system will have an efficiency of 95 % from the onshore battery to the vessel battery. (An efficiency of 97 % may also be achievable) If a DC system requires galvanic isolation, then the efficiency will be closer to the value of an induction system. A DC-DC converter with galvanic isolation keeps the output and input mechanically separated [80]. Without galvanic isolation, a simple DC-DC converter supplied with a DC plug may achieve an efficiency of 98 %. This number is however based on pure speculation, given the characteristics of simple DC-DC converters."

Given this statement, an approximation of an efficiency of 97 % will be used for further evaluation of both systems.

8.4 Mooring

Maintaining a somewhat static range between the ferry and the onshore charging system will be crucial for both an induction system as well as for a plug-in system. An induction system can experience a varying current and voltage if the transmission distance changes, this may cause damage to the onboard electronics. For a plug-in solution, automatic connection systems will break if the vessel deviates from the berth. The vessel crashing into the dock must also be avoided. All these complications can be solved using a mooring system, such as the one shown in Figure 8.2. [79]

Figure 8.2: Cavotec MoorMaster and Wärtsilä's induction system in action on MF Folgefonn [81].

In Figure 8.2, the mooring system can be observed making contact with MF Folgefonn. The system developed by Cavotec relies on a vacuum in order to keep the vessel steady. This system is expensive and requires space and a solid foundation on the dock. Some docks may not be eligible for a mooring system. The vessels will then have to utilize the thrusters, this will result in some energy consumption from the onboard ESS.

8.5 Battery Swap

Another way to charge an electric ferry is to swap the battery every time it is at the quay. This will require two or three batteries where one is powering the ferry while the others are charging on land. With two batteries taking turns, the batteries need a sufficient capacity to cross two times and only use one quay for battery swap. With three batteries there will always be a battery at each quay charging while one is utilized by the ferry. This method gives the batteries a longer time to charge and reduces the strain on both the grid and the batteries. This makes the solution viable in areas with a weak grid. The ability to charge with a lower C-rate due to the longer charging time available is also beneficial to the cycle lifetime. A system like this will however require a large infrastructure at the quay as well as more batteries than what is originally required. A product called SHIFTR, displayed in Figure 8.3, developed by SEAM and Norled is a form of battery swap concept. They claimed that it can swap two battery packs in about three minutes. There is a charging station at the quay with a long arm that replaces the batteries. The batteries on the vessel are placed on top of the ferry. [82]

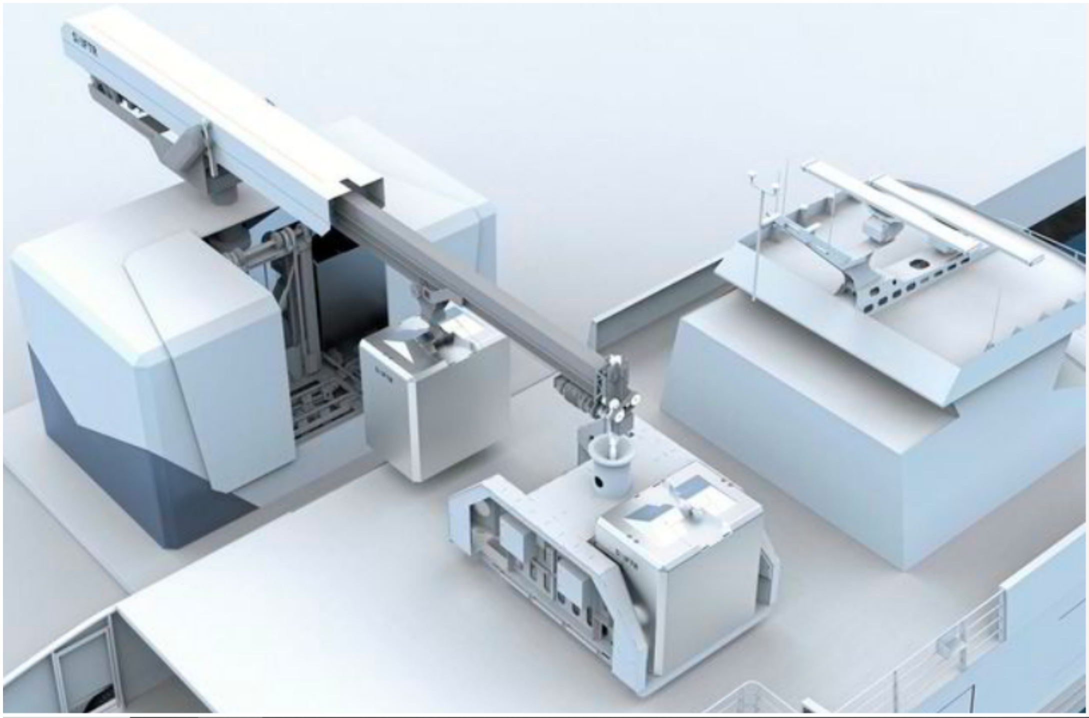


Figure 8.3: SHIFTR swapping batteries on a ferry [82].

8.6 Electrolyte Change

In addition to conventional charging methods such as plug-in and induction, there is also the possibility for the RFB electrolyte to be changed. This can be done either by changing the electrolyte through a tube or replacing the tanks of electrolyte by bringing in new ones with a truck. Bryte Batteries and Boreal have looked at these solutions in a study from 2023 [83]. The tube solution was deemed not fast enough to meet the required charging time. The truck solution seems more promising. With this method, there will be one RFB on the quay that charges the electrolyte and one RFB to power the ferry. When the ferry is at the quay the charged electrolyte tanks are driven onto the ferry by truck. The discharged electrolyte tanks are removed and placed to charge while the fully charged ones are connected to the ferry. It is only the tanks of electrolytes that are moved and not the whole battery. A common truck is capable of carrying 10-12 tonnes, which will generally be enough for this solution. This is investigated later in the thesis. [84]

8.7 Corvus ORCA ESS Battery

Corvus is among the top distributors of energy storage systems (ESS) for Norwegian ferries. One of their most popular ESS is based on the Orca ESS modules, specifications for this module and pack are given in the Appendix B. The data for a module is given in Table 8.1.

Table 8.1: Orca ESS module specifications [85].

Chemistry	Lithium ion NMC / gaphite
Energy	5.6 kWh
Capacity	128 Ah
Weight	58 kg
Maximum Voltage	50 VDC
Continuous C-rate charge/discharge	3C/3C
Single Pack Range	38-136 kWh / 350-1200 VDC

Multiple modules are connected in arrays forming a pack. A single pack can be manufactured with a range of 38-136 kWh with a voltage between 350-1200 VDC [85]. A car ferry usually has a DC-bus voltage in the range of 600-1000 VDC. A simplification of a system with a DC-bus voltage of max 1000 VDC will require a pack of 20 modules in series. This pack will have an energy capacity of 112 kWh. 9 of these packs will have to be connected in parallel in order to create a system capable of storing 1008 kWh, this is a total of 180 modules. The pack can deliver a C-rate of up to 3C and by utilizing equation 3.2, a battery with a capacity of 128 Ah will be able to charge with a current of 42.7 A.

In an email from Michael Blume, Manager of Innovation & Technology at Teknotherm, it is stated that one module is assumed to generate around 20 W at normal operation and a maximum of 300 W when discharging. A 1008 kWh ESS will result in a heat generation of approximately 3.6 kW at normal operation and 54 kW at discharge. Sufficient heat dissipation is crucial in order to maintain a low cell temperature. The LIBs are guaranteed by the supplier to operate at a constant 20 °C, ensuring a lifespan of 10 years. Operating them at a higher temperature than 20 °C reduces this lifespan. The minimum operation temperature for the lithium is 10 °C and at this temperature, the efficiency will be lower.

Figure 8.4 is an example of an Orca ESS configuration distributed by Corvus. In order to keep the modules cool, an air intake is present at the bottom of the cabinet. The cabinets are installed with certain safety features such as Passive single-cell Thermal Runaway (TR) Isolation and systems beyond what is required for TR gas venting. [85]

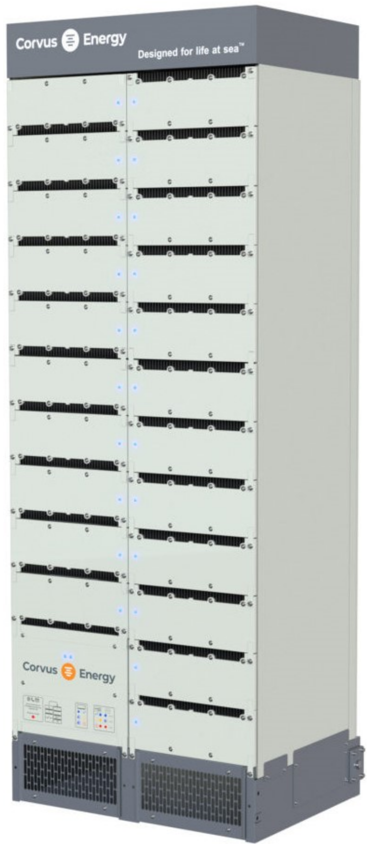


Figure 8.4: Corvus Orca ESS Battery example cabinet [85].

These features will affect the overall energy density of the battery pack. NMC lithium batteries are expected to have a theoretical energy density between 150-220 Wh/kg, but this only includes the active components of a battery. The Orca ESS battery pack claims to have an energy density of only 77 Wh/kg. Prioritizing safety rather than energy density is especially important when considering the battery pack may operate on a vessel.

9 Battery Safety

DNV-GL, now DNV, published a report in 2017 called ”Considerations for ESS Fire Safety”. Numerous tests were executed on different types of batteries, and some of the results from the report will be applied to further understand the difference between lithium NMC (called NCM in the DNV report) and vanadium-based ESS. The potential temperatures a system can reach during failure will be analyzed first. The batteries tested in Figure 9.1 are denoted by their chemistry, manufacturer, and SoC.

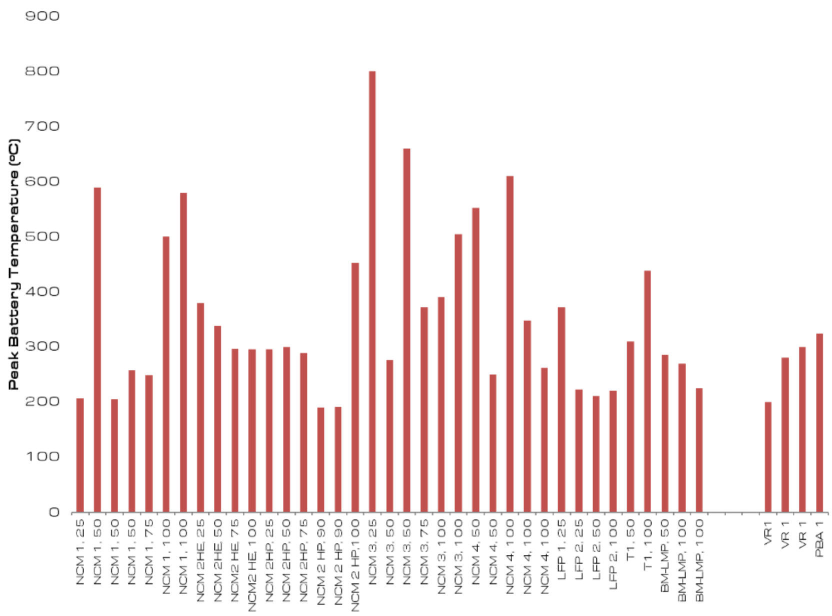


Figure 9.1: Peak battery temperature at failure for types of batteries and at different SoC [86].

The x-axis in Figure 9.1 are given further specifications in Table 9.1 below.

Table 9.1: Elaboration off the x-axis in Figure 9.1.

Denotion	Chemistry	Manufacturer
NCM 1	Li-ion NCM	LG Chem
NCM 2 HE	Li-ion NCM	Samsung SDI
NCM 2 HP	Li-ion NCM	Samsung SDI
NCM 3	Li-ion NCM	Kokam
NCM 4	Li-ion NCM	Electrovaya
LFP 1	Li-ion $LiFePO_4$	BYD
LFP 2	Li-ion $LiFePO_4$	XO Genesis
T 1	Li-ion LTO	Toshiba
BM-LMP	Li-ion BM-LMP	C4V
VR 1	Vanadium Redox	UET
PBA 1	Lead Acid	EnerSys

The temperature for a VRFB is plotted to the right in Figure 9.1. The highest temperature measured for the VRFB is 300 °C, this temperature was reached as a result of the heat applied during the test. The highest temperature plotted comes from the NCM 3 at 25 % SoC, it reached a temperature above 800 °C. Any battery using polymer cases is flammable and will act as fuel for a preexisting fire and a source of toxic emissions. The report concludes that vanadium and lead acid electrolytes are not flammable. These electrolytes do however create a toxicity hazard when heated. The vanadium electrolytes emit hydrogen chloride (HCl) and Hydrofluoric acid (HF), with HCl occurring in greater quantities. HCl is a common toxic emission factor for all the batteries tested and it is also flammable as gas. One of the main concerns with LIBs ESS installed within structures is the production of flammable gases during TR and cell venting. The rate of gas release can potentially exceed the capacity of the exhaust system. Some general numbers concerning ventilation are presented in Table 9.2. These numbers may be outdated and describe a system in a building requiring a moderate C-rate. [86]

Table 9.2: Implications based on extrapolated findings from testing [86].

System size (kWh)	System Chemistry	Estimated Mass (kg)	Energy density (Wh/kg)	Estimated Room Size (m^2)	Ventilation Requirement (m^3/min)	(m^3/min) / (m^2)
1000	Li-ion	6 666.7	150	28	3.3	0.12
1000	Vanadium Redox	20 000.0	50	139	9.9	0.07

A LIB system with fast charging capabilities will have a lower energy density than what is evaluated in the table. The energy density will affect the room size, which will also affect the ventilation requirements, given in cubic meters per minute (m^3/min). The volume of a room dictates the ventilation rate, batteries in a larger room will have fewer Air Changes per Hour (ACH) requirements and the volume of the room will act as a buffer for the peak emission rate. The ACH is often determined by the HCl emissions associated with the battery. An ACH rating of 3 - 4 would be appropriate considering the size of the testing facility. It was discovered that the vanadium would suffice with an ACH rating of 0.25. [86]

Major distributors of batteries often offer ESS typically housed in shipping-container-like structures with integrated BMS, ventilation and cooling, and fixed fire suppression. The chemistry of the ESS in these structures will dictate the specifications of the technical features. [86]

9.1 Battery Hazards

Table 9.3 gives a direct comparison between the battery types when considering risks. An elaboration of the different risk categories will follow.

Table 9.3: Typical Hazards by ESS Type [86].

Risk	Lithium-ion	Flooded Cell	Sodium Sulfur	VRB Flow Battery
Voltage	X	X	X	
Arc-Flash/Blast	X	X	X	
Toxicity	X	X	X	X
Fire	X	X	X	
Deflagration	X	X		
Stranded Energy	X	X	X	

Electrical Shock/Arc Flash

Most ESS cannot be shut down if the system is damaged as this will cause a risk of electrical shock if the system is interacted with. Damaged batteries with stored energy unable to safely discharge are also referred to as batteries with ”stranded energy”. If a system operates at voltages above 100 V, then arc flashes will also become a potential hazard. A flow battery system is dependent on pumps circulating the electrolytes and turning off the pumps will ensure the ESS is completely shut off. [86]

Toxicity

Toxicity risks may be present in aqueous electrolytes or from off-gassing produced by overheating aqueous or vaporized electrolytes, scenarios involving fire may also cause the batteries to generate toxic gas. [86]

Fire/Deflagration

When lithium-ion cells experience temperatures exceeding 80 °C, they may generate heat more rapidly than they can release it, leading to a potential TR hazard. Such a scenario can arise from various forms of mistreatment, including thermal stress, physical damage, or flaws in manufacturing. TR fires from LIBs can reach temperatures exceeding 1000 °C, releasing vaporized flammable and toxic electrolyte gases through forceful venting. Traditional gas or aerosol-based fire suppression systems are not advisable for use in LIB setups due to doubts about their effectiveness in halting TR progression or complete combustion. Cooling, rather than oxygen reduction, is deemed necessary to interrupt the TR or combustion cycle. [86]

In confined or enclosed spaces, deflagration risks may arise when significant quantities of flammable gases reach both the explosive range and auto-ignition temperatures, particularly considering the presence of ignition sources inherent to the electrical components. Given the compact arrangement of numerous lithium-ion cells within modules, averting TR is critical, constituting one of the primary roles of a battery management system. [86]

9.2 Corvus BOB Containerized Battery Room

The distributors of the Orca ESS modules also offer a complete system housed inside a 10 ft (3 meters) or 20 ft (6 meters) container portrayed in Figure 9.2. The risks previously addressed are all accounted for. The container is fitted with cooling-, firefighting-, and TR exhaust systems attuned to the characteristics of the Orca battery modules. [87]

Figure 9.2: 20 ft. Corvus BOB [87].

10 Case Forvik - Boost Battery on Shore

Chapter 8.2 mentions that many ferry crossings are located in areas where the existing power grid is too weak to provide charging capabilities for ferries directly. This part will evaluate if a flow battery can be used as a power bank at a dock. Boreal Sjø has provided insight into their dock at Forvik, Nordland, as it has a weak power grid. This part will investigate the current infrastructure, and evaluate the possibility of utilizing a VRFB instead.

10.1 Background for the Forvik Ferry Dock

Forvik is the southern endpoint of the Tjøtta-Forvik ferry line. The distance between Forvik and Tjøtta is 17,4 km and the ferry trip is approximately 50 minutes, operated by the electric MF Stokkafjord. Sometimes the route includes stops at ports along the way, in which case the trip is 70 minutes. This longer route is operated by the diesel-powered ferry called the MF Tjøtta. Both ferries are owned by the Norwegian ferry operator Boreal Sjø. The map in Figure 10.1 shows the direct route with Forvik at the bottom end of the line. [88], [89]

Figure 10.1: Map of ferry crossing [89].

MF Stokkafjord has LIBs installed and runs on electricity as long as the conditions allow it. The carrying capacity for MF Stokkafjord is 60 PBE and 249 passengers. MF Tjøtta has a capacity of 20 PBE and 200 passengers. [90]

10.2 Forvik Ferrydock

The dock facilities at Forvik are owned by Nordland County but are operated by Boreal Sjø during their contract period. The dock facilities at Forvik consist of a technical charging building, a battery building, and charging towers. Figure 10.2 shows the dock. [88]

Figure 10.2: The ferry dock in Forvik. Provided by Boreal.

The ESS at Forvik has two LIBs installed to boost charge MF Stokkafjord every time it docks as MS Stokkafjord is the only electric ferry operating the crossing. On a normal weekday, MS Stokkafjord docks at Forvik five times. The ferry is also charged at Tjøtta on the other end of the crossing, but this study will only look into Forvik. Boreal Sjø has provided the following data about the ESS at Forvik dock shown in Table 10.1.

Table 10.1: Information about Forvik ferry dock. All numbers are provided by Boreal sjø.

	System on shore
Grid voltage	600 V AC 3 phases
Grid power	The grid can deliver 350 kW
LIB installation	Two battery packs of 672 kWh Total capacity of 1345 kWh
SOC and C-rate	The batteries operate at 26-80 % SOC C-rate up to 3
Charge power to ferry	2500 kW from LIBs + 350 kW from grid 2850 kW total
Charge voltage	750 - 950 V DC
Charge time	10 to 15 minutes

Boreal states that the batteries are over-scaled to prevent degradation and to extend their lifetime. At the time of installation, when the LIBs are new, the operation only requires 56 % DoD. This means that the available energy from the batteries is 750 kWh when DoD is considered. As the batteries age, they will require a higher DoD of up to 73 % at the end of life. Figure 10.3 is a charge profile of the ESS at Forvik as it was intended to operate from the design phase. It is observed that the unit discharges five times throughout the day with a charging power of 2850 kW. When charging, the battery and grid together provide a power of 2850 kW to the ferry. The state of charge never drops below 26 % or rises above 80 % as it is meant for the beginning of life.

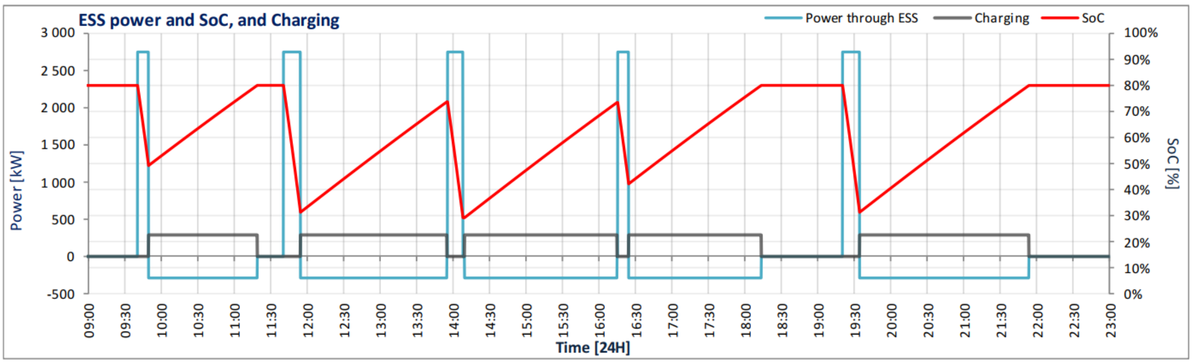


Figure 10.3: Charging profile for the LIB onshore at Forvik. Provided by Boreal.

The ferry needs approximately 600 kWh of energy every time it docks, depending on the weather conditions. Arne Brynlund from Boreal also suggests that the yearly energy consumption of the technical building at Forvik is approximately 70 000 kWh, with a noticeable uptick during the summer months. The energy consumption is mainly due to the cooling of the batteries, hence a higher consumption during warmer weather.

Figure 10.4 illustrates the floor plan for the technical building. The batteries are isolated from the rest of the ESS. Given the calculations made in chapter 8.7, the ESS at Forvik will require 240 Orca modules, this will result in a passive heat generation from the modules of 4.8 kW and a peak heat generation during discharge of 72 kW.

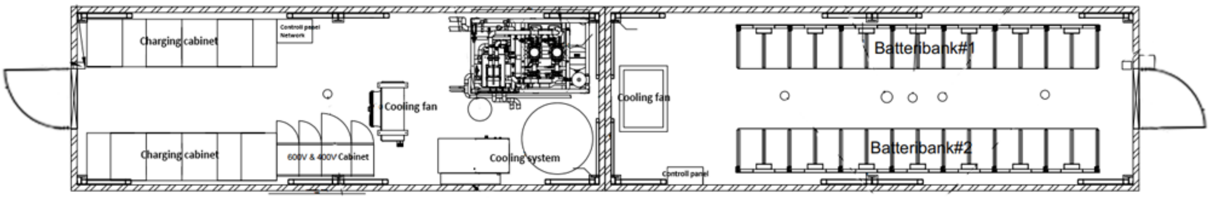


Figure 10.4: Floor plan for the technical building. Provided by Boreal.

10.3 Assumptions

In the following calculations, the current LIB installation is compared with a hypothetical VRFB installation. The LIBs are as stated the Corvus Orca ESS. The efficiency of these batteries is not given in their datasheet in Appendix B, but it is however assumed to be 95 % as is the theoretical. For the VRFB the DoD is assumed to range from 3 to 80 %. The AC/AC efficiency for Visblue's module is 67 % as seen in appendix A. However, since the module only needs to deliver DC to the charging system, the DC/DC efficiency of 87 % is more relevant and is therefore assumed. Bryte batteries have assured that the use of pumps is accounted for in the efficiency as well.

As explained in chapter 4.7 when a high power output is required from a flow battery it will determine the C-rate and in turn the electrolyte tank volume. In this study, the C-rate will be assumed to be 1/3 as informed by Bryte Batteries. For an ESS in this order of magnitude, there are a lot of other components like control systems and such. Since the purpose of this study is to compare RFBs to LIBs as a boost battery on shore, all surrounding components like control systems or the charging tower will assumed equal in each case. This way, the only system losses that will be included will be the batteries themselves. However, because RFBs require little to no cooling, the energy consumption for the technical building will be neglected whereas for the case of the current ESS with LIBs, the consumption will be included.

10.4 Equations

The battery's weight based on needed capacity and energy density can be calculated using equation 10.1.

$$Weight\ (kg) = \frac{Capacity\ (Wh)}{Energydensity\ (Wh/kg)} \tag{10.1}$$

Losses due to the efficiency of a system can be found using the given efficiency η and the output energy E_{out} over a given time. equation 10.2 shows how the losses can be calculated.

$$Losses\ (Wh) = \frac{E_{out}}{\eta} - E_{out} \tag{10.2}$$

Flow batteries and LIBs each have their typical C-rate. If the needed power capacity is very high, the C-rate can become a limiting factor of how large the energy capacity of the batteries must be. The required capacity can be calculated with the following equation 10.3.

$$Capacity\ (Wh) = \frac{Batterypower\ (W)}{C - rate\ (h^{-1})} \tag{10.3}$$

10.5 Results

Based on the timetables given in Appendix C and D, the total number of charges in a year can be calculated, as shown in Table 10.2.

Table 10.2: Charges done at Forvik for one year.

Day	Number of days	Number of charges per day
Weekday	260	5
Saturday	39	0
Saturday during summer	13	4
Sunday	39	2
Sunday during summer	13	4
Total(year)	**364**	**1482**

The total amount of charges is approximately 1482. With an average of 600 kWh of energy transferred to the ferry for each charge, a total of 889 200 kWh is effectively transferred in a year. With this value, the yearly system losses with LIB or VRFB can be calculated with equation

10.2, and the results are shown in Table 10.3.

Table 10.3: Yearly system losses due to efficiency.

System Losses	
LIB (MWh)	VRFB (MWh)
46,8	222,5

Since VRFBs typically operate with a C-rate of around 1/3, the battery capacity needs to be larger due to the power requirement of 2.5 MW. This capacity can be calculated with equation 10.3 and the results are shown in Table 10.4.

Table 10.4: Capacity needs based on C-rate.

Capacity need	
LIB (kWh)	VRFB (kWh)
1345	7500

10.6 Analysis

Since the battery systems are installed on land, the energy density and total weight of the systems are less relevant. This analysis will therefore look at other aspects for comparison. The values in Table 10.3 show that the yearly system losses for the current LIB installation are 46.8 MWh. The cooling need of 70 MWh adds to the yearly total loss of 116.8 MWh. This is still only 52 % of the losses with the VRFB system.

Table 10.4 shows that the VRFB installation needs to be scaled to 7500 kWh to meet the power requirement to charge the ferry. The reason for this high number is due to the significantly lower C-rate for VRFB than for the LIB. This would mean that the electrolyte tanks would be volumetrically very large and certainly much larger than what the current technical building can fit.

The SoC profile in Figure 10.3 is based on a capacity of only 1345 kWh. The profile suggests that there is no need to charge the LIBs at night. Since a VRFB system must be scaled to 7500 kWh to meet the same power requirements, a large portion of the capacity would be unused. However, an ESS with a higher energy capacity could be advantageous. The current installation is not capable of extracting more energy from the grid and can only deliver 600 kWh five times a day. With the extra capacity of a VRFB system, it could potentially be capable of storing more energy and consequently provide more charges to several ferries. Figure 10.5 shows a simplified charge profile of such an installation.

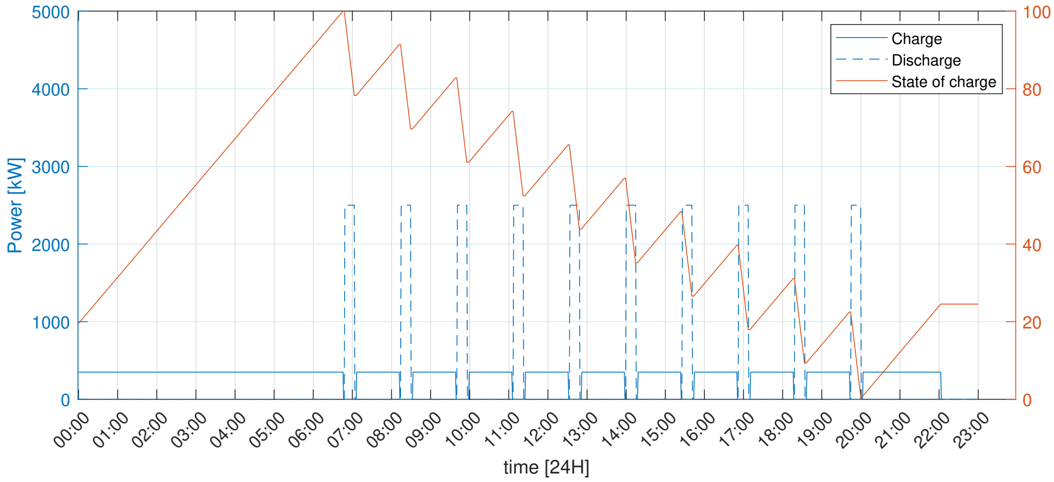


Figure 10.5: A rudimentary charging profile for Forvik utilizing a VRFB system. Made with MATLAB.

The charging values are the same as assumed for the LIB system with a grid power of 350 kW and an output charge power of 2500 kW while every discharge lasts 15 minutes. The VRFB in this scenario is also charged during the night and can accumulate more energy. It is calculated such a system can deliver 700 kWh 10 times throughout one day if 350 kW is drawn continuously from the grid except for 2.5 minutes before and after every discharge. In this scenario, the maximum capacity just before the first discharge at 7 o'clock is 3.1 MWh. The VRFB would have to be scaled to 4 MWh when DoD is considered. This means that with the C-rate of 1/3 and the needed capacity of 7.5 MWh, it would still be a large amount of unused capacity.

11 Case Study Valset-Brekstad

This part examines the possibilities of installing flow batteries as the power source on ferries. To do this, a simplified case study of the crossing between Valset and Brekstad in Trøndelag, Norway has been done. Different solutions for incorporating flow batteries powering the ferry will be explored and compared to each other to find the best result.

11.1 Background for the Valset-Brekstad Ferry

Valset-Brekstad is a ferry connection in Trøndelag between Brekstad in Ørland and Valset in Orkland which crosses the outer of Trondheimsfjorden. The distance between the two docks is 5,7 km. The Ferry company Fjord1 has operated the ferry connection since 2019 with the electric ferries MF Austrått and MF Vestrått displayed in Figure 11.1. The ferries travel from each dock every 30 minutes Mondays to Fridays and every hour on Saturdays and Sundays. The travel duration is 25 minutes from dock to dock. Five minutes is used at the docks to load and unload cars and people and to charge the batteries. [91], [92]

Figure 11.1: The electric ferry MF Vestrått [92].

Both the MF Austrått and MF Vestrått operate the same route, shown in Figure 11.2. A Corvus Orca ESS with 1 MWh supplies power to the Scania DI16 90M electric motor. The motor has a rated power of 511 kW. The ferries are capable of loading 50 PBE and 200 passengers. The maximum load of both vessels is 2100 tonnes. [92]

Figure 11.2: Map of the ferry route Valset-Brekstad [93].

11.2 Technical Assumptions

The values for the VRFB are based on the VisBlue datasheet in Appendix A. The values for the LIB are based on the Corvus Energy ORCA battery [85]. The values for the ZBFB are from the research done by Fan Shi in [18]. As mentioned in chapter 8.7 the energy density of the Corvus ORCA battery is not as high as the theoretical. Due to the importance of safety infrastructure, the energy density is reduced to approximately 50 % of the lowest theoretical value. The same will most likely be the case for the RFBs as well. As RFBs have never been used on a ferry before it is unknown what infrastructure is necessary. However, the water-based electrolyte of the RFBs makes them safer compared to the LIBs concerning fire hazards. A leakage in the RFBs would be dangerous, but it would not have the ability to spread to the rest of the battery and vessel like a fire. It is consequently assumed that the additional safety infrastructure for

RFBs will not reduce the energy density to the same degree as for LIBs. A reduction in energy density of 15 % is therefore assumed. The energy density of the VRFB is decreased from the theoretical value of 30 Wh/kg to 25.5 Wh/kg. For the ZBFB the energy density is reduced from 65 Wh/kg to 55.75 Wh/kg.

In the VisBlue datasheet, it is stated that their VRFB has a DoD of 3-80 %. This will be assumed as the DoD for the ZBFB in these calculations as well. The round-trip efficiency of the flow batteries is assumed to be 87 % for VRFB and ZBRF. The LIBs are assumed to have a DoD of 60 % and an energy efficiency of 95 %. The Valset ferry uses a plug-in system as a charging solution. The efficiency of the plug-in charger is assumed to be 97 %. The weight of one PBE is assumed to be 1300 kg with 4 passengers. All relevant parameters can be found in Table 11.1.

Table 11.1: Parameters of the LIB, VRFB, and ZBFB.

Parameter	Li-ion	VRFB	ZBFB
Energy density (Wh/kg)	77	25.5	55.75
Efficiency(%)	95	87	87
Capacity range for extended life (% SoC)	20-80	3-80	3-80
Expected lifetime (Years)	10	25	10-20
Number of cycles	2000	20000	2500
Self discharge	Yes	No	No
Risk for thermal runaway	Yes	No	No

11.3 Energy Consumption

To perform calculations of the battery, it is necessary to know how much energy is consumed in each crossing. As it was not possible to obtain this information from the operator of the ferry, a regression analysis was carried out by using other ferry crossings with known energy consumption. The data is gathered from a report done by DNV [77]. 24 different ferry crossings were included in the analysis. There were, however, not enough crossings with exactly 50 PBE to do the analysis. Therefore, the ferries included range from 36 to 80 PBE. The analysis was carried out by using Geogebra and is displayed in Figure 11.3. The regression yields the linear expression $y = 39.06x + 82.5$. The Valset-Brekstad crossing is 5.7 km which results in an energy consumption of 305 kWh based on the regression.

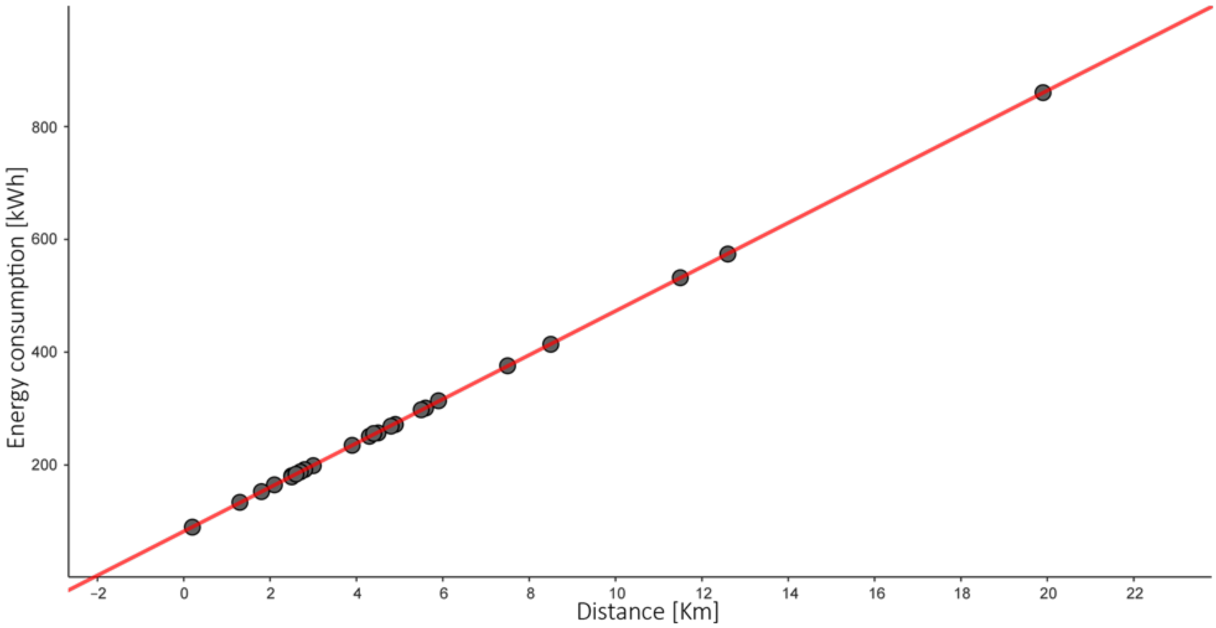


Figure 11.3: Regression analysis as a function of distance and energy consumption. Data from DNV [77].

11.4 Flow Battery Ferry

The weight of the LIB packs installed in the ferries today has a total weight of 13 024 kg and an energy density of 77 Wh/kg. The capacity of the battery is 1 MWh. By using equation 10.1 the weight of VRFB and ZBFB can be calculated if they have the same capacity as the current LIB. This is shown in Table 11.2.

Table 11.2: Weight requirement of different batteries for a 1 MWh on a ferry.

Chemistry	Li-ion	VRFB	ZBFB
Weight (kg)	13 024	39 215	17 937
Capacity (MWh)	1	1	1

By assuming that the weight of the battery should stay the same as it is today, at 13 024 kg, the energy capacities for the VRFB and the ZBFB can be found by using equation 10.1. This is shown in Figure 11.3.

Table 11.3: Capacity of different batteries with a fixed weight.

Chemistry	Li-ion	VRFB	ZBFB
Weight (kg)	13 024	13 024	13 024
Capacity (MWh)	1	0.33	0.73
Capacity with DoD (MWh)	0.6	0.25	0.56

The ferries MF Austrått and MF Vestrått have a capacity of 50 PBE. According to a survey from 2017, an average weight of 1 PBE can be assumed to be 1300 kg, [94]. Changing from LIB to VRFB will increase the weight of the battery by 26 191 kg to 39 215 kg, as shown in Table 11.2. If nothing else is done to reduce the weight of the ferries the capacity has to be reduced by 20 PBE (20 normal cars and 80 people). That equals a cargo capacity loss of 40 %. Changing the battery from LIB to ZBFB will increase the weight of the battery by 4913 kg to 17 937 kg as shown in Table 11.2, which equals the same as approximately 3.7 PBE. This equals a cargo capacity loss of 7 %.

Analysis

By using the battery weight as the major factor for switching from a LIB to an RFB, the ZBFB is just a little bit heavier and should therefore be considered. Switching to a VRFB would increase the battery weight significantly and would reduce the cargo capacity as mentioned by 16 normal cars and 80 passengers, making it a much less attractive option than ZBFB. There may be other options to reduce the weight of the ferries so that the cargo capacity can be maintained, but for now, it is assumed that it is not.

Ferry companies have expressed that the PBE capacity is one parameter they want to maintain. By keeping the same weight of the battery on the ferries the ZBFB would still be very suitable with its battery capacity of 0.73 MWh. The VRFB would not be suitable with a battery capacity of 0.33 MWh. The estimated energy consumption of one ferry crossing was 305 kWh. Even though it is possible to use a higher DoD on the VRFB, 0.33 MWh is barely enough energy for one overpass. When considering bad weather conditions, needed buffer capacity, and other uncertainties, it is clear that it is not enough. The ZBFB on the other hand could be a viable solution. If a DoD of 60 % is assumed for the original LIB capacity of 1 MWh, the true capacity of the LIBs is only 0.6 MWh. According to the datasheet from VisBlue, their VRFB has a DoD from 3-80 %. This is also assumed to apply to ZBFB. When this is considered the true capacity of the ZBFB is 0.56 MWh.

11.5 Flow Battery on Shore

The following part will investigate the possibility of using a flow battery as a power bank in this scenario. Information about the power grid at Valset or Brekstad is not obtained, but it is assumed that such an installation would be useful to either relieve the power grid or to increase the power capacity.

Using an RFB on shore and LIB on the vessel will lessen the required power from the grid, but it will also increase the total required energy. This is because the energy would flow through another battery system with its round-trip efficiency before it reaches the batteries on board. To know what power a buffer battery has to be charged with it is necessary to calculate the total energy consumption of the ferry. On weekdays when most departures occur, there are 31 departures from each quay. There will be batteries on both quays, but only one quay will be studied here as the energy requirement will be the same on the other one. Every crossing requires approximately 305 kWh, which results in a total of 9455 kWh of energy consumption throughout the day per ferry before any losses are accounted for. The ferry has a 7-hour brake during the night and the 9455 kWh of energy has to be delivered during the 17 hours of operation.

There will be energy losses in multiple parts of the process of transferring energy from the grid to the ferry. Losses will occur in the LIB and the plug-in charger. These losses will always be present. Additionally, there will be losses in the RFB. The losses are displayed in Table 11.4.

Table 11.4: Energy losses in 24 hours of operation with flow battery on shore.

	Losses(kWh)
LIB on ferry	498
Plug-in charger	307
Flow battery on shore	1533
Total	**2338**

The total energy demand is 11 793 kWh per ferry every day. Supplying 11 793 kWh in 17 hours yields a constant charging power of 694 kW. Because of the low round-trip efficiency of the RFB, there is a lot of energy loss. It is however necessary if the grid can not supply a high enough power. By charging directly from the grid it is necessary to consume 305 kWh in 5 minutes. This is equal to charging with a power of 3660 kW. The power drawn from the grid is reduced by approximately 5.3 times. Upgrading the grid to be able to supply 3660 kW might be more expensive than paying for the energy loss.

Analysis

In the case of a LIB on the vessel and an RFB on shore, it is not pivotal what kind of RFB is on the shore. If there are any space restrictions on the quay the ZBFB is favourable. If not, the VRFB might be the better option due to the longer lifetime. As mentioned in Chapter 4.7

a flow battery can only charge with a C-rate of 1/3. As calculated earlier the ferry requires a charging power of 3660 kW. This means that the flow battery on land must have a capacity of approximately 11 MWh. If a ZBFB is to be the power source on a ferry it would not be possible to charge this with induction or plug-in charging because this would require the battery to charge with a power of 3660 kW. Due to the assumed C-rate for RFBs in this thesis, it would end up in the same case as the flow battery onshore where it was overscaled to 11 MWh.

The solution to this is to charge the ferry by changing the electrolyte of the flow battery in the ferry. This can be done by having a flow battery both on land and on the ferry. The charged electrolyte in the battery on land replaces the discharged electrolyte from the ferry. The flow battery on shore would naturally also have to be a ZBFB. It would be extensive to replace all the electrolytes as only about 0.3 MWh is consumed, and the capacity on the ferry is 0.56 MWh when DoD is considered. To move the whole weight of the 13 024 kg battery on trucks would not be possible. It would be more practical to change only 0.4 MWh of the electrolyte. This gives the electrolyte on land more time to charge as well because it could be cycled. The weight of 0.4 MWh would be 7442 kg. This is well inside the amount a truck can carry. Alternatively, a solution similar to the SHIFTER battery swap could be considered where a crane is used to lift the tanks of electrolytes on and off the ferry.

12 Discussion

The main goal of this thesis is to investigate if flow batteries can be used on electric ferries or as a boost battery at the ferry docks. It is interesting to evaluate flow batteries as a potential solution for electrifying some of the remaining ferry routes and ferry docks in Norway. Figure 2.1 shows the expected developments, confirming the demand for battery technology in this sector. The flow battery will compete with LIBs, which is the technology used today. Different key factors will be discussed in this chapter, which will later come into play when a conclusion is drawn. A comparison of the battery technologies, concession time, environmental impact, charging technologies, battery safety, and economy will be elaborated. The results and analysis of our two case studies, case Forvik and case Valset-Brekstad, will also be an important part of the discussion in this chapter.

Environmental Impact

When it comes to the environmental impact of the different battery types, it seems that both VRFBs and ZBFBs could be a more sustainable option than LIBs based exclusively on the numbers extrapolated from Table 6.1 and Figure 6.1. The VRFB does not initially score better than the LIBs on all impact categories as shown in Table 6.1. It was later shown that reusing the electrolyte by 50 % would substantially reduce the environmental impact. From Figure 6.2 it is observed that Visblues VRFB outscored a standard LIB on all the different impact categories. It is noted that the CO_2 footprint of their VRFB is almost 2/3 less than for a LIB. It should be noted that this LCA was conducted by Visblue, who would be naturally very positively inclined towards VRFB technology. There are currently no LCA studies for ZBFB technology, but a potentially commercialized product would likely score the same or even better than a VRFB. Zinc and bromine are generally more accessible and less environmentally damaging to extract compared to vanadium and lithium. The environmental impact is one of the key evaluation factors in this thesis, and by the reports and data that have been analyzed, it seems that both VRFB and ZBFB score better than LIB on this key factor.

Economic Impact

Economic cost is a less researched subject in this thesis and will not be discussed thoroughly. Figure 8.1 gives an estimated cost for improved power at some quays in Norway. Batteries onshore will help reduce the amount of power necessary which in turn will reduce the cost. The economic cost is an important factor when deciding which battery technology is most suitable for a given application. This thesis has nevertheless deliberately avoided a full economic analysis of FB technologies due to a lack of tangible data and time. Based on reviewed sources, the price of a LIB for grid-scale energy storage is around 350-400 $/kWh, VRFB in the range of 264-713 $/kWh, and ZBFB with 428-478 $/kWh. Considering the maturity of the ZBFB technology, prices are likely to drop in the near future. For the VRFB, the variation in price makes it harder to compare it to a LIB. Only a simplified economic analysis is possible because of these uncertainties. As prices stabilize in the future, more credible results may be achieved.

Concession

The concession period for a ferry crossing in Norway is usually 10 years. This time aspect aligns well with the lifetime of LIB. However, 10 years is half the expected life period for RFBs. This means that if an RFB is used on a ferry or onshore, then the ESS should not be replaced after the concession period. A possible solution to this is to extend the period of concession for ferries if the company proposes the use of RFB technology in their solution. Alternatively, if the ferry company builds an infrastructure that lasts for more than 10 years, it will have priority when a new concession is put up for tender. Another possibility would force a company to buy the existing infrastructure. The ferry industry would probably not appreciate this solution because most companies have their own way of realizing projects. As mentioned in the introduction, the government is working on a support plan for charging infrastructure. This plan may help solve complications involving the responsibility of providing energy to the ferry. The government could also add incentives for infrastructure based on greener technology.

Safety Considerations

In Chapter 9, the DNV report made in 2017 concluded that vanadium-based electrolytes are not flammable. This means that the VRFB will not act as a heat catalyst, unlike some lithium-based batteries, as shown in Figure 9.1. A fire-extinguishing system with a high cooling potential will be the most efficient way of preventing a lithium fire from aggravating. Water is an effective coolant, but will conduct electricity, causing complications and additional hazards during a failure of batteries containing stranded energy.

Table 9.3 in chapter 9.1 helps distinguish the pros and cons when comparing different types of batteries. It is obvious that the VRFB is the safest option of all the batteries tested, due to the aquatic properties of the electrolyte and the ability to easily turn the ESS off. The vanadium-based electrolyte will however release toxic and flammable gasses when heated. This is a common hazard concerning batteries and only a sufficient ventilation system will solve the problem. The measured ACH number for vanadium was substantially lower than what many building codes have set as a standard. It is fair to assume a vanadium-based ESS will require less energy in terms of ventilation requirements and heat dissipation than a LIB ESS. Smaller ventilation systems will essentially mean a lower cost. Savings can also be achieved with regard to the fire extinguishing system because of the lack of fire hazards concerning vanadium. These savings will however not be significant when considering the price difference between the two systems as it stands today. A commercialized VRFB onshore system would most likely look somewhat like the Corvus BOB container. Containers are already a standardized shipping size. They can also be stacked on top of each other, granting a scalable system.

Case Studies

The case study of the Valset-Brekstad crossing has uncertainties connected to it as assumptions had to be made about the ferry and the battery technology. This is because Fjord1, the ferry company that manages the connection, was reluctant to share general and technical information directly. There is also uncertainty around the numbers concerning the batteries. Various tests have been conducted on flow batteries, yielding different results. In reality, it is hard to know exactly how they will perform. However, it is still interesting to study the results of the case study. When considering what type of battery could be on the ferry, LIB is the preferred choice in reality but in this case study the ZBFB was calculated to have the same energy capacity with the same weight, albeit based on many assumptions. Using RFB on the ferry is a possible solution. The VRFB is too heavy to be considered as a possible solution as it would be almost three times as heavy as the LIB. This causes a reduced carrying capacity of 20 PBE which is not sustainable for the ferry and car traffic. A capacity reduction of this magnitude will cause longer car queues and increase waiting times for users. For the ZBFB on the other hand, the calculations show that it is a viable option. The calculated energy capacity when assuming the same weight of battery was practically the same as the LIB, with only a 40 kWh difference favoring the LIB. This was because of the ZBFB's relatively high energy density and ability to use a broader DoD than the LIB.

The only possible way to utilize a flow battery on the ferry is to have a flow battery on shore as well. This is due to the challenges caused by conventional charging options in combination with the low C-rate of the flow battery. The high charging power caused by these charging methods causes the requirement for a flow battery of 11 MWh on the ferry. This is too big, and therefore not a possibility.

One way to bypass this is to charge the ferry by changing the electrolyte as explained in Chapter 11.5. One positive side of this solution is that the energy only flows through one roundtrip efficiency before powering the ferry. However, due to the poor energy efficiency of RFBs, there is a substantial energy loss compared to an all-LIB solution. Another advantage of this solution is the reduced strain on the grid. The battery on shore makes it possible to charge with a power 5.3 times lower than without one. This is an interesting concept in theory but has yet to be tested in real life. As mentioned earlier a challenge with most RFBs is the cross-contamination that reduces the functionality. More research and development is necessary before it can be considered a viable option.

Many ferry connections have difficulties in becoming electrified because of weak grid capabilities on-site. LIB banks designed to boost charge ferries while docking are already in use in several ferry ports today. A flow battery would be suited for this purpose as well due to fewer restrictions concerning weight and volume. In the case study done for the Forvik ferry dock, it was found that using a VRFB instead of the existing LIB would lead to twice as much yearly losses due to the efficiency even when the favorable DC/DC efficiency was assumed for the VRFB. With a VRFB, the energy capacity would also have to be scaled much larger than the LIB to achieve the required power of 2.5 MW. This is again due to the significantly lower C-rate for the VRFB compared to the existing LIB. The remaining arguments in favor of a VRFB over LIBs in this scenario will then rely on the mentioned advantages like higher cycle lifetime, less degradation, and a more environmentally friendly life cycle.

For the Forvik Ferry dock specifically, the existing batteries are only scaled to support five discharges a day where 600 kWh is delivered to the ferry each time. However, the extra capacity that comes along with the VRFB in the Forvik case can be utilized to support more discharges. It was calculated that with the power of the existing grid, it would be possible to support 10 discharges a day where 700 kWh is delivered every time. In this scenario, the VRFB would have to be scaled to 4 MWh which would still be much less than the needed 7.5 MWh due to the power requirement. Any future developments, that would allow a faster discharge rate without sacrificing efficiency, are necessary to avoid over-scaling due to high power requirements.

As briefly mentioned in Chapter 2, the number of electric buses and trucks would likely increase if they were granted access to the ferry charging infrastructure. The ferry company can either increase its number of crossings or utilize the extra capacity as a new revenue stream, offering charging to electric vehicles. It would indeed be possible to scale up the LIBs to do the same, but with the VRFB it wouldn't be necessary to consider DoD and degradation to the same degree. Flow batteries are probably more suited for stationary storage and they are easily scaled up in terms of capacity because of the electrolyte tanks being separate from the energy conversion.

13 Conclusion

The primary contribution of this thesis is to evaluate whether flow batteries can contribute to the ongoing electrification of ferries in Norway, either as the main power source on board or as a battery bank at ferry docks.

13.1 Electrification Of Ferries

The electrification of ferries has already come a long way in Norway using LIBs as the main power source. However, concerns are related to the safety and the environmental impact of LIBs. Flow batteries stand out as a good option to compete with the LIB because of their lower fire risk and better environmental impact. The concern of the RFB is the low energy density, especially the most developed VRFB. The weight of the VRFB necessary to obtain the required energy reduces the capacity of the vessel too much to be considered as an alternative, as proven in the Valset-Brekstad case study. However the ZBFB, with a higher energy density, has the potential to compete with the LIB due to the higher range of DoD. The capacity of the vessel with the ZBFB was slightly reduced in the Valset-Brekstad case study. With more research and development, and testing in practical scenarios ZBFB can become a competing solution to LIBs as a way of supplying power onboard a ferry.

13.2 Boost Batteries On Shore

If flow batteries can not compete as a mobile energy system, a stationary application might be more suitable. This thesis has investigated the possibility of using an RFB as a battery bank on a ferry dock. With the currently developed flow battery technology, it was found that it would yield significantly more energy losses compared to LIBs. The high power needed for such an installation would also be a challenge for RFBs as it could be challenging to obtain a high enough C-rate. To be able to provide the required power, the RFB energy capacity must be scaled up to potentially over what is necessary. Extra capacity for the battery bank on the ferry dock could be useful to employ the full potential of the existing power grid. The increase in capacity can also be utilized for ferry connections at locations with a higher amount of electric vehicle traffic as an available charging station. Further development in obtaining faster discharge rates without sacrificing efficiency could be desirable.

14 Further Work

The subject of flow batteries has many areas that are interesting to look more thoroughly into. Many of these areas are either not studied in sufficient depth or not included at all because of this project's limited time, resources, and available information. The following subjects should be investigated in the case of further work.

This thesis has performed a general study of several aspects of electrifying ferries and the possible usage of flow batteries. The case studies that have been done have calculated if the application of flow batteries would be viable in terms of energy and effect. It would then be relevant to investigate thoroughly how an application of a flow battery, either on board or as a boost battery on land, would perform in a more practical perspective. It is possible that flow batteries would present different challenges in comparison to LIBs. Flow batteries' operation depends on pumps and the reaction components are held in a specific temperature range. This could lead to challenges regarding response time.

The types of flow batteries focused on in this thesis have mainly been VRFB and ZBFB. It would be interesting to look deeper into some of the other flow battery technologies to see if they could be more suited for ferries. Some promising technologies that could be interesting to look further into are the nanoelectrofuel Flow Battery and the Aqueous Organic Flow Battery. The nanoelectrofuel flow battery has a potentially higher energy density than ZBFB while the aqueous organic flow battery has easily acquired components. Some of these could be compelling to apply for other ferry routes with different ferry sizes, travel distances, and weaker/stronger power grids on the docks than our two ferry cases, Valset-Brekstad and Forvik-Tjøtta.

It may be that other appliances are more suited for flow batteries than for ferries alone. Exploring the use of flow batteries on ferries in combination with various hybrid solutions, such as solar panels or hydrogen, could be of interest.

It could be interesting to compare lithium-based and flow-based battery technologies analyzing the cost per increased kWh, if given reliable data.

References

1. Nations U. The Paris Agreement. en. Publisher: United Nations. Available from: https://www.un.org/en/climatechange/paris-agreement [Accessed on: 2024 May 11]
2. Doyle J. Patent of Zinc-Bromine Flow Battery. 1880 Feb. Available from: https://patents.google.com/patent/US224404A/en [Accessed on: 2024 May 15]
3. Richard. A Brief History of Flow Batteries. en-US. 2017 Jun. Available from: https://blog.upsbatterycenter.com/flow-batteries-history/ [Accessed on: 2024 May 11]
4. Tilnull.no. Elektriske fergesamband. nb. Available from: https://www.tilnull.no/ferger [Accessed on: 2024 Feb 13]
5. Regjeringen.no. Krav om nullutslipp av klimagasser til ferjer og hurtigbåter. nb. Available from: https://www.regjeringen.no/contentassets/edd669ae846e4dac837bed93a9fcde8d/horingsnotat-om-krav-til-nullutslipp-av-klimagasser-fra-ferjer-og-hurtigbater2287016.pdf [Accessed on: 2024 May 4]
6. NVE. Elektriske biler, busser og ferger gir økte nettinvesteringer. nb. Available from: https://www.nve.no/nytt-fra-nve/nyheter-energi/elektriske-biler-busser-og-ferger-gir-oekte-nettinvesteringer/ [Accessed on: 2024 Feb 13]
7. Torghatten.no. Sør-Troms får elektriske ferjer fra 2025. nb. Available from: https://kommunikasjon.ntb.no/pressemelding/17956217/sor-troms-far-elektriske-ferjer-fra-2025?publisherId=17848259 [Accessed on: 2024 May 11]
8. The Government's action plan for green shipping. en. Norwegian Government. Available from: https://www.regjeringen.no/contentassets/2ccd2f4e14d44bc88c93ac4effe78b2f/the-governments-action-plan-for-green-shipping.pdf
9. Prevljak NH. 17 shore power projects get $13.6M from Enova. en-US. 2024 Mar. Available from: https://www.offshore-energy.biz/17-shore-power-projects-get-13-6m-from-enova/ [Accessed on: 2024 Apr 23]
10. Brevig AN. Vil la tungtransport bruke fergeladere: – Her ligger infrastrukturen klar. nb-NO. Section: dk. 2023 May. Available from: https://www.nrk.no/vestland/vil-la-tungtransport--bruke-fergeladere_-_-her-ligger-infrastrukturen-klar-1.16391639 [Accessed on: 2024 May 19]

11. Mischa. How a battery works. en. 2016 Feb. Available from: https://www.science.org.au/curious/technology-future/batteries [Accessed on: 2024 Mar 21]
12. Carruthers T. Battery power explained. en. 2018 Jan. Available from: https://www.science.org.au/curious/technology-future/battery-power-explained [Accessed on: 2024 Apr 23]
13. Team MEV. A Guide to Understanding Battery Specifications. en. 2008 Dec. Available from: https://web.mit.edu/evt/summary_battery_specifications.pdf
14. PennState. Interpreting Battery Parameters and Specification Sheets — AE 868: Commercial Solar Electric Systems. en. Available from: https://www.e-education.psu.edu/ae868/node/896 [Accessed on: 2024 Apr 23]
15. Zhang L, Feng R, Wang W, and Yu G. Emerging chemistries and molecular designs for flow batteries. en. Nature Reviews Chemistry. 2022 Aug; 6. Publisher: Nature Publishing Group:524–43. DOI: 10.1038/s41570-022-00394-6. Available from: https://www.nature.com/articles/s41570-022-00394-6 [Accessed on: 2024 Mar 20]
16. Kraj M. Flow battery - what you need to know about flow batteries. en-US. Section: Articles. 2020 Apr. Available from: https://codibly.com/news-insights/flow-batteries-what-you-need-to-know/ [Accessed on: 2024 May 22]
17. Badwal SPS, Giddey SS, Munnings C, Bhatt AI, and Hollenkamp AF. Emerging electrochemical energy conversion and storage technologies. en. Frontiers in Chemistry 2014 Sep; 2:79. DOI: 10.3389/fchem.2014.00079. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4174133/ [Accessed on: 2024 Apr 10]
18. Shi F. Reactor and Process Design in Sustainable Energy Technology. en. 2014 Jan :1–289
19. IFBF. What is a flow battery? - The International Flow Battery Forum. en. 2020 Feb 6. Available from: https://flowbatteryforum.com/what-is-a-flow-battery/ [Accessed on: 2024 Mar 20]
20. Skyllas-Kazacos M, Chakrabarti MH, Hajimolana SA, Mjalli FS, and Saleem M. Progress in Flow Battery Research and Development. en. Journal of The Electrochemical Society 2011 Jun; 158. Publisher: IOP Publishing:R55. DOI: 10.1149/1.3599565. Available from: https://iopscience.iop.org/article/10.1149/1.3599565/meta [Accessed on: 2024 May 8]

21. Pan F and Wang Q. Redox Species of Redox Flow Batteries: A Review. en. Molecules 2015 Nov; 20. Number: 11 Publisher: Multidisciplinary Digital Publishing Institute:20499–517. DOI: 10.3390/molecules201119711. Available from: https://www.mdpi.com/1420-3049/20/11/19711 [Accessed on: 2024 Apr 10]
22. Invinity. How Vanadium Flow Batteries Work. Invinity. 2020 Mar 30. Available from: https://invinity.com/how-vanadium-flow-batteries-work/ [Accessed on: 2024 Mar 20]
23. Prifti H, Parasuraman A, Winardi S, Lim TM, and Skyllas-Kazacos M. Membranes for Redox Flow Battery Applications. en. Membranes 2012 Jun; 2. Number: 2 Publisher: Molecular Diversity Preservation International:275–306. DOI: 10.3390/membranes2020275. Available from: https://www.mdpi.com/2077-0375/2/2/275 [Accessed on: 2024 Apr 9]
24. Maisch M. Iron-chromium flow battery for renewables storage. en-US. 2023 Feb. Available from: https://www.pv-magazine.com/2023/02/15/iron-chromium-flow-battery-for-renewables-storage/ [Accessed on: 2024 Mar 20]
25. Zhu Z, Jiang T, Ali M, Meng Y, Jin Y, Cui Y, and Chen W. Rechargeable Batteries for Grid Scale Energy Storage. Chemical Reviews 2022 Nov; 122. Publisher: American Chemical Society:16610–751. DOI: 10.1021/acs.chemrev.2c00289. Available from: https://doi.org/10.1021/acs.chemrev.2c00289 [Accessed on: 2024 Apr 5]
26. Cmblu.com. Organic SolidFlow Battery Technology. en. 2024 Nov. Available from: https://www.cmblu.com/en/technology/ [Accessed on: 2024 Apr 26]
27. Jing DY, Gordon RG, and Aziz MJ. Chapter 6.1 Aqueous organic flow batteries. en. 2023
28. nanoFlowcell - The New Energy. en. Available from: https://www.nanoflowcell.com// [Accessed on: 2024 May 3]
29. Duchak A. How Do Nanoelectrofuels Work? en. 2022 Jan. Available from: https://www.influitenergy.com/post/same-research-topic [Accessed on: 2024 May 3]
30. Flarecompare. Evaluating the Advantages and Disadvantages of Redox-Flow Batteries vs. Lithium-Ion batteries. en. Available from: https://flarecompare.com/Energy%20Storage%20Technology/Evaluating%20the%20Advantages%20and%20Disadvantages%20of%20Redox-Flow%20Batteries%20vs.%20Lithium-Ion%20batteries/ [Accessed on: 2024 May 14]

31. Stauffer NW. Flow batteries for grid-scale energy storage. en. 2023 Apr. Available from: https://news.mit.edu/2023/flow-batteries-grid-scale-energy-storage-0407 [Accessed on: 2024 Mar 21]
32. Bryans D, Amstutz V, Girault HH, and Berlouis LEA. Characterisation of a 200 kW/400 kWh Vanadium Redox Flow Battery. en. Batteries 2018 Dec; 4. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute:54. DOI: 10.3390/batteries4040054. Available from: https://www.mdpi.com/2313-0105/4/4/54 [Accessed on: 2024 Apr 24]
33. Invinity. Vanadium Flow Battery Lifespan. en-US. Available from: https://invinity.com/vanadium-flow-battery-lifespan/ [Accessed on: 2024 Mar 21]
34. IRENA. Battery storage and renewables: costs and markets to 2030. en. 2017 Oct. Available from: https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets [Accessed on: 2024 May 14]
35. Abiola SS and Al-Amin SN. Flow battery electrolytes and challenges: A review. Journal of Energy Storage 2021; 34:101839
36. Harrison KM and Chidsey CED. Advances and Challenges in Flow Batteries for Energy Conversion and Storage. ACS Energy Letters 2019; 5:8–18
37. DNV. Can Flow Batteries compete with Li-ion? en. Available from: https://www.dnv.com/article/can-flow-batteries-compete-with-li-ion--179748/ [Accessed on: 2024 May 14]
38. Chen R. Redox flow batteries: Mitigating cross-contamination via bipolar redox-active materials and bipolar membranes. Current Opinion in Electrochemistry 2023 Feb; 37:101188. DOI: 10.1016/j.coelec.2022.101188. Available from: https://www.sciencedirect.com/science/article/pii/S2451910322002538 [Accessed on: 2024 Apr 11]
39. Ke X, M. Prahl J, D. Alexander JI, S. Wainright J, A. Zawodzinski T, and F. Savinell R. Rechargeable redox flow batteries: flow fields, stacks and design considerations. en. Chemical Society Reviews 2018; 47. Publisher: Royal Society of Chemistry:8721–43. DOI: 10.1039/C8CS00072G. Available from: https://pubs.rsc.org/en/content/articlelanding/2018/cs/c8cs00072g [Accessed on: 2024 Apr 25]
40. Skyllas-Kazacos M, Chakrabarti MH, Hajimolana SA, Mjalli FS, and Saleem M. Progress in Flow Battery Research and Development. en. Journal of The Electrochemical Society

2011; 158:R55. DOI: 10.1149/1.3599565. Available from: https://iopscience.iop.org/article/10.1149/1.3599565 [Accessed on: 2024 May 19]

41. Tolmachev Y. Flow Batteries From 1879 To 2022 And Beyond. en. Qeios 2022 Dec. DOI: 10.32388/G6G4EA. Available from: https://www.qeios.com/read/G6G4EA [Accessed on: 2024 May 19]
42. Ding C, Zhang H, Li X, Liu T, and Xing F. Vanadium Flow Battery for Energy Storage: Prospects and Challenges. The Journal of Physical Chemistry Letters 2013 Apr; 4. Publisher: American Chemical Society:1281–94. DOI: 10.1021/jz4001032. Available from: https://doi.org/10.1021/jz4001032 [Accessed on: 2024 Apr 4]
43. World's largest flow battery connected to the grid in China. en-US. Section: Energy. 2022 Oct. Available from: https://newatlas.com/energy/worlds-largest-flow-battery-grid-china/ [Accessed on: 2024 Apr 12]
44. CORPORATIVA I. Lithium-ion batteries, essential for energy storage. en-US. Available from: https://www.iberdrola.com/innovation/lithium-ion-batteries [Accessed on: 2024 Mar 15]
45. Liu Z. The History of the Lithium-Ion Battery. en-US. 2019 Oct. Available from: https://www.thermofisher.com/blog/materials/the-history-of-the-lithium-ion-battery/ [Accessed on: 2024 Mar 15]
46. Aquametals. What Are Battery Anode and Cathode Materials? en-US. 2023 Apr. Available from: https://aquametals.com/recyclopedia/lithium-ion-anode-and-cathode-materials/ [Accessed on: 2024 Mar 15]
47. Samsung. The Four Components of a Li-ion Battery. ko. Available from: https://www.samsungsdi.com/column/technology/detail/55272.html [Accessed on: 2024 Mar 15]
48. Daniel C. Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2014 Symposium at NAP.edu. en. DOI: 10.17226/18985. Available from: https://nap.nationalacademies.org/read/18985/chapter/11 [Accessed on: 2024 Mar 18]
49. Ghiji M. The principle of the lithium-ion battery (LiB) showing the... en. Available from: https://www.researchgate.net/figure/The-principle-of-the-lithium-ion-battery-LiB-showing-the-intercalation-of-lithium-ions_fig1_344448023 [Accessed on: 2024 Mar 19]

50. Lithium-Ion Battery - Clean Energy Institute. en-US. 2015 Nov. Available from: https://www.cei.washington.edu/research/energy-storage/lithium-ion-battery/ [Accessed on: 2024 Mar 19]
51. Li-Ion Battery Advantages / Disadvantages: Lithium Ion » Electronics Notes. Available from: https://www.electronics-notes.com/articles/electronic_components/battery-technology/li-ion-lithium-ion-advantages-disadvantages.php [Accessed on: 2024 Mar 18]
52. Mongird K, Viswanathan V, Alam J, Vartanian C, Sprenkle V, and Baxter R. 2020 grid energy storage technology cost and performance assessment. Energy 2020; 2020:6–15
53. Zhong O. What are lithium battery advantages and disadvantages. en-US. Publisher: Orson Zhong Section: FAQ. 2023 Dec. Available from: https://www.prostarsolar.net/faq/what-are-lithium-battery-advantages-and-disadvantages.html [Accessed on: 2024 Mar 18]
54. Zhang X. Classification and Review of the Charging Strategies for Commercial Lithium-Ion Batteries. Available from: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8669683 [Accessed on: 2024 Apr 16]
55. Batteryinside. Battery Glossary – CC/CV Charging - Battery LAB. en-US. 2022 Nov. Available from: https://inside.lgensol.com/en/2022/11/battery-glossary-cc-cv-charging/ [Accessed on: 2024 Apr 16]
56. Kostopoulos ED, Spyropoulos GC, and Kaldellis JK. Real-world study for the optimal charging of electric vehicles. Energy Reports 2020 Nov; 6:418–26. DOI: 10.1016/j.egyr.2019.12.008. Available from: https://www.sciencedirect.com/science/article/pii/S2352484719310911 [Accessed on: 2024 Apr 18]
57. Sepasi S, Roose LR, and Matsuura MM. Extended Kalman Filter with a Fuzzy Method for Accurate Battery Pack State of Charge Estimation. Energies 2015; 8:5217–33. DOI: 10.3390/en8065217. Available from: https://www.mdpi.com/1996-1073/8/6/5217
58. Silva Lima L da, Quartier M, Buchmayr A, Sanjuan-Delmás D, Laget H, Corbisier D, Mertens J, and Dewulf J. Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems. Sustainable Energy Technologies and Assessments 2021 Aug; 46:101286. DOI: 10.1016/j.seta.2021.101286. Available from: https://www.sciencedirect.com/science/article/pii/S2213138821002964 [Accessed on: 2024 Apr 15]

59. Ondrey G. Recycling electrolyte from vanadium RFBs - Chemical Engineering redox-flow batteries. en-US. 2021 Apr. Available from: https://www.chemengonline.com/redox-flow-batteries/ [Accessed on: 2024 Apr 16]
60. VisBlue. VisFlow. Available from: https://assets-global.website-files.com/6159d2d30913697c253f8c2e/662a053d86d305625bea1dda_Data-sheet-VisFlow10_EN.pdf [Accessed on: 2024 Apr 17]
61. Summerfield D. Vanadium. en. Text. Archive Location: Australia Last Modified: 2023-12-19T11:42:58+11:00 Publisher: Commonwealth of Australia. 2023 Dec. Available from: https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/vanadium [Accessed on: 2024 Apr 29]
62. Plananska J. Europe's urgent need for primary vanadium extraction • Norge Mineraler. en-GB. Section: Opinion piece. 2023 Jul. Available from: https://www.norgemineraler.com/en/media/europes-urgent-need-for-primary-vanadium-extraction/ [Accessed on: 2024 Apr 30]
63. rsc.org. Vanadium - Element information, properties and uses — Periodic Table. Available from: https://www.rsc.org/periodic-table/element/23/vanadium [Accessed on: 2024 Apr 30]
64. CGEP C—. Fact Sheet: Lithium Supply in the Energy Transition. en. 2023 Dec. Available from: https://www.energypolicy.columbia.edu/publications/fact-sheet-lithium-supply-in-the-energy-transition/ [Accessed on: 2024 Apr 30]
65. Pistilli M. Top 10 Cobalt Producers by Country. en. Available from: https://investingnews.com/where-is-cobalt-mined/ [Accessed on: 2024 Apr 30]
66. Davey C. The Environmental Impacts of Cobalt Mining in Congo. en. 2023 Mar. Available from: https://earth.org/cobalt-mining-in-congo/ [Accessed on: 2024 May 1]
67. worldpopulationreview.com. Zinc Production by Country 2024. Available from: https://worldpopulationreview.com/country-rankings/zinc-production-by-country [Accessed on: 2024 May 9]
68. Tolcin A. Zinc Statistics and Information — U.S. Geological Survey. Available from: https://www.usgs.gov/centers/national-minerals-information-center/zinc-statistics-and-information [Accessed on: 2024 May 9]

69. USGS. Mineral Commodity Summaries. en. Tech. rep. 2021. Available from: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021.pdf [Accessed on: 2024 May 9]
70. mordorintelligence.com. Bromine Market - Outlook, Size & Overview. en. Available from: https://www.mordorintelligence.com/industry-reports/bromine-market [Accessed on: 2024 May 9]
71. BloombergNEF. Lithium-Ion Battery Pack Prices Hit Record Low of $139/kWh. en-US. Section: Uncategorized. 2023 Nov. Available from: https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/ [Accessed on: 2024 Apr 30]
72. Hope D. Battery Tech Report: Lithium-Ion vs Vanadium Redox Flow Batteries (VRFB). en-CA. 2022 Jul. Available from: https://capital10x.com/battery-tech-report-lithium-ion-vs-vrfbs/ [Accessed on: 2024 Apr 30]
73. Energy WC. Lithium Ion Battery Cell Prices Set to Decrease To Record Low $50 Per Kilowatt Hour in 2024, Surpassing Expectations by 6 Years. en. 2024 Mar. Available from: https://www.westchestercleanenergy.com/post/record-low-lithium-ion-battery-cell-prices [Accessed on: 2024 May 3]
74. Zinc-Bromine Flow Battery - an overview — ScienceDirect Topics. Available from: https://www.sciencedirect.com/topics/engineering/zinc-bromine-flow-battery [Accessed on: 2024 May 3]
75. Ferrell M. 137 Year Old Battery Tech May Be The Future of Energy Storage - Undecided with Matt Ferrell. en-US. 2022 Dec. Available from: https://undecidedmf.com/137-year-old-battery-tech-may-be-the-future-of-energy-storage/ [Accessed on: 2024 Apr 30]
76. Brudevoll BA and Rabbevåg F. ferge. no. 2023 Nov. Available from: https://snl.no/ferge [Accessed on: 2024 Apr 30]
77. DNV. Elektrifisering av bilferger i Norge – kartlegging av investeringsbehov i strømnettet. Available from: https://www.fornybarnorge.no/contentassets/0ae3a2b651ae4e83a0487ad493c3270c/elektrifisering-av-bilferger-i-norge.pdf [Accessed on: 2024 Apr 23]
78. Karimi S, Zadeh M, and Suul JA. Shore Charging for Plug-In Battery-Powered Ships: Power System Architecture, infrastructure, and Control. IEEE Electrification Magazine 2020; 8:47–61. DOI: 10.1109/MELE.2020.3005699. [Accessed on: 2024 Apr 16]

79. Guidi G, Suul JA, Jenset F, and Sorfonn I. Wireless Charging for Ships: High-Power Inductive Charging for Battery Electric and Plug-In Hybrid Vessels. en. IEEE Electrification Magazine 2017 Sep; 5:22–32. DOI: 10.1109/MELE.2017.2718829. Available from: http://ieeexplore.ieee.org/document/8025701/ [Accessed on: 2024 Apr 9]
80. alenconsystems.com. The New Current War: The Isolated vs. Non-Isolated DC:DC Converter. en. Available from: https://alenconsystems.com/learning/new-current-war-isolated-vs-non-isolated-dcdc-converter/ [Accessed on: 2024 Apr 24]
81. MoorMaster and charging Folgefonn. en. 2018 Jan. Available from: https://www.mynewsdesk.com/cavotec/images/moormaster-and-charging-folgefonn-170920-1053237 [Accessed on: 2024 May 22]
82. seam.no. Project Update: SHIFTR - SEAM. Available from: https://www.seam.no/insights/project-update-shiftr [Accessed on: 2024 May 2]
83. Bryte. Vurdering av flowbatteri for elektrifisering av kystnære fergesamband i Norge. [Accessed on: 2024 May 3]
84. ostkran.no. Hvor mange tonn tar en lastebil? nb-NO. 2018 Mar. Available from: https://ostkran.no/hvor-mange-tonn-tar-en-lastebil/ [Accessed on: 2024 May 8]
85. Corvus Orca ESS. en-US. Available from: https://corvusenergy.com/products/energy-storage-solutions/corvus-orca-energy/ [Accessed on: 2024 Apr 21]
86. CSLB. CONTRACTORS STATE LICENSE BOARD Licensing Committee Meeting Handouts. en. 2018 Feb. Available from: https://www.cslb.ca.gov/Resources/BoardPackets/2-23-18_licensing_committee_mtg_handouts.pdf [Accessed on: 2024 Apr 30]
87. Corvus BOB Containerized Battery Room. en-US. Available from: https://corvusenergy.com/products/energy-storage-solutions/corvus-bob-container/ [Accessed on: 2024 May 14]
88. Corvus. MF Stokkafjord. en-US. Available from: https://corvusenergy.com/projects/stokkafjord/ [Accessed on: 2024 May 2]
89. MinGat. Ferge Tjøtta Forvik: Timer og priser — All informasjon - Alt du trenger å vite. en. 2023 Jul. Available from: https://mingat.info/ferge-tjotta-forvik/ [Accessed on: 2024 May 3]

90. skipshistorie. Available from: https://skipshistorie.net/Sandnessjoen/SNS103Helgelandske/Tekster/SNS10319650100000%20TJOTTA.htm [Accessed on: 2024 May 2]

91. Fjord1. Brekstad-Valset. no-NO. 2024 Apr. Available from: https://www.fjord1.no/Ruteoversikt/Troendelag/Brekstad-Valset [Accessed on: 2024 Apr 24]

92. Markussen HM. Havyard overleverer el-ferge. nb-NO. Section: nyheter. 2018 Oct. Available from: https://www.skipsrevyen.no/cruise-og-ferger/havyard-overleverer-el-ferge/357738 [Accessed on: 2024 Jan 11]

93. Moovit. 870 Rute: rutetider, holdeplasser og kart - Brekstad Kai (Oppdatert). nb-NO. Available from: https://moovitapp.com/index/nb/kollektivtransport-line-870-Norway-1679-2082655-38270369-0 [Accessed on: 2024 May 3]

94. Svendsen HJ. Utgiftsbehov til Ferjer og Hurtigbåter. Tilgjengelig fra Norges Regjeringens nettsted. 2023. Available from: https://www.regjeringen.no/contentassets/2b467537ed414b63b2cfa611ca2196be/utgiftsbehov_til_ferjer_og_hurtigbater.pdf [Accessed on: 2024 May 15]

Appendix

A Datasheet of Visblues 10 kW unit

VisFlow

10 kW
Indoor module

Energy storage
- for a greener future

Energy storage is an important part of a green and sustainable future. Burning coal and gas must be a thing of the past, which we will look back on within 10 years as a former necessity. Instead, we must focus on renewable energy sources such as solar and wind energy.

With passion for sustainability, we at VisBlue have developed a battery where it is possible to store this solar and wind energy and use it at a desired time. The battery is scalable and can therefore be designed as needed. In addition, the battery is non-flammable, non-explosive and 99% recyclable, making it a very safe and sustainable solution.

The typical owner of a solar system uses only approximately 30% of the solar energy - the rest is sold back to the grid, usually for a small settlement price. Our smaller battery solution enables the owner to utilise up to 75%, which makes solar energy a significantly better investment. And with a sufficiently large battery, the owner can strictly utilise all of the stored energy.

Green investments can provide green figures on the bottom line and can thus generate cash savings.

Sustainable

Long lifetime - 20+ years

Safe - cannot burn or explode

Scalable

VisBlue A/S
Bautavej 1A
8210 Aarhus V
Denmark

General Contact
(+45) 71 996 996
sales@visblue.com
visblue.com

visblue
energy in the flow

TECHNICAL SPECIFICATIONS

FOR LARGER SYSTEMS MULTIPLE MODULES CAN BE ASSEMBLED

POWER AND CAPACITY

POWER [kW]	10
CAPACITY [kWh]	SCALABLE UP TO 100
PEAK CHARGE/DISCHARGE POWER	1.1 X NOMINAL POWER | 5. MIN. ON/OFF
DC EFFICIENCY (STACK) [%]	87 | DC ROUNDTRIP INCLUDES BOTH CHARGE/DISCHARGE EFFICIENCY *Depending on load profile*
AC EFFICIENCY (SYSTEM) @ NOMINAL POWER [%]	67 | AC ROUNDTRIP INCLUDES BOTH CHARGE/DISCHARGE EFFICIENCY *Depending on load profile*
DC VOLTAGE [V]	40 TO 60
AC VOLTAGE [VAC]	1 X 230 | 3 X 400 50Hz
GRID CONNECTION [PHASE(S)]	1 | 3
DEPTH OF CHARGE/DISCHARGE [%]	3 TO 80
RESPONSE TIME [MS]	<20
SELF-DISCHARGE	<1% annually

REMOTE ACCESS

COMMUNICATION	REMOTE ACCESS THROUGH LAN | MODBUS TCP (ADDRESS LIST UPON REQUEST)
BATTERY CONTROL	CHARGE/DISCHARGE IS CONTROLLED BY INPUT FROM ENERGY METER | CHARGE/DISCHARGE IS CONTROLLED BY INPUT FROM EXTERNAL MASTER

REMOTE MONITORING

CLOUD ACCESS	DATA ACCESSIBLE FROM CLOUD
WEBPAGE	VISUALISATION OF FRONT-END DATA | VISUALISATION OF BACK-END DATA

SIZE AND MASS

BATTERY SIZE [kW/kWh]	10/40 | 10/50
TANK SIZE [L]	1000 | 1250
FOOTPRINT [mm] (W x D)	2081 x 1240
HEIGHT [mm]	1800 | 2100
WEIGHT TANKS/RACK [kg]	2800/450 | 3300/450
DESIGN LIFE [CYCLES/YEAR]	20,000/20

ENVIRONMENT

ELECTROLYTE TEMPERATURE [°C]	0 TO +35
HUMIDITY	95% RH NON-CONDENSING
VENTILATION	SITE-DEPENDENT | COOLING/HEATING CAN BE INSTALLED
SAFETY	NON-FLAMMABLE AND NON-EXPLOSIVE | WATER-BASED ELECTROLYTE

B Datasheet of Corvus ORCA

Corvus Orca

The Corvus Orca ESS represented a shift in the maritime industry when launched in 2016. No other Energy Storage System can compete with the installation count of the Corvus Orca. Offering outstanding results and the highest level of safety, it set the new industry standard for maritime batteries.

Corvus Energy combined industry-leading research and development capabilities with its experience as the leading provider of marine ESS with the most installations worldwide to build the industry's safest, most reliable, high-performing and cost-effective ESS.

Applications

The Corvus Orca ESS is ideal for applications that need both energy and a high amount of power, moving large amounts of energy at an inexpensive lifetime cost per kWh.

Typical Vessel Types:

- Ferries
- Cruise ships
- Ro/Ro – Ro/Pax
- Yachts
- Offshore vessels
- Rigs
- Tugs
- Fishing vessels
- Merchant vessels
- Port cranes
- Shore charging
- Fish farms

Features

- High C-Rate – up to 3C continuous
- Installed on 400+ vessels around the world
- Designed for voltages up to 1200 VDC
- Low installation and commissioning time
- Low life cycle cost
- Enhanced reliability with contained power connections
- Flexible and modularized design
- Passive single-cell Thermal Runaway protection
- Scalable capacity and voltage according to vessel requirements
- Industry-proven Battery Management System (BMS)
- Remote monitoring capabilities
- Enhanced EMI immunity design for maritime environments

Corvus Energy safety innovations

Passive Single-cell-level Thermal Runaway (TR) Isolation

- True cell-level thermal runaway isolation
- TR does not propagate to neighbouring cells
- Isolation NOT dependant on active cooling

Exceeds Class and Flag standards TR Gas venting

- Integrated thermal runaway gas exhaust system
- Easily vented to external atmosphere

Technical Specifications | Corvus Orca ESS

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
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
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, Lloyds Register, Bureau Veritas, ABS, RINA
Type Approval	DNV, 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

2023-09-05

C Timetable Tjøtta - Forvik, Normal operation

18-162 Tjøtta-Mindland-Tro-Stokkasjøen-Vågsodden-Forvik

Gyldig fra 01.10.2023 til 31.05.2024

Mandag - fredag

Merknad	Lx	Lx	D	Lx	D	D	Le	Lx	D	Lx	D	Lx
Tjøtta ferjekai	05:45	08:15	08:50	10:50	10:50	13:05	14:45	15:25	15:25	17:55	18:30	20:35
Mindland ferjekai	06:05 Lx	08:35 Lx	|	11:10 Lx	|	|	15:00 Le	15:45 Lx	|	18:15 Lx	|	20:55 Lx
Tro ferjekai	06:15 Lx	08:45 Lx	|	11:20 Lx	|	|		15:55 Lx	|	18:25 Lx	|	21:05 Lx
Stokkasjøen ferjekai	06:20 Lx	08:50 Lx	|	11:25 Lx	|	|		16:00 Lx	|	18:30 Lx	|	|
Vågsodden ferjekai	06:40 Lx	09:15 Lx	|	11:50 Lx	|	|		16:25 Lx	|	18:55 Lx	|	21:25 Lx
Forvik ferjekai	06:50	09:25	09:40	12:00	11:40	13:55		16:30	16:10	19:05	19:20	21:30

Merknad	Lm	Lx	D	Lx	D	D	Le	Lx	D	Lx	D	Lx
Forvik ferjekai	06:55	09:35	09:55	12:10	11:55	14:10		16:35	16:25	19:15	19:35	21:35
Vågsodden ferjekai	07:05 Lm	09:45 Lx	|	12:20 Lx	|	|		16:45 Lx	|	19:25 Lx	|	21:45 Lx
Stokkasjøen ferjekai	07:20 Lm	|	|	12:30 Lx	|	|		17:00 Lx	|	19:40 Lx	|	22:00 Lx
Tro ferjekai	07:35 Lm	10:05 Lx	|	12:40 Lx	|	|		17:15 Lx	|	19:55 Lx	|	|
Mindland ferjekai	07:45	10:15 Lx	|	12:50 Lx	|	|	15:00 Le	17:25 Lx	|	20:05 Lx	|	22:15 Lx
Tjøtta ferjekai	08:05	10:35	10:35	13:20	12:45	15:00	15:15	17:45	17:15	20:25	20:25	22:35

	Lørdag					Søndag						
Merknad	Lx	Lx	Lx	Lx	Lx	Lx	Lx	Lx	D	Lx	D	Lx
Tjøtta ferjekai	05:45	08:15	10:50	15:25	17:55	08:15	10:50	15:25	15:25	17:55	18:30	20:35
Mindland ferjekai	06:05 Lx	08:35 Lx	11:10 Lx	15:45 Lx	18:15 Lx	08:35 Lx	11:10 Lx	15:45 Lx	|	18:15 Lx	|	20:55 Lx
Tro ferjekai	06:15 Lx	08:45 Lx	11:20 Lx	15:55 Lx	18:25 Lx	08:45 Lx	11:20 Lx	15:55 Lx	|	18:25 Lx	|	21:05 Lx
Stokkasjøen ferjekai	06:20 Lx	08:50 Lx	11:25 Lx	16:00 Lx	18:30 Lx	08:50 Lx	11:25 Lx	16:00 Lx	|	18:30 Lx	|	|
Vågsodden ferjekai	06:40 Lx	09:15 Lx	11:50 Lx	16:25 Lx	18:55 Lx	09:15 Lx	11:50 Lx	16:25 Lx	|	18:55 Lx	|	21:25 Lx
Forvik ferjekai	06:50	09:25	12:00	16:30	19:05	09:25	12:00	16:30	16:10	19:05	19:20	21:30

Merknad	Lx	Lx	Lx	Lx	Lx	Lx	Lx	Lx	D	Lx	D	Lx
Forvik ferjekai	06:55	09:35	12:10	16:35	19:15	09:35	12:10	16:35	16:25	19:15	19:35	21:35
Vågsodden ferjekai	07:05 Lx	09:45 Lx	12:20 Lx	16:45 Lx	19:25 Lx	09:45 Lx	12:20 Lx	16:45 Lx	|	19:25 Lx	|	21:45 Lx
Stokkasjøen ferjekai	07:20 Lx	|	12:30 Lx	17:00 Lx	19:40 Lx	|	12:30 Lx	17:00 Lx	|	19:40 Lx	|	22:00 Lx
Tro ferjekai	07:35 Lx	10:05 Lx	12:40 Lx	17:15 Lx	19:55 Lx	10:05 Lx	12:40 Lx	17:15 Lx	|	19:55 Lx	|	|
Mindland ferjekai	07:45 Lx	10:15 Lx	12:50 Lx	17:25 Lx	20:05 Lx	10:15 Lx	12:50 Lx	17:25 Lx	|	20:05 Lx	|	22:15 Lx
Tjøtta ferjekai	08:05	10:35	13:20	17:45	20:25	10:35	13:20	17:45	17:15	20:25	20:25	22:35

D Direkterute.

L Lokalrute.

Le Lokalrute. Mindland ved behov. Meldes på tlf: 4807 7010 innen kl: 14.30.

Lm Lokalrute. Vågsodden, Stokkasjøen og Tro ved behov. Meldes på tlf: 4807 7010 innen ruteavgang.

Lx Lokalrute. Alle mellomsteder på behov. Meldes på tlf 4807 7010 innen rutestart.

Bevegelige helligdager

	Lokalrute	Direkterute
Skjærtorsdag	Søndagsrute	Søndagsrute
Langfredag	Søndagsrute	Søndagsrute
Påskeaften	Lørdagsrute fra kl.08:15	Innstilt
1.påskedag	Søndagsrute	Søndagsrute
2.påskedag	Søndagsrute	Søndagsrute
01.mai	Søndagsrute	Søndagsrute
17.mai	Søndagsrute	Søndagsrute
Kr.himelfartsdag	Søndagsrute	Søndagsrute
Pinseaften	Ordinær rute	Ordinær rute
1.pinsedag	Søndagsrute	Søndagsrute
2.pinsedag	Søndagsrute	Søndagsrute
Julaften	Søndagsrute til ankomst tjøtta kl.13:20. Ekstratur fra Tjøtta kl.13:20 med retur fra Forvik kl.14:10	Innstilt
1.juledag	Innstilt	Innstilt
2.juledag	Søndagsrute fra Tjøtta kl.10:50	Søndagsrute
Nyttårsaften	Søndagsrute til ankomst tjøtta kl.13:20. Ekstratur fra Tjøtta kl.13:20 med retur fra Forvik kl.14:10	Innstilt
1.nyttårsdag	Søndagsrute fra Tjøtta kl.10:50	Søndagsrute

D Timetable Tjøtta - Forvik, Summer operation

18-162 Forvik-Vågsodden-Stokkasjøen-Tro-Mindland-Tjøtta

Gyldig fra 01.06.2023 til 31.08.2023

Mandag - fredag

Merknad	Lm	S	D	Lx	S	D	Lx	S	D	Le	S	D	Lx	S	D	Lx	Lx
Forvik ferjekai	06:55	08:05	09:50	09:35	10:55	11:55	12:10	13:15	14:10		15:40	16:25	16:35	18:30	19:35	19:15	21:35
Vågsodden ferjekai	07:05 Lm	|	|	09:45 Lx	|	|	12:20 Lx	|	|		|	|	16:45 Lx	|	|	19:25 Lx	21:45 Lx
Stokkasjøen ferjekai	07:20 Lm	|	|	|	|	|	12:30 Lx	|	|		|	|	17:00 Lx	|	|	19:40 Lx	22:00 Lx
Tro ferjekai	07:35 Lm	|	|	10:05 Lx	|	|	12:40 Lx	|	|		|	|	17:15 Lx	|	|	19:55 Lx	|
Mindland ferjekai	07:45	|	|	10:15 Lx	|	|	12:50 Lx	|	|	15:00 Le	|	|	17:25 Lx	|	|	20:05 Lx	22:15 Lx
Tjøtta ferjekai	08:05	08:55	10:40	10:35	11:45	12:45	13:10	14:05	15:00	15:15	16:30	17:15	17:45	19:20	20:15	20:25	22:35

Lørdag

Merknad	Lx	Lx	D	S	D	Lx	S	D	S	D	Lx	Lx	Lx	-	-	-	-
Forvik ferjekai	06:55	09:35	09:50	10:55	11:50	12:10	13:15	14:10	15:40	16:25	16:35	19:15	21:35	-	-	-	-
Vågsodden ferjekai	07:05 Lx	09:45 Lx	|	|	|	12:20 Lx	|	|	|	|	16:45 Lx	19:25 Lx	21:45 Lx	-	-	-	-
Stokkasjøen ferjekai	07:20 Lx	|	|	|	|	12:30 Lx	|	|	|	|	17:00 Lx	19:40 Lx	22:00 Lx	-	-	-	-
Tro ferjekai	07:35 Lx	10:05 Lx	|	|	|	12:40 Lx	|	|	|	|	17:15 Lx	19:55 Lx	|	-	-	-	-
Mindland ferjekai	07:45 Lx	10:15 Lx	|	|	|	12:50 Lx	|	|	|	|	17:25 Lx	20:05 Lx	22:15 Lx	-	-	-	-
Tjøtta ferjekai	08:05	10:35	10:40	11:45	12:40	13:10	14:05	15:00	16:30	17:15	17:45	20:25	22:35	-	-	-	-

Søndag

Merknad	Lx	S	D	Lx	S	D	S	D	Lx	S	Lx	D	Lx	-	-	-	-
Forvik ferjekai	09:35	10:55	11:55	12:10	13:15	14:10	15:40	16:25	16:35	18:30	19:15	19:35	21:35	-	-	-	-
Vågsodden ferjekai	09:45 Lx	|	|	12:20 Lx	|	|	|	|	16:45 Lx	|	19:25 Lx	|	21:45 Lx	-	-	-	-
Stokkasjøen ferjekai	|	|	|	12:30 Lx	|	|	|	|	17:00 Lx	|	19:40 Lx	|	22:00 Lx	-	-	-	-
Tro ferjekai	10:05 Lx	|	|	12:40 Lx	|	|	|	|	17:15 Lx	|	19:55 Lx	|	|	-	-	-	-
Mindland ferjekai	10:15 Lx	|	|	12:50 Lx	|	|	|	|	17:25 Lx	|	20:05 Lx	|	22:15 Lx	-	-	-	-
Tjøtta ferjekai	10:35	11:45	12:45	13:10	14:05	15:00	16:30	17:15	17:45	19:20	20:25	20:15	22:35	-	-	-	-

D Direkterute.
L Lokalrute.
Le Lokalrute. Mindland ved behov. Meldes på tlf: 4807 7010 innen kl: 14.30.
Lm Lokalrute. Vågsodden, Stokkasjøen og Tro ved behov. Meldes på tlf: 4807 7010 innen ruteavgang.
Lx Lokalrute. Alle mellomsteder på behov. Meldes på tlf 4807 7010 innen rutestart.
S Suppleringsrute i perioden **23.06.2023 - 20.08.2023**

NTNU

Norwegian University of
Science and Technology