Master's thesis

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

Jesper Wimann Ingebretsen

Electrification of Fish Farms with Hydrogen

Retrofitting vs Building a New Feed Barge

Master's thesis in Energy and Environmental Engineering
Supervisor: Steve Völler
June 2022

NTNU
Kunnskap for en bedre verden

Jesper Wimann Ingebretsen

Electrification of Fish Farms with Hydrogen

Retrofitting vs Building a New Feed Barge

Master's thesis in Energy and Environmental Engineering
Supervisor: Steve Völler
June 2022

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

NTNU
Norwegian University of
Science and Technology

Preface

This master thesis concludes my two years in Energy and Environmental Engineering at the Norwegian University of Science and Technology, NTNU. The thesis is written in cooperation with Renewable Energy Cluster (Renergy), NTE, and H2 Marine. The main focus is to analyse the electrification of offshore fish farms with hydrogen. I want to express gratitude to my supervisor at NTNU, Steve Völler, for giving essential guidance and support in writing this project. Furthermore, I would like to thank my external contacts from Renergy, Thomas Bjørdal, and Edgar Kvernevik from Kvernevik AS for providing guidance and valuable information. I will also like to thank Steingrim Holm from Midt-Norsk Havbruk for providing the essential data for executing the thesis. Lastly, a huge thanks to family and friends for the support throughout the semester.

Trondheim, June, 2022

Abstract

This thesis is written in cooperation with Renewable Energy Cluster, NTE, Midt-Norsk Havbruk AS, and H2 Marine. The aim is to find the most suitable way to electrify an offshore fish farm, where it is too expensive to connect to the power grid. Two scenarios have therefore been introduced where the first is a retrofit of an existing feed barge with fuel cells and batteries. The second is building a new feed barge with the newest technologies and efficiency measures. Waterborne feeding is a prominent new technology that can drastically decrease load demand and fuel usage.

The load data for three fish farms are analysed. They are Eiterfjorden, Skrosen and Årsetfjorden. The fuel cell and battery size were calculated by analysing the average load profile of the month with the highest load for a locality. This was performed for all three fish farms and both scenarios. The new build scenario used the same data set for the retrofit scenario but adjusted for the efficiency measures. Eiterfjorden got a fuel cell size of 140 kW and a battery size of 360 kWh for the retrofit scenario. For the new build scenario, were the fuel cell size 60 kW and the battery size 230 kWh at Eiterfjorden.

In analysing the given feed barge schematic, it was decided that two containers were the best for storage, but this can be further optimised. A basecase was also created to weigh against the two scenarios. This case shows how much fuel expenses can be saved by changing to hydrogen.

From the given dataset, cycles were created. This was to simulate an economic analysis. The cycles were four years for Eiterfjorden, two years for Skrosen, and four years for Årsetfjorden. In these cycles, the fuel consumption for periods with fish and without were included. The yearly expenses were used for the net present value analysis.

The total CAPEX was calculated to be around 16 million kr for the retrofit scenarios and 32 million kr for the new build scenarios. The significant difference in initial investment can be attributed to the cost of building a new feed barge, which was found to be 25 million kr. From the resulting yearly expenses, which are hydrogen and maintenance, the difference is about 700 thousand to one million kr, in favour of the new build scenario.

From the net present value analysis, the retrofit scenario for Eiterfjorden broke even after about 17 years and did not break even for the new build scenario. This was with a fixed diesel and hydrogen price. If the diesel price increases and the hydrogen price decreases, the retrofit breaks even after 11 years and the new build after 16 years. The other fish farms showed the same tendencies. Furthermore, the Eiterfjorden had a payback time of 13 years and 14.1 years for the retrofit and new build scenario, respectively. The other fish farms have a higher payback time. From this, it can be concluded that the bigger the fish farm, with higher energy usage, the more yearly expenses can be saved by performing one of the scenarios.

From this thesis, it can be concluded that a retrofit is the most cost-beneficial choice for fish farms with a life expectancy left of over ten years. If the fish farm has under five years, it can be concluded that it is better to live out its lifetime and then build a new feed barge with all the newest technologies and efficiency measures implemented because there is much to save from the yearly expenses.

Sammendrag

Denne masteroppgaven er skrevet i samarbeid med fornybarklyngen, NTE, Midt-Norsk Havbruk AS og H2 Marine. Målet med oppgaven er å finne den best mulige måten å elektrifisere et offshore fiskeoppdrettsanlegg, hvor det er for dyrt å koble til strømnettet. To scenarioer har dermed blitt introdusert. Det første scenarioet er en retrofit av en eksisterende forflåte med brenselceller og batterier. Det andre scenarioet er å bygge en ny forflåte, med de nyeste teknologiene og energieffektiviserende metodene. Vannboren mating er en ny teknologi, som kan drastisk redusere energiforbruket.

Lastdatene til tre oppdrettsanlegg er analysert. De er Eiterfjorden, Skrosen og Årsetfjorden. En brenselcelle og batteri størrelse er regnet ut med å analysere snitt lastprofilen til måneden med høyest forbruk. Dette var gjort for alle anleggene og begge scenarioer. Nybyggings scenarioet bruker samme data som retrofit scenarioet, men det er justert for de energieffektiviserende teknologiene. Eiterfjorden fikk en brenselcelle størrelse på 140 kW og batteri størrelse på 360 kWh, for retrofit scenarioet. For nybyggings scenarioet, ble brenselcelle størrelsen 60 kW og batteri størrelsen 230 kWh i Eiterfjorden.

I en analyse av forflåtetegningene, ble det bestemt at to containere er optimalt, men videre analyse burde gjennomføres. Et grunnleggende scenario ble også laget, for å sammenlignes med de to andre. Dette var gjort for å kunne vise drivstoff kostnadene som kan bli spart ved å bytte til hydrogen.

Fra det gitte data grunnlaget, ble det laget en driftssyklus. Dette var for å kunne simulere en økonomisk analyse. Syklusene var på fire år for Eiterfjorden og Årsetfjorden, og to år for Skrosen. I disse syklusene, ble drivstoff forbruket for periodene med og uten fisk, inkludert. De årlige utgiftene ble dermed brukt i nåverdianalysen.

Den totale CAPEX ble utregnet til å være rundt 16 millioner kroner for retrofit scenarioet og rundt 32 millioner kroner for nybyggings scenarioet. Den store forskjellen kostnader skylles kostnadene for å bygge en ny forflåte, som ble funnet til å være rundt 25 millioner kroner. Fra de årlige utgiftene, var det en forskjell på mellom 700 tusen til en million kroner, i fordel nybygging scenarioet.

Fra nåverdianalysen, ble det utregnet at Eiterfjorden gikk i null etter 17 år for retrofit scenario og gikk aldri i pluss for nybyggings scenarioet. Hvis diesel øker og hydrogen priser minker, går den i null etter 11 år for retrofit scenario og for nybyggings scenarioet går det 16 år. De andre oppdrettsanleggene viste de samme tendensene, men med lengre tid før de går i null. Videre, hadde Eiterfjorden en tilbakebetalingstid på 13 år for retrofit scenarioet og 14,1 år for nybyggings scenarioet. De andre oppdrettsanleggene hadde noe høyere tilbakebetalingstid. Ut ifra disse resultatene kan det bli konkludert, at ved større oppdrettsanlegg og større energibruk, blir utgiftene hvert år mindre.

Denne oppgaven kan videre konkludere med at en retrofit av en forflåte er det mest kostnads effektive valget, for fiskeoppdrettsanlegg med en levetid på over ti år igjen. Hvis forflåten har under fem år igjen, kan det være smart å la den leve ut tiden sin og deretter bygge en ny med alle de nyeste teknologiene. Dette er fordi det er mye å spare hvert år på drivstoff utgifter.

Table of Contents

List of Symbols

Symbol	**Unit**	**Description**
E	kWh	Electric Energy
p	bar	Pressure
y	y	Years
η_{el}	-	Electrical efficiency

Chemical symbol	**Description**
e^-	Electron
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2	Hydrogen gas
H^+	Proton
H_2O	Water
O_2	Oxygen gas

List of Terms and Abbreviations

Term	Description
Acidic solution	pH below 7
Anode	The electrode where the oxidation occurs
Bunkering	Filling the fuel containers to a ship.
Cathode	The electrode where the reduction occurs
Electrolyte	A medium which conduct ions
Feed Barge	A floating structure with living quarters, energy system, pumps, feeding silos and other equipment for operating a fish farm
Inflation rate	The rate of which the average price of goods and services increase over time
Intersection point	A point share by two curves
Smolt	Young salmon
Separator	A permeable membrane designed to keep the electrodes apart
Specific energy	Energy per unit of mass
Specific power	Power per unit of mass

Abbreviation	Description
AFC	Alkaline fuel cell
CAPEX	Capital expenditures
DoD	Depth of Discharge
FC	Fuel Cell
GDL	Gas diffusion layer
IRR	Internal rate of return
MEA	Membrane electrode assembly
MCFC	Molten carbonate fuel cell
NPV	Net present value
OPEX	Operational expenses
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
SoC	State of Charge
SOFC	Solid oxide fuel cell
S.R.	Stack Replacement

List of Figures

List of Tables

1 Introduction

This thesis cooperates with Renewable Energy Cluster (Renergy), NTE, Midt-Norsk Havbruk AS, and H2 Marine. They are working on "the Pilot E" project, "Zero-emission workboat for the maritime industry." This project also tries to develop a flexible solution for delivering green hydrogen to the maritime industry. The end goal is to develop and demonstrate a complete value chain for green hydrogen. The green hydrogen is produced from renewable energy sources through water electrolysis at Kråkøya harbour, which is in Nærøysund municipality. The concept art for Kråkøya harbour is shown in figure 1. The goal is to make this location a green hub for the local maritime region. Hence, this project can help to enable the transmission to zero maritime emission for the region. The "Pilot E" project is under the "ZeroKyst" initiative. This project aims to develop Norwegian value creation and export through green growth. It also aims to contribute considerably to the 50 % cut in emissions from the maritime industry within 2030 [1].

Figure 1: Concept art of Kråkerøya harbour. [2]

The new solution for delivering hydrogen will be a combined hydrogen transport/bunkering unit. This fleet will enable much more flexibility for the maritime industry. Instead of building fuelling stations in remote areas, the mobile bunkering unit will come to the customer. The development of this unit may also enable the complete electrification of fish farms. Today, about 60 % of fish farms are electrified. For the remaining 40 % is a subsea cable too expensive because of the distance to the grid, or the local energy grid is too weak [3]. Instead, those fish farms using e.g. diesel generators for energy supply, which shall be replaced to reduce emissions and costs. One possible solution for this problem can be hydrogen produced onshore at e.g. Kråkerøya harbour, where the diesel generator is replaced with fuel cells and batteries for support.

Exchanging the diesel generators with fuel cells and batteries was first explored in the specialisation project connected to this master thesis. It aimed to analyse the potential hydrogen demand from fish farms by analysing the load demand for Eiterfjorden fish farm during 2019. A fuel cell and battery size were also calculated from the given dataset. The project concluded that two fuel cells would give the safest operation and lessen hydrogen usage in the long run compared to one. The method and results from this thesis have been expanded upon in this thesis.

1.1 Research Question

This thesis aims to determine the most optimal between a retrofit and building a new feed barge when electrifying a fish farm with fuel cells and batteries. This is specifically for fish farms that are too expensive to connect to the electrical grid. Working vessels and other types of boats connected to the localities are not included in this analysis. Furthermore, it will be done by analysing the load demand from three fish farms, Eiterfjorden, Skrosen, and Årsetfjorden. Because they are connected to the grid, they have load measurements that can be analysed.

There are many possibilities to reduce energy usage at a fish farm extensively. They are best implemented by building a new feed barge, therefore, are two scenarios created. If the cut in energy usage is relatively large, the following reduction in fuel costs may considerably impact the cost of fish production. Hence, making the fish cheaper and business more profitable for fish farming companies. Furthermore, if either one of the scenarios is feasible, several tonnes of CO_2 emissions can be cut, and a new customer to the hydrogen market can be added.

1.2 Objectives

In order to find out if either a retrofit or new build scenario is the most feasible, several sub-goals need to be addressed and solved. They are stated as follows:

- Size a fuel cell
- Size a battery
- Calculate hydrogen demand
- Decide storage space
- Gather cost data
- Cost-benefit analysis of retrofit and new build scenario.
- Interpretation of the results

1.3 Background - Literature

There have been performed several studies on the electrification of fish farms. A summary of the most prominent ones has been presented in this chapter. This is also background information for this thesis.

Bellona and ABB 2018 [4]. This report concludes that further electrification of the fish farms can cut 360 000 tons of CO_2 per year when the total emission estimation from localities and boats is 400 000 tons of CO_2. When the report was published, 50 % of fish farms were electric. Based on the given data, full electrification of feed barges and electrical solutions on boats lessen the fuel consumption by up to 80%. The most considerable reduction potential is for feed barges with up to 57 %. The well-boats follow with a reduction potential of 33 %, service boats with 5 %, and locality vessels with 5 %. The basis of the analysis is four requirements: (1) Land energy or hybrid solutions are used for all feed barges. (2) All the work vessels can be powered electrically. (3) Well boats can be used with either hybrid or fully electric. (4) The same goes for the service boats.

DNV-GL 2018 [5]. This report shows that 80 % of production at Norwegian feed barges can be electrified with economic gain or at a low cost. The rest of the facilities are placed further away from the energy grid and hence have a lower production capacity and will be more to supply with grid power. The economic benefits of electrification are sensitive to diesel price and the energy use per produced fish. For this analysis, about 80 litres of diesel per ton of slaughtered fish is used. The cost from the electrification of up to 80 % of the fish farms is estimated to be 650 kroners per ton yearly CO_2 emission reduction.

Furthermore, the study concludes that electrification of work boats is not profitable, but a power coupling at the docking space can be profitable, given that the location is electrified.

Energi NORGE [6]. Thema Consulting, on behalf of Energi Norge, created guidance that described the best way to connect to the energy grid for fish farms. Estimations state that 50 - 60 % of the fish farms are connected to the grid. The supervisor took experiences from the electrification processes and found these main points: (1) The energy grid business is hard to understand and requires technical consultants to be often used. (2) Connection to the energy grid is expensive because the localities are often in areas with weak local grid and limited capacity. (3) The fish farming companies own the net station and wish for the energy grid companies to take the task.

Sophie Møller 2019 [3]. In this master thesis, the energy and power consumption for a fish farm in Trøndelag was mapped and considered for connection to the energy grid. 50 % of the localities were electrified before this thesis was written. Based on this, Sofie Möller found that the yearly average energy per kg fish produced was 0.35 kWh. Electrified and offshore localities had an energy usage of 0.26 and 0.44 kWh, respectively. The significant difference is the electrical efficiency between the electrified and non-electrified locations. The study shows that the percentage of electrified fish farms can be increased to 83 % without further investments in the energy grid. Furthermore, several energy efficiency measures need implementation if more localities in the same area want electrification.

Thea Mørk [7]. This master thesis studies the economic profits and emissions from an energy turnaround of all fossil fuel driven fish farms in Finnmark, including work boats. From an extensive information gathering from the fish farms, which gave information. The status quo is as follows: 53 % use diesel, 38 % from the energy grid, 5 % has hybrid systems, and 4 % has cannon feeding from boats. It averaged 52 litres of diesel per MTB but varied from 20 to 90 litres. The analysis concludes that the grid can power 66 % of the facilities, and the remaining 34 % can use hybrid energy solutions, including all electric work boats. This implementation corresponds to a reduction of 16410 tons CO_2 emission per year for facilities in Finnmark.

2 Theory

The theory section delves into different theories used in this project. Firstly, it will introduce the fish farm industry, where the Rainbow trout, lumpfish and Atlantic salmon combine for 97.5 % of the total farmed Norwegian fish [8]. The main focus will be Atlantic salmon. Furthermore, will the different fuel cell types and storage technologies of hydrogen be described. The thesis will then explore batteries storage technologies and focus on lithium-ion batteries. Lastly, it will focus on economic terms and analysing tools. The foundation of the theory section is based on the specialisation project written autumn 2021 in the subject TET 4510.

2.1 Norwegian Seafood Industry

The Norwegian seafood industry exported seafood for 105.7 billion Norwegian kroner in 2020. 70 billion of the total value was Atlantic salmon, corresponding to 1.1 million tons of salmon. In 2019, seafood was the second-largest export behind oil and gas. This shows how vital salmon farming is for the Norwegian industry. Salmon farming started around the 1970s in Norway, and the first slaughtered farmed salmon was in 1971. This laid the foundation for modern fish farms in Norway. The industry had an annual growth of about 6.5 percent from 1997 to 2017. Over half of the world's farmed salmon is produced in Norwegian waters. The industry's growth stagnated in 2012 in Norway and globally. This is because of stricter regulations and challenges with fish diseases, salmon lice, and other environmental impacts. [8–10]

Midt-Norsk Havbruk AS (MNH) is a cooperation partner of this thesis. MNH has a long history in the Norwegian seafood industry from 1984, with ten concessions in Norway. Their facilities at Eiterfjorden, Skrosen, and Årsetfjorden have given their load demand data for this project to be analysed. [11]

2.1.1 Concession

Norway has a long coastline and cold water, which is perfect for Atlantic salmon farming. The Norwegian coastline is one of the longest in the world. Scattered along the coast are fish farms, all the way from the north to the south. Because of the fish farms' environmental impact, the coastline was divided into 13 production areas. These regulations were implemented in 2017 and are called the traffic light system. An area is given a red, yellow, or green light based on the industry's environmental impact on the local ecology. It is measured by how salmon lice affect the environment. The different colours are then again impacting the growth of the salmon farming industry. If the area has a green light, it is allowed for a growth of 6 % per year. If the area has a yellow light, the capacity is frozen, and if there is a red light, the capacity has to decrease by 6 % per year. Aquaculture is also a permit-based industry. Each permit has maximum allowed biomass (MTB), divided into two sections: company (the whole business) and locality (the fish farming location). A permit holder cannot exceed the MTB at the locality or company level. The size of this permit varies from 780 to 7020 tons.[3]

2.1.2 Atlantic Salmon Farming Production Cycle

It is essential to understand the process of Atlantic salmon farming to understand the industry's environmental impacts and potential for improvement. Cultivating a salmon from spawn to slaughter takes about three years, as shown in figure 2. The process begins on land, where the eggs are kept in tubs with fresh water and 8 °C. The eggs are fertilised and hatched after about 60 days. After one and a half months, the eggs have grown into fish fry and moved to a larger tub. When 10-16 months have passed, the salmon are now classified as smolt and ready to be transferred to the sea. [12, 13]

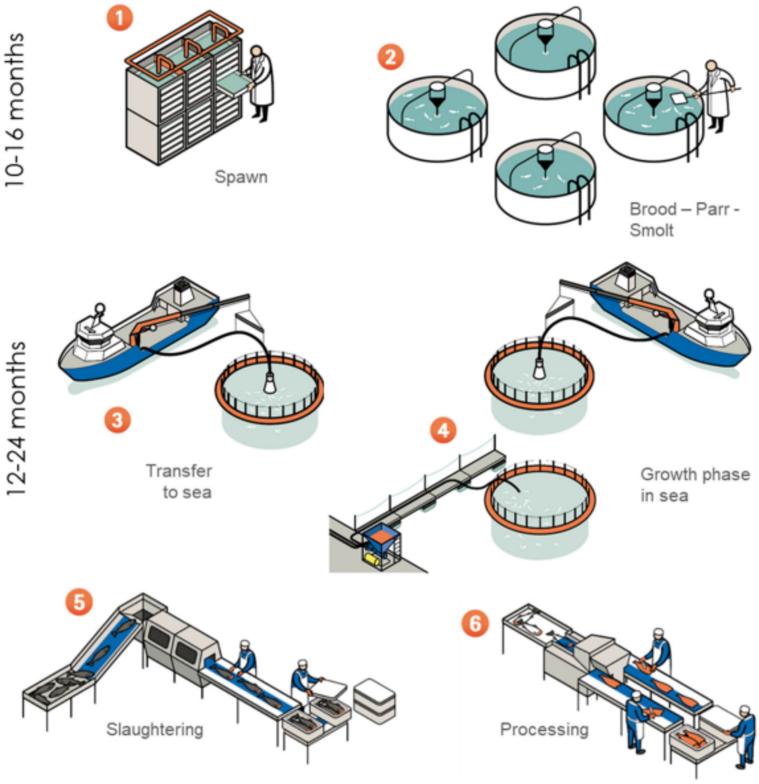


Figure 2: Atlantic salmon farming production cycle. [13]

The time in the tubs is an important period for the salmon. During this period, the fish undergo many changes to live in seawater. When the fish are ready to be transported to the sea, they weigh between 60 to 100 grams. The fish are transported to the offshore production site and kept in open net pens. The pens connect to a feed barge and are fed through feeding hoses. The salmon are kept in the pens until they are between 4 to 6 kilos, which takes 12 to 22 months. The fish are then sent to slaughtering and processing. This is the last procedure before the salmon is in the local shops. [12, 13]

2.1.3 Environmental Impacts

Production of food has environmental impacts, some more than others. As showcased in figure 3 there are significant CO_2 emissions during feeding and transportation of the salmon. The largest polluter is offshore feeding, where fish are kept in saltwater. An exception is bar three, where the salmon are transported to Shanghai via air and road. Pollution from transportation is not covered in this thesis. Tonnes of CO_2 emissions have been cut during the electrification of fish farms, where the leading polluter are diesel generators. As the primary pollution comes from the feed barges caused by diesel generators, this task focuses on the electrification of offshore fish farms. [14]

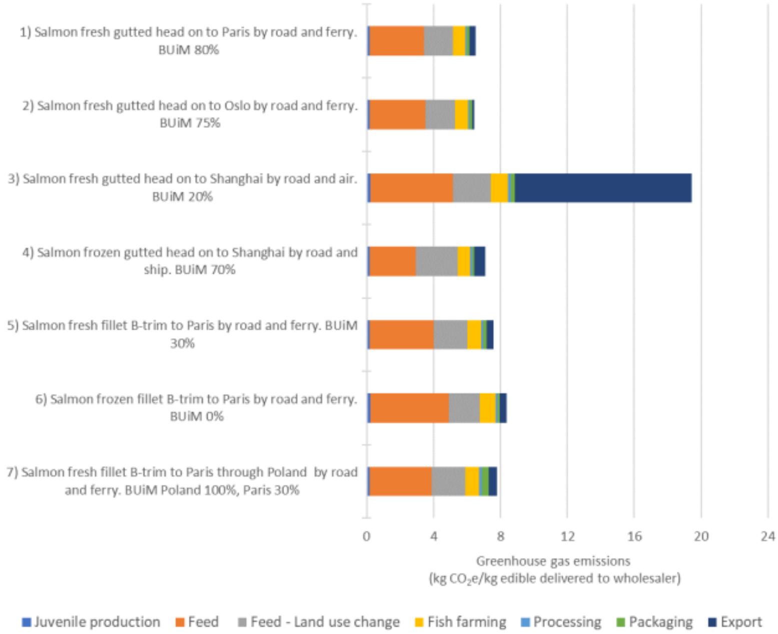


Figure 3: CO_2 emission from salmon products, from production to wholesaler. [14]

There are several other environmental impacts from the salmon industry, which are not greenhouse gas emissions. Fish lice is a parasite that feeds on the salmon skin, blood and slime. The lice create wounds on the skin of the fish host, which decreases resistance against other bacteria and fungus. It is calculated that the Norwegian salmon industry loses about 500 million Norwegian kroner because of the fish lice yearly. These losses are connected to the loss of fish and increased usage of chemicals. Because of the high density of the salmon in the open net pens, there is also an unnaturally large quantity of fish lice. These lice are also transferred to wild salmon with the escaping the salmon. The escaped fish greatly impact the genetic make-up of the wild salmon. The escaped salmon find their way to the salmon spawning grounds and mate with the wild salmon. Hence drastically changing the salmon, which have adapted to the local environment for thousands of years in a short time. [7, 15, 16]

The government has strict limits on how much lice per fish is allowed. Hence, several different medicines are used to hinder the growth of lice. These types of chemicals can damage shellfish, such as lobsters and crabs. Overuse of the chemicals is also prevalent, making the lice resistant to the medicines. There are other wastes from the fish farm than just the used medicines. For example, are 5 - 10 % of the food and excrement gathered on the sea floor. The high concentration of nutrients on the seabed can induce the large growth of algae and cause eutrophication in shielded fjords. The over-fertilising can also impact wild fish, which eat food nearby, such as pollock and mackerel. There have already been implemented several methods to solve these problems. The feeding process is constantly improving to lessen food waste. Fish farms in locations with low water currents are moved to better locations with higher currents to prevent the accumulation of waste at the same spot. Even though the pollution per fish is decreasing, the amount of farmed fish is increasing, keeping the total pollution increasing. [7, 15, 16]

2.2 Energy Consumption on Fish Farms

The main focus of this thesis will be off-grid fish farms. They have a layout as shown in figure 4, where the construction is centred around the feed barge. The feed barge uses the most energy. It has the task of securing a safe and efficient feeding of the fish in different working environments. The feed barge is floating on water and must be able to handle rough waters and weather to secure safe work space. The feed barge requirements depend on the working location and concession. For example, within a fjord are the waves, on average, much lower than offshore, making the wave height requirement lower. This can then again infer less cost of construction of the feed barge. Each type of feed barge is customised for the location. For example, the heating requirement of the living quarters will be different in tropical or arctic locations. The feed barge's size also depends on the production capacity set by the concession. A typical range of production capacity is between 780 and 7020 tonnes of fish. Furthermore, work vessels and transport vessels are used on fish farms. They are run on diesel and have significant CO_2 emissions, but they are not covered in this thesis. [3, 17]

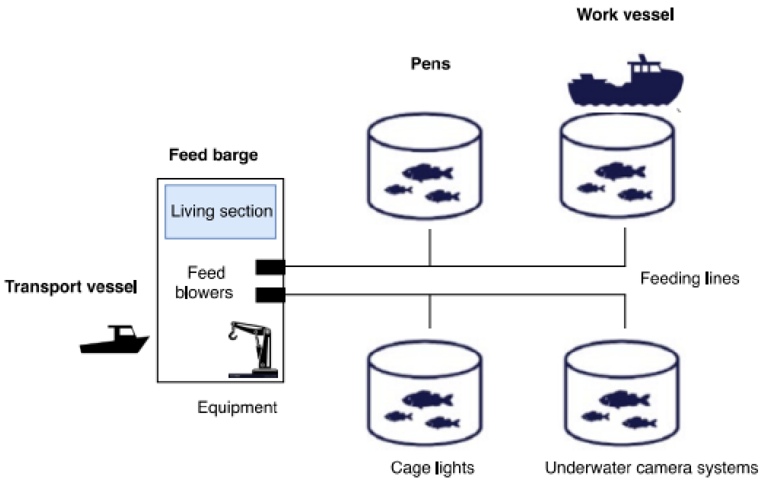


Figure 4: Schematic of an offshore fish farm. [3]

The feed barge includes a living section, control room, feeding system, and other equipment. The other equipment can be a crane or a dead fish handling system. The feed barge is the place where energy is both stored and created. For example, can the energy be stored as diesel and created by a diesel generator. For this thesis, will the energy be stored as hydrogen and in batteries and created through fuel cells. If the feed barge is connected to the power grid, is the feed barge distributing the energy. In figure 5 is there a picture of a feed barge.

Figure 5: Picture of a feed barge from AKVAGroup. [18]

Connected to the feed barge are open nets pens. The amount of pens depends on the concession for the location. In each pen, there is technical equipment that is important for both the welfare and feeding of the fish. These are cage lights, underwater camera systems, and environmental sensors. The feeding hoses are attached to the connection from the pens to the feed barge. All the different types of equipment connected to the feed barge or pens have different types of load demand. A description of the equipment and power demand are shown in table 2.2. [3, 17]

Table 1: Description of the components on a fish farm with estimated power demand. [3]

Components	**Description**	**Power Demand**
Feeding system	Feed blowers are connected to a pen and silos containing pellets by a plastic hos. The pellets are blown through the hoes by compressed air, generated by compressors.	Per feed blower: 22 to 30 kW
Cage lights	Underwater lights which are used to repress pubescence, increase growth and appetite. They are used mostly during winter.	Per light: 6 kW
Living system	Components which are used for heating and lighting in the living quarters. Panel ovens are normally used for heating, which are the most energy demanding component.	Total: 10 to 20 kW
Camera system	For monitoring the fish.	1 to 3 kW
Dead fish handling system	Take away dead fish	2.5 to 26 kW
Crane	Lifting heavy objects.	5 to 30 kW
Ballast pumps	For elevating and lower pens.	22 to 33 kW

The equipment has a different use, as shown in figure 6, where the energy distribution between the components in percentage is depicted. The feeding process is the largest energy consumer, with around 70 % of the total energy consumed. As described in table 1, pellets are blown through feeding hoses by air, powered by a compressor. This process is done during daylight and makes it difficult to peak shave, as there is a specific window for feeding. If there is a power outage and the fish is not fed, can the biggest fish farm lose up to 100 tons of fish per day. Optimal feeding is essential for fish welfare, pellet usage, and economy. [19]

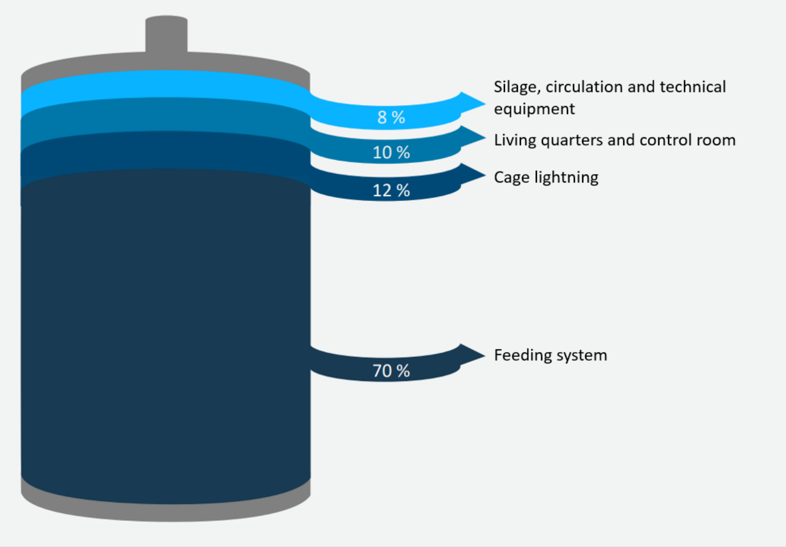


Figure 6: Energy distribution from an average fish farm in percentage, edited from [19].

Cage lighting is the second biggest energy consumer with around 12 %. They are important for sustainable and effective production. The lights are used to delay the sexual maturity of the fish and to increase the efficiency of food consumption. There have also been experiments performed to make the fish swim deeper with the use of cage lights, worsening the living conditions for fish lice. [19]

The living quarters and control room consume about 10 % of the energy. Most of the energy is used by temperature regulations of the indoor environment. The rest is for lights, computers, and cameras. The energy used by this group can be seen as the baseload and are relatively constant throughout the day. This does vary from season to season. For example, the colder it is, the more energy is used for heating. It also depends on the number of people on board and the size of the feed barge. The bigger the facility, the larger the energy demand. The silage, circulation, and technical equipment take around 8 %. It is not the most energy intensive, but it is crucial for secure operation, maintaining critical functions, and having a proper operation. [19]

Based on information gathered from different salmon companies, a consumption profile for a typical day in summer and a typical day in winter was made. These graphs are shown in figure 7 and are based on the energy demand of the components in table 1. This is a salmon farm with a production capacity of 3120 tons. The four feeding systems run at 50 % power during the peaks. This is a total of 40-50 kW, a considerable increase from the baseload at around 10-20 kW. [3]

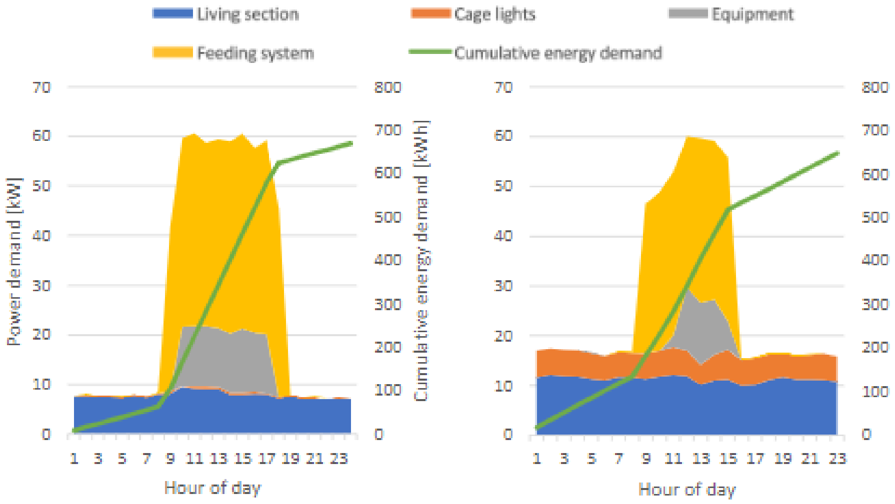


Figure 7: Constructed load profiles for a fish farm. The left is during summer and the right is during the winter. [3]

Cultivating salmon is equal for most companies, both the used technology and type of location. The load profiles for different locations will follow the same curve but have different magnitudes, dependent on the location and size of production. Furthermore, it is expected that the amount of energy demanded should increase during the production cycle. Salmon with a weight of one kg should need less to food grow than a salmon weighing two kg. More food infers more time transporting food from the feed barge to open net pens, and hence more used energy. [3, 17]

2.2.1 Energy Reducing Measures

Going from fossil fuel to hydrogen is a good way of reducing the CO_2 emissions of the feed barge. From a financial perspective, are fuel cells an expensive method but getting cheaper each year. Another way of handling this problem is by reducing the need for energy through energy efficiency improvements. Hence, decrease fuel usage and lessen the cost of fuel and storage. [19]

The feeding system has the largest energy demand, as shown in figures 6 and 7, and with new technologies, it is possible to reduce the energy by 70-90 %, as stated by AKVA Group. This can be done by using waterborne feeding. Here the energy is reduced by replacing the air with water. The energy reduction is optimised when it is implemented while building a new feed barge and not replacing an old feeding system on an existing barge. There are several other advantages. Where AKVA group states that the feeding capacity can be tripled, it can also minimise micro plastics emissions, and the transport of pellets with water is more gentle with the pipes and food. Another advantage is that the feeding depth can be adjusted. For example, if the fish is fed at seven meters depth, there is a possibility that they er less exposed to lice. However, as with new technologies, they are expensive and have few suppliers. [18, 19]

Another energy-efficient improvement is changing the cage lights with LED lights. They are more efficient than the old halogen lights, but this is a process that has already been performed, and most salmon companies have already changed their cage lighting. Furthermore, can the living quarters and control room be more energy efficient. These improvements can be the same as done to a house. For example, changing the panel ovens to a water-water heat pump system. [3, 19]

2.3 Fish Farming Localities

For this thesis, data has been given for three fish farms. They are placed in Eiterfjorden, Skrosen and Årsetfjorden. These fish farms are located close to shore and have all been electrified. Their locations are in the north Trøndelag county and are shown in a screenshot from google maps in figure 8.

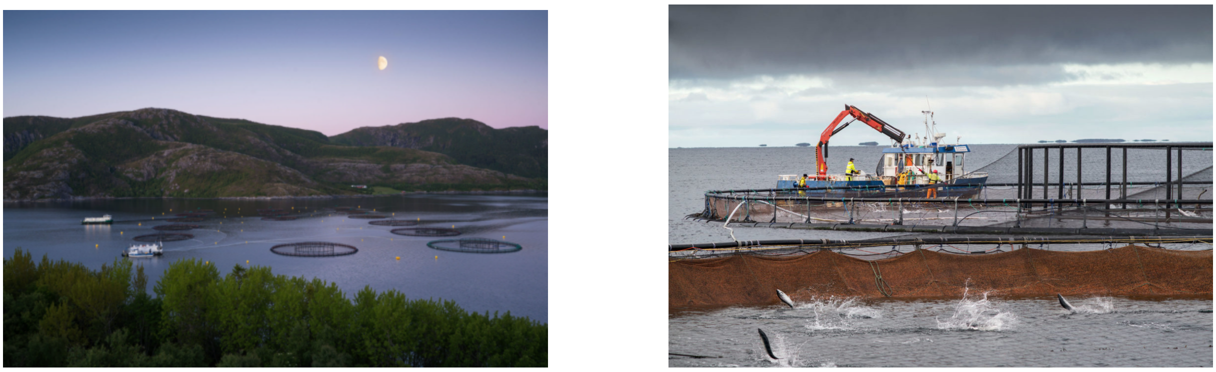
Figure 8: The red markers show the location of Eiterfjorden, Skrosen and Årsetfjorden north in Trøndelag county. Screenshot from Google Maps.

The fish farms are of different sizes, and their maximum allowed biomass (MTB) is shown in table 2. Eiterfjorden and Årsetfjorden are the biggest, with a MTB of 4680 tons, and Skrosen has a MTB of 3900 tons. This indicates that their load demand will differ as both Eiterfjorden and Årsetfjorden would have more fish to feed than Skrosen.

Table 2: MTB for each of the fish farms.

Facility	**MTB [tons]**
Eiterfjorden	4680
Skrosen	3900
Årsetfjorden	4680

A picture of Eiterfjorden, Skrosen, and Årsetfjorden fish farm is shown in figure 9. As shown in this picture, there are several open net pens. Furthermore, the feed barge shown in the picture is an ARENA 400, created by ARENA aquaculture. From the given technical datasheet, the feed barge is 30m in length and 10m in width. It has four silos with a volume of 185 m^3 each. Connected to each silo is a compressor with a power of 22 kW and a hose for transporting the blown pellets from the silo to the open net pen.[20]



(a) Picture of Eiterfjorden fish farm.

(b) Picture of Skrosen fish farm.

(c) Picture of Årsetfjorden fish farm.

Figure 9: Pictures of the three localities. [11]

The feed barges are assumed to be the same for each farm and get power from the electrical grid. This is through a subsea cable with a different length for each fish farm. The cables connect to a transformer on both ends, one at the grid side and one at the feed barge. For the three farms, the electrical system is 3x400 V 50 Hz. Two generators are also present, one at 200 kVA and the other at 60 kVA. In combination with the generators, there is also a 30 m^3 diesel tank. An illustration of the feed barge is shown in figure 10. [20]

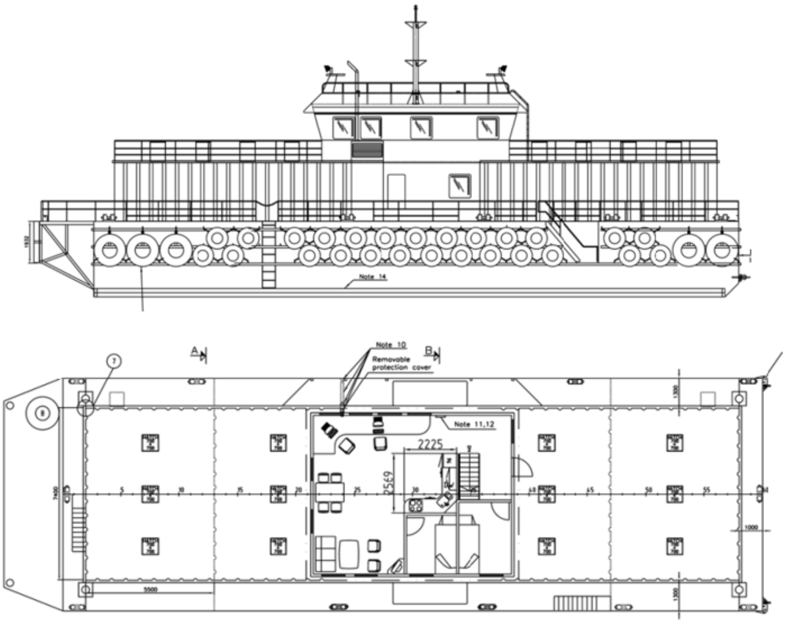


Figure 10: Illustration of the feed barge, seen in profile and aerial view. [20]

2.4 Fuel Cells and Hydrogen

This thesis aims to electrify offshore fish farms with fuel cells combined with batteries fueled by green hydrogen. Hydrogen can be categorised into three main types, grey, blue and green. Grey hydrogen is most commonly used and is hydrogen formed from fossil fuels. One method is refining hydrogen through steam methane reforming (SMR) from natural gas. Blue hydrogen uses the same method as grey hydrogen, but the CO_2 emission is captured and stored. Green hydrogen is produced from water electrolysis with a renewable energy source, hence in theory, no emissions. The thermodynamics of a fuel cell is the opposite of water electrolysis, where hydrogen and oxygen are used as fuel, and water, electricity, and heat are the products. A basic fuel cell schematic is depicted in figure 11. [21, 22]

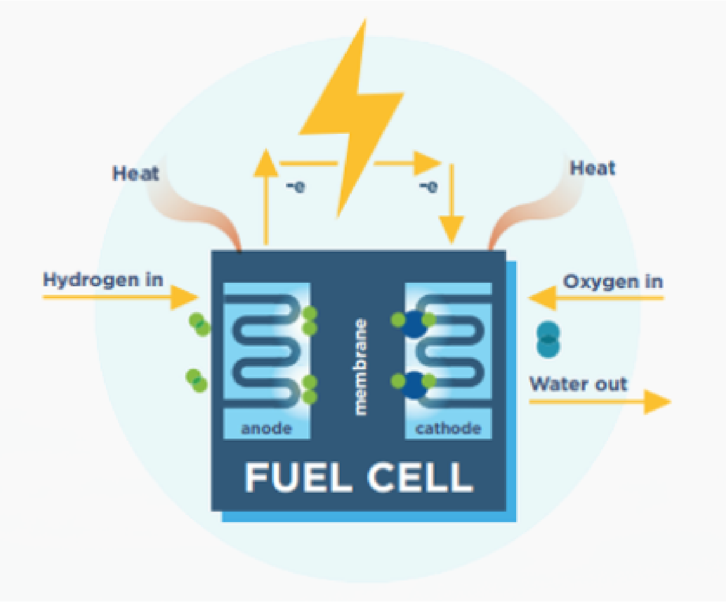


Figure 11: Basic overview of a fuel cell. [22]

The fuel cell consists of a cathode, an anode, and an electrolyte membrane, where chemical energy is turned into electricity. The hydrogen is sent through the anode and the oxygen through the cathode. At the anode is the hydrogen split into electrons and protons. The electrons are sent through an external circuit and generate electricity and heat. The protons pass through the porous electrolyte membrane. Finally, the protons, electrons, and oxygen combine at the cathode to produce water. Voltage of about 0.7 V is produced from one individual fuel cell. Hence, many cells are coupled in series to create the required voltage for different applications. A series of cells is called a fuel cell stack. There are no moving parts in a FC, making it operate with little noise. [21–23]

Many types of fuel cell technologies are shown in table 3. Important attributes such as operating temperature, electrical efficiency, relative cost, and lifetime are compared in this table. Electrical efficiency is defined as the energy output divided by the energy input[24]. The Alkaline fuel cell (AFC) is the oldest and most developed technology. It has a relatively low cost and medium lifetime but several drawbacks. CO_2 poisoning is a huge problem because the carbon dioxide can react with the electrolyte and damage the efficiency and lifetime of the cell. It is, therefore, crucial to have pure hydrogen and pure oxygen as fuel. The Proton Exchange Membrane fuel cell (PEMFC) is another commercially available fuel cell. Compared to the other technologies, it has a low operating temperature, making it flexible and safer. Challenges regarding the PEMFC are removing excess water from the cathode and sustaining the proper humidity of the air. The PEMFC is best suited for maritime operation and will be discussed in greater detail in the next chapter. [21, 23]

Table 3: Different type of fuel cell technologies with different attributes. [21, 23]

Type	**Operating Temperature [°C]**	**Electrical Efficiency**	**Relative Cost**	**Lifetime**
AFC	60 - 200	50 - 60 %	Low	Medium
PEMFC	65 - 85	50 - 60 %	Low	Medium
MCFC	650 - 700	50 - 55 %	High	Good
SOFC	500 - 1000	50 - 60 %	High	Medium

The Molten Carbonate fuel cell (MFCF) is more expensive and operates at a much higher temperature than the AFC and PEMFC. Because of the high operating temperature, several fuels like LNG, hydrocarbons, and methanol can be used. The MCFC has a slow start-up and does not respond well to changing load demand. The last fuel cell technology to be cowered is the Solid Oxide fuel cell (SOFC). Like the MCFC, the SOFC has a high operating temperature and costs. The MCFC and SOFC technology is not mature enough for the maritime industry and will not be further discussed in this thesis. [21, 23]

2.4.1 Proton Exchange Membrane Fuel Cell

A basic schematic of a proton exchange membrane fuel cell (PEMFC) is shown in figure 12. The orange plate is the proton exchange membrane (PEM). It is responsible for the proton conductivity, where the transport of protons from the anode to the cathode occurs. A common material used for the membrane is nafion. Nafion has good proton conductivity and separates the reacting gases in the electrode. A challenge with nafion is that the proton conductivity decreases when the operating temperature goes over 90 °C. It is therefore vital to have an excellent cooling system for the PEMFC. The membrane electrode assembly (MEA) is the core of the PEMFC, which constitutes a PEM with coated catalyst layers on both sides. The thickness of the PEM is in the range of 20 to 60 micrometers. The ion which is transferred through the membrane is the H^+ ion. The material used for the electrodes is platinum for both the anode and cathode. Platinum fits because it has the attributes of electric and ionic conductivity and is permeable for reacting gases. As the MEAs are very thin, the cells can be compact. It starts quickly because the PEMFC works at low temperatures compared to the other FC, as shown in table 3. [21, 25, 26]

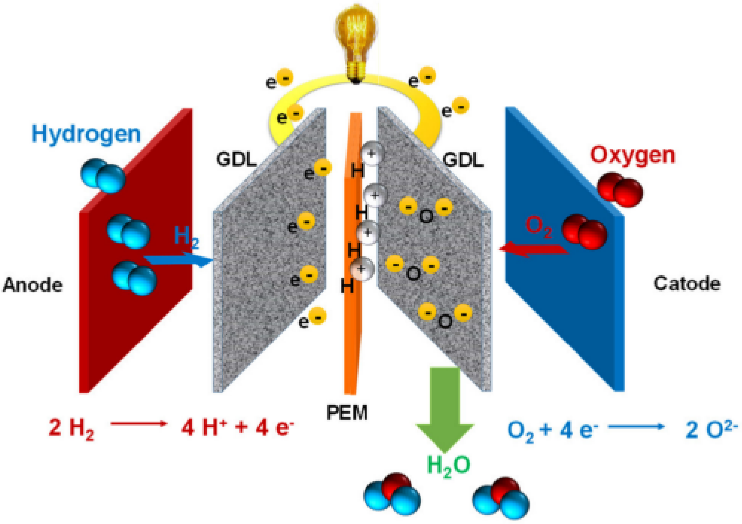


Figure 12: General schematic of a PEMFC. [26]

Outside the MEA is the gas diffusion layer (GDL), which is the grey layer in figure 12. GDL has the task of removing water and making the feed gases flow through. During the electricity production from a PEMFC, a substantial amount of heat is also produced. It is crucial to remove this heat to prevent overheating. If not done correctly, it will cause degradation of the cell. Several different kinds of strategies can be implemented to avoid this problem. One is air cooling, and another is cooling via liquid such as oil or water. There is a problem with air cooling for maritime use, as the salty air affects the efficiency of the cell. [21, 26, 27]

Degradation in the cell stack can also occur due to electrode poisoning by carbon monoxide (CO) and carbon dioxide (CO_2). An impure hydrogen feed typically causes this. If the hydrogen comes from methane reforming, it will contain small amounts of CO_2 and CO. Therefore, purifying the hydrogen before usage is important, but this is costly. For this project, the used hydrogen will come from water electrolysis, which has high purity, depending on the electrolyzer. Therefore hydrogen purification will not be needed and significantly lower costs. [21, 26, 27]

In figure 13, the PEMFC electrical efficiency (η_{el}) vs the nominal load are shown. It can be observed that the PEMFC has the highest η_{el} with an estimated 55 % around 20 % nominal load. [28]

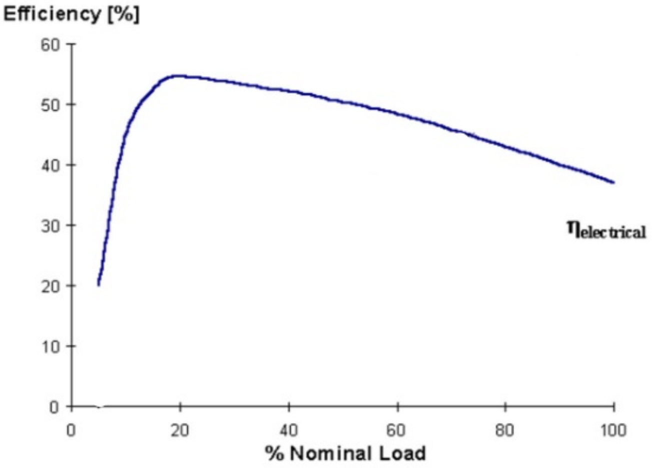


Figure 13: Electrical efficiency of a PEMFC versus load. Edited from [28].

Even with clean hydrogen, the cell stacks will degrade over time. This infers lower electrical efficiency and higher hydrogen use. Increasing the lifetime of a fuel cell requires, therefore, the replacement of the cell stack. The branch standard is to change the cell stack when the energy efficiency is below 90 % of the nominal load. Furthermore, the degradation percentage depends on how the fuel cell is operated. For this thesis, the assumed loss of electrical efficiency will be 1 % per year. [29]

2.4.2 Hydrogen Storage

Hydrogen is the lightest element in the periodic table with an extremely low density. For example, 1 kg of hydrogen at atmospheric pressure has a volume of 11 m^3. That is why it is important to find the most suitable storage method. As previously explained in chapter 1, the hydrogen fuel will be transported to the fish farm via a floating mobile bunkering unit. The hydrogen will most likely be transported as compressed gas. There are other types of storage, such as in liquid form or either a metal or chemical hydride. The latter two are too expensive and underdeveloped for commercial use, and liquid storage is too energy demanding in small-scale use. Hence, compressed hydrogen is the preferred method with the most advanced technology and low cost. [30]

Storing hydrogen requires a large amount of energy. This work is done by the compressor when compressing the fuel. For example, pressurising 1.0 bar of hydrogen to 350 bar will require about 9 % of the energy of the compressed hydrogen. From 1.0 to 750 bar, it will require 12 %. If the hydrogen had been liquefied, up to 30 % would have been required. The specific energy required for compression of 1 kg hydrogen from 1 bar to higher pressure is given in figure 14. The stipulated line is the theoretical minimum, and the grey line includes losses. For example, marked in the graph, a theoretical minimum for compressing hydrogen from 1 bar to 90 bar is about 1.6 kWh/kg_{H_2}. [21, 30]

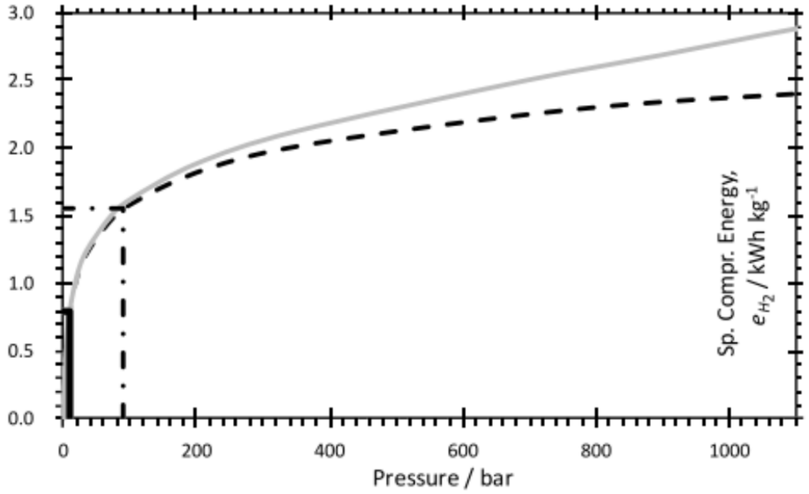


Figure 14: Specific energy needed for compression from 1 bar to higher pressures. The stipulated line is the theoretical minimum, and the grey line includes losses. The marked points are the theoretical minimum for compressing hydrogen from 1 to 90 bar. [21]

2.5 Batteries

The chosen type of fuel cell is the PEMFC. Compared to the other fuel cells, they have a quick response but are not fast enough for the quickest load changes. Therefore, batteries are essential for covering the highest peaks and the quickest load changes. The demand for batteries has increased over the years, which has led to the rapid development of technology. A wide variety of battery technology is available, from lead-acid to lithium-ion batteries. [31]

Batteries consist of several electrochemical cells. The cells store energy as chemical energy, which is turned into electrical energy when a load is connected. There are two types of batteries. These are primary and secondary batteries. Primary batteries cannot be recharged and will not be discussed further in this project. Secondary batteries are rechargeable because the chemical reaction in the cells can be reversed by applying electrical energy to the battery. The fundamental design of a secondary battery is shown in figure 15, which consists of one electrolyte, two electrodes, a separator, and two current collectors. The materials of the electrodes or the electrolytes depend on the battery type. For example, can the electrolyte be solid or liquid. [31, 32]

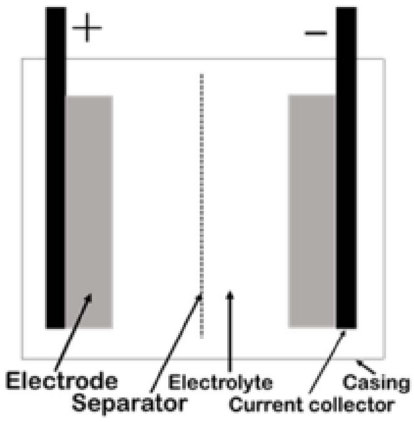


Figure 15: Design of a secondary battery cell. [32]

There are several different secondary types of batteries that are feasible for utility-scale operation. These are lead-acid, flow, sodium-sulphur, and li-ion batteries. The most favourable to use is the li-ion battery. It has the highest capacity and is widely used in many applications today. The battery technology is continually improving, hence, costs have dropped by 80 % from 2010 to 2017[33]. In figure 16 a Ragone plot is shown for batteries. It illustrates how lithium batteries have the highest specific energy, specific power, and C-rate potential. These attributes are important for fish farms, as there is limited space. [31]

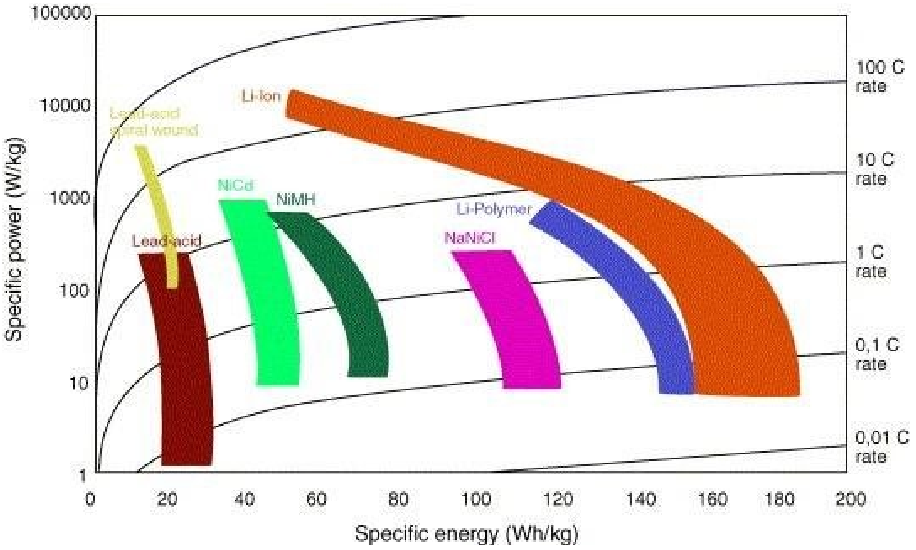


Figure 16: Ragone chart of different type of batteries. [34]

Battery Terminology

An important battery parameter is the State of Charge (SoC), and the calculation of SoC is given in equation 1. This denotes the amount of energy currently available at the rated capacity. SoC varies between 0 and 100 %. A SoC at 100 % is fully charged. A SoC is depleted at 0 %. By ageing will, the maximum SoC decrease. For example, a one-year-old battery at max SoC will have more energy stored than a three-year-old battery at max SoC. [35]

$$SoC = \frac{Available\ amount\ of\ charge}{Maximum\ available\ amount\ of\ charge} \cdot 100\% \tag{1}$$

Depth of Discharge (Dod) is another parameter for batteries. How it is calculated is shown in equation 2. It is defined as the amount of removed charge from a battery at any given state. [35]

$$DoD = \frac{Removed\ amount\ of\ charge}{Maximum\ available\ amount\ of\ charge} \cdot 100\% \tag{2}$$

The life cycle is the amount of discharge/charge cycles it can undergo before it can still meet the design criteria. For the fish farm, the chosen batteries must have many life cycles. Also, the C-rate of the battery is of importance. The C-rate measures how fast a battery is discharged compared to the maximum capacity. For example, if the battery has a 1C rate, it will be depleted within one hour. [35]

2.5.1 Lithium Batteries

Li-ion batteries have higher capacity and more reliable operation compared to other batteries. There are several different types of lithium batteries, but they all share common elements. The anode is made from graphite-based materials. This is due to the high availability of carbon and low cost. The cathode normally compromises lithium metal oxide materials. Examples are $LiMn_2O_4$ and $LiFePO_4$. Different cathode materials will give different performances from the battery. The electrolyte can be either liquid or semisolid/solid-state. Both types of electrolytes normally consist of different types of lithium salts. Besides having high specific energy and specific power, the lithium battery has a long life cycle with 3000 cycles on 80 % DoD. [36]

In 2017, li-ion batteries accounted for almost 90 % of utility-scale battery storage additions. There are several examples where the LIB has been implemented. In the United Kingdom, li-ion batteries have been installed in Glassenbury (40MW) and Cleator (10MW) for frequency regulation of the energy grid. Together, these two installations provide a quarter of the total frequency regulation capacity in the UK. Another lithium battery storage project was in California in the United States. Here they developed a 30 MW/120 MWh li-ion battery storage near one of the substations in Escondido. The purpose is to store excess energy from renewable energy and serve as a reserve. [33]

2.6 Economics

Two different terms have to be explained to determine if an investment will be profitable. These are capital expenditures and operational expenditures. They will be referred to as CAPEX and OPEX, respectively. CAPEX are significant purchases that a company uses over a longer term. Furthermore, it usually is purchases of assets that improve the company. New machinery for a factory, which increases production efficiency, can be an example. OPEX is the day-to-day expenses that go to keep a business operating. For example, for a factory, can OPEX be wages or machine rent. [37, 38]

If a more considerable investment has been executed, the investor would like to know when the investment might be profitable. Calculating the payback period is shown in equation 3. CAPEX is the initial cost, and C_t is the annual cash flow. The term payback period is the time before an investment recovers the cost. Hence, when the investment breaks even. A shorter payback period makes the investment more attractive. The problem with the payback period is that it does not consider the time value of money. That is the concept that an amount of money today is worth more than the same amount in the future because of the money's earning potential. [39]

$$Payback\ period = \frac{CAPEX}{C_t} \tag{3}$$

To further explore a financial investment, a net present value (NPV) calculation is an excellent addition to the payback period. The NPV does consider the time value of money. NPV is the difference between the present value of cash inflows and the present value of cash outflows over time. It is calculated by using equation 4.C_t is the annual cash flow, t is periods in, for example, years, and r is the discount rate. C_0 is the total initial investment. The discount rate is the factor that expresses the time value of money and can therefore be the difference if an investment is viable or not. Net present value can be used to compare different investment alternatives. If the NPV value is positive, the investment can be profitable; if it is negative, it should not be considered. [40, 41]

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} - C_0 \tag{4}$$

A further extension of the net present value calculation is to find the internal rate of return, IRR. This is a percentage that is used to estimate the profitability of an investment. The IRR is the discount rate that makes the net present value zero. The higher the IRR is, the more desirable a project is. It is calculated on the same basis as NPV, but by solving for IRR when the NPV is zero, as shown in equation 5. Furthermore, is IRR uniform for all types of investment and can therefore be used to compare different investments. [42]

$$0 = NPV = \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_0 \tag{5}$$

3 Methodology

A solution for making offshore fish farms emission free is by introducing hydrogen fuel cells run on green hydrogen. Simultaneously, adding batteries to optimise energy efficiency and secure safe operation. The new system must be able to cover almost all possible scenarios for operation. If the new system is not working, a power outage may cause enormous losses for the fish farming company. Furthermore, the system must be cost-efficient. If it is too expensive, businesses will not buy it, and too cheap might lead to critical system failures.

Datasets for three different fish farms have been analysed in this thesis, which are Eiterfjorden, Skrosen, and Årsetfjorden. They are close geographically and have the same weather conditions, as shown in figure 8. Two different scenarios are explored for each farm.

- Scenario one, **retrofit**: Retrofitting an existing feed barge with a new energy system comprised of fuel cells and batteries.
- Scenario two, **New build**: Building a new feed barge with all the new energy efficient technologies, fuel cells, and batteries.

The first scenario is the retrofit of an existing feed barge. This is the cheapest and quickest way to change CO2 emissions. The second scenario is a more extensive and costly project, building a new feed barge. New energy efficient measures will be implemented, such as waterborne feeding, which will minimise the fuel consumption. Many energy reducing measures are best implemented by building a new feed barge. Both scenarios will be weighed against each other and a base case. The base case is the continuation of regular operation with fossil fuels. A python script is used to analyse the load data. The python script output is fuel cell size, battery size, consumed hydrogen, and refuels per month. These results will then be weighed against each other in a cost-benefit analysis to find the most cost-efficient solution.

3.1 Sorting of Data

The python script's main task was to sort the given data and calculate fuel cell size, battery size, hydrogen, and amount of refuels per month. This was performed by calculating the total energy used for each month and finding the month with the highest load. An example is shown in figure 17, where the total amount of used energy each month for 2019 is plotted. Here it can be observed that January 2019 has the highest consumption. Tables with consumption data for Eiterfjorden, Skrosen, and Årsetfjorden are in appendix A.

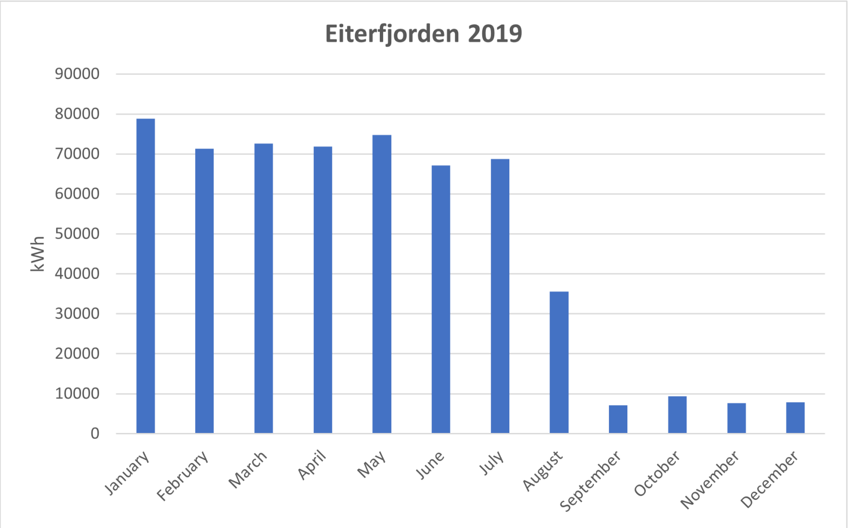


Figure 17: Total amount of load for each month in 2019 at Eiterfjorden fish farm.

After finding the month with the highest consumption, an average load profile for a day in that month is created. This is shown in figure 18. Here the orange curve is the daily load. The blue curve is the daily load's duration curve, and the red line is the average load. The duration curve shows how long each load demand, for example, during a day, is consumed. This type of curve makes it easier to spot the highest peaks and how long they appear. This load profile coincides with the created load profiles in figure 7. Furthermore, it can be observed that the feeding hours are from 9 to 16.

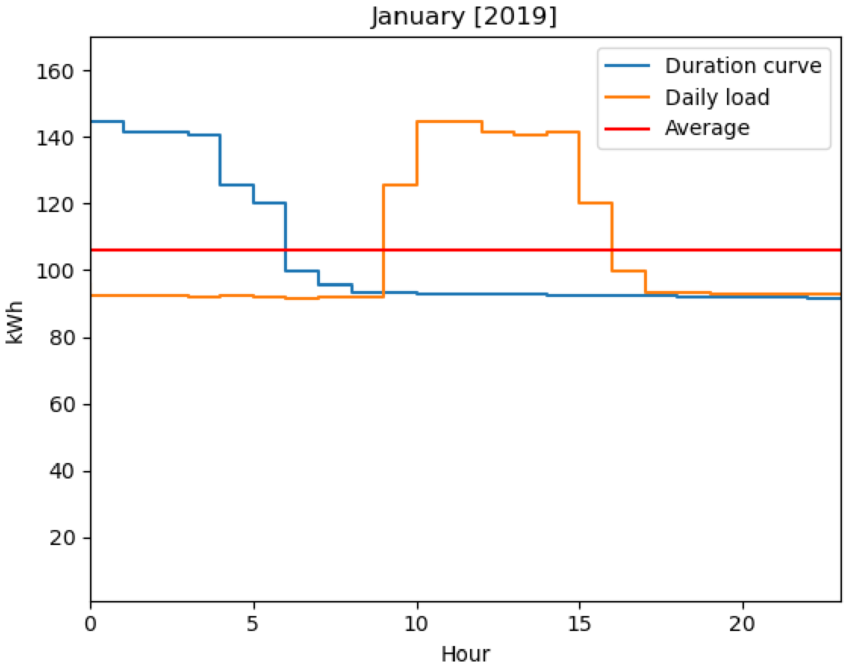


Figure 18: Average daily load profile from January 2019 at Eiterfjorden fish farm.

3.2 Implementing Efficiency Measures

Sizing the fuel cell and batteries for a new build could not be performed with the same values from the original dataset. These values needed to be adjusted. This was performed by taking into account the efficiency measures mentioned in chapter 2.2.1. The given dataset does not include detailed information about the hourly load, such as how it is divided between appliances. Hence, assumptions are made to separate feeding hours from the baseload. Load above the average red line is feeding time. As described in figure 6 the feeding takes about 70 % of the total energy consumption, and by implementing waterborne feeding instead, it can be reduced by 70 - 90 %. Therefore it was decided that the feeding hours will reduce by 60 %, which is coloured in red in figure 19. The rest of the baseload, which is the living quarters and cage lighting, can be reduced by 50 %. Hence, it was decided that the baseload or everything under the average will be reduced by 40 %, as coloured in blue in figure 19.

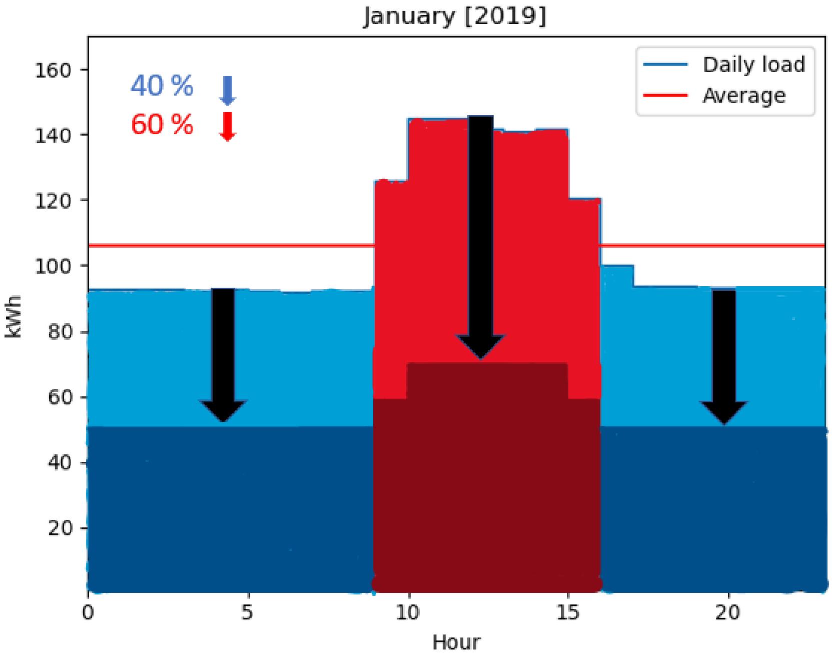


Figure 19: Implementation of efficiency measures.

The adjusted load profile for the new build is shown in figure 20. By comparing the load profiles in figure 18 and 20, it can be observed that the load demand has decreased significantly, and the difference between feeding hours and baseload has been minimised. Tables for new build scenario consumption each month for Eiterfjorden, Skrosen, and Årsetfjorden are in appendix A.

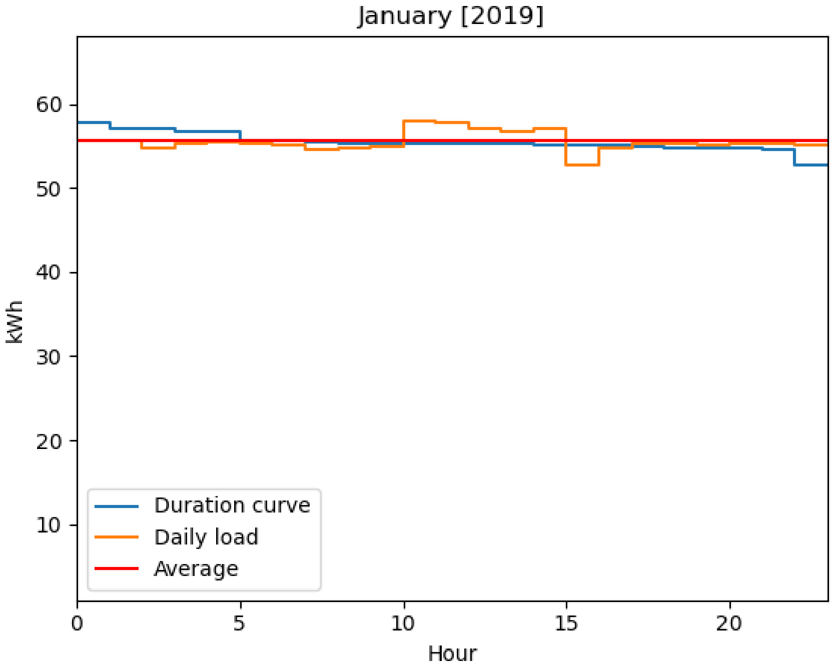


Figure 20: Average daily load profile from January 2019 at Eiterfjorden fish farm, for a new build.

3.3 Fuel Cell and Battery Sizing

The sizing of the fuel cell and battery size is based on the month with the highest total load. That is because most of the operating cases are then covered. The specialisation project explores the difference between one and two fuel cells. It concludes that two fuel cells will be better financially than one fuel cell because of better electrical efficiency and lower hydrogen usage. This will not be the case in this thesis because the fuel cell price is doubled, instead of the 13000 kr/kw used in the specialisation project, from personal communication to the new price of 28000 kr/kw. The lesser hydrogen usage does not save enough expenses from earning the difference in cost. Furthermore, a diesel generator as a backup is much cheaper and a better way financially to secure safe operation and reliability of the system. [43]

The load profile will be covered on the same principle as the specialisation project. The fuel cell will cover peak hours, and the batteries will cover swings in load demand. Furthermore, will the batteries be sized to cover the baseload during non feeding hours. This will depend on the season and how long into the seawater process the fish farm is. The swings in load demand are not further explored in this thesis. This is because the given data is hourly and not in minutes or seconds. Based on these assumptions, the fuel cell will operate from 6 - 12 hours a day, and the batteries will cover the rest. This is shown in figure 21. The red coloured area is where the load is covered by the fuel cell, and the battery will therefore cover the load in the blue area. This has been decided based on minimising hydrogen usage so that the fuel cell can run with maximum efficiency when charging the batteries and have a good efficiency when covering the peaks.

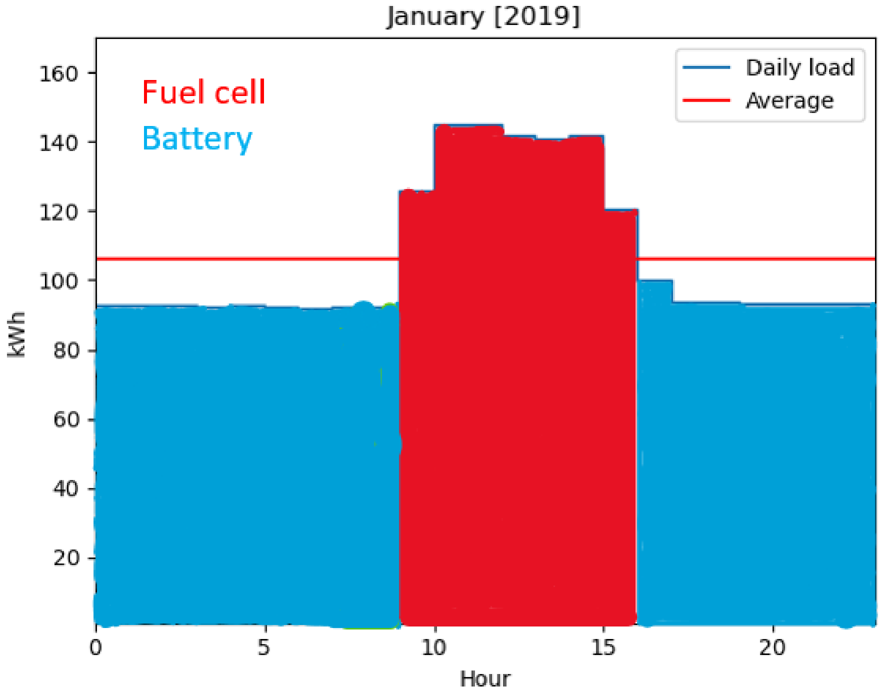


Figure 21: Operational scenario where the fuel cell covers the load demand in the red area, and the battery covers the load in the blue area.

Based on the assumptions in the previous paragraph, the fuel cell size will be roughly 10 % higher than the average peak value during the feeding hours. This is based on the month with the highest consumption from the given dataset. The battery size will be calculated from 1/4 of the total energy used during the feeding hours. Therefore, the battery can sustain the feed barge for 2 hours if the feeding lasts 8 hours. This value will also be multiplied by 1.25 because the SoC of the battery for the chosen battery type work best from 20 to 100 % SoC, as described in chapter 2.5.1.

3.4 Hydrogen Demand Calculation

In figure 13, the efficiency of a fuel cell is dependent on the percentage of the load. For example, it can be seen that the highest electrical efficiency is around 20 % nominal load. It is important to note that this depends on the fuel cell, but the graph is a good indicator. This curve is represented in equation 6, where E is the percentage of the load and the output is the electrical efficiency, η_{el}. This equation was created through a polynomial fit with the code in appendix B.

$$\eta_{el}(E) = -8.41e-6 \cdot E^4 + 1.99e-3 \cdot E^3 - 1.63e-1 \cdot E^2 + 5.12 \cdot E + 4.41 \tag{6}$$

The sizing of the fuel cell is such that the fuel cell will cover the peak hours and the battery the baseload. During the calculation of the hydrogen needed, the difference in η_{el} is differentiated as shown in figure 22. The peak hours, which are all load above the average, will have an efficiency based on equation 6. The rest of the load uses the max efficiency at 60 %. This is because the batteries will supply at that time, and they will be charged by the fuel cell at maximum electric efficiency. Furthermore, it is assumed zero losses from the battery charging and output.

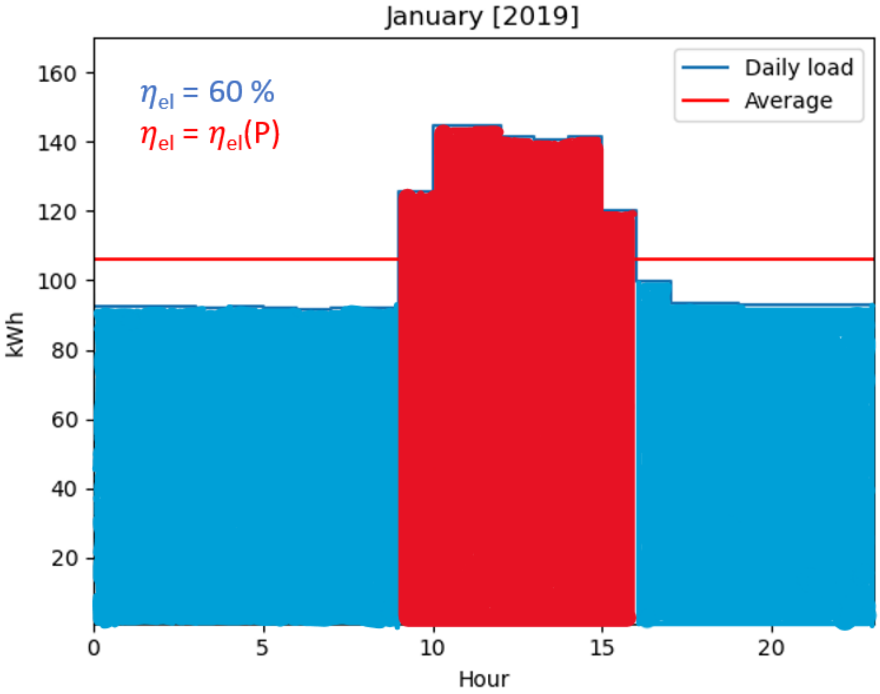


Figure 22: When the different electrical efficiencies will be used. Blue colour is the max efficiency and red colour follows the efficiency graph.

After the efficiency is calculated, the amount of hydrogen is calculated with equation 7. This was done for every data point in the dataset and added together for a total each month. E is the load at each hour, and 33 kWh/kg is the amount of energy in one kilogram of hydrogen.

$$H_2[kg] = \frac{E[kWh]}{\eta_{el}(E) \cdot 33[kWh/kg_{H_2}]} \tag{7}$$

By using equation 7 the total amount of hydrogen per month for Eiterfjorden in 2019 is shown in figure 23. The amount for both scenarios is shown. The figure indicates a clear difference in the needed hydrogen between the retrofit and new build scenarios.

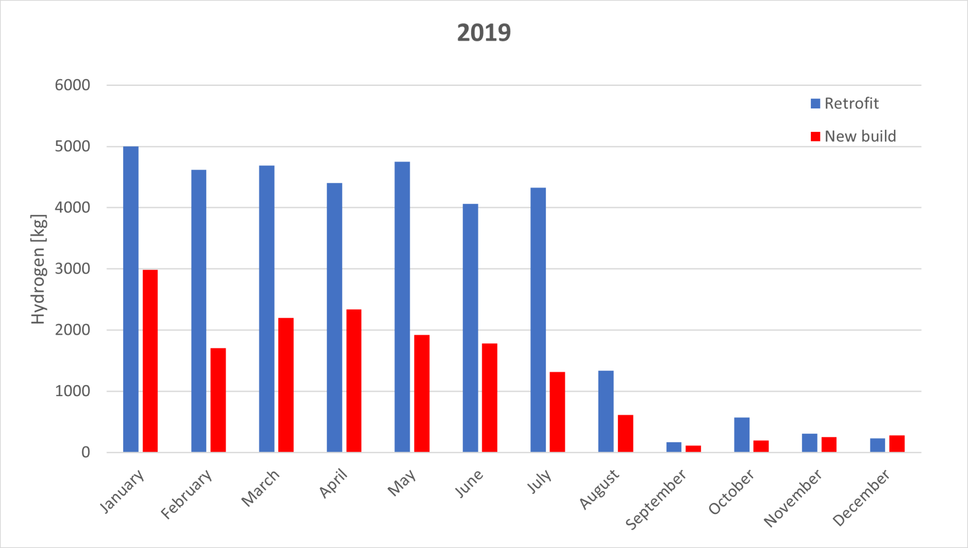


Figure 23: Amount of hydrogen per month for Eiterfjorden 2019 for scenarios 1 and 2.

3.5 Refuel

The amount of refuels per month is also calculated during the calculation of the hydrogen. It was decided to use two 20 fots containers for each fish farm. These are containers with a length of 6 meters, a width of 2.4 meters, and a height of 2.9 meters. Hence, a container covers an area of 14.4 m^2. These containers can store 487 kg of hydrogen at 350 bar and 20 °C [43]. The amount of space the containers take is shown in figure 24. The red box is two containers, taking up an area of 28.8 m^2.

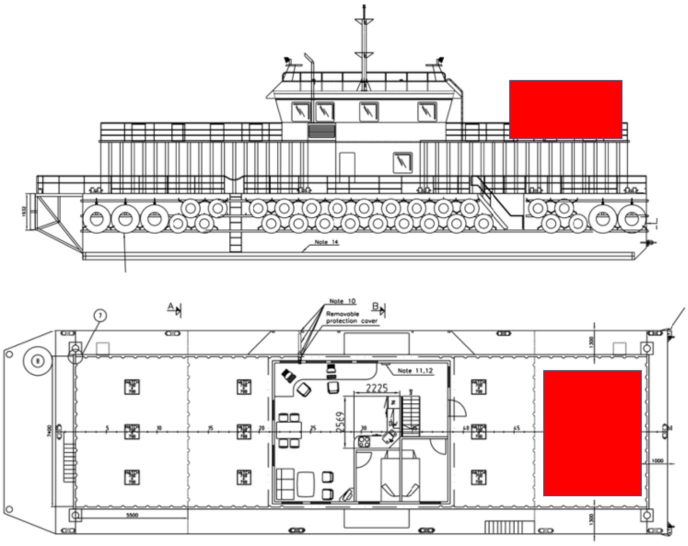


Figure 24: Two containers on the top deck in profile and aerial view. Edited from [20].

A refuelling occurs when the containers are below 10 % of hydrogen. The amount of refuels for Eiterfjorden per month is shown in figure 25. It can be observed that the needed amount of refuels goes down for the new build scenario.

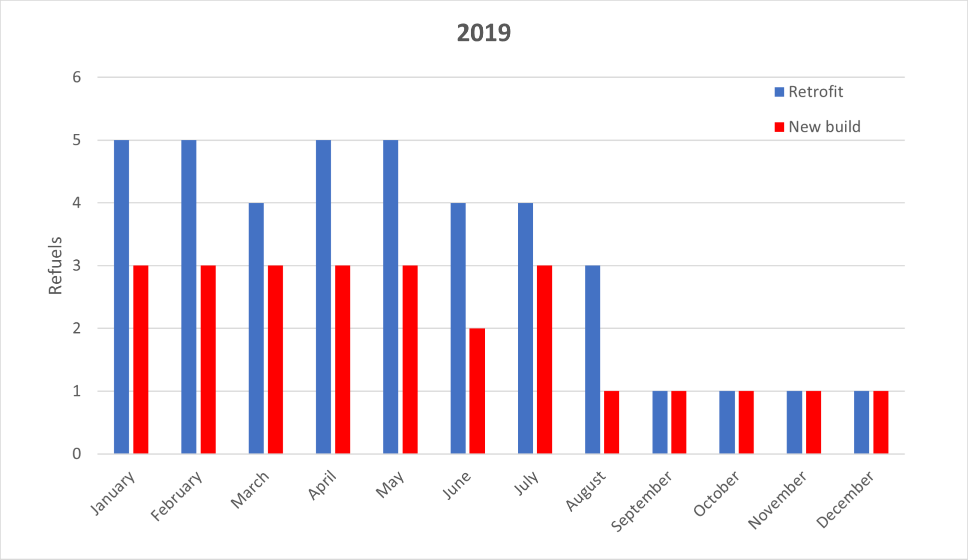


Figure 25: Amount of refuels per month for Eiterfjorden 2019 for retrofit and new build scenario.

3.6 Datasets

There are three different dataset given for this thesis, which has the time periods:

- Eiterfjorden: 09.10.2018 to 14.02.2022
- Skrosen: 27.09.2016 to 13.02.2022
- Årsetfjorden: 28.09.2018 to 13.02.2022

The data is incomplete, with several periods without load readings. These values were adjusted bys exchanging a month without demand with another at the same point in the cycle. Another datasheet was also given, which held the production data of the fish farm. It explains the amount of fish transported, the total biomass at the beginning and end, and the deployment and harvest of the fish. The month with the first arrival and last month of harvest is shown in table 4. The deployed amount of fish and harvested is also presented.

Table 4: Date of deployment and harvest of fish for the fish farms, with corresponding fish biomass.

Facility	**Deploy**	**Harvest**	**Deploy**	**Harvest**
Eiterfjorden	May 2018	September 2019	May 2020	September 2021
Biomass [kg]	128 351	4 782 845	100 073	3 564 153
Skrosen	August 2018	February 2020	August 2020	January 2022
Biomass [kg]	79 603	3 667 594	202 048	2 599 605
Årsetfjorden	April 2018	June 2019	January 2020	September 2021
Biomass [kg]	191 727	4 607 773	139 451	4 950 982

The fish farms deploy most fish on the same date, but they harvest the fish over a longer period. The harvest date in table 4 is the last month before the fish farms are empty. There are still fish in Skrosen fish farm January 2022, because the given data ended January 2022. Furthermore, figure 26 shows the correlation between energy usage and when fish are present at the fish farm. From January to September 2019, there are fish present at Eiterfjorden, and that is the bars coloured in green. Compared to the bars in orange, there is a clear difference in energy usage at the feed barge.

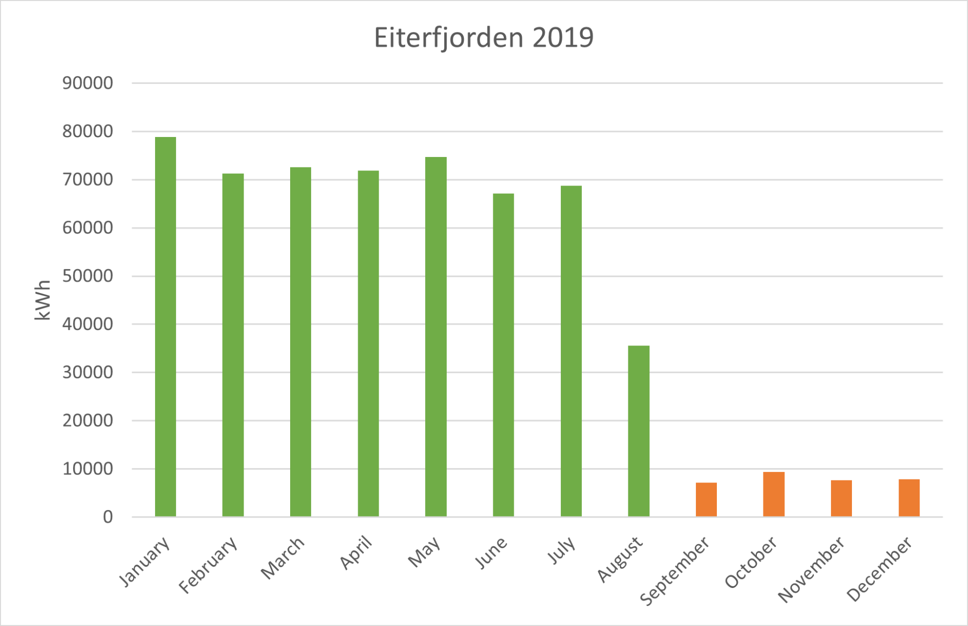


Figure 26: The total amount of load for each month in 2019 at Eiterfjorden. The bars coloured in green are when the fish farm has fish and the orange coloured is when the fish farm is empty.

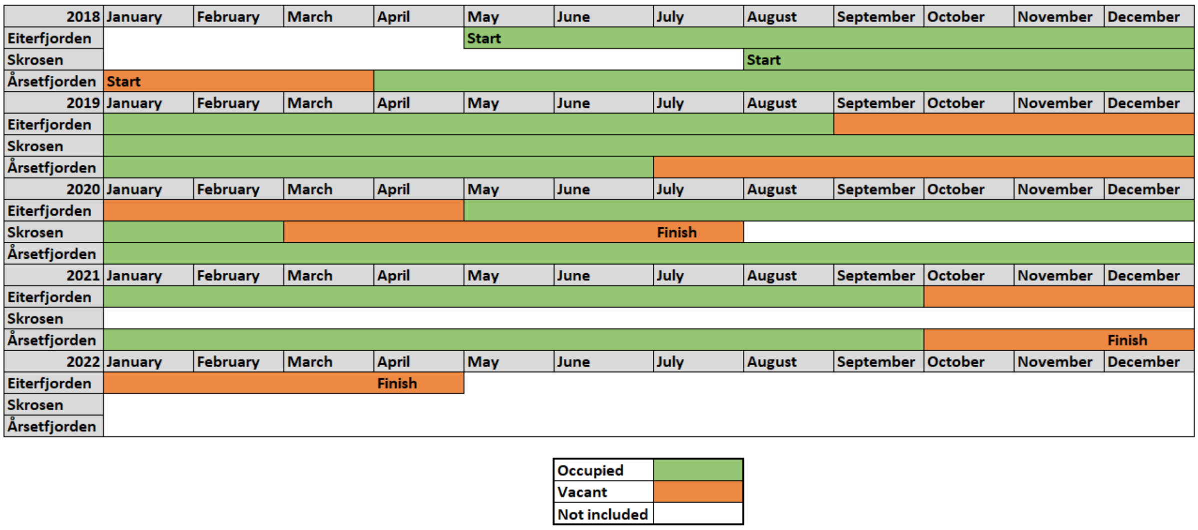
3.7 Decided Cycles

An operational cycle was constructed for each fish farm for the financial analysis. This cycle needed to include a regular fish farm operation for several years. It includes the growth time of the fish in the sea and the time the fish farm is vacant. Based on the given data, it was decided that each fish farm will have a repeated cycle, as shown in table 5. The data set is not complete for these cycles. Hence some modifications have been performed. They are explained later sections.

Table 5: Facilities with the allocated cycle, with the corresponding start and finish according to the given data set.

Facility	Cycle span	Start	End
Eiterfjorden	4 Years	May 2018	April 2022
Skrosen	2 Years	August 2018	July 2020
Årsetfjorden	4 Years	January 2018	December 2021

Figure 27 shows a graphical representation of the cycles. The green colour indicates that the fish farms operate, the orange colour indicates that the fish farm is vacant, and the white are outside the scope of the economic analysis.



2018	January	February	March	April	May	June	July	August	September	October	November	December
Eiterfjorden	⬜	⬜	⬜	⬜	🟩 Start	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Skrosen	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩 Start	🟩	🟩	🟩	🟩
Årsetfjorden	🟧 Start	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2019	January	February	March	April	May	June	July	August	September	October	November	December
Eiterfjorden	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧
Skrosen	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Årsetfjorden	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧
2020	January	February	March	April	May	June	July	August	September	October	November	December
Eiterfjorden	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Skrosen	🟩	🟩	🟧	🟧	🟧	🟧	🟧 Finish	⬜	⬜	⬜	⬜	⬜
Årsetfjorden	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2021	January	February	March	April	May	June	July	August	September	October	November	December
Eiterfjorden	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧
Skrosen	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Årsetfjorden	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧 Finish
2022	January	February	March	April	May	June	July	August	September	October	November	December
Eiterfjorden	🟧	🟧	🟧	🟧 Finish	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Skrosen	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Årsetfjorden	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜

Occupied	🟩
Vacant	🟧
Not included	⬜

Figure 27: A graphical representation of the schedule for the fish farms. The green indicates that the fish farm has fish, the orange colour indicates that it is empty, and the white colour is months outside the scope of the analysis.

The cycles are as follows. For Eiterfjorden, a four-year repeating cycle starts in May 2018 and ends in April 2022. This cycle has two rounds of fish. The first one is 16 months, from May 2018 to August 2019. Then the fish farm will be vacant for eight months, from September 2019 to April 2020. The second period will be 17 months, from May 2020 to September 2021. The cycle will end with seven months vacant from October 2021 to April 2022.

For Skrosen, the cycle will be two years, starting with fish for 19 months, from August 2018 to February 2020. Then the fish farm will be vacant for five months, from April 2020 to July 2020. For Årsetfjorden, will the cycle be four years, starting vacant for three months from January 2018 to March 2018. Then be occupied for 16 months from April 2018 to July 2019, and then be vacant for five months from August 2019 to December 2019. The second round of fish will be for 21 months, starting January 2020 and ending September 2021, before being vacant for three months from October 2021 to December 2021.

The given dataset was incomplete because either the fish farm was not connected to the grid or there was a problem with the electrical system at the fish farm, and it had to run on fossil fuel. Hence, these adjustments have been performed on the dataset, as shown in table 6. These adjustments are based on the months in the same timeframe of the fish cycle. The months replaced with 5000 kWh have no load or fish, and 5000 kWh have been an average baseload for the vacant fish farms. For the new build scenario, this is set to 4000 kWh, corresponding to 250 and 200 kg of hydrogen, respectively.

Table 6: Adjustments to the load dataset.

Facility	**Incomplete**	**Replaced with**
Eiterfjorden	May to September 2018	May to September 2020
Eiterfjorden	March and April 2018	March and April 2020
Skrosen	April to July 2020	April to July 2018
Årsetfjorden	January to March 2018	5000 kWh
Årsetfjorden	April to September 2018	April to September 2021
Årsetfjorden	August to December 2019	5000 kWh
Årsetfjorden	January to May 2020	January to May 2019
Årsetfjorden	August to September 2020	August to September 2021
Årsetfjorden	October 2020	October 2018
Årsetfjorden	December 2021	5000 kWh

3.8 Hydrogen and Refuels

The needed amount of hydrogen per year for each fish farm in scenario one is shown in figure 28. The amount of hydrogen is calculated on the principles as explained in section 3.4. In all of the fish farms, the needed amount of hydrogen goes down in the second year. This is because the cycles start when the fish farms get fish and are vacant for around half the second year. The degradation of the fuel cell has been taken into account. The hydrogen total for years 2, 3, and 4 have been divided by 0.99^y. This is to adjust the drop in efficiency by one percent per year, y. The tables these histograms are based on is in appendix C.

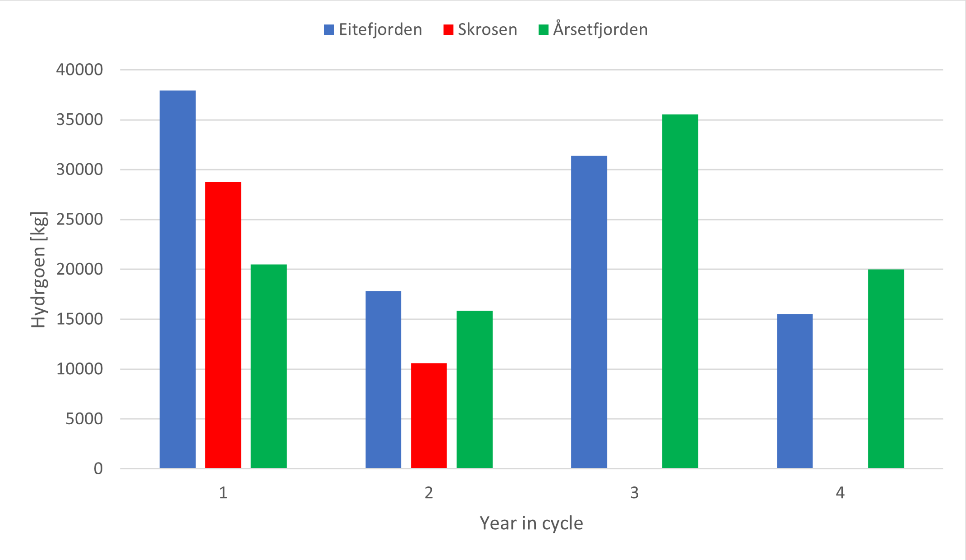


Figure 28: The calculated amount of hydrogen during each year in the retrofit scenario cycles.

The needed amount of hydrogen per year for scenario two is shown in figure 29. Comparing the two figures shows how much less hydrogen is needed with the implemented efficiency measures, which is about halved for each fish farm.

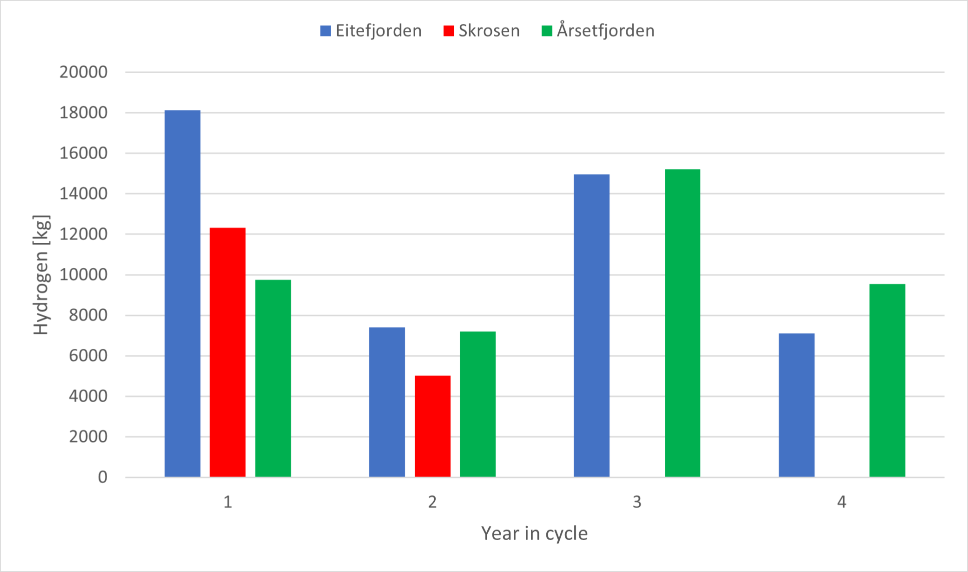


Figure 29: The calculated amount of hydrogen during each year in the cycles for the new build scenario.

The number of refuels per year for each fish farm is shown in figure 30, which is for the retrofit scenario. Following the same pattern of the hydrogen demand, the refuels go down during periods with no fish. The tables these histograms are based on is in appendix C.

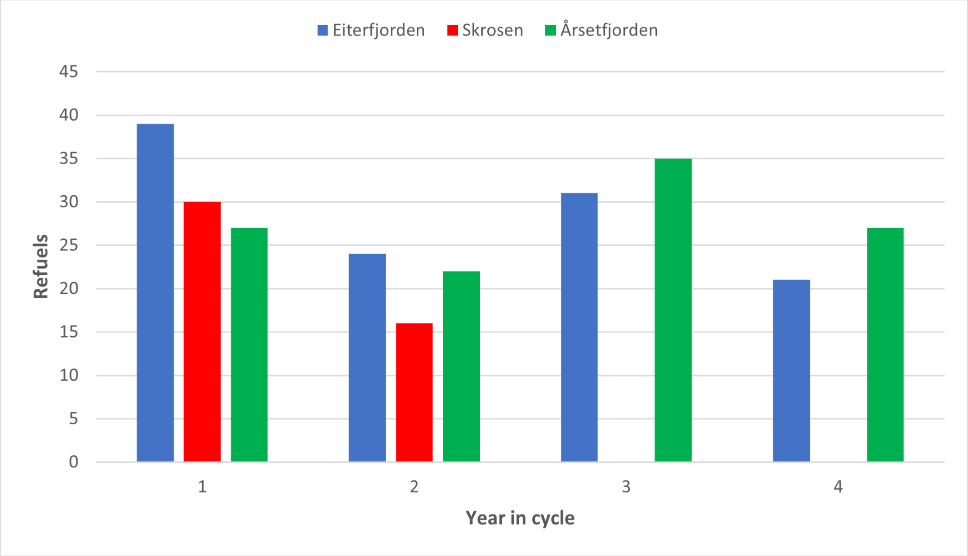


Figure 30: Number of refuels per year for retrofit scenario.

The number of refuels per year for each fish farm is shown in figure 31, which is for the new build scenario. Compared to figure 30, the amount of refuels goes down significantly.

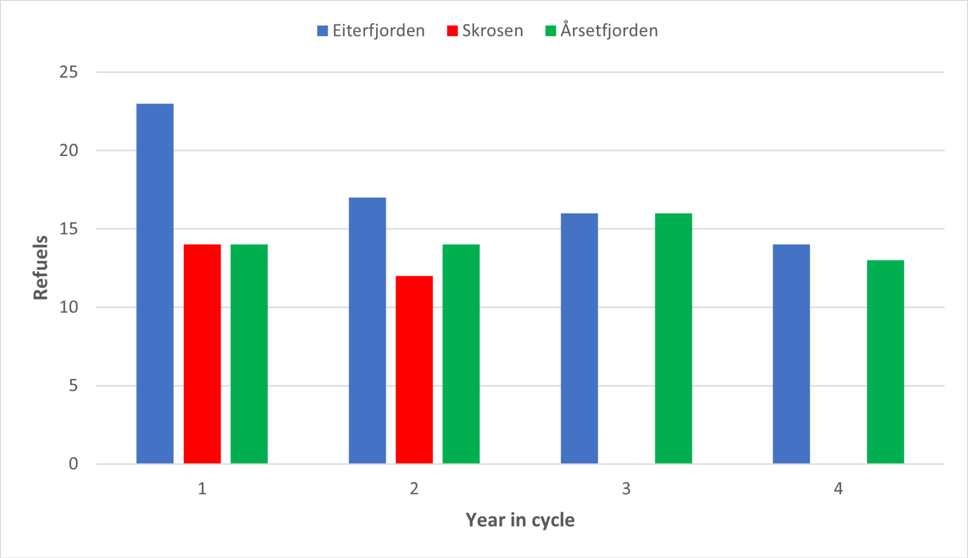


Figure 31: Number of refuels per year for the new build scenario.

3.9 Basecase - Diesel Operation

Both scenarios needed a basecase for comparison, and this is by calculating the diesel usage and CO_2 emission with continuing to run the fish farms on diesel fuel. This was calculated on the decided cycles. The average efficiency of 25 % was used, and an energy density of 9.7 kWh/L. For the same decided cycles as decided in section 3.7, the amount of diesel needed for that load each year and the corresponding CO_2 emission are shown in figures 32, 33 and 34. For the CO_2 emission calculation, it was found that 2.64 kg/L is released. These plots are based on the tables in appendix D. [44–46]

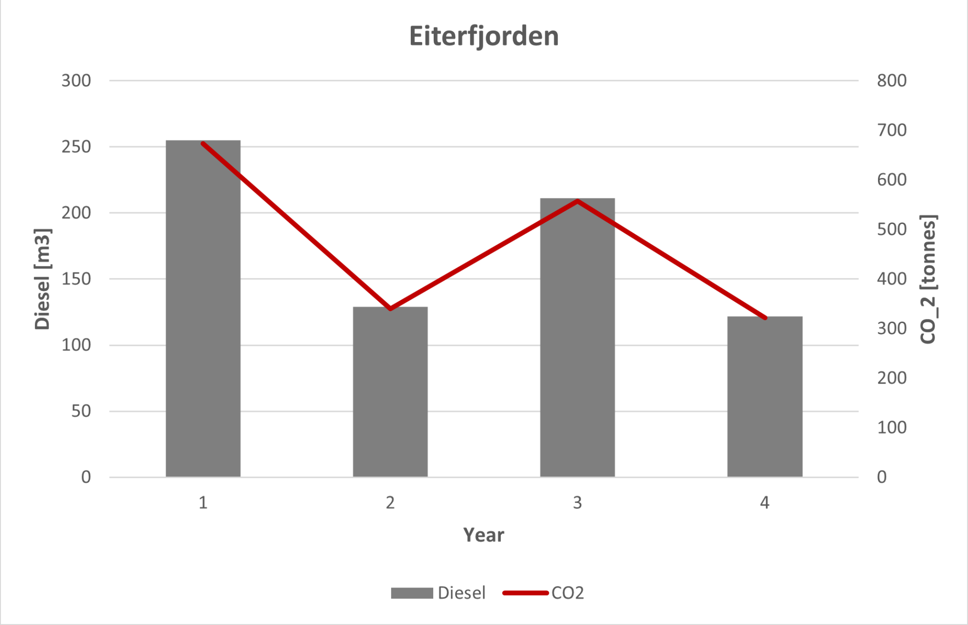


Figure 32: Needed diesel in m^3 and corresponding CO_2 emissions in tonnes for Eiterfjorden.

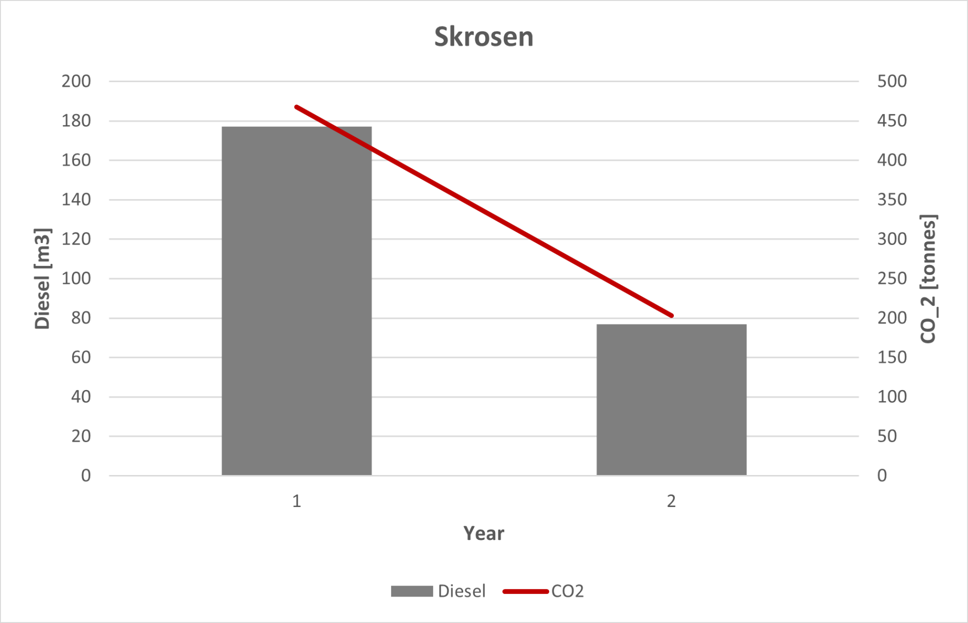


Figure 33: Needed diesel in m^3 and corresponding CO_2 emissions in tonnes for Skrosen.

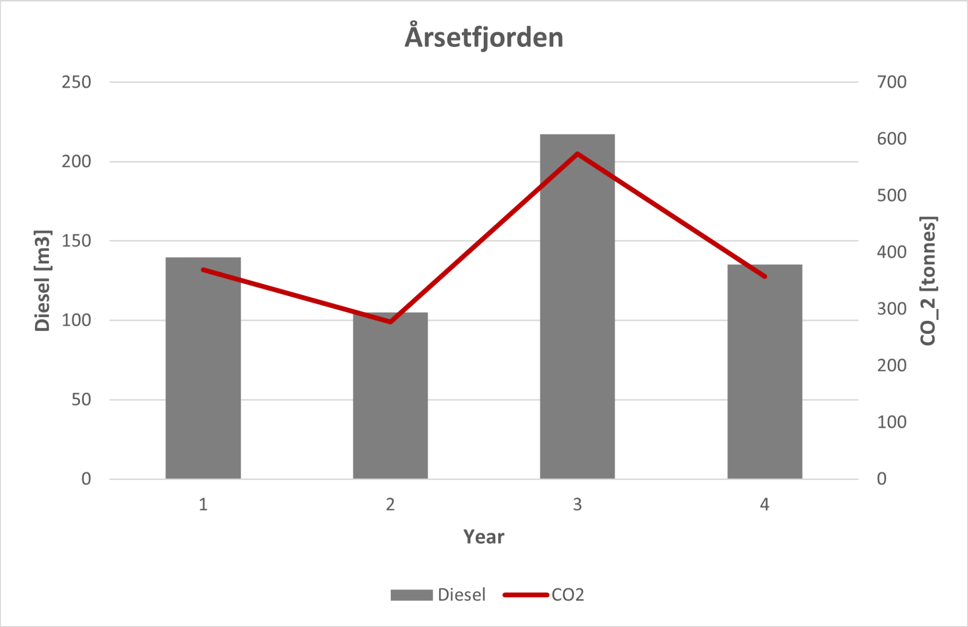


Figure 34: Needed diesel in m^3 and corresponding CO_2 emissions in tonnes for Årsetfjorden.

3.10 Costs

Performing an economical analysis needs cost data for most components and fuel. The cost for each of the different components is shown in table 7. For both the battery and fuel cell, the CAPEX is assumed to be linear, such that a fuel cell at 250 kW will therefore cost 7 000 000 kr, doubling the price when the size is doubled from 125 kW.

Table 7: The CAPEX and OPEX for each component.

Component	**CAPEX**	**Unit**	**OPEX**	**Source**
Fuel cell	3 500 000	kr/125 kw	2 % of CAPEX	[43]
Stack replacement	-	-	50 % of CAPEX FC	[29]
Battery	900 000	kr/125 kWh	2 % of CAPEX	[43]
Container	2 000 000	kr/container	2 % of CAPEX	[43]

The cost for a new feed barge and installation for the retrofit scenario is shown in table 8. Both contain the cost of the electrical system, project management, and wages of employees. The cost of a feed barge also includes the newly implemented technologies, such as waterborne feeding and heat pumps.

Table 8: The feed barge and installation cost.

Project	**CAPEX**	**Unit**	**Source**
Feed Barge	25 000 000	kr	[47]
Installation	35 % of CAPEX	kr	[48]

The price for hydrogen, diesel and CO_2 emission is shown in table 9. The transportation cost of hydrogen were set to be 10 kr/kg, because it was around the same percentage of the on transportation cost of the diesel transportation cost. [43]

Table 9: Fuel prices and emission tax.

Component	**Production**	**Unit**	**Transport**	**Unit**	**Total**	**Unit**	**Source**
Hydrogen	55	kr/kg	10	kr/kg	65	kr/kg	[43]
Diesel	13.0	kr/L	3.85	kr/L	16.85	kr/L	[49, 50]
CO_2 tax	-	-	-	-	550	kr/tons	[51]

Through personal communication with the Ministry of Trade, Industry, and Fisheries, it is expected that the CO_2 tax will slowly increase to 2000 kr/ tons CO_2 up until 2030. 550 kr/ tons CO_2 is from 2020, this infer an increase of 14 % each year. [52]

3.11 Cost-Benefit Analysis

The CAPEX and OPEX can now be calculated and used to find which project will be the cheapest. However, there are differences in yearly costs for the cases. As the needed hydrogen is less for the new build scenario than retrofit, net present value analysis has been performed to find the most profitable investment over time.

The lifetime of a feed barge usually is 20 years. If a feed barge is retrofitted with a new energy system, which is the case in this thesis, it is not known if the feed barge gets another 20 years of lifespan. This is because the concrete structure of a feed barge has a lifespan of 50 to 100 years, which does not include the living quarters, energy system, and equipment. This can be a source of uncertainty for a retrofit scenario. It has been decided that the scenarios will be analysed for a 20 years life span. [47]

Furthermore, the decided cycles from section 3.7 will be used on "repeat" for the facilities. For Eiterfjorden and Årsetfjorden will, the cycles repeat five times during the 20 years, and for Skrosen will, the cycles repeat ten times. This implies that there will be no change in the MTB for each fish farm. The stack replacement will occur at year ten, as the fuel cell loses one percent electrical efficiency each year and therefore will be at 90 % at year ten. The CO_2 tax will increase by 14 %. The decided discount rate will be 8 % [53]. In this NPV analysis, will both scenarios be weighed against the base case scenario, such that equation 4 will look like equation 8.

$$NPV = \sum_{t=1}^{n} \frac{Fuel_{Diesel} - Fuel_{H_2} - OPEX}{(1+r)^t} - CAPEX \tag{8}$$

CAPEX is the total investment of cost projects. OPEX is the operation and maintenance of the new components, and $Fuel_{H_2}$ is the yearly cost of hydrogen fuel. $Fuel_{Diesel}$ is the savings of diesel and CO_2 emission cost each year. Hence, it is possible to see if the energy systems will make fish production cheaper in the long run.

There is no certainty that the fuel prices will stay fixed. Therefore, an NPV analysis with rising diesel prices and decreasing hydrogen prices will be conducted. Following the diesel price over the last decade has increased slowly. Hence, it was decided that the diesel price would increase by 3 % each year [54]. It is also expected that the hydrogen price will decrease [55]. This source expected a 50 % within 2030. A more pessimistic approach was used in this thesis, where it was set to mirror the diesel price with a decrease of 3 % each year.

Several of the gathered and used costs in the financial analysis are not constant. For example, is the fuel cell price expected to decrease over time or the hydrogen price. Hence, a sensitivity analysis of the net present value will also be performed to check which components strongly influence the project. This will only be done for Eiterfjorden, and the decided prices will be the fuel cell price, hydrogen price, and feed barge price varying with ± 20 %. The discount rate will also be adjusted to 6, 8, and 10 %. That is because, in this case study [53], it was found that almost all hydrogen project works with a discount rate within that range.

Another metric is also looked into to investigate the profitability of the scenarios. That is the payback period. This will be performed by using equation 3. The cycles used in NPV analysis have a changing cash flow each year because of different load demands. Hence, the $Fuel_{Diesel}$ represents the average savings during the cycles, and the same goes for $Fuel_{H_2}$, which represents the average hydrogen cost for the cycles.

$$Payback\ period = \frac{Fuel_{Diesel} - Fuel_{H_2} - OPEX}{CAPEX} \tag{9}$$

The IRR will be calculated using equation 5 for comparing the profitability of the retrofit and new build scenario on an even basis. The last parameter to be calculated is the cost of one kilogram of salmon based on the cost of energy used during the period of the fish in the seawater. This was calculated using equation 10 to showcase the difference in energy costs between the scenarios and compare the fish production and energy usage of the different localities.

$$Cost\ of\ fish = \frac{Cost\ of\ Energy\ [kr]}{Harvested\ fish\ [kg]} \tag{10}$$

4 Results

The following section will represent results from the method and the analysis based on these results. The main focus will be the financial aspect of the two scenarios for each fish farm, focusing on both CAPEX and OPEX. Furthermore, NPV analysis will also be performed with varying costs, such as decreasing hydrogen cost and increasing diesel cost. The second to last section will look at the payback period and IRR, and the last section will show the energy cost per fish.

4.1 Calculated Expenses

The calculated fuel cell size and costs are shown in table 10. The S.R. stands for stack replacement. It can be observed that the fuel cell is larger for Eiterfjorden compared to the other two fish farms. This also infers higher CAPEX and OPEX. Furthermore, the sizing of the fuel cell is, as expected, about halved. Which then again infers lower investment and operational expenses.

Table 10: Size and cost of fuel cells for both scenarios at the facilities.

	Retrofit [MNOK]				**New build [MNOK]**			
Facility	**FC [kW]**	**CAPEX**	**OPEX**	**S.R.**	**FC[kW]**	**CAPEX**	**OPEX**	**S.R.**
Eiterfjorden	140	3.92	0.078	1.96	60	1.68	0.034	0.84
Skrosen	110	3.08	0.062	1.54	50	1.4	0.028	0.70
Årsetfjorden	110	3.08	0.062	1.54	50	1.4	0.028	0.70

The battery sizes and cost are shown in table 11. There is a much bigger difference in the battery sizes than fuel cell sizes, which goes for both scenarios. An interesting observation is that the battery size is the largest for the retrofit case in Årsetfjorden, but Eiterfjorden is the largest in the new build scenario.

Table 11: Size and cost of batteries for both scenarios at the facilities.

	Retrofit [MNOK]			**New build [MNOK]**		
Facility	**Battery [kWh]**	**CAPEX**	**OPEX**	**Battery[kWh]**	**CAPEX**	**OPEX**
Eiterfjorden	360	2.59	0.052	230	1.66	0.033
Skrosen	290	2.09	0.042	120	0.86	0.017
Årsetfjorden	400	2.88	0.058	150	1.08	0.022

The cost and amount of containers are shown in table 12. As expected, it cost the same for each scenario and fish farm because it was assumed that all the fish farms use the same feed barge. [47, 48]

Table 12: Amount and cost of containers for both scenarios at the facilities.

	Retrofit and New build		
Facility	**Containers**	**CAPEX [MNOK]**	**OPEX [MNOK]**
Eiterfjorden	2	4.00	0.08
Skrosen	2	4.00	0.08
Årsetfjorden	2	4.00	0.08

The cost for installation and feed barges are shown in table 13. There is a clear difference in the cost of a new feed barge compared to installing new equipment on an older feed barge, with about 20 million kroner.

Table 13: Cost for installation and feed barge for both scenarios.

[MNOK]	**Retrofit**	**New build**
Facility	**Installation**	**Feed barge**
Eiterfjorden	5.66	25.0
Skrosen	4.94	25.0
Årsetfjorden	5.36	25.0

The total calculated CAPEX and OPEX are shown in table 14. It can be observed that the CAPEX for the new build is larger than for the retrofit for all the fish farms. Furthermore, is the OPEX lower for the new build compared to the retrofit. The stack replacement is not included in the total CAPEX.

Table 14: Total CAPEX and OPEX for each scenario and facility.

[MNOK]	**Retrofit**		**New build**	
Facility	**CAPEX**	**OPEX**	**CAPEX**	**OPEX**
Eiterfjorden	16.17	0.21	32.34	0.15
Skrosen	14.10	0.18	31.64	0.13
Årsetfjorden	15.32	0.20	31.48	0.13

A cake diagram of the shares of the CAPEX is shown in figure 35. The illustration is for Eiterfjorden for retrofit. Installation cost is as per the FCH model, 35 % [48]. Furthermore, it can be observed that both the fuel cell and container shares have almost the same size. The cake diagram is only shown for Eiterfjorden because the shares are almost identical for the other fish farms.

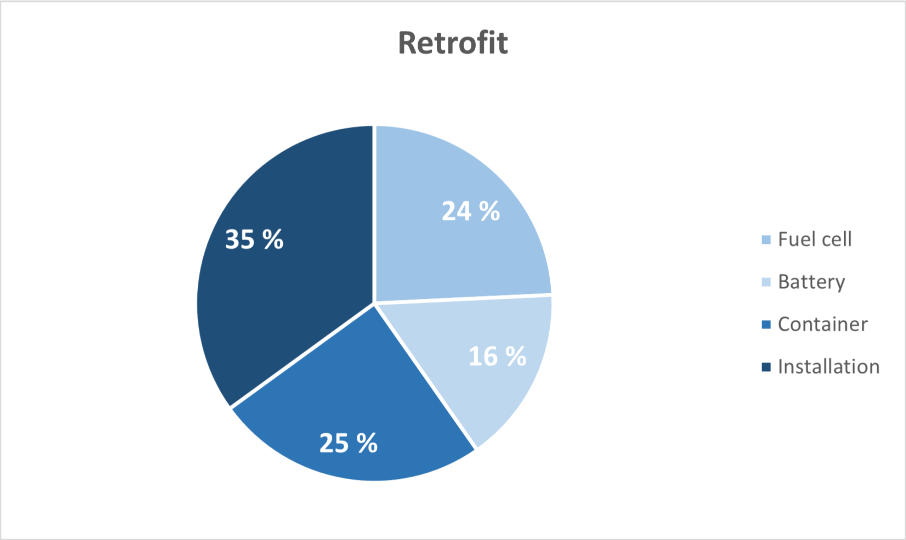


Figure 35: Sector diagram, which gives a visual representation of CAPEX shares for Eiterfjorden.

A cake diagram of the shares for CAPEX for the new build for Eiterfjorden is shown in figure 36. The cost of the feed barge takes up a considerable amount of the total share with 77 %. Furthermore, this time the battery and fuel cell is the same. The cake diagram is only shown for Eiterfjorden because the shares are almost identical for the other fish farms.

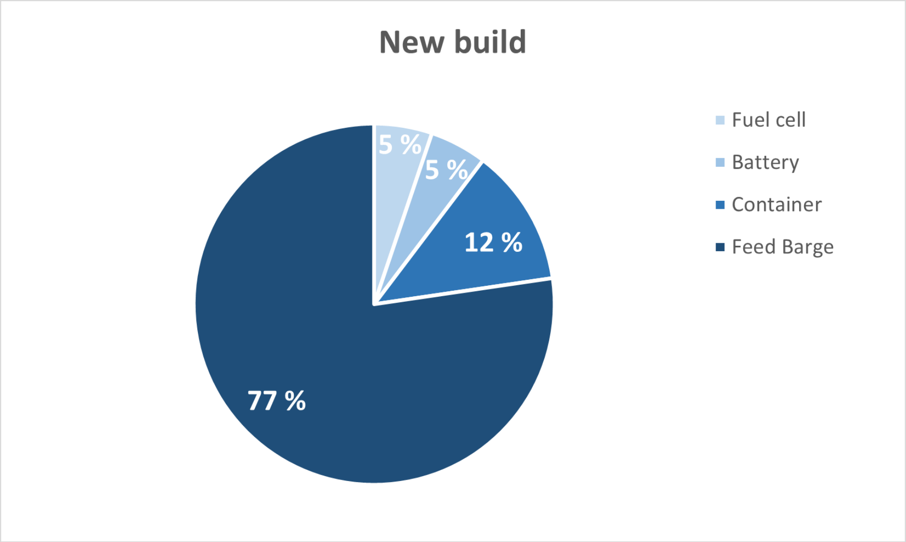


Figure 36: Sector diagram, which gives a visual representation of CAPEX shares.

From the cycles given in the method chapter, the OPEX is not only the components but also the consumed fuel. The demand for hydrogen will vary each year depending on which part of the fish cycle the year contains, as shown in figure 28. Hence, the average cost for each year during the cycles is shown for both scenarios in table 15. It can be observed that fuel costs decrease by about 50 % for each farm from retrofit to new build scenario.

Table 15: Average hydrogen expenses each year.

[MNOK]	**Fuel cost**	
Facility	**Retrofit**	**New build**
Eiterfjorden	1.70	0.773
Skrosen	1.28	0.564
Årsetfjorden	1.49	0.678

If the fish farm continues operation with diesel fuel, the average cost for each year is shown in table 16. Here both the diesel cost and CO_2 emission cost are shown. Comparing the diesel and hydrogen costs shows that fuel expenses can be reduced.

Table 16: Average diesel expenses each year.

[MNOK]	**Basecase**	
Facility	**Diesel**	CO_2
Eiterfjorden	3.02	0.26
Skrosen	2.14	0.18
Årsetfjorden	2.52	0.22

4.2 Net Present Value Analysis

After establishing both CAPEX and OPEX for all three fish farms and scenarios, a net present value analysis was performed, which was calculated with equation 4. This was done for 20 years because that is the lifetime of a feed barge. The OPEX is fixed at the same rate each year, and the discount rate is 8 %, which will also be the case for the other fish farms. The NPV analysis for Eiterfjorden is shown figure 37. The solid lines are the NPV analysis with fixed hydrogen and diesel price. The dark green box show that the NPV analysis breaks even at about year 17 for the retrofit scenario.

A certainty is that the diesel price will not be at a fixed rate in the coming years. Furthermore, is the hydrogen industry young when it comes to fuels. The hydrogen price is excepted to decrease in the future. Hence, a NPV analysis is conducted where the diesel price increase by 3 % each year, and the hydrogen price decrease by 3 % each year. These are the dashed lines in figure 37. This graph shows that the break even point has decreased considerably for both scenarios, down to 11 years for the retrofit and 16 years for the new build scenario, as shown with the light green boxes. The data points for the graphs are in appendix E.

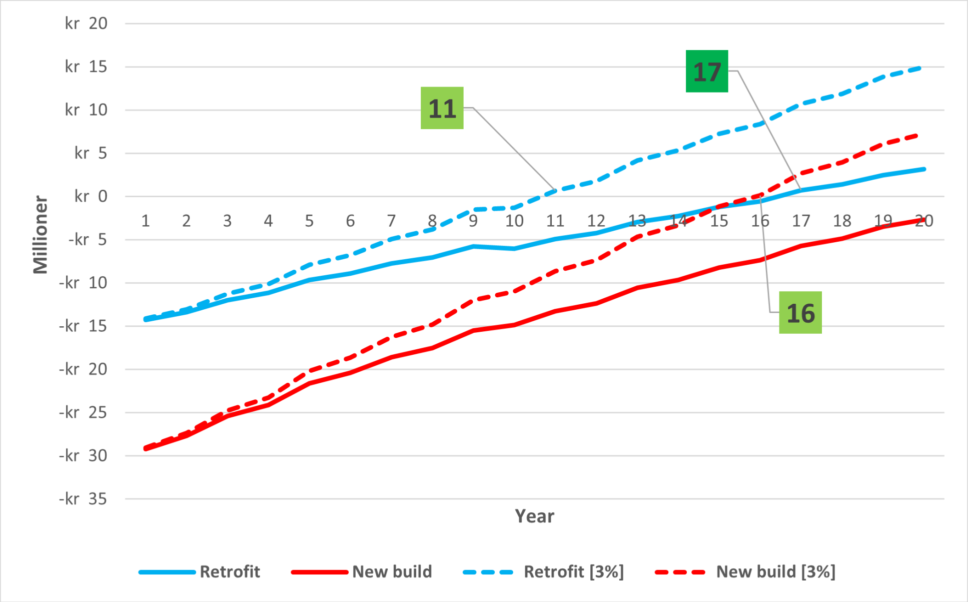


Figure 37: Net present value for Eiterfjorden over 20 years with both cases.

The NPV analysis for the Skrosen is shown in figure 38. Here it can be observed that the retrofit breaks even after 14 years, with increasing diesel prices and sinking hydrogen prices. For the new build scenario, it does not break even during the 20 years. The data points for the graphs are in appendix E.

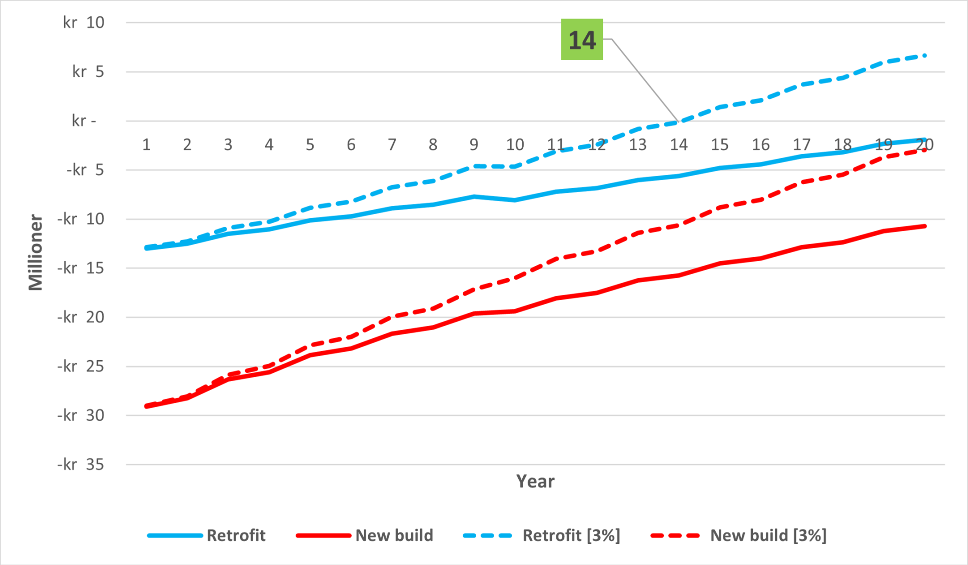


Figure 38: Net present value for Skrosen over 20 years for both cases.

The result of the NPV analysis for Årsetfjorden is shown in figure 39. None of the scenarios break even with fixed hydrogen and diesel price, but the retrofit is close. When the fuel prices increase and decrease, the retrofit scenario breaks even at about 13 years and the new build at about 20 years. The data points for the graphs are in appendix E.

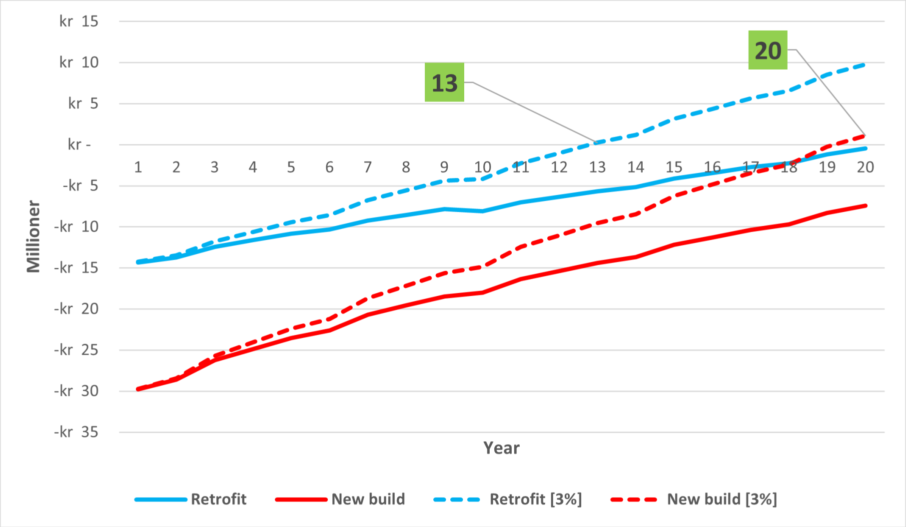


Figure 39: Net present value for Årsetfjorden over 20 years for both cases.

4.3 Net Present Value Sensitivity Analysis

When conducting a net present value analysis, several assumptions have to be made, such as a fixed price for diesel or hydrogen. In reality, this is highly unlikely. Hence, a sensitivity analysis has been performed on both scenarios on the cost for Eiterfjorden. In figure 40, it can be observed that an increase or decrease in hydrogen price will have a more significant effect on the NPV value than the fuel cell price. The higher the incline, the more impact on the net present value. To better understand the figure, the crossing point of the two graphs at zero percentage is the original cost value for the fuel cell and hydrogen. Moving right on the x-axis decreases the hydrogen cost as much as 20 % to the far right and increases it by 20 % to the far left. The y-axis is the net present value after 20 years. Decreasing the hydrogen price by 20 percent increases the net present value from about 3 million to about 6.5 million kr.

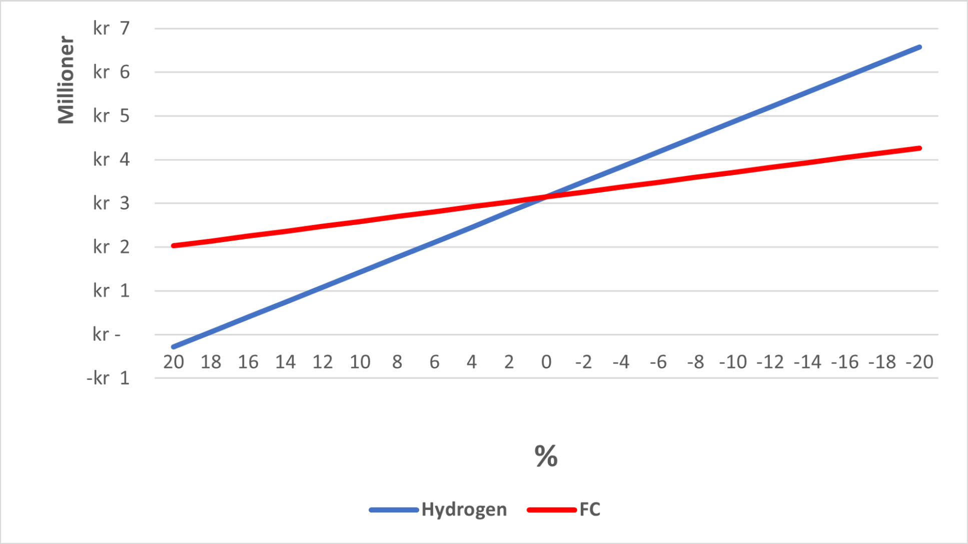


Figure 40: Sensitivity analysis adjusting hydrogen and fuel cell price, for retrofit scenario.

For the new build scenario, it can be observed in figure 41 that the price of the feed barge has the largest impact, followed by the hydrogen price and then the fuel cell price.

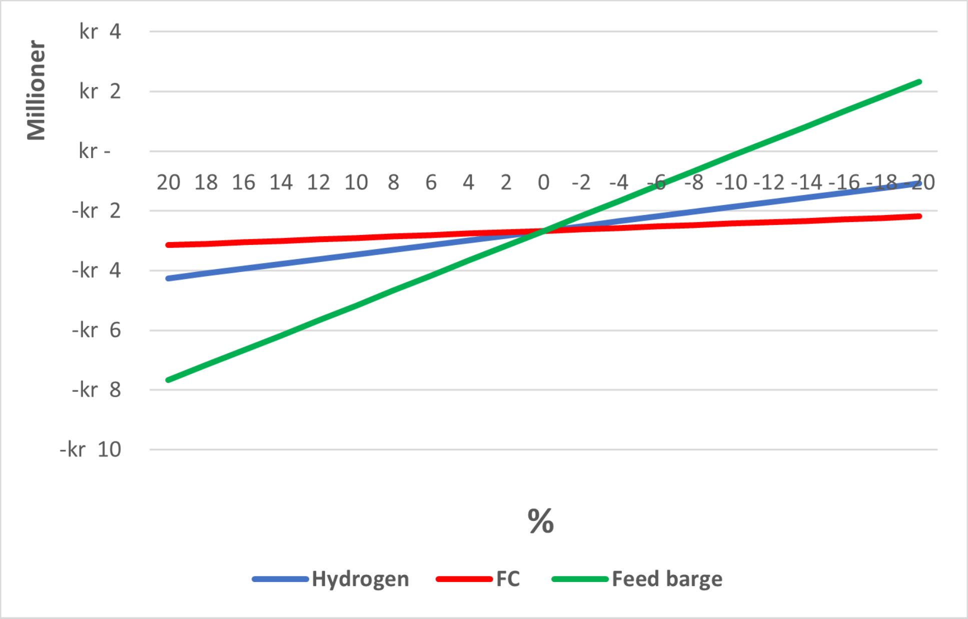


Figure 41: Sensitivity analysis adjusting hydrogen, fuel cell and feed barge price, for new build scenario.

The final sensitivity analysis was performed with a discount rate at six, eight, and ten %. It can be observed that it has a considerable impact on the NPV and a lower discount rate is preferable, where it goes from about 4 million kr to about negative 7 million kr for the new build scenario.

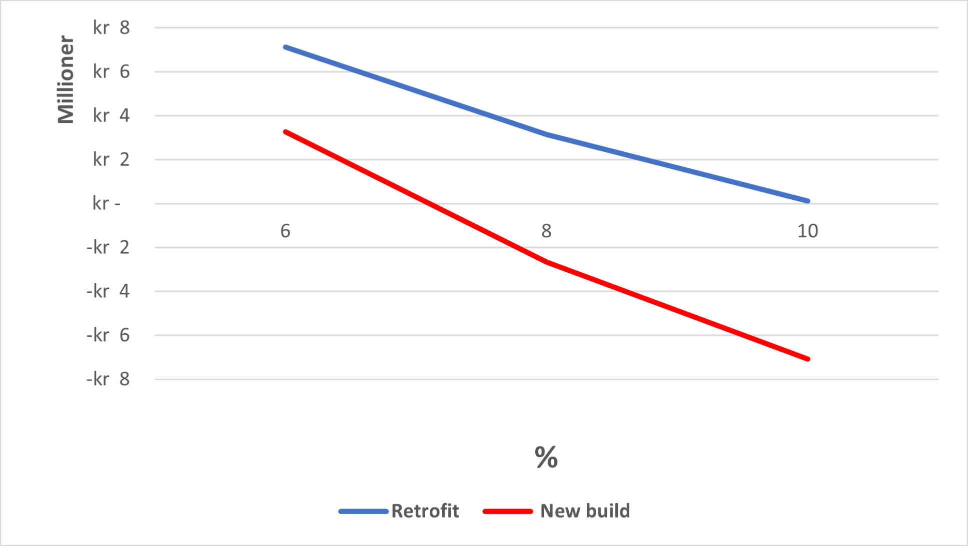


Figure 42: Sensitivity analysis adjusting discount rate for both scenarios.

4.4 Payback Period and Internal Rate of Return

The payback period for both scenarios and fish farms are shown in table 17, and they are calculated with equation 3. It can be observed that the payback period is lower for all scenarios when compared to the net present value analysis with fixed hydrogen and diesel price.

Table 17: Payback period for each facility with both scenarios.

[y]	Payback time	
Facility	**Retrofit**	**New build**
Eiterfjorden	13.0	14.1
Skrosen	15.0	17.6
Årsetfjorden	16.2	16.7

The internal rate of return is calculated by solving equation 5 for IRR. This was done for all scenarios as shown in table 18. Here it can be observed that the retrofit scenario has a higher IRR for all fish farms.

Table 18: IRR for each facility with both scenarios.

	IRR	
Facility	**Retrofit**	**New build**
Eiterfjorden	10.1 %	7.0 %
Skrosen	6.4 %	4.5 %
Årsetfjorden	7.8 %	5.1 %

4.5 Cost of Fish

The final parameter calculated is the cost of one kilogram of salmon based on the energy cost during the period the fish farm has fish, which is calculated with equation 10. For Eiterfjorden this is shown in table 19. This is done for the first and second deploy and harvest of fish from the collected data. It can be seen that the cost is going down with each scenario.

Table 19: Cost of fish for Eiterfjorden in kr/kg_{salmon}.

Eiterfjorden	**First**	**Second**	**Average**
Basecase	1.26	1.40	1.33
Retrofit	0.71	0.75	0.73
New build	0.32	0.35	0.34

Table 20 is calculated only for the first round of fish for Skrosen because the second round is not completed in the given data set.

Table 20: Cost of fish for Skrosen in kr/kg_{salmon}.

Skrosen	**First**
Basecase	1.10
Retrofit	0.66
New build	0.29

In table 21 is the cost of fish for Årsetfjorden. Compared to the other fish farms, Årsetfjorden has the cheapest fish production based on energy cost.

Table 21: Cost of fish for Årsetfjorden in kr/kg_{salmon}.

Eiterfjorden	**First**	**Second**	**Average**
Basecase	0.83	1.18	1.00
Retrofit	0.46	0.70	0.58
New build	0.21	0.31	0.26

5 Discussion

In this section, the results will be elaborated on and discussed. However, first, the methodology will be examined and addressed. Then the fuel cell, battery, storage size, and costs will be discussed. The final aspect is the cost-benefit analysis. The scenarios will also be weighed against each other throughout the chapter.

5.1 Efficiency Measures and Sizing

The implementation of efficiency is the basis of the new build scenario. As described in 2.2.1 the largest impact is going from airborne feeding to waterborne feeding, which is optimised when building a new feed barge. For analysing the new build scenario, the load has been reduced by 60 % during feeding hours and 40 % the rest of the time. As the given load is not divided into how much each machine uses, the reduction in load might be misleading. On the other hand, by observing figure 6, the feeding system takes about 70 % of the total energy used. Reducing the feeding system's required energy by 80 % is the same as reducing the total energy use of the feed barge by about 50 %. By comparing figure 28 and 29, it can be observed that the required hydrogen is about halved for each fish farm. This verifies the energy reduction method and shows it is a good indication of the reduced load demand.

The fuel cell and battery sizing were performed on the month with the highest load. This is to make the new energy system able to withstand almost all operating scenarios. If the required amount of energy is not given, there might be a substantial loss in lost revenue for the fish farm owners. The given datasets are over several years. There is a high possibility that the energy systems are based on the month with the highest load demand for each fish farm. Hence, the resulting fuel cell and battery size have good operational reliability. Further optimisation of the battery size could be future work. That is because the given load data is per hour, and for optimal sizing based on operation, it should be in minutes or seconds. That is because the highest peaks are not given from an hourly load, which is the average during that hour. Therefore, the highest peaks will be higher than those given in the data set. This will undoubtedly impact both the sizing of the fuel cell and battery and is an uncertainty on the given calculated size in this thesis.

The energy system sizing is also based on the operational scenario from 21. The fuel cell mainly covers the peak hours with the battery adding energy in the load swings. The rest of the day will be covered by the batteries. This is done to maximise the fuel cell's electrical efficiency while minimising the energy system's CAPEX. This is an optimisation problem that should be delved into deeper. The goal is to minimise battery, fuel cell, and hydrogen costs. It is also essential to consider the available space on the feed barge. This was outside the scope of the thesis.

5.2 Fuel Cell

The fuel cell sizes for the retrofit scenario go from 110 kW at Årsetfjorden and Skrosen to 140 kW at Eiterfjorden, as shown in table 10. The fuel cell is approximately halved to 50 kW and 60 kW for the new build scenario. This show how drastically the energy need is reduced for the new build. Hence, the fuel cell's investment and maintenance are cheaper than the new build scenario. The sizes for the new build scenario might be a little small, as the difference between the peak and baseload has been drastically reduced, as shown in figure 20. However, it is the month with the highest consumption, so most operating scenarios are probably covered. An increase of about 10 or 20 kW could be implemented for an additional safety margin and better operational reliability.

The fuel cell type which is chosen for this project is the PEMFC. The advantage of quick response and starting time makes it the favourite compared to other fuel cell types. These are important parameters based on this thesis's chosen type of operational profile. Quick start up is vital for battery charging, as it will likely need several charges to cover the baseload when it is not feeding hours. Furthermore, a quick response in cooperation with the battery is also needed when the load demand swings during feedings hours. This flexibility and a broader range of operations favours the PEMFC. The other possible solution, an AFC, is cheaper than the PEMFC, but the absence of the purification system may shorten the difference. The purification system will not be needed because of the pure hydrogen delivered, reducing the CAPEX of PEMFC significantly.

5.3 Battery

The battery size is the biggest for Årsetfjorden with 400 kWh and, therefore, is the most expensive compared to the other fish farm. The cost and size is shown in table 11. An interesting observation is that Eiterfjorden has the largest battery size for the new build scenario, with 230 kWh. This can be attributed to how the battery size is calculated and may infer that it was not the most accurate. The size is still a good estimate, but further optimisation of the battery size, with more data is needed. Dataset with per minute or seconds instead of per hour will most likely help. The smaller batteries for the new build scenario weigh in it is favour. That is because more space on the feed barge may be freed and give room for other necessary equipment, and even make the feed barge as a whole be cheaper because less space is required.

For this thesis, the battery type chosen is lithium-ion batteries. As shown in figure 16, they have both the highest specific energy and power. Lithium types are most widely used by looking at other utility scale projects with batteries. This type of battery allows a DoD of 80 %. Therefore, were the original battery size multiplied by 1.25. This was to increase the battery's lifetime and give it more flexibility. This is another significant advantage of the Lithium battery because of the extensive range of Soc compared to other batteries.

5.4 Hydrogen Storage

As the three fish farms have almost the same MTB, it was decided that they have the same feed barge. This may not be the case, but a good approximation. From figure 24, it can be observed that two containers take up a considerable amount of space on the feed barge. There may be space for more, but more containers are too costly as one costs 2 000 000 kr. Only one container will hold too little hydrogen, and the need for more refuels will be too many and cost even more. Therefore it was decided on two because it is the most cost-efficient and stores enough hydrogen without too many refuels.

For the retrofit scenario, the number of refuels, as seen in figure 30, for example, Eiterfjorden, is between every week and every other week. This is almost the same frequency for Årsetfjorden but slightly lower and even less frequent for Skrosen. This may be too frequent for many fish farms because the frequency with diesel fuel is way less, with about one refuel every month [50]. This weighs in favour of the new build scenario, where the refuelling frequency is about every three weeks for each fish farm, as this is closer to the status quo. It is important to remember the difference between an occupied or vacant fish farm, as the refuelling frequency is even more frequent when there are fish in the localities. For the retrofit, a solution to the problem is more storage containers, but a more thorough analysis needs to be done to see if there is enough space on the feed barge. For the new build, it can be easier to implement the storage containers, but with the reduced load demand, it might not be necessary, as two containers are enough.

The future perspective is hopefully looking bright with storage. Slowly storage containers with higher pressure are becoming commercially available, making it possible to store more hydrogen in the same space. This might solve refuelling problem and quickly lower the refuelling frequency. That is because there is space for more hydrogen, and there will be no need for more containers. This can also make it more attractive for the work vessel at the fish farm to go over to hydrogen because there can be enough hydrogen at the feed barge to refuel the working boats.

5.5 Hydrogen and Refuels

The calculated amount of hydrogen per year for each scenario and fish farm is shown in figure 28 and 29. As expected, does the amount of hydrogen decrease for the new build scenario compared to the retrofit scenario, which favour the new build scenario. The needed hydrogen amount is still an indication because the fuel cell operation probably does not follow the electrical efficiency graph in figure 13. This is an older graph, and the newest technology has probably a higher efficiency over a wider range of nominal load. This may infer a lesser need for hydrogen than calculated in this thesis. This will also impact the financial analysis, making both scenarios more profitable in the long run, with less hydrogen usage.

The decided operational profile, which impacts the efficiency of hydrogen, can be even further optimised. This must be weighed against the size of the battery and fuel cell and the cost of the components. The proposed solution in figure 21 is the most optimised if the battery covers everything and the fuel cell can charge the battery at maximum efficiency. However, this will also infer an unnecessary large fuel cell and battery cost. Further optimisation is therefore needed.

A refuelling analysis was also performed while calculating the needed amount of hydrogen. As shown in figure 30 and 31, the amount of refuels needed were considerably less for the new build scenario. This weighs in favour of the new build scenario. It is important to remember that this was with two containers for all the scenarios. If there is room for more than two containers, the refuelling frequency will drop. This is dependent on the individual feed barge. There is more room for more containers in new build scenarios, as the feed barge can be built with that in mind. It can only make do with what is available in a retrofit. The retrofit scenario and the chosen type of container have space for four containers. This must be discussed with the operator of the feed barge. The containers and solution for refuelling make it so that the containers must be on deck as the refuelling is done by changing one container with another. This can be a shortcoming because it limits the number of containers.

5.6 Gathered Costs

Most of the costs gathered are from personal communication with the industry. That is for the battery, fuel cell, container, and stack replacement cost. These are reliable, but they will probably vary depending on the feed barge and type of location. Furthermore, the fuel cell and battery costs were assumed to be linear. This may not be the case, and as the calculated sizes are both bigger and smaller than the given cost at 125 kW and 125 kWh, the prices may vary significantly. Furthermore, are the fuel cells and batteries considered dimensionless and precisely as the calculated size. For example, there is no fuel size at 140 kW, but the standard may be at 125 or 200 kW. This can infer that a specially made fuel cell for the feed barge can be even costlier because it is custom made. This also probably be the case for the cost of the battery. The cost of hydrogen production is set value at 55 kr/kg. The transportation cost have been found to be 10 kr/kg. Both of these will likely vary in the future and hopefully decrease. It is predicted that the with a growing demand the price will go down.

The cost of diesel is also an unstable cost for the future. With the growth of renewable energies, the diesel price may continue to rise, as it has done for the past several years. If more global conflicts arise, they will also affect the diesel price. This is a large incentive for switching to green hydrogen, regardless of the scenario. Diesel fuel will likely not get any cheaper, and more emissions are cut the earlier change to hydrogen. The CO_2 emission tax will also impact the stoppage of using fossil fuels. Within 2030 it will almost be quadrupled in size, which has been added in the NPV analysis. If this continues to rise is not known, but it will also impact the choice of fuel in the future for maritime operations.

The installation cost was 35 % of the total CAPEX for the components. This is an uncertain cost, as it is hard to find any specific cost for such a project. It can be both higher and lower, but it is considered high. Which have a considerable impact on the profitability of the retrofit scenario, as showcased with the large share compared to the other components in figure 35. All costs, which are hard to predict, have therefore been assumed to be a part of this share. Examples are the electrical system, the wage of employees, installing the energy system, or part of the administrative cost.

The cost of the feed barge is the largest contributor to the CAPEX of the new build scenario, as shown in figure 36. The 25 million kroner is assumed to be the cost for everything, excluding the new components. There is a possibility that the cost for the fuel cell, battery, and storage may overlap with the feed barge. For example, it is uncertain whether installing a fuel cell is part of the feed barge or the fuel cell cost. It is an uncertainty of the new build example, which may be lower or higher. If the cost of the feed barge varies, it impacts the NPV value, as shown in figure 41. If the cost goes down, building a new feed barge can be more attractive and weigh in favour of the new build scenario. The cost of the new technologies for energy efficient measures is assumed to be part of the feed barge cost. These may, in reality, make the feed barge more expensive. For example, the waterborne feeding technology is still new and few on the market, therefore being a tad more expensive than the traditional feeding system. A new heating pump may also increase the cost of a feed barge because it is more expensive than regular panel ovens.

5.7 CAPEX and OPEX

The financial aspect of the scenarios is the main driver for choosing one case over another. By looking at the initial investment, CAPEX, the retrofit scenarios has the favour. The CAPEX for all three fish farms is about 16-17 million kr cheaper than the new build scenario. The total cost of building a new feed barge is the key difference. As explained in the previous chapter, it takes almost 80 % of the total CAPEX for the new build scenario. The battery and fuel cell share are considerably less in the new build scenario than in the retrofit scenario. The energy system cost has a total of 65 % share in retrofit scenario. Where the battery and fuel cell has the largest shares. The new build scenario is the opposite, where the container share is larger than the battery and fuel cell.

The difference in expenses is turned around for the day-to-day cost, OPEX. By looking at the total OPEX for the components, the new build scenarios are cheaper, with about 50 - 80 thousand kr difference, depending on the fish farm. Furthermore is, the needed energy system smaller because of less energy demand. This difference is not enough. The difference in fuel cost is the main factor, as shown in table 15. It goes from about 700 thousand to almost a million kr, between the cost for fuel at the retrofit and the new build scenario. The difference here weighs in favour of choosing the new build scenario.

5.8 Net Present Value Analysis

The decided cycles to analyse in the net present value analysis goes over a four and two year period, depending on the fish farm. It is assumed that the load demand during these cycles will be steady over the 20 years. In reality, this will not be the case, where the load demand can go up and down, depending on weather, temperature, or fish in the localities. This will, in turn, affect the hydrogen usage. Furthermore, it is assumed that there will be no change in the MTB of the fish farms. No environmental threats are also assumed not to happen. These problems are difficult to predict and therefore assumed to be of no interference, but there is at least a risk factor that can extend the allotted time for a potential investment return. For example, if the areas get a red light or yellow light from the traffic system. This can potentially hinder the development of the fish farms.

The NPV analysis was such that each fish farm was weighed against regular operation with the fossil fuel. Hence, the difference in fuel cost between hydrogen and diesel was the annual cash saved each year. The diesel usage for the basecase was on the efficiency of 25 %. This may vary greatly dependent on the load demand, making it so that the average diesel demand may have been more than what is shown in figures 32, 33 and 34. Using more diesel further affects the CO_2 emissions and increases the cost in CO_2 tax. The production volume is fixed to the total in table 4, with no increase or decrease during the 20 years. This will probably not be the case. That is also an uncertainty with the NPV analysis. If there is an increase in production volume, the energy demand will likely also increase. This weighs in favour of choosing one of the scenarios as the increased usage of hydrogen will still be cheaper than diesel.

The result of the NPV analysis is shown in figures 37, 38 and 39. The retrofit scenario is the cheapest and fastest to break even for all three fish farms. It is only for the Eiterfjorden that it breaks after 17 years with fixed hydrogen and diesel price. If the diesel price increases and the hydrogen price decreases, the retrofit scenario breaks even at year 11 for Eiterfjorden, year 14 for Skrosen, and year 13 for Årsetfjorden. The increase and decrease in fuel prices have a significant impact on the profitability of the scenarios. For example, there is a six year difference for Eiterfjorden, with and without the changing fuel prices. There is a high possibility that the fuel prices will follow the expected trend because of the political instability and slow but rapid increase in hydrogen projects.

For the new build scenario, none of the NPV analysis breaks even after the 20 year lifetime, with fixed fuel prices. This does not weigh in favour of the new build scenario. With changing fuel prices, does Eiterfjorden break even after 16 years and Årsetfjorden about year 20. It was close to breaking even at Skrosen, but it did not happen. This analysis in total shows that from a financial point of view, the retrofit scenario is in favour. Furthermore, from the hydrogen used in figure 28 and 29, Eiterfjorden has the largest energy demand. In all NPV analyses, Eiterfjorden has the quickest time before breaking even, so it is more advantageous to either go for a retrofit or a new build the larger the fish farm is. It also goes in descending order where Årsetfjorden is behind Eiterfjorden in both net present value over the 20 years and lesser energy usage than Eiterfjorden, but bigger than Skrosen.

5.9 Sensitivity

The sensitivity analysis spans several years, and many used costs may vary. That depends on when the project is set in motion. For example, the cost of a fuel cell can be cheaper in five years than today. Hence a sensitivity analysis has been performed to see the impact on the different costs. For the retrofit scenario, both the fuel cell and hydrogen price were decreased and increased by 20 % as shown in figure 40. Here it can be observed that the hydrogen price has a more significant impact than the fuel cell price because the graph has a larger incline. This clearly shows that cheaper hydrogen can be the catalyst to make the project profitable. If the hydrogen is more expensive than first assumed, the project may cause a loss of revenue. This is because the project is negative in total, with a 20 % increase in the hydrogen price. The fuel cell has an impact as well, but not as much.

For the new build scenario, the cost of the feed barge is added as shown in figure 41. The lower energy use in the new build scenario infers a smaller energy system and less hydrogen used. These costs do not have the same impact on the NPV analysis as for the retrofit scenario. The largest impact is the feed barge which in this case has the steepest incline. The feed barge is an uncertain cost because it is a problematic estimate for such a project. The building of a new takes time and needs customisation for new localities. Even though the gathered cost comes from communication with the industry, the impact of the new energy system on the feed barge cost is not known. For this thesis, the energy system and feed barge have been seen as two separate costs, which in reality may overlap and make the whole scenario cheaper.

The discount rate was also adjusted to find the impact. This is shown in figure 42. It was adjusted to 6, 8 and 10 %. This is because of the article [53], which states that most projects operate from 6 to 10 %. A clear impact of the discount rate is that the lower it is, the more profitable the scenarios are. For example, is the net present value positive for the new build scenario with a 6 % discount rate when it is negative at 8 %. The difference between the scenarios is bigger with the larger discount rate, and therefore a lower discount rate is better for the new build scenario, but it is still not more profitable than the retrofit scenario.

5.10 Payback Period and Internal Rate of Return

The payback period does not consider the time value of money, but it is still a good tool for the financial aspect of the scenarios. The payback time for all three fish farms is the lowest for the retrofit scenario. The shortest payback period is for Eiterfjorden fish farm with 13 years. The difference to the new build scenario is much closer in the payback period calculation than the NPV analysis. It is also shorter for all three scenarios. However, the time aspect is different in this case. The shorter the time, the more accurate the NPV analysis, and over 13 years, much could have changed. The payback time weighs in favour of the retrofit scenario, but the difference is not as big as with the NPV analysis. As stated earlier, the payback time calculation also operates with a fixed hydrogen and diesel price, which will likely not be the case. This is an uncertainty with the payback time calculation, but if the prices go the way predicted, the payback time will be shorter for all the fish farms.

The internal rate of return is another tool used to compare the different analyses on the same basis. From table 18, it can be observed that the retrofit scenario for Eiterfjorden has the highest IRR with 10.1 %. This shows the same result as the NPV analysis and payback period, making Eiterfjorden the most profitable. Furthermore, is the new build scenario the least profitable for all the localities. The lowest is for Skrosen with 4.5 %. The IRR also weighs in favour of the retrofit scenario. It could be used to help businesses decide which projects to develop first if these farms were to be electrified. The IRR also follows the ranking that the fish farm with the most energy use is the most profitable where it goes Eiterfjorden, Årsetfjorden, and the lowest with Skrosen.

The last parameter to look at was the cost of fish per the energy cost. This parameter shows the difference in cost of fish production for the different scenarios. In table 19, 20 and 21 it is clear that going from fossil fuel to hydrogen is cheaper in the cost energy per fish. For example, going from 1.33 to 0.73 kr/kg_{salmon} and even cheaper for the new build scenario going all the way down to 0.34 kr/kg_{salmon}. This showcases how the new build scenario is the cheapest to operate long term when the investment has been implemented. This parameter only takes the energy used when fish is in the localities. Therefore, some costs of energy are neglected. Also, the fish farms have different lengths with the occupation of fish. Hence, the values may not be comparable between the fish farms.

6 Conclusion

This thesis aims to analyse which is the most financially beneficial, a retrofit or building a new feed barge when going from diesel to hydrogen fuel. This was explored for three fish farms: Eiterfjorden, Årsetfjorden, and Skrosen. The two scenarios were created from the same dataset, but the load was greatly reduced for the new build scenario. It is not certain how accurate the load demand was reduced, but it is a good indication. The fuel consumption and cost have been halved from the retrofit scenario to the new build scenario.

Furthermore, the calculated battery and fuel cell sizes indicate what needs to be implemented for the specific localities. From observing the technology of fuel cells, the PEMFC is the most optimal type of fuel cell, and lithium batteries will most likely be the best type of battery. There are still many uncertainties with the calculation. Hence, further optimisation is recommended, where the main focus is to limit hydrogen usage and fuel cell, battery, and storage cost.

The chosen amount of containers was based on observation of the schematics of the feed barge. More talks with the operator of the feed barge need to be done to find out if there is space for more. On the other hand, it might not be needed more, but this depends on how often the hydrogen can be delivered. If the delivery frequency is low, such as one time per month, more containers are needed for the fish farms during occupancy with fish to store more hydrogen.

The NPV analysis, payback period, and internal rate of return all favour the retrofit scenario. Looking at the operational expenses, cost of hydrogen, and energy cost of fish, the new build scenario will eventually be the most profitable in the long run. Therefore, it can be concluded that a retrofit can be performed if a locality has a relatively new feed barge, with 10 to 15 years left of the original expected lifetime. If there are five to ten years left of the feed barge, a retrofit should be considered, but an even more thorough analysis should be performed. Finally, if the feed barge has less than five years left, it could be smartest to let it live out its lifetime and build a new feed barge with all the newest technologies and efficiency measures. That is because fuel expenses will be lower with efficiency measures, which is observed with the cost of energy per kilogram of fish going drastically down. Another aspect is that waiting a few years may decrease hydrogen, fuel cell, or other costs.

7 Further Work

Further optimisation with a focus on lowering fuel cell, battery, storage, and hydrogen costs should be performed. This needs to be done with more detailed data input and precise costs. Furthermore, even though a new build with technologies is recommended in this thesis, for a feed barge with a low lifetime left, a more thorough cost calculation with a new feed barge with all the new technologies and battery and fuel cell should be performed.

It is not only the feed barge that should change from fossil fuel to hydrogen. This also applies to the work boats and well boats. These vessels have not been taken into account in this thesis. For example, if they also change to hydrogen, the amount of hydrogen that needs to be stored on the feed barge should be even more. Hence, more space on the feed barge might be used to store hydrogen. How to solve these problems should be focused on so that these vessels can refuel at the feed barge.

Reference List

[1] Sintef. *Zerokyst*. `sintef.no/prosjekter/2021/zerokyst/`. (Data from 10.09.2021).

[2] InnovaArena. *Utreder Kråkerøya som energi- og klimahub*. `https://innovarena.no/2020/04/utreder-krakoya-som-energi-og-klimahub/`. (Data from 28.04.2020).

[3] Sofie Møller. "Reduction of CO2 Emissions in the Salmon Farming Industry: The Potential for Energy Efficiency Measures and Electrification". In: *NTNU* (2019). (accessed: 07.12.2021).

[4] BELLONA. "Grønt skifte i havbruk Laks på landstrøm kan kutte 300 000 tonn CO2". In: (2018).

[5] DNV-GL. "Fullelektrisk fiskeoppdrett". In: (2018).

[6] Thema Consulting. "Nettilkobling av oppdrett ved elektrifisering". In: (2020).

[7] Thea Mørk. "Energiomlegging av oppdrettsanlegg i Finnmark". MA thesis. Norwegian University of Life Sciences, Ås, 2020.

[8] Bård Misund. *Fiskeoppdrett*. `https://snl.no/fiskeoppdrett`. 2021. (accessed: 07.12.2021).

[9] Asgeir Aga Nilsen. *Norge eksporterte sjømat for 105,7 milliarder i 2020*. `https://e24.no/naeringsliv/i/M36WoB/norge-eksporterte-sjoemat-for-1057-milliarder-i-2020`. (Data from 06.01.2021).

[10] OEC. *Historical Data*. `https://oec.world/en/profile/country/nor?compareExports0=comparisonOption1&compareSelector=compare5`. 2021. (accessed: 13.12.2021).

[11] Midt nors Havbruk AS. *Historien*. `https://www.mnh.no/om-mnh/historie/`. (Data from 07.12.2021).

[12] Laks.no. *Norsk laks fra fjord til bord*. `https://laks.no/lakseproduksjon/`. (Data from 07.12.2021).

[13] MOWI. *Salmon Farming Industry Handbook*. `https://corpsite.azureedge.net/corpsite/wp-content/uploads/2021/05/Salmon-Industry-Handbook-2021.pdf`. (accessed: 07.12.2021).

[14] Ulf Winther et al. "Greenhouse gas emissions of Norwegian seafood products in 2017". In: (2017), p. 116. (accessed: 07.12.2021).

[15] Helleik L Syse. "Investigating off-grid energy solutions for the salmon farming industry". In: *University of Strathclyde: Glasgow, UK* (2016).

[16] Naturvernforbundet. *Oppdrett*. `https://naturvernforbundet.no/oppdrett/`. (accessed: 07.12.2021).

[17] Øyvind Hokland. "Modeling and simulation of power and energy demands to dimension an alternative energy supply for the aquaculture industry." MA thesis. UiT The Arctic University of Norway, 2020.

[18] AKVAgroup. *Waterborne feeding*. `https://www.akvagroup.com/sea-based-aquaculture/feed-systems/waterborne-feeding`. 2022. (accessed: 08.03.2022).

[19] Thomas Bjoerdal. "Energi i Havnbruk Optimal Energibruk på oppdrettsanlegg". In: (2021).

[20] *Teknisk spesifikasjon ARENA 400*. Received from mail correspondes with Midt-Norsk Havbruk AS.

[21] Odne Stokke Burheim. *Engineering Energy Storage*. Vol. 1. Academic Press, 2017.

[22] FCHEA. *Fuel Cell Basics*. `https://www.fchea.org/fuelcells`. 2021. (accessed: 15.12.2021).

[23] Hui Xing et al. "Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives". In: (2021), p. 34. (accessed: 02.12.2021).

[24] JOn Andreas Støvneng. *Virkningsgrad*. `https://snl.no/virkningsgrad`. 2021. (accessed: 15.12.2021).

[25] James Larminie and Andrew Dicks. *Fuel Cell Systems Explained*. Vol. 2. Wiley, 2009.

[26] Miriam M. Tellez-Cruz et al. "Proton Exchange Membrane Fuel Cells (PEMFCs): Advances and Challenges". In: (2021), p. 54. (accessed: 02.12.2021).

[27] Qingfeng Li et al. "The CO poisoning effect in PEMFCs operational at temperatures up to 200 degrees C". In: (2003), p. 8. (accessed: 08.12.2021).

[28] Steve Völler. *Hydrogen Electrolyser, Storage, Fuel cells, Applications*. subject TET4175 Design and Operation of Smart Grid Power Systems. 2019. (accessed: 02.12.2021).

[29] *Personal communication with Anders Ødegård*. Personal communication through meetings with Anders Ødegård.

[30] Gronkvist S Andersson J. "Large-scale storage of hydrogen". In: *International Journal of Hydrogen Energy* (2019). `https://www.sciencedirect.com/science/article/pii/S0360319919310195`. (accessed: 08.12.2021).

[31] Electronic notes. *Battery technology.* `https://www.electronics-notes.com/articles/electronic_components/battery-technology`. 2021. (accessed: 10.12.2021).

[32] AKM Ahasan Habib, SMA Motakabber, and Muhammad I Ibrahimy. "A comparative study of electrochemical battery for electric vehicles applications". In: *2019 IEEE International Conference on Power, Electrical, and Electronics and Industrial Applications (PEEIACON).* IEEE. 2019, pp. 43–47.

[33] International Renewable Energy Agency. *Utility-Scale Batteries Innovation Landscape Brief.* 2019.

[34] Simon Engelke. "Current and future sodium-ion battery research". In: 1 (Mar. 2013).

[35] MIT Electric Vehicle Team. "A Guide to Understanding Battery Specifications". In: (2008). (accessed: 10.12.2021).

[36] Tianmei Chen et al. "Applications of lithium-ion batteries in grid-scale energy storage systems". In: *Transactions of Tianjin University* 26.3 (2020), pp. 208–217.

[37] Will Kenton. *Capital Expenditure – CapEx Definition.* `https://www.investopedia.com/terms/c/capitalexpenditure.asp`. 25.06.2019. (accessed: 10.05.2022).

[38] Will Kenton. *Operating Expense.* 15.07.2019. URL: `https://www.investopedia.com/terms/o/operating_expense.asp`. (accessed: 10.05.2022).

[39] Julia Kenton. *Payback Period.* 10.03.2022. URL: `https://www.investopedia.com/terms/p/paybackperiod.asp`. (accessed: 10.05.2022).

[40] Jason Fernando. *Net Present Value (NPV).* 29.08.2021. URL: `https://www.investopedia.com/terms/n/npv.asp`. (accessed: 10.05.2022).

[41] Adam Hayes. *Discount Rate.* 29.08.2021. URL: `https://www.investopedia.com/terms/d/discountrate.asp`. (accessed: 10.05.2022).

[42] Jason Fernando. *Internal Rate of Return.* 24.02.2022. URL: `https://www.investopedia.com/terms/i/irr.asp`. (accessed: 15.05.2022).

[43] *Personal communication with Kvernevik Engineering AS.* Meetings with Edgar Kvernevik.

[44] The Physics Factbook. *Energy density of diesel fuel.* URL: `https://hypertextbook.com/facts/2006/TatyanaNektalova.shtml`. (accessed: 19.05.2022).

[45] Blue diamond. *What is a diesel generator?* URL: `https://www.bluedm.com.au/blog/what-is-a-diesel-generator/`. (accessed: 19.05.2022).

[46] Ecoscore. *How to calculate the CO2 emission from the fuel consumption?* URL: `https://ecoscore.be/en/info/ecoscore/co2`. (accessed: 19.05.2022).

[47] *Personal communication with AKVAgroup.* Phone calls with AKVAgroup.

[48] Maria Sidelnikova with several (NVE). "Kostnader i Energisektoren". In: (2015), pp. 28, 30. URL: `http://publikasjoner.nve.no/rapport/2015/rapport2015_02a.pdf`. (accessed: 11.03.2020).

[49] DRIV energi. *Produkter og priser.* URL: `https://drivenergi.no/produkter-og-priser`. (accessed: 19.05.2022).

[50] *Personal communication with Thomas Bjørdal.* Meetings with Thomas Bjørdal.

[51] Nærings og Fiskeridepartementet. *Del 3 Muligheter og utfordringer for norsk maritim næring.* URL: `https://www.regjeringen.no/no/dokumenter/meld.-st.-10-20202021/id2788786/?ch=4`. (accessed: 15.05.2022).

[52] *Mail correspondence with Ministry of Trade, Industry and Fisheries.* Information from private mails between the student and Ministry of Trade, Industry and Fisheries.

[53] Farhad Taghizadeh-Hesary Et al. "Financing Solutions for the Economic Feasibility of Hydrogen Projects: Case Study in China". In: (2021). URL: `https://www.eria.org/uploads/media/Research-Project-Report/RPR-2021-19/12_Chapter-6-Financing-Solutions-for-the-Economic-Feasibility-of-Hydrogen-Projects_Case-Study-in-China.pdf`. (accessed: 11.05.2022).

[54] Drivkraft Norge. *Prisstatistikk.* URL: `https://www.drivkraftnorge.no/Tall-og-fakta/prisstatistikk/`. (accessed: 13.05.2022).

[55] PWC. *The green hydrogen economy.* URL: `https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html`. (accessed: 30.05.2022).

Appendix A

Loads for the Fish Farms

The loads for each month for the retrofit scenario at Eiterfjorden is shown in table A1.

Table A1: Load each month for retrofit scenario, at Eiterfjorden.

[kWh]	**2018**	**2019**	**2020**	**2021**	**2022**
January	0	78 824	7 556	46 164	20 662
February	0	71 256	8 754	49 891	12 189
March	0	72 590	9 605	61 366	0
April	0	71 831	8 444	60 148	0
May	0	74 711	25 580	61 350	0
June	0	67 084	40 996	48 425	0
July	0	68 721	40 794	38 348	0
August	0	35 519	34 112	38 489	0
September	0	7 152	36 182	21 481	0
October	20 982	9405	42 487	7 119	0
November	52 810	7656	37 484	10 395	0
December	72 240	7880	36 882	18 800	0

The loads for each month for the new build scenario at Eiterfjorden is shown in table A2.

Table A2: Load each month for new build scenario, at Eiterfjorden.

[kWh]	**2018**	**2019**	**2020**	**2021**	**2022**
January	0	41 323	3 800	23 133	10 736
February	0	36 523	4 063	24 910	6 044
March	0	36 045	4 322	30 645	0
April	0	36 742	4 486	30 342	0
May	0	37 921	11 619	30 435	0
June	0	34 155	18 200	24 457	0
July	0	33 506	18 044	19 250	0
August	0	17 081	15 847	17 897	0
September	0	3 817	16 677	9 665	0
October	10 031	4 834	20 355	3 422	0
November	23 626	3 881	18 253	5 348	0
December	38 292	4 186	18 677	9 704	0

The loads for each month for the retrofit scenario at Skrosen is shown in table A3.

Table A3: Load each month for retrofit scenario, at Skrosen.

[kWh]	**2018**	**2019**	**2020**	**2021**	**2022**
January	6 411	40 889	10 141	33 035	20 434
February	5 624	38 810	12 259	33 718	9 157
March	5 604	45 075	5 469	37 618	0
April	6 071	35 533	0	37 986	0
May	6 029	35 915	0	33 321	0
June	4 173	25 806	0	27 252	0
July	11 232	22 074	413	22 613	0
August	29 287	26 613	5 266	27 751	0
September	39 573	28 478	23 725	27 879	0
October	38 683	32 826	29 491	29 734	0
November	39 929	23 904	32 967	28 551	0
December	37 836	19 261	32 677	28 770	0

The loads for each month for the new build scenario at Skrosen is shown in table A4.

Table A4: Load each month for new build scenario, at Skrosen.

[kWh]	**2018**	**2019**	**2020**	**2021**	**2022**
January	3 307	20 149	4 731	16 061	9 664
February	2 904	18 595	6 138	15 960	4 189
March	2 266	21 280	2 187	17 566	0
April	3 078	16 786	0	17 663	0
May	3 010	16 807	0	15 236	0
June	1 686	12 321	0	12 313	0
July	5 146	10 706	199	10 018	0
August	12 476	12 730	2 562	12 487	0
September	17 070	13 767	11 002	12 731	0
October	17 422	15 836	14 153	13 620	0
November	18 782	11 865	16 273	13 312	0
December	18 695	8 946	16 236	13 526	0

The loads for each month for the retrofit scenario at Årsetfjorden is shown in table A5.

Table A5: Load each month for retrofit scenario, at Årsetfjorden.

[kWh]	**2018**	**2019**	**2020**	**2021**	**2022**
January	0	51 650	0	41 041	32 639
February	0	46 496	0	33 449	17 469
March	0	43 205	0	38 444	0
April	0	30 940	0	39 691	0
May	0	33 950	0	27 001	0
June	0	18 055	51 531	42 562	0
July	0	5 205	58 594	25 992	0
August	0	0	13 966	31 042	0
September	2 905	0	0	31 568	0
October	56 699	0	14 347	5 126	0
November	38 261	0	42 540	7 230	0
December	31 236	0	48 880	22 966	0

The loads for each month for the new build scenario at Årsetfjorden is shown in table A6.

Table A6: Load each month for new build scenario, at Årsetfjorden.

[kWh]	**2018**	**2019**	**2020**	**2021**	**2022**
January	0	26 367	0	19 999	16 520
February	0	23 019	0	15 704	8 627
March	0	19 191	0	18 304	0
April	0	14 881	0	19 254	0
May	0	15 421	0	12 190	0
June	0	8 736	22 581	20 750	0
July	0	2 082	27 543	11 904	0
August	0	0	5 597	14 176	0
September	1 298	0	0	13 301	0
October	28 574	0	5 747	2 629	0
November	18 523	0	20 879	3 563	0
December	14 896	0	23 401	11 935	0

Appendix B

Electrical Efficiency Curve Fit

The equation for electrical efficiency, which is based of figure 13, is based on the following code:

```
import numpy as np
from scipy.optimize import curve_fit

# Polyfit of electrical efficiency curve

# Estimated datapoints from the efficiency curve
x = np.array([5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100])
y = np.array([20, 50, 52.5, 55, 53.5, 52, 50, 47.5, 45, 42.5, 40, 35])

# Finding coefficients
z = np.polyfit(x,y,4)

#Print the coefficients
print(z)
```

Appendix C

Hydrogen

The amount of hydrogen used per year in the cycles for the retrofit scenario is shown in table C1.

Table C1: Used hydrogen per year in kg for each fish farm for retrofit scenario

Year	Eiterfjorden	Skrosen	Årsetfjorden
1	37 950	28 769	20 475
2	17 843	10 619	15 831
3	31 381	-	35 537
4	15 546	-	20 011

The amount of hydrogen used per year in the cycles for the new build scenario is shown in table C2.

Table C2: Used hydrogen per year in kg for each fish farm for new build scenario.

Year	Eiterfjorden	Skrosen	Årsetfjorden
1	18 117	12 332	9 743
2	7 403	5 018	7 193
3	14 955	-	15 207
4	7 103	-	9 554

Refuels

The amount of refuels per year in the cycles for the retrofit scenario is shown in table C1.

Table C3: Refuels per year for the retrofit scenario

Year	Eiterfjorden	Skrosen	Årsetfjorden
1	39	30	27
2	24	16	22
3	31	-	35
4	21	-	27

The amount of refuels used per year in the cycles for the new build scenario is shown in table C2.

Table C4: Used hydrogen per year in kg for each fish farm for new build scenario.

Year	Eiterfjorden	Skrosen	Årsetfjorden
1	23	14	14
2	17	12	14
3	16	-	16
4	14	-	13

Appendix D

Diesel and CO2 Emission

The amount of diesel used per year in the cycles for the basecase scenario is shown in table D1.

Table D1: Used diesel per year in m^3 for each fish farm for the basecase scenario.

Year	**Eiterfjorden**	**Skrosen**	**Årsetfjorden**
1	255	177	140
2	129	77	105
3	211	-	217
4	122	-	135

The amount of CO_2 emissions per year in the cycles for the basecase scenario is shown in table D2.

Table D2: CO_2 emissions per year in tonnes for each fish farm for the basecase scenario.

Year	**Eiterfjorden**	**Skrosen**	**Årsetfjorden**
1	673	467	369
2	340	203	277
3	557	-	574
4	321	-	357

Appendix E

Net Present Value Data Points

Data points for the net present value analysis for Eiterfjorden, Skrosen, and Årsetfjorden are shown in tables D1, D2, and D3.

Table D1: Data points for NPV analysis for Eiterfjorden.

Year	**Retrofit**	**New build**	**Retrofit** [3%]	**New build** [3%]
1	-kr 14 283 705	-kr 29 194 929	-kr 14 095 864	-kr 29 042 898
2	-kr 13 389 103	-kr 27 664 057	-kr 13 029 128	-kr 27 374 276
3	-kr 11 992 108	-kr 25 369 024	-kr 11 228 809	-kr 24 749 940
4	-kr 11 163 320	-kr 24 090 178	-kr 10 125 529	-kr 23 242 871
5	-kr 9 650 252	-kr 21 620 520	-kr 7 899 941	-kr 20 189 718
6	-kr 8 919 494	-kr 20 404 541	-kr 6 776 577	-kr 18 655 494
7	-kr 7 763 348	-kr 18 562 754	-kr 4 905 258	-kr 16 223 072
8	-kr 7 068 335	-kr 17 524 773	-kr 3 791 602	-kr 14 833 195
9	-kr 5 770 198	-kr 15 495 974	-kr 1 517 916	-kr 11 996 419
10	-kr 6 036 763	-kr 14 873 688	-kr 1 285 721	-kr 10 964 820
11	-kr 4 914 224	-kr 13 275 080	kr 667 287	-kr 8 663 523
12	-kr 4 245 604	-kr 12 367 644	kr 1 803 246	-kr 7 354 142
13	-kr 2 939 884	-kr 10 554 928	kr 4 151 584	-kr 4 656 943
14	-kr 2 286 892	-kr 9 644 573	kr 5 323 375	-kr 3 309 629
15	-kr 1 217 319	-kr 8 211 543	kr 7 259 436	-kr 1 136 065
16	-kr 573 488	-kr 7 385 735	kr 8 381 533	kr 104 965
17	kr 720 559	-kr 5 704 448	kr 10 719 707	kr 2 680 804
18	kr 1 381 267	-kr 4 847 463	kr 11 892 205	kr 3 973 450
19	kr 2 480 663	-kr 3 470 560	kr 13 833 434	kr 6 076 720
20	kr 3 147 140	-kr 2 665 396	kr 14 959 842	kr 7 284 762

Table D2: Data points for NPV analysis for Skrosen.

Year	**Retrofit**	**New build**	**Retrofit** [3%]	**New build** [3%]
1	-kr 12 972 268	-kr 29 088 611	-kr 12 837 442	-kr 28 983 463
2	-kr 12 486 594	-kr 28 241 015	-kr 12 249 150	-kr 28 051 696
3	-kr 11 477 516	-kr 26 320 476	-kr 10 888 175	-kr 25 854 829
4	-kr 11 040 135	-kr 25 567 372	-kr 10 271 896	-kr 24 954 146
5	-kr 10 125 447	-kr 23 856 190	-kr 8 846 612	-kr 22 839 301
6	-kr 9 724 739	-kr 23 180 048	-kr 8 211 842	-kr 21 968 989
7	-kr 8 879 328	-kr 21 638 595	-kr 6 743 689	-kr 19 931 938
8	-kr 8 505 116	-kr 21 024 085	-kr 6 097 091	-kr 19 090 222
9	-kr 7 706 948	-kr 19 617 646	-kr 4 600 943	-kr 17 124 681
10	-kr 8 063 546	-kr 19 375 508	-kr 4 660 178	-kr 15 984 696
11	-kr 7 208 280	-kr 18 037 111	-kr 3 084 889	-kr 14 056 731
12	-kr 6 832 009	-kr 17 493 201	-kr 2 405 649	-kr 13 254 115
13	-kr 5 997 489	-kr 16 236 498	-kr 827 706	-kr 11 385 049
14	-kr 5 626 957	-kr 15 719 726	-kr 147 836	-kr 10 602 842
15	-kr 4 795 811	-kr 14 519 648	kr 1 433 199	-kr 8 781 466
16	-kr 4 423 810	-kr 14 020 068	kr 2 114 785	-kr 8 014 975
17	-kr 3 579 970	-kr 12 853 826	kr 3 702 054	-kr 6 229 266
18	-kr 3 199 757	-kr 12 362 308	kr 4 387 440	-kr 5 473 417
19	-kr 2 328 097	-kr 11 208 902	kr 5 986 374	-kr 3 710 618
20	-kr 1 933 249	-kr 10 716 943	kr 6 678 507	-kr 2 959 993

Table D3: Data points for NPV analysis for Årsetfjorden.

Year	**Retrofit**	**New build**	**Retrofit** [3%]	**New build** [3%]
1	-kr 14 344 559	-kr 29 791 131	-kr 14 242 149	-kr 29 708 098
2	-kr 13 712 332	-kr 28 617 841	-kr 13 465 451	-kr 28 418 788
3	-kr 12 427 706	-kr 26 228 925	-kr 11 751 100	-kr 25 691 756
4	-kr 11 612 223	-kr 24 862 651	-kr 10 615 601	-kr 24 062 778
5	-kr 10 823 873	-kr 23 532 697	-kr 9 438 672	-kr 22 414 063
6	-kr 10 301 734	-kr 22 598 346	-kr 8 587 529	-kr 21 212 233
7	-kr 9 229 427	-kr 20 682 723	-kr 6 754 554	-kr 18 690 076
8	-kr 8 538 590	-kr 19 571 975	-kr 5 576 885	-kr 17 175 172
9	-kr 7 856 655	-kr 18 477 042	-kr 4 362 769	-kr 15 638 735
10	-kr 8 103 019	-kr 18 020 230	-kr 4 191 796	-kr 14 838 593
11	-kr 7 028 615	-kr 16 360 491	-kr 2 237 411	-kr 12 457 019
12	-kr 6 341 218	-kr 15 380 891	-kr 1 009 509	-kr 11 017 912
13	-kr 5 647 680	-kr 14 400 054	kr 253 155	-kr 9 553 521
14	-kr 5 154 712	-kr 13 688 341	kr 1 178 833	-kr 8 476 811
15	-kr 4 116 020	-kr 12 202 662	kr 3 134 221	-kr 6 230 322
16	-kr 3 443 531	-kr 11 307 418	kr 4 358 597	-kr 4 861 281
17	-kr 2 750 161	-kr 10 394 985	kr 5 622 066	-kr 3 459 686
18	-kr 2 241 498	-kr 9 719 657	kr 6 557 021	-kr 2 421 055
19	-kr 1 157 660	-kr 8 294 454	kr 8 530 111	-kr 249 506
20	-kr 450 228	-kr 7 417 186	kr 9 767 114	kr 1 086 665

NTNU
Kunnskap for en bedre verden