Bachelor's thesis

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

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Opportunities and challenges related to a hydrogen-electric fishing vessel

Assessing the competitiveness of a zero-emission fishing vessel

Bachelor's thesis in Renewable Energy
Supervisor: Jacob Joseph Lamb (NTNU) and Astrid Petterteig (Siemens Energy)
May 2022

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Preface

This bachelor thesis is written by tree students in the subject FENT2900 - Bachelor thesis Renewable Energy, spring 2022. The thesis is written during the last semester of the bachelor engineering program Renewable Energy at Norwegian University of Science and Technology. The goal of the thesis is to investigate whether a hydrogen-electrical fishing vessel is competitive with traditional technology.

The fishery industry accounts for a significant amount of Norway's greenhouse gas emissions. The goal is to reduce these emissions with 50 % by 2030. The project description was given by Siemens Energy, that owns the project of the driveline in the ZeroKyst project. However, the bachelor group decided the limitations in the bachelor thesis. In this thesis the ZeroKyst project is introduced. Further, all the sub-project with related background is listed. A simulation of the vessel is performed in Simulink by MATLAB as well as cost analysis and literature research.

First we would to thank Siemens Energy who let us write our bachelor thesis about this exciting project in collaboration with the ZeroKyst project. We would like to thank our internal supervisor in the subject, Associate Professor Jacob Joseph Lamb for weekly guidance, and support during the whole project period. We would also like to thank our external supervisors Astrid Petterteig at Siemens Energy and Olav Rygvold at Renewable Energy Cluster, for help and feedback. Further, we would like to thank Trude Birgitte Byre at Siemens Energy for always providing help and guidance with the simulation model. Lastly, for motivation and support during the semester, a thank is given to friends and family.

Abstract

Norway is a country with a strong relation to the coast and its resources. The fishing industry contributes as income for both many Norwegians and Norway as a country. Most fishing vessels in Norway today run on a diesel propulsion system. Due to the global warming, air pollution and acidification, the industry needs to reduce its emissions. The ZeroKyst project want to decarbonize the seafood industry through a transition to hydrogen-electric propulsion, to demonstrate solutions for mobile energy supply in Lofoten in addition to other sub-projects. The Zerokyst project is a research collaboration between industry, interest groups and municipalities, with Selfa Arctic AS as project manager.

There are many technical and financial challenges which introducing new technology. A major challenge is that the technology must be able to offer the same properties as traditional technology, and still be emission-free. Hydrogen propulsion is a immature technology compared to diesel, in the marine sector. Therefore the regulations are still in development for the optimal hydrogen solutions for vessels. The operating costs for the hydrogen-electric fishing vessel includes bunkering of hydrogen and charging of the battery. For diesel vessels, it only includes the bunkering of diesel, and with hybrids, charging of battery must also be taken into account.

The thesis aims to investigate how competitive is a hydrogen-electric fishing vessel, compared to traditional technology. A combination of simulation, cost calculation and literature study is used to consider this. The simulations is performed in a model in Simulink by MATLAB. The results from the simulations was used to understand the energy consumption of a hydrogen-electric fishing vessel during four different 12-hour operating profile. The cost calculations demonstrated that as of today, when the fishers get diesel compensation, this is not competitive price-wise. However, in the future the compensation is likely to be removed, which can make it profitable to use the zero-emission vessel. The range is shorter with a zero-emission vessel, and this might be satisfying for some fishers. The vessel will have a diesel generator installed. The vessel will also provide a working environment with less noise, given that it runs on the zero-emission propulsion system, and not the generator. In conclusion, the ZeroKyst project will develop a fishing vessel with the potential for lower operating costs and emissions. However, it is important that the solution meets the fisher's need in terms of range.

Sammendrag

Norge er et land med et sterkt forhold til kysten og dens ressurser. Fiskeindustrien bidrar til inntekt både for mange nordmenn og Norge som land. De fleste fiskefartøy i Norge har i dag dieselfremdrift. På grunn av global oppvarming, luftforurensning og forsuring, må industrien ta grep og redusere utslipp. ZeroKyst-prosjektet ønsker å avkarbonisere sjømatnæringen gjennom en overgang til hydrogenelektrisk fremdrift, samt å demonstrere løsninger for mobil energiforsyning i Lofoten i tillegg til andre delprosjekter. Zerokyst-prosjektet er et forskningssamarbeid mellom industri, interesseorganisasjoner og kommuner, med Selfa Arctic AS som prosjektleder.

Det er mange tekniske og økonomiske utfordringer ved å introdusere ny teknologi. En stor utfordring er at teknologien skal kunne tilby de samme egenskapene som tradisjonell teknologi, i tillegg til å være utslippsfri. Hydrogenfremdrift er en umoden teknologi sammenlignet med diesel i maritim sektor. Derfor er regelverket fortsatt under utvikling for optimale hydrogenløsninger. Driftskostnadene for det hydrogenelektriske fiskefartøyet inkluderer hydrogenbunkring og lading av batteriet. For dieselfartøy inkluderer det kun bunkring av diesel, og med hybrid farttøy må lading av batteri også tas i betraktning.

Oppgaven tar sikte på å undersøke hvor konkurransedyktig et hydrogenelektrisk fiskefartøy er, sammenlignet med tradisjonell teknologi. En kombinasjon av simulering, kostnadsberegning og litteraturstudie brukes til vurdere dette. Simuleringene er utført i en modell i Simulink av MATLAB. Resultatene fra simuleringene ble brukt til å forstå energiforbruket til det hydrogenelektriske fiskefartøyet i løpet av fire forskjellige antatte 12-timers driftsprofiler. Kostnadsberegningene viste at per i dag, når fiskerne får dieselkompensasjon er ikke dette konkurransedyktig prismessig. Derimot, i fremtiden vil kompensasjonen sannsynligvis bli fjernet, noe som kan gjøre det lønnsomt å bruke nullutslippsfartøy. Rekkevidden er kortere med et nullutslippsfartøy, og dette kan være tilfredsstillende for noen fiskere. Som sikkerhet vil fartøyet ha en dieselgenerator installert. Fartøyet vil gi et arbeidsmiljø med mindre støy, gitt at det kjører på nullutslippsfremdriftssystemet, og ikke generatoren. ZeroKyst-prosjektet utvikler et fiskefartøy med potensial for lavere driftskostnader og utslipp, men det er viktig at løsningen møter fiskerens behov med tanke på rekkevidde.

Contents

List of Figures

List of Tables

List of Terms and Abbreviations

Terms	**Description**
Anode	Electrode which oxidizes in a electrolytic cell.
Bunkering	Supply of fuel for the use in vessels.
DC Bus	Circut connecting all components in the system.
Cathode	Electrode which reduces in a electrolytic cell.
Carnot efficiency	The theoretical maximum efficiency one can get when a heat engine is operating between two temperatures.
C-rate	The C-rate is a measure of the rate at which a battery is charged and discharged.
DC-DC converter	Device which convert one DC voltage level to another DC voltage level.
Diesel generator	A diesel engine that powers an electrical generator.
Fisher	A person having fishing as their full time job.
Grønn Plattform	An initiative that provides support for research and innovation-driven green transformation in the business community.
Electrode	Collective term for anode and cathode.
End of Life	A component's end-of-life performance is the lowest it will achieve during its life span.
Fuel Cell	Electrochemical cell which provides electricity with a fuel by making it react with oxygen.
Greenhouse gases	Gases which trap heat in the earth's atmosphere, warming the planet. An example of greenhouse gas is Carbon dioxide.
Hydrogen	Unless other is stated, it is referring to hydrogen gas.
Limitation	Restricting energy supply to the system.
Ocean acidification	The decrease in pH-value in the ocean, caused by CO_2 from the atmosphere.
Oxidation	When electrons are emitted.
Polarization	Collective term for mechanical side-effects of an electrochemical process.
Propulsion	Propulsion is the force of driving and propelling.
Separator	Porous material which separates the anode and the cathode.
Pilothouse	It is the area or space from which a vessel is steered.
Reduction	When electrons are received.
Zero-emission	Refers to a process or energy source that emits no waste products.

Abbreviations	**Description**
AC	Alternating current
AFC	Alkaline fuel cell
AWE	Alkaline water electrolysis
BPP	Bipolar plates
CCS	Carbon capture and storage
CHP	Combined heat and power
CL	Catalyst layer
DC	Direct current
DNV	Det Norske Veritas (The Norwegian Veritas)
EMS	Energy management storage
EoL	End-of-Life
EU	European Union
FC	Fuel cell
GDL	Gas diffusion layer
GFF	Garantikassen for fiskere
GHG	Global greenhouse gas
HHV	Higher heating value
HSE	Health, safety and environment
LHV	Lower heating value
LH2	Liquid hydrogen
LIB	Lithium Ion Battery
LNG	Liquefied natural gas
MCFC	Molten carbonate fuel cell
MCWE	Molten Carbonate Water Electrolysis
MEA	Membrane electrode assembly
NMC	Nickel Manganese Cobalt
PAFC	Phosporic acid fuel cell
PEMFC	Proton exchange membrane fuel cell / Polymer electrolyte membrane Fuel Cell
PEM	Proton electrolyte membrane
SoC	State of charge
SOEC	Solid oxide electrolyzer cell
SOFC	Solid oxide fuel cell
SoH	State of health
SoH2	State of hydrogen

List of symbols

Symbol	**Description**
E_{rev}	Reversible voltage [V]
F	Faradays constant [C/mol]
m	Mass [g]
M	Molar mass [g/mol]
n	Number of electrons [-]
n_m	Number of moles [mol e$^-$]
p	Pressure [bar]
R	Gas constant $[\frac{liter \cdot\ bar}{mol \cdot K}]$
T	Temperature [K]
V_N	Volume [liter]
Va	Actual voltage [V]
ΔG	Gibbs free energy [J]
ΔH	Enthalpy [J]
ΔS	Entropy [J/K]

1 Introduction

This chapter presents the background, motivation, objective, scope, information gathering and outline for the thesis topic. The thesis is provided by Siemens Energy in collaboration with the ZeroKyst project.

1.1 Background and motivation

Norway is a country with strong relation to the coast and its resources, with a long tradition of harvesting from the ocean. Norway is a major exporter of seafood. Fish and shellfish are exported to countries all over the world, both caught wild and farmed fish. However, the maritime sector accounts for a significant proportion of global greenhouse gases (GHG). In Norway, the maritime industry accounts for 6 % of Norway's total emissions. In order to reduce the emissions, it is crucial to change the energy production and storage, as well as reducing the emissions [1].

Most of today's fishing vessels in Norway run on diesel propulsion systems. The ocean, as an ecosystem, suffers from pollution and the consequences of global warming, like the rest of the environment. The maritime sector is taking action, especially regarding ferries. It has become more common with electric ferries for small distances. Although to drastically reduce the world's GHGs emissions, the seafood sector must also contribute. In Norway in 2020, fishing vessels emitted around 878 000 ton CO_2 emissions, which corresponds to $\sim$2 % of Norway's yearly emissions [2].

1.1.1 ZeroKyst

Zerokyst is a collaboration between industry, research, interest groups and municipalities, with *Selfa Arctic AS* as the project manager. The main goals are to decarbonize the seafood industry through a transition to hydrogen-electric propulsion and to demonstrate solutions for mobile energy supply in Lofoten. Figure 1.1 shows the different parts of the Zerokyst project [3]. ZeroKyst wants to create a rapid technology change for all types of vessels in the seafood industry.

The project will develop a zero emission driveline, a new zero emission fishing vessel, 10 vessels prepared for conversion, services for conversion and maintenance, and a complete solution for flexible supply of electricity and green hydrogen as a maritime fuel. The goal is that this will contribute to a 50 % cut in emissions from fishing and aquaculture vessels by 2030 and have the potential to create values of 100 million NOK.

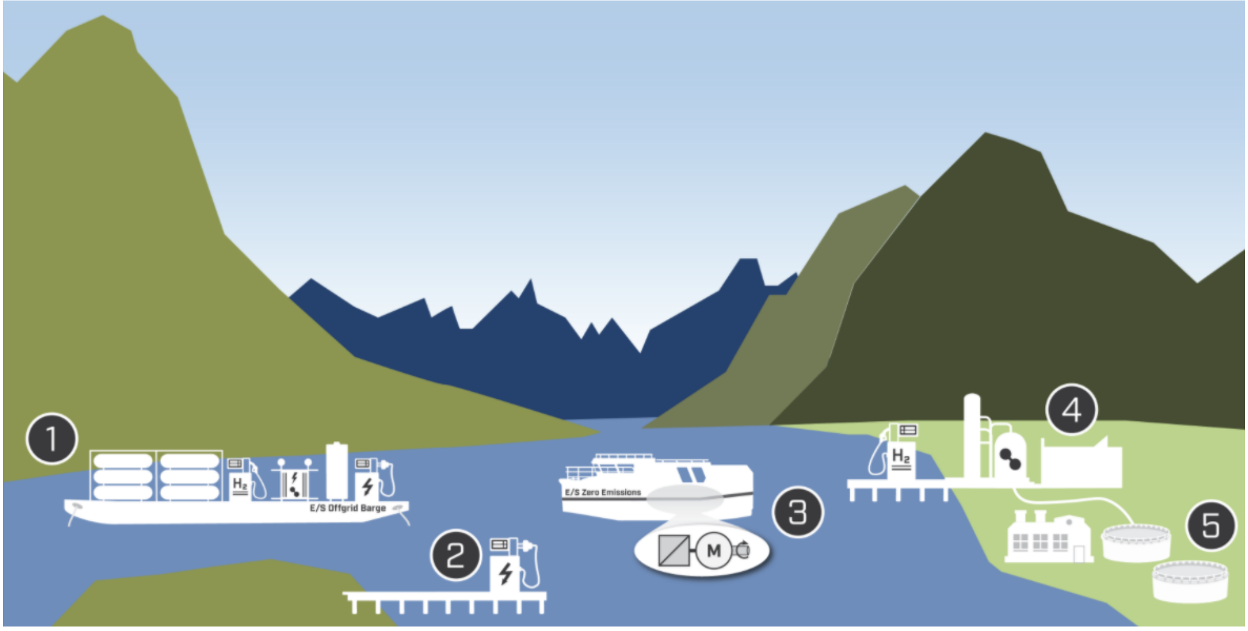

Figure 1.1: *Zerokyst concept sketch of solutions for hydrogen-electric vessels, mobile energy supply and infrastructure [4].*

Zerokyst's pilot project is located in Flakstad municipality in Lofoten, Norway. It is a small municipality with approximately 1300 residents. Flakstad has five fishing ports and a high density of fishing vessels, which makes them a central part of the fishing industry in Lofoten. The five fishing ports in Flakstad are Napp, Nusfjord, Ramberg, Fredvang and Sund, and are represented as red dots in Figure 1.2. Flakstad joined the ZeroKyst project as the only municipality. This is, among other things, due to their earlier development work in climate projects and the municipality's climate investment in coastal fishing [5, 6]. The ZeroKyst project consists of five sub-projects, which are described below [3].

Sub-project 1: Zero emission driveline

Siemens Energy AS is in charge of sub-project 1 in collaboration with *Hymatech AS* and *SINTEF*. Together they will develop a safe hybrid zero emission driveline called Siemens Blue Drive ECO. This involves the design of driveline, design of flexible solutions for zero emission fuel, design of standard modules, an energy management system and integration of all these systems [3].

Sub-project 2: Zero emission vessel

Selfa Arctic AS together with *Øra AS* is developing and building a hydrogen-electric vessel. This includes building the vessel with the zero emission driveline, Siemens Blue Drive ECO. The new propulsion system will be adapted to the already existing hybrid vessel design, with regard to the location of storage and bunkering system for battery and hydrogen. As part of sub-project 2, it is also intended to contribute to regulatory development of vessels of this type to adapt to the new driveline. The installation with this technology is expected to be frequently used in the fishing industry [3].

Sub-project 3: Flexible and competitive hydrogen supply

This sub-project consists of the hydrogen production, bunkering and storage, with *H2 Marine* as the sub-project owner. *Lofotkraft Muligheter AS* is planning local hydrogen production that will give predictable access for the zero emission vessels. From the hydrogen production it is also planned to develop a circular solution for utilization of heat and oxygen to hatchery fish production. The zero emission onshore facilities is planned to produce 300 kg of hydrogen each day. Sub-project 3 also involves a mobile energy supply unit, which will contribute with flexible supply of hydrogen and electricity [3].

Sub-project 4: Regional energy infrastructure

Zero-emission vessels will need a sufficient charging offer to ensure proper utilization. This includes a combination of charging at home and fast charging. *Plug AS*, *Lofotkraft Muligheter AS*, *Ballstad Slip AS*, *H2 Marine AS* and Flakstad municipality are partners in sub-project 4 and *Renergy* is the sub-project owner. The six partners will analyse energy needs to develop and establish charging infrastructure for up to four fishing ports in Lofoten [3].

Sub-project 5: Competence project

The competence project in Zerokyst will investigate how to use to hydrogen-electric vessel to achieve the goal of 50 % emission reduction in the fishing industry by 2030. *SINTEF* and *NTNU* are the ownes of this sub-project. There is a plan that the compound competence will put Norway in the driver's seat for the new technology shift [3].

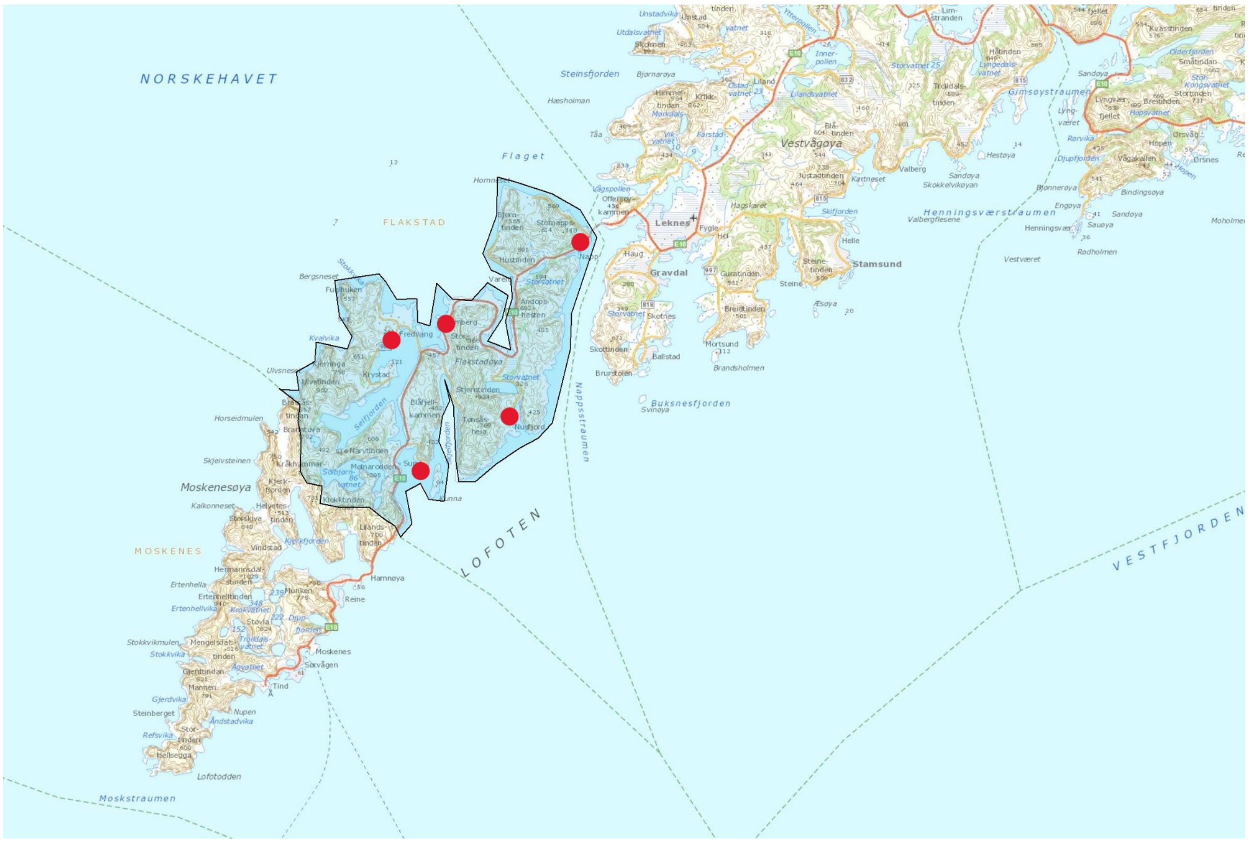

Figure 1.2: *Flakstad municipality with five fishing ports. Figure modified from [7].*

In this bachelor thesis, the main focus is sub-project 2, the hybrid zero emission vessel, consisting of battery and fuel cell technology. The goal for this vessel is that it will have long range and short bunkering time. The project will also develop new solutions for flexible and cost-effective hydrogen production, distribution and bunkering, as well as developing and testing charging infrastructure with efficient solutions and utilization of the power grid. The main project will demonstrate solutions aimed at both national and international markets. The competence project will develop the necessary knowledge to achieve the target emission cuts throughout the seafood industry.

The thesis will simulate the hydrogen-electric fishing vessel. In the theory section, the focus is on both battery and hydrogen, but mostly on hydrogen technology. This is because the hydrogen technology makes this a new and unique vessel. In 2016, the world's first diesel hybrid fishing vessel was launched, which is the predecessor to the hydrogen-electric vessel. There are about 5900 fishing vessels in Norway, so this project can contribute to great value creation [8].

1.2 Objective and scope

The objective of this thesis is to assess whether a hydrogen-electric fishing vessel is competitive with a traditional diesel fishing vessel. The assessment applies to both function and price. This thesis is based on the project taking place in Flakstad municipality. The fisher, whom the group has been in contact with, lives here.

The thesis is a combination of simulating, cost calculation and literature study. The simulations are performed using the modelling program Simulink by MATLAB. The group received a partially completed simulation model from Siemens Energy. Therefore, some adjustments were made. One 12 hour operating profile was made to this model before use in the project. This was based on information from one specific fisher, who also is the costumer of the new hydrogen-electric fishing vessel.

This thesis does not include an analysis of investment costs. The costs of new technology will be significantly higher than traditional technology, but this is outside the scope of this work. ZeroKyst's project is a pilot that will lay the foundation for further adoption within the industry. The research question for this thesis is:

How competitive is a hydrogen-electric fishing vessel compared to traditional technology? The range and operating costs are essential factors for fishers, and this is examined more closely with simulations and cost calculations.

1.3 Information gathering

This thesis contains information gathered from multiple sources. There have been meetings both online and in person with several of the industry and research partners in the ZeroKyst project, especially with the industrial supervisor Astrid Petterteig. Most of the information, in addition to literature research, was gathered in meetings and through e-mail correspondence. Siemens Energy and fisher Bent Gabrielsen contributed to the simulations and case study.

1.4 Outline

This thesis is divided into 5 chapters. Chapter 1 is the introduction chapter. This contain the background, motivation and outline. Chapter 2 contains the theory and the background information necessary to understand the results. Further, Chapter 3 contains the methodology used to perform the calculations and simulation to get the results. It also describes the model used to perform the simulation. Chapter 4 presents the results and discussion. Lastly, Chapter 5 presents the conclusion in this thesis, and suggestions for future work.

2 Theory

The theory described in the following chapter is the background and basis of the study. This is the relevant information that makes it possible to understand the results. This section includes theory about existing technology, the maritime sector, the transition from fossil fuel to emission-free fuel, the hydrogen-electric fishing vessel, hydrogen, and lithium-ion batteries.

2.1 Norwegian seafood industry

Norway has a long tradition of harvesting from the ocean. Each day, fish from Norway is on the plate in countries worldwide. Seafood harvesting and production is an important source of income both for many Norwegians privately and for Norway's economy. However, the seafood industry also accounts for a large part of the GHGs Norway emits. The EU has set requirements for Norway to reduce their GHG emissions for the non-quota sector from 2005 to 2030 for an emission reduction of 40 % [2].

2.1.1 Coastal fishing

There are different types of fishing. The different ways of fishing that are discussed in this thesis is coastal fishing, were the fisher returns to port every day. In the past, it was common to separate between coastal fishing, bank fishing and deep-sea fishing. The difference between coastal and bank fishing is not as clear today, as some coastal fishing vessels also freeze the catch on board and make longer trips. The reason that they freeze the fish is to keep the fish fresh for as long as possible. The most important coastal fishery in quantity and value is cod fishing, but the coastal fishing fleet fishes for a number of different fish species and shellfish [9].

2.1.2 Emissions

Food production, distribution and consumption contribute to a quarter of the world's GHGs, and are therefore one of the largest contributors to global warming [10]. In 2004 the emissions from the Norwegian fishing fleet reached a peak with 1.8 million tons of CO_2 equivalents. This was reduced to 1.1 million tonnes in 2015. The reduction is mainly due to the fact that fewer fishing vessels are fishing larger quotas each [11]. The Norwegian fishing industry emits more than one million CO_2 equivalents a year [2]. Emissions from shipping and fishing vessels have a significant impact on the global climate change. In addition to being harmful to the environment air pollution is also bad for the public health, with a variety of health risks [12].

In addition to air pollution, studies show that Norway is at risk of ocean acidification. It is threatening the fundamental chemical balance of the ocean. It has not yet been proven that the fish are in direct danger in Norway, but that organisms further down the food chain have begun to suffer from the acidification [13]. The maritime sector causes large amounts of ocean acidification. It is also expected that this will increase in the years to come [14]. Additionally, the fishers in Lofoten have noticed that the fish are migrating north due to the warmer water. The fishers are forced to fish new places and travel further north as a result of this. A zero-emission propulsion system might be an attractive option for some fishers due to this (Kurt Atle Hansen, Personal communication, 10/02/2022).

2.2 Existing technology

In order to develop new technologies and more sustainable solutions, it is important to know the existing technology. One must look at what benefits of the existing technology, and whether it is possible to transfer them to new and sustainable technologies.

2.2.1 Diesel propulsion

The traditional and most common technology used on coastal fishing vessels in Norway is diesel engines. Diesel is a typical fuel for both old and new vessels. A diesel fishing vessel around 11 meters consumes up to 40 000 liters of diesel per year. Diesel provides the opportunity to store a lot of energy. In addition, diesel can be stored wherever there is room in the vessel [2]. This propulsion system provides the opportunity to be out fishing for several days without bunkering more diesel, in addition there is infrastructure that facilitates bunkering [15].

2.2.2 Diesel-electric propulsion

The further development from a traditional diesel engine is a diesel-electric engine. Several diesel engines, which drive an electric generator, produce the electric power that energizes the electric motors. These are connected to the propellers and the other electrical loads on the ship. The first diesel-electric fishing vessel was launched in 2009. The diesel-electric engine has advantages such as reduces wear and tear, since it is possible to reduce the engine speed. This makes less noise and vibrations, in addition to less fuel consumption [16].

2.2.3 Diesel hybrid propulsion

The diesel hybrid propulsion system is based on similar technology as the diesel-electric system. The difference is when the vessel is in the fishing field, it is powered by electric energy from battery instead of diesel. By using onshore power supply, the fuel consumption will be reduced. As a consequence to that, the emissions will also increase. In addition, operating costs will reduced in countries where electricity prices is cheaper than diesel prices. the electricity produced from a diesel generator. Norway is such country [17].

Using an electric motor out in the fishing field improves the working environment because of the reduced noise. In addition, other operations on the vessel will be easier to hear. Thus it will be easier to detect a failure and unwanted noise, and there will be better maintenance on the vessel with a quieter workplace [18].

2.2.4 Karoline

In 2015, the worlds first hybrid fishing vessel was launched. It was built by Selfa, who named the model Selfa Arctic El-Max 1099. It was bought by the shipowner Bent Gabrielsen, who named it *Karoline*, and she has been operated flawlessly since it was launched, and still is. *Karoline* consumes diesel on trips to the fishing field, she also uses electricity when fishing. When *Karoline* was built, it was the first of this kind of fishing vessel. At the time, information did not exist about how much energy a diesel-electric fishing vessel demand [18].

Figure 2.1: *Worlds first hybrid fishing vessel, Karoline [18].*

2.2.5 LNG

In 2021, the worlds first fishing vessel operating on LNG, *Libas*, was launched. This vessel is 86 m long, much longer than the hydrogen-electric vessel considered in this thesis will be. According to the general manager in Liegruppen, by acquiring this vessel, the company will be able to meet the government's climate target of a 50 % reduction in emissions by 2030 already now. In other vessels, LNG is also used to reduce emissions. LNG is the fuel that was intended to be an environmentally friendly replacement for diesel. LNG is more climate friendly, but more expensive and has larger storage volume per energy content [19].

Figure 2.2: *The worlds first LNG fishing vessel, Libas [19].*

2.3 Transition

It order to meet the emission reduction demand of the future, there is a precarious need to reduce emissions in the maritime sector significantly. In Norway, the worlds first electrical car ferry, *MS Ampere* started operating in 2015. Since then, several full-electric and hybrid marine vessels have been built [20]. Also, there are hydrogen vessels for the aquaculture industry under construction, in addition to ammonia vessels, more about this in Section 2.8.3 [21].

There is a need for a shift in the maritime industry. All sectors within the marine industry have to reduce their emissions. In Norway, there is political support for this transition, and it have been provided support for several projects [22]. In 2019, the Minister of Transport and the Minister of Climate and the Environment presented the section plan for infrastructure for alternative fuels in transport [23].

Figure 2.3: *The worlds first electrical car ferry, MS Ampere [24]*

Grønn Plattform is an initiative that provides financial support for research and innovation-driven green transformation in the business community. They support a lot of project from research and technology development to finished solutions. The purpose is to develop a sustainable business community that takes care of the climate and environment, and creates economic value [11, 22].

2.3.1 Compensation

For many years the fishers in Norway were exempted from paying taxes. However, from 2020 they must pay a CO_2 tax on the diesel they use. Nevertheless, they receive compensation for this from Garantikassen for fiskere (GFF), which is an executive agency under the Ministry of Trade and Industry. GFF administers the fishers social schemes. During the next few years, this solution is scheduled to be phased out. In addition to tightening compensation for bunkering in Norway, fishers will no longer be compensated for CO_2 if they bunker abroad. This is a measure to speed up the green shift. This will hopefully increase the engagement among the fishers to invest in new technology. However, fishers are requesting benefits for choosing green technology, rather than punishment for their emissions [11, 25].

2.3.2 Regulations and limitations

For fishing vessels in Norway, the fishing quotas are set in relation to the length of the vessel [26]. Therefore, many vessels have been expanded in the width to access the cheapest quotas. A design with a narrower vessel could move more efficiently through the water, and use less fuel [15].

Storing hydrogen is challenging, one of the reasons is that it have to be stored above deck, due to regulations. This requires large space above deck, and means that the vessel must be made longer to be able to store the hydrogen. This is not ideal for a fisher, as it is their working area. For the hydrogen-electric fishing vessel, the fuel takes up more space than in a diesel vessel [2]. Therefore, the ZeroKyst project wants a dispensation for the law stating that quotas are related to the length of the fishing vessel. The desire is to have 13 meter long vessel, with the quota for a 11 meter vessel. This application has unfortunately been rejected, which speaks against the call to invest in zero-emission technology. However, ZeroKyst is continuing the work for getting dispensation (Bent Gabrielsen, Personal communication, 26/04/22).

It took almost ten years to establish the regulations for the use of LNG as a fuel in the maritime sector. Norway led the way in this pioneering work in the 1990s. Based on that experience, it is not so unnatural that changing the regulations for hydrogen vessels is a time consuming process. In order to get a rapid change in the maritime sector the time-frame for the regulation changes would ideally be shorter [27]. There are requirements for external energy supply source on vessels. Therefore, there is a requirement for an external generator also on hydrogen-electric vessels [28].

2.4 Hydrogen electric vessel

Hybrid Z is the name of the emission-free driveline for the ZeroKyst project. This project is based on a 11 m long costal fishing vessel. It is planned for the fishing vessel to operate in Flakstad in Lofoten, using a hydrogen-electric propulsion system. The vessel is equipped with a battery pack of 330 kWh and 31.75 kg of compressed hydrogen. Further, a 100 kW polymer electrolyte membrane fuel cell (PEMFC) is placed in a room on the main deck and separated from the machinery and other electrical installations. The fuel cell (FC) delivers electric energy. The battery package is located in the bottom of the vessel in a separate room [15]. Figure 2.4 shows a sketch of a zero-emission vessel with the same length as the fishing vessel ZeroKyst is planning to build.

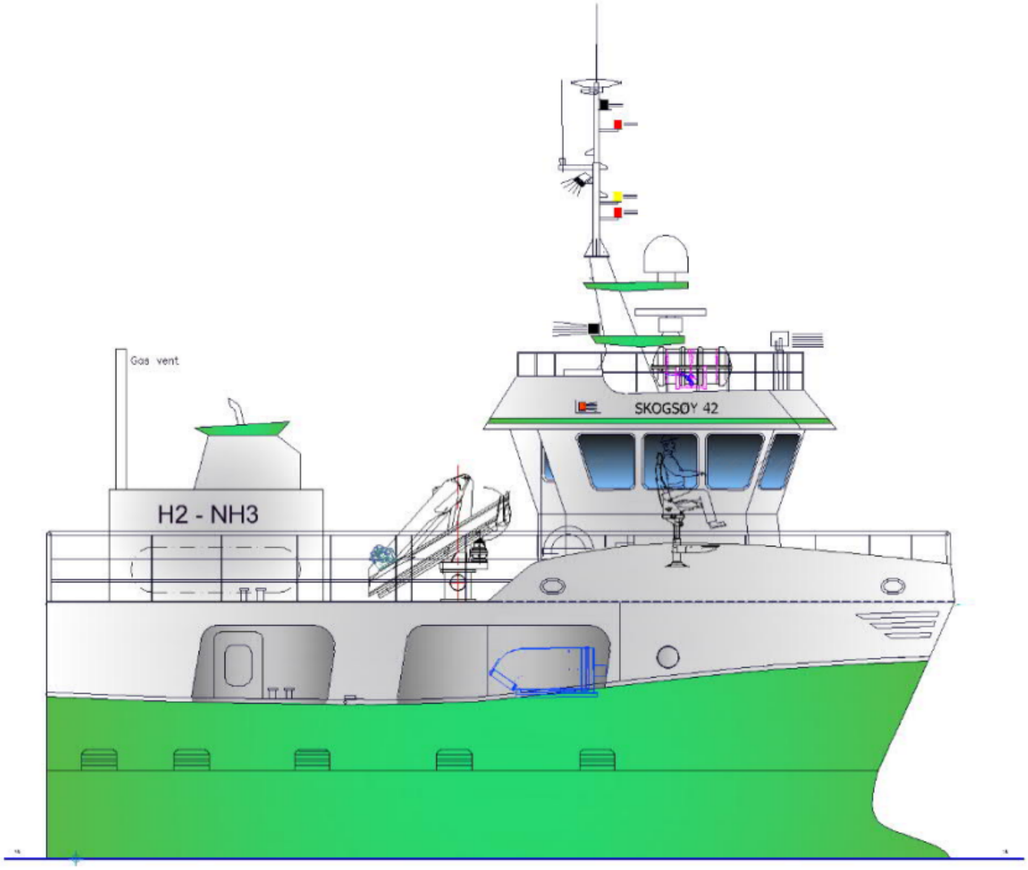

Figure 2.4: *Sketch of a zero-emission vessel [15].*

The hydrogen tanks is stored on shelter deck in accordance with current regulations. It is used Magnum 5 Hexagon pressurized cylindrical tanks with a pressure of 250 bar. This relatively low pressure is advantageous to lower the costs and energy loss regarding compression. In addition to the FC and the battery, there is a 110 kW diesel generator on the vessel. This is due to the immaturity of the technology, and the fishermen want the extra security a diesel generator can provide [15].

2.4.1 Challenges

One of the major challenges with a hydrogen-electric fishing vessels is that the technology must be able to offer the same properties as traditional technology, and still be emission-free. The lack of adequate infrastructure is another challenge. If vessels are electrified and charged at site, they will have an impact on the power grids capacity. A consequence of this is that the power grid potentially have to be expanded [29]. Further, there is limited options for bunkering with hydrogen per now. Facilities for hydrogen production and bunkering are expensive. It is therefore an advantage to ensure that the infrastructure will be used, if private or public investors are going to invest [30].

As of today, hydrogen alone is not competitive with diesel, but if the diesel subsidy to the fishers is removed, it may be in the future. Today the fishers pay ∼7.9 NOK/kg diesel. In the future, it is likely that the price will be higher, and then the hydrogen can be able to compete price-wise [15].

With the technology that exists today, the range is shorter with a hydrogen-electric propulsion system than with diesel. This could causes range anxiety for the fishers. They want to be able to fish as much as usual, even if they have to change fuel. Unlike diesel, it is difficult to receive fuel from another vessel if they run out. One can not just receive a tank of hydrogen from a vessel nearby. For short distance ships and vessels, batteries can most likely cover all consumption. This applies for ferries with a short distance ferry connection that can charge many times a day. Fishing vessels need a longer range, and do not have the same predictable operation as ferries. Therefore, hydrogen can be used to extend the range without increasing the emissions (Kurt Atle Hansen, Personal conversation, 16/02/22), [15].

Charging batteries takes time, and requires careful planning for the fisher. This also requires available charging options. Hydrogen bunkering is a less time consuming process than charging. For hydrogen vehicles, it takes 3-5 minutes to filling up a full tank of 5 kg and 700 bars. The same filling technology can be used with fishing vessels. However, it does have more safety related challenges, more about this in Section 2.9 [15, 31].

2.5 Operating costs

The operating cost for the hydrogen-electric fishing vessel includes hydrogen bunkering and charging of the battery. For diesel vessels, it only includes the fueling of diesel, and for diesel hybrids, charging of battery must also be taken into account. For customers who want to purchase hydrogen, the price is dependent on the whole hydrogen value chain. This includes costs from production to the finished product. Compression of hydrogen is a part of this costs, and will increase for higher pressures [15].

The production size and transport of hydrogen also affects the price. When the demand for hydrogen is still relatively low, local production close to costumers can be beneficial. For a potentially larger demand in the future, it may be advantageous to have more extensive centralized production facilities, that transport to smaller filling stations. The production of hydrogen, demands a large amount of electricity, and national variations in electricity prices will therefore affect the costs [31].

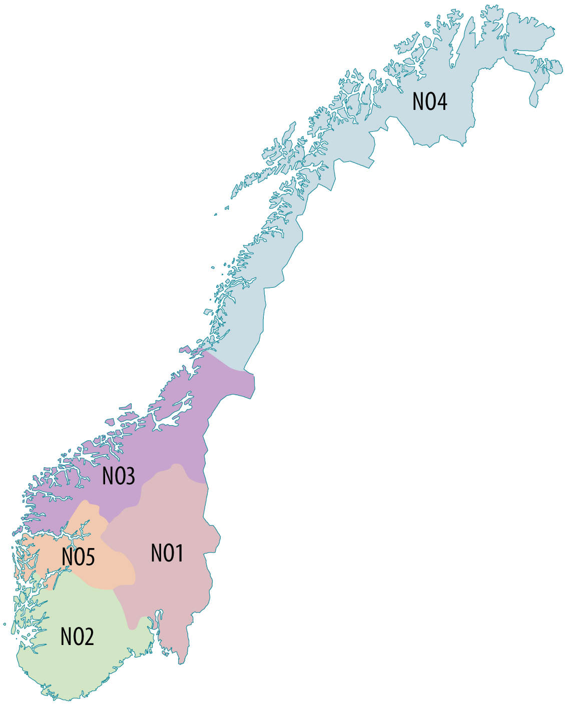

Figure 2.5: *Price ranges in Norway [32].*

For charging the battery, the price of electricity is essential. In Norway, it often has considerable variations with the location. Norway is divided into five price ranges for electricity; east (NO1), south-west (NO2), central (NO3), northern (NO4), and west (NO5). The division of the five price ranges are illustrated in Figure 2.5 [33].

Large parts of southern Norway have power grids connected to Europe, and will occasionally be affected by the high price level. In northern Norway, most electricity is locally produced and used. The capacity for transporting electricity from north to southern Norway is limited, and will therefore be less affected by other price ranges. This often gives northern Norway lower electricity prices then the rest of the country electricity price than usual [33]. In 2021, the average electricity price in Tromsø, in price range NO4, was 357.38 NOK/MWh. For comparison, the price in Oslo, in price range NO1, was 758.18 NOK/MWh the same year [34]. This was a year with more national differences in electricity price than usual [33].

2.6 Fuel Cells

In recent years, FC have gained attention because they are a promising alternative to traditional power sources. In ship applications, FCs have several advantages over conventional maritime propulsion, such as zero- or low emissions and relatively high fuel efficiency. Further, FCs operate silent, and has lower operating and maintenance costs [35].

A common principle for all FCs is that the fuel reacts at the anode, while air or oxidant reacts at the cathode. It is an electrochemical reaction with electric power and excess heat as the outcome. FCs are conceptually similar to batteries in the form of electrochemical cells generating electricity through a chemical redox reaction. However, FCs differ in that they require a continuous external supply of oxygen and fuel [36].

2.6.1 Construction of a fuel cell

The basic construction of a hydrogen FC consists of two electrodes, an electrolyte, a fuel (hydrogen) and an external DC power source connecting the two electrodes. The positive electrode is referred to as the cathode, while the negative electrode is called the anode. Separating two electrodes is an electrolyte, which is an ion conducting material that allows ions to pass freely. At the anode, hydrogen molecules are separated into protons and electrons. The electrons are forced through an external circuit to the cathode, producing a flow of electricity. The protons move through the electrolyte to the cathode, where they merge with oxygen and the electrons to generate water and heat [37–39].

With an output voltage of less than 1 V for a single FC, individual FCs are normally connected in series into a FC stack to achieve the desired voltage. Figure 2.6 shows how FCs can be stacked. Various factors, such as FC type, cell size, operating temperature and the pressure of the gases entering the cell, determine how much power a FC produces [38].

A FC stack will not operate stand-alone, but needs to be integrated into a FC system. Several FC auxiliary systems are required in order for the FC stack to work. This includes electronic controller, a hydrogen and oxygen delivery system, a cooling system, as well as a water management system [40]. Even though using pure oxygen can increase the efficiency, there is little improvement to gain for some FCs. Therefore, air is often fed to the cathode side [35].

Figure 2.6: *FC stacks [41].*

2.6.2 Types of FCs

FCs are generally characterized by the type of electrolyte material. There are many types of FC technologies with difference advantages and disadvantages for both stationary and mobile applications. The most common ones consist of: alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC) and phosporic acid fuel cell (PAFC) [42]. For this thesis, the three former FC devices are focused on, and Table 2.1 compares the different technologies.

Table 2.1: *Comparison of different types of fuel cells*

	AFC	**PEMFC**	**SOFC**	**Source**
Maturity	Mature	Commercial	Demonstration	[31]
System respons	Seconds	Seconds	$\sim$ 30 minutes	[43]
Temperature [°C]	60-80	50-85	700-1000	[35]
Efficiency [%]	56-73	48-65	45-60	[35]

The FC performance depends on three factors, especially ohmic resistance during charge transportation, the catalytic and mass transport losses due to limitations with transportation through the cell components. Losses with transportation can be reduced with altering the FC design. A reduction of resistance and mass losses can be made by varying the thickness of the cell materials. However, it is important to keep the material costs and strength in mind [44].

Alkaline Fuel Cell

AFC is a relative mature technology, and is the first developed FC [31]. The technology is cheapest in terms of investments compared to alternative FCs. This is mainly because of avoidance of precious materials. Nickel and nickel oxide electrodes can be utilized, which is a much more durable and reasonable option compared with platinum [31, 36, 45]. Other advantages with AFC is the compact design and low temperatures. Commonly the operating temperatures are between 60-80 °C [35].

A drawback for AFC is its low CO_2 tolerance. Solidifying alkaline carbonates will be formed with occurrence of CO_2 in the electrolyte, resulting in both loss in conductivity and precipitation of carbonate species. Pure hydrogen must be supplied, limiting its applications. Space exploration and submarines are the main applications for which AFC have been successful [31, 36].

AFCs consist of an anode and a cathode immersed in a liquid solution, as seen in Figure 2.7. The aqueous solution usually consist of potassium or sodium hydroxide (KOH/NaOH). At the anode, as seen in Equation 2.1, each molecule of hydrogen (H_2) which reacts with hydroxide ions (OH^-) will release electrons (e^-) and water (H_2O). The electrons are forced through an external circuit, which generates electricity [45].

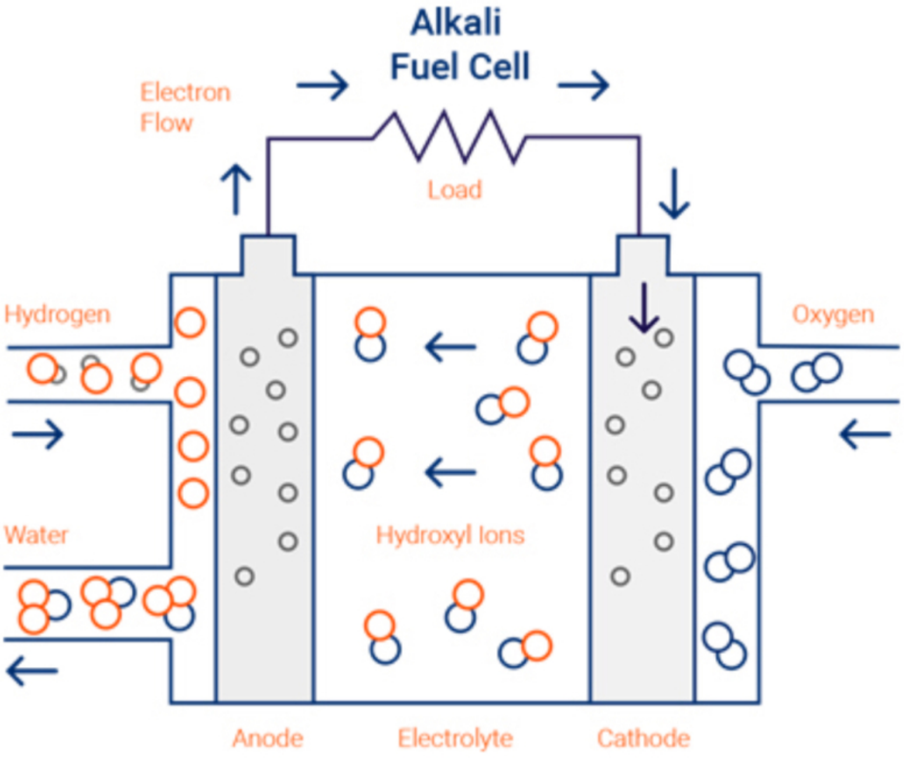

Figure 2.7: *Schematic of a typical AFC [46].*

$$\begin{aligned} 2H_2 + 4OH^- &\longrightarrow 4H_2O + 4e^- && Anode \\ O_2 + 2H_2O + 4e^- &\longrightarrow 4OH^- && Cathode \\ 2H_2 + O_2 &\longrightarrow 2H_2O && Total\,reaction \end{aligned} \tag{2.1}$$

Following, at the cathode side, the electrons migrating from the anode side will react with incoming oxygen (O_2) and water molecules. Hydroxide ions are than formed, and transfer the charges through the electrolyte [45].

Polymer Electrolyte Membrane Fuel Cell

In comparison with other types of FCs, PEMFC produce higher power densities, higher efficiencies, are lighter, more compact, less expensive, and have lower operating temperatures [47]. PEMFCs typically have a efficiency of about 50 %, meaning about half of the input energy is converted to heat. It has a potential to achieve an efficiency of 60 %, and are well-suited for both mobile and stationary applications. For mobile application the PEMFC has a lifetime of 8000 hours [48, 49].

In contrast to AFC, a PEMFC consist of a solid membrane which separates the anode and cathode. The membrane inhere a thin layer of polymeric electrolyte, which conducts protons from the anode to the cathode, explaining why it also can be refereed to as a proton exchange membrane (PEM). Nafion, a polymer made from perfluorosulfonic acid, is commonly used for the membrane. Preferable membrane materials are those that have high ionic conductivity and prevent the transfer of electrons and hydrogen fuel from the cathode and oxygen reactant from the anode [36, 48].

Further, it consist of thin porous layers of the electrodes on each side, making the electrode catalyst layer (CL). The catalyst material often consists of platinum and iridium for the cathode and the anode, respectively. This is where the hydrogen oxidation reaction or oxygen reduction reaction takes place. Hydrogen oxidation results in hydrogen loss, while hydrogen reduction leads to hydrogen gain [48]. Additionally, the reactant gases and electrons are diffused in the gas diffusion layers (GDL). Despite its name, diffusion is not the most important mechanism. The GDL also removes water and prevents flooding inside the cell while keeping some water on the surface for conductivity through the membrane. Together, the PEM, GDL and CL forms the membrane electrode assembly (MEA). The general features are shown in Figure 2.8 [36, 45].

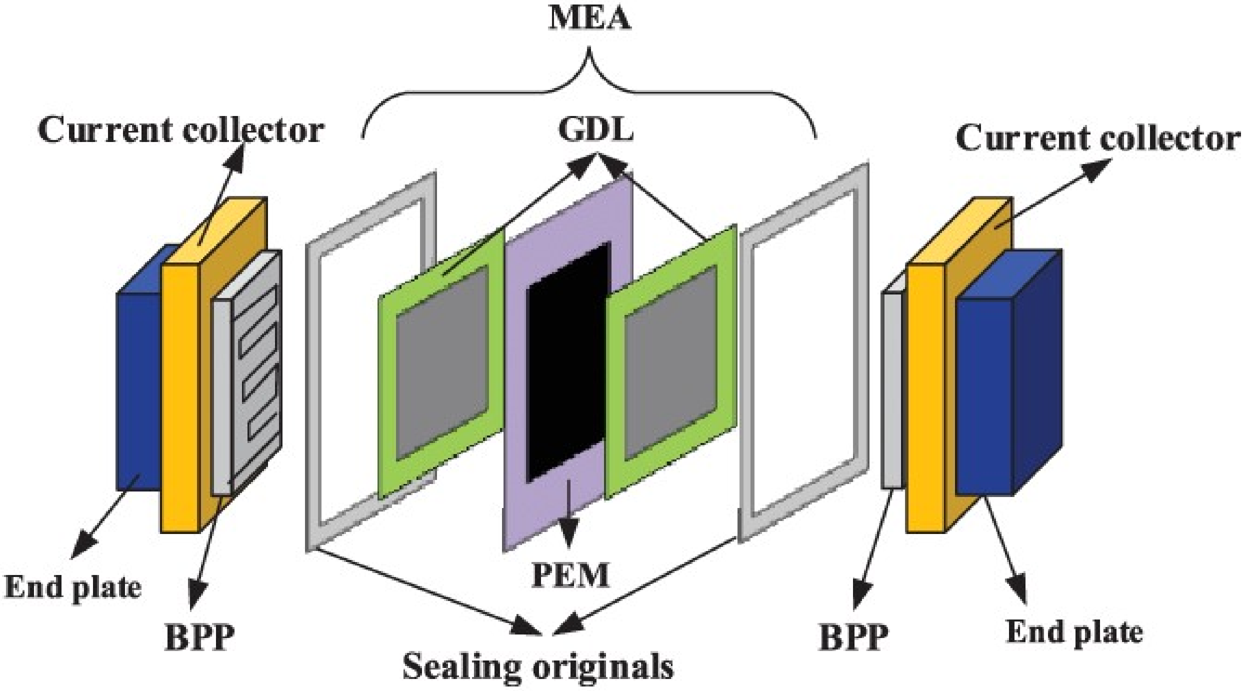

Figure 2.8: *Single layer of PEMFC structure [50].*

Bipolar plates (BPP) can be found at each side of the MEA. Besides providing the physical framework of the FC stack, BPPs also conduct current between the individual cells. The plates also regulate the temperature through cooling channels and uniformly distribute reactant gas by gas channel flow patterns. BPPs are typically constructed from graphite composites in order to prevent corrosion and surface contact resistance. On each side of the BPPs, current collectors are placed. The plates provide corrosion protection and electrical contact through the cell. Futher, end plates are added at each side to provide support and apply compression to the components [47].

In the half-cell reaction shown in Equation 2.2, hydrogen and oxygen are fed into the anode side and the cathode side, respectively. At the anode, hydrogen is oxidised into protons and electrons. Only protons can pass through the membrane to the cathode side. The electrons are forced to follow an external power circuit. As a result, a driving force and cell voltage is generated for the reaction. Water and heat is produced at the cathode when the electrons react with protons and oxygen, as shown in Figure 2.9 [47, 48].

$$\begin{aligned} H_2 &\longrightarrow 2H^+ + 2e^- && Anode \\ \frac{1}{2}O_2 + 2H^+ + 2e^- &\longrightarrow H_2O && Cathode \\ H_2 + \frac{1}{2}O_2 &\longrightarrow H_2O && Total\,reaction \end{aligned} \tag{2.2}$$

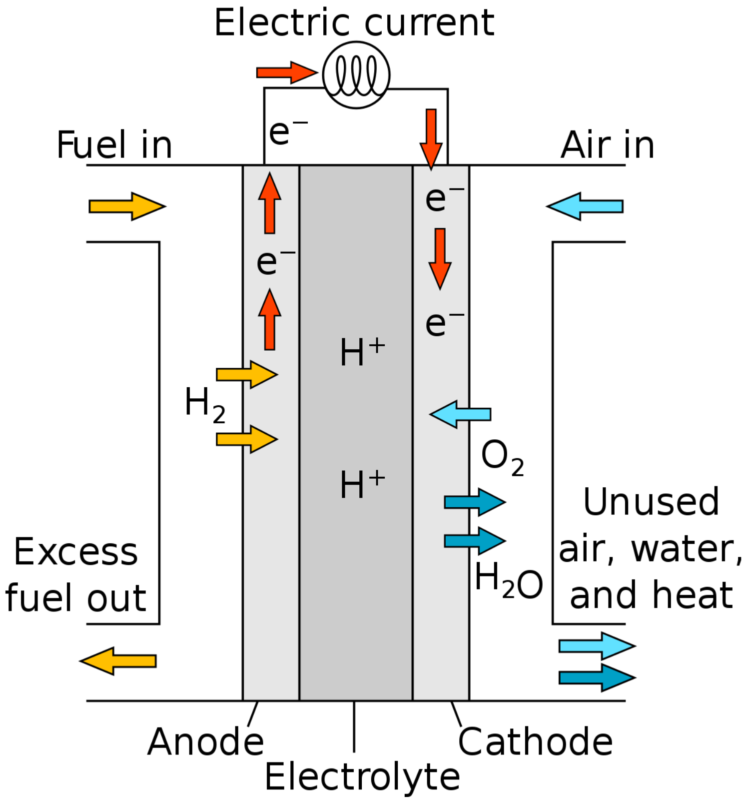

Figure 2.9: *Illustration of a PEMFC [51].*

For the commercialization of PEMFC, high cost has been a barrier. Therefore, reducing platinum-group-metal loading of MEA and maintaining high efficiency has remained a crucial challenge. Further, the catalyst has low tolerance to carbon monoxide and sulfur, limiting its use to hydrogen of high purity. It can however utilize air as oxidant, compared with AFC which require pure oxygen [31, 48].

Solid Oxide Fuel Cell

Solid oxide fuel cell (SOFC) is a high temperature FC. Its operating point is between 700-1000 °C, and the temperature gives it the advantage of higher efficiency compared to other types of fuel cells. It can also be used backwards as a SOEC [31, 52]. The SOFC technology is still under development, but it has great potential due to its high durability, fuel flexibility, high efficiency, low emissions and low operating costs. Unlike PEMFC which require high-purity hydrogen to run, SOFC can operate on multiple fuels including hydrogen, ammonia, LNG, LPG, LOHC and methanol [36, 53]. This makes the FC suiting for maritime use, especially for medium to long distance ship applications [54]. Compared to conventional FCs, SOFCs have the advantage of separating the fuel and oxidant streams by design, allowing for high levels of carbon capture without incurring additional costs [31]. The surplus heat generated can also be used for combined heat and power (CHP) systems. The combination of electric and thermal efficiency can reach over 90 %. However, the biggest disadvantage is the high operating temperature, which results in long startup and break-in times [55].

SOFC contains of an anode and a cathode. As illustrated in Figure 2.10, an solid oxide electrolyte separates the electrodes. To handle the high temperature, the electrolyte is of a oxygen ion-conducting ceramic material [31, 52].

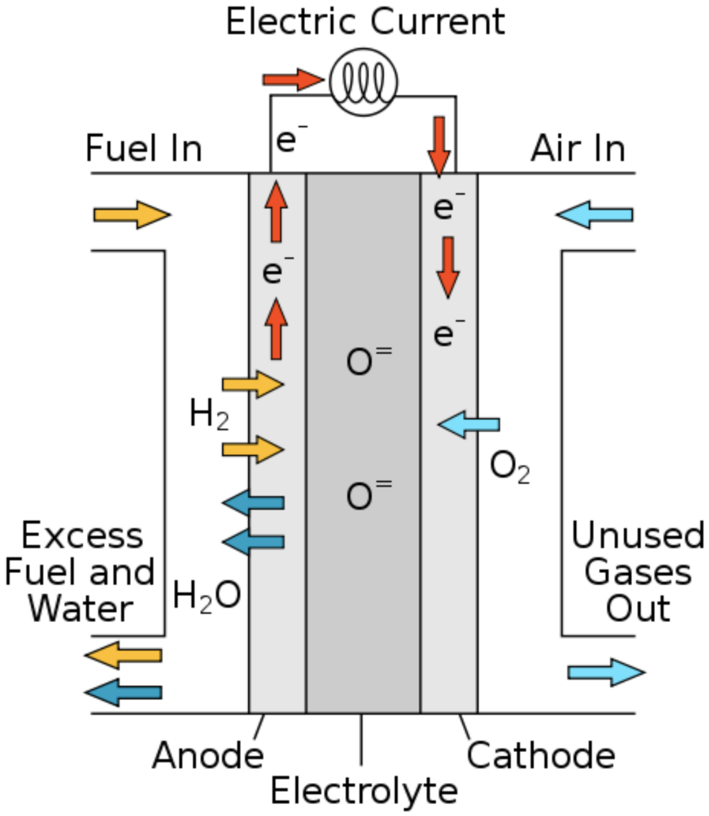

Figure 2.10: *Illustration of the working principles of a SOFC [56].*

As seen from Equation 2.3, fuel oxidation and oxygen reduction happens at the anode and the cathode, respectively. For this case hydrogen is fed to the cell, and usage of different fuel types would alter the half cell reaction at the anode side. Moreover, air is supplied at the cathode and reacts with electrons entering from an external circuit. Oxide ions are formed and migrate through the electrolyte to the anode, where oxide ions combine with hydrogen to form water molecules. In addition, the reaction releases electrons. The electrons flow through the external circuit from the anode to the cathode [42, 55].

$$\begin{aligned}
&H_2 + O^{2-} \longrightarrow H_2O + 2e^- && \qquad Anode \\
&\frac{1}{2}O_2 + 2e^- \longrightarrow O^{2-} && \qquad Cathode \\
&H_2 + \frac{1}{2}O_2 \longrightarrow H_2O && \qquad Total\ reaction
\end{aligned} \tag{2.3}$$

Although, there are still issues associated with the SOFCs reduction of stability and degradation which must be improved before it can be commercialized on a large scale. SOFCs generate a lot of heat from their ohmic electrode overpotential and their reversible heat [52].

2.6.3 Fuel Cell Efficiency

The FC efficiency is influenced on both thermodynamic performance and electrical efficiency. It relies on the ratio between the electricity generated by the FC and the consumed hydrogen as a fuel. Electrical losses can be due to ohmic, activation, and concentration losses, which all goes under polarization. In terms of thermodynamic efficiency, the FC is highly dependent on its variation in temperature [35].

Thermodynamics Basis of Fuel Cells

FCs are a well-known technology to convert chemical energy into electrical energy. A general overall reaction for a fuel cell is given in Equation 2.4.

$$H_2 + \frac{1}{2}O_2 \rightarrow Energy + Heat + H_2O \tag{2.4}$$

The thermodynamics of its electrochemical reactions determine the FCs theoretical efficiency. Because FCs are not constrained by Carnot efficiency, FCs' theoretical efficiency is higher than internal combustion engines [36]. The thermodynamic efficiency is the ratio between ΔG and ΔH, as described in Equation 2.5.

$$Thermodynamic\ Efficiency = \frac{\Delta G}{\Delta H} \tag{2.5}$$

For an electrochemical cell operating reversibly at constant temperature and pressure, Gibbs free energy, ΔG, represent the electrical work available for use. In addition to electrical work, heat is also an outcome of the electrochemical reaction. The total energy composed of both thermal and electrical energy is known as enthalpy, ΔH. This is expressed in Equation 2.6. Irreversible energy, also known as entropy, is denoted as ΔS [57].

$$\Delta H = \Delta G + T\Delta S \tag{2.6}$$

ΔH could either be based on a lower heating value (LHV) or higher heating value (HHV), depending on whether the produced water is gaseous or liquid. Generally, FC efficiency is derived from LHV, which is based on gaseous water. Thus, it can be compared with internal combustion engines, whose efficiency has traditionally been expressed in terms of LHV [57].

Irreversible heat results from irreversibility of the electrochemical reactions in the FC. This could come from inherent resistance of the components, such as ohmic resistance in the electrolyte, electrodes and BPP. Further, entropic heat could be generated from condensation and evaporation of water within the membrane and GDL [47]. The cathode CL contributes to large heat generation, resulting in why the most severe water and heat management problems occur here. Further research and improvement of water and heat management of the FC could lead to better efficiency [35, 47].

Polarization

Thermodynamics can be used to determine the maximum voltage that a FC can theoretically produce at a specific temperature and pressure. Given the Gibbs potential of $\Delta G_f = -229$ kJ/mol for water at LHV standard conditions, the reversible voltage, E_{rev}, is derived in Equation 2.7. In this context n represent the number of electrons taking part in the reaction, while F denote Faraday's constant [57].

$$\Delta G = -nFE_{rev} \rightarrow E_{rev} = -\frac{\Delta G}{nF} = 1.18\ V \tag{2.7}$$

It is theoretically possible to operate a hydrogen FC at 1.18 V. However, the actual voltage output is always less than the ideal voltage. The actual voltages are closer to 0.6-0.7 V. For a FC based on LHV, the electrical performance in the cell can be determined by Equation 2.8. V_a is the actual voltage, and 1.18 V represent the theoretical voltage [57].

$$Voltage\ Efficiency = \frac{V_a}{1.18\ V} \tag{2.8}$$

In electrochemistry, polarization is a collective term for certain mechanical side effects caused by the development of barrier systems at the interface between electrode and electrolyte [37]. Polarization can as well be seen as the kinetic deviation from equilibrium because of an electric current flowing through a cell. It is most common for the polarization to occur at the cathode, but it can also appear at the anode side [37].

The polarization curve, also known as a i-V curve, is derived from three types of losses in the FC: activation polarization, ohmic, and mass transport polarization losses. The polarization curve of a typical PEMFC can be seen in Figure 2.11. At low current densities there is a rapid drop in output voltage. As a result of oxygen reduction reactions, activation losses occur, which describe the activation polarization region. The following region has a linear voltage drop caused by the ions flowing inside the electrolyte. This is referred to as the ohmic polarization region. The last region is related to concentration polarization losses. The reactant gas is transported through the CLs during higher current densities. As result, the voltage sudden drops [35, 37].

Since both the rapid initial voltage drop during startup and the increase in current can be avoided, the FC operates best in the ohmic polarization region. Although polarization cannot be eliminated, material choice and electrode designs can contribute to its minimization [35].

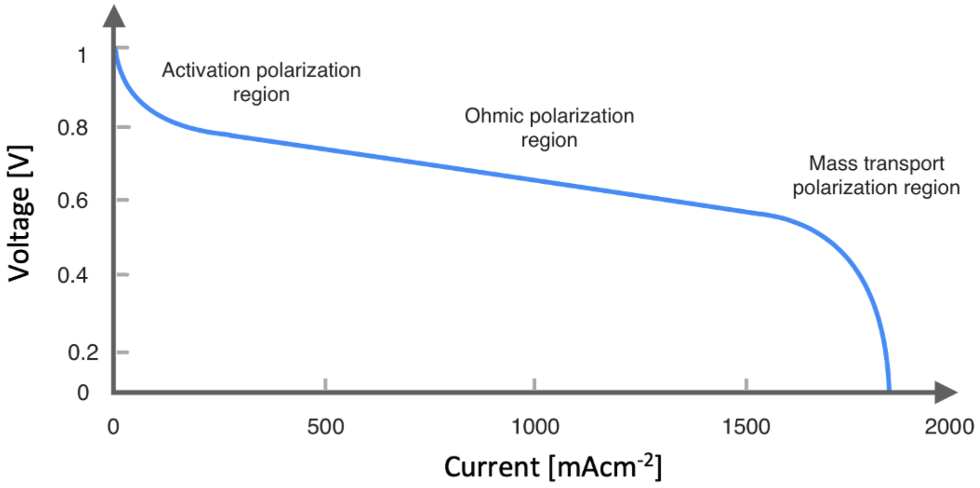

Figure 2.11: *A typical polarization curve for a PEMFC.*

Polarization and power density curve

By multiplying the voltage at each point on the i-V curve by the corresponding current density, the power density curve is constructed, as seen in Figure 2.12. A FCs power output and fuel efficiency are determined by the external load that is applied to it. Maximum power density and fuel efficiency can not be achieved simultaneously. When the external load is equal to the internal resistance of the FC system, the power performance curve peaks. Fuel efficiency increases as the ratio of the external load to the internal resistance increases, but total power output decreases. Thus, there is always a trade-off between power and efficiency [58]. A FC with a larger effective area of the MEA can draw a more substantial amount of total current, hence why a larger FC system can be an alternative for better performances [59].

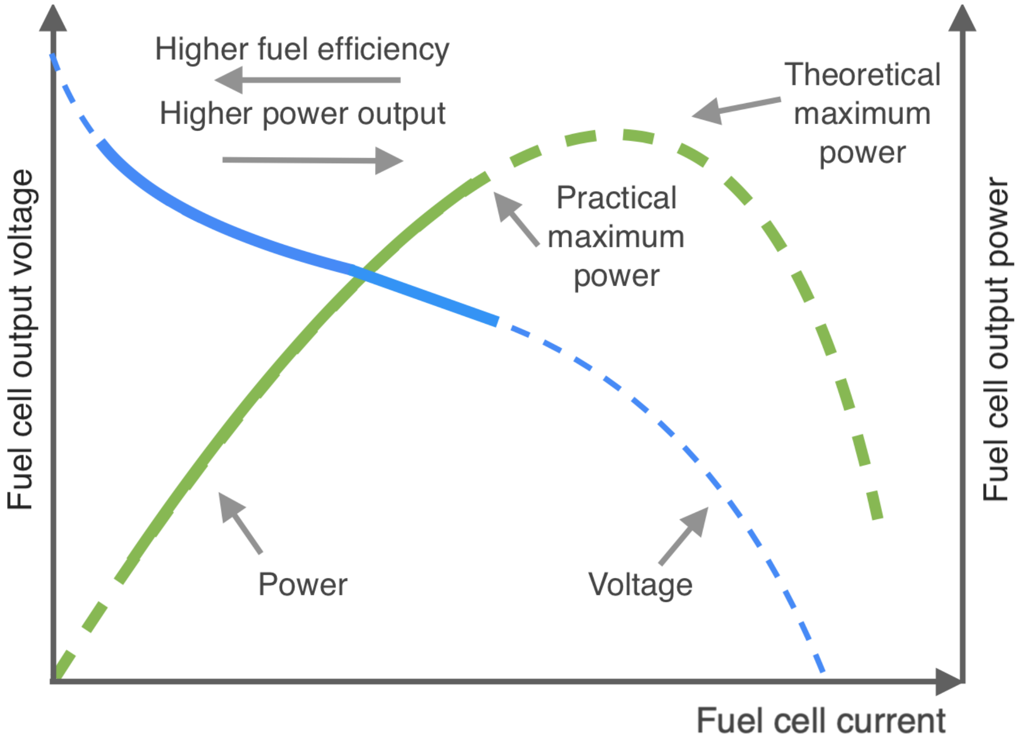

Figure 2.12: *A typical polarization and power density curve for a PEMFC. Modified from [60].*

Fuel cell starvation

FC starvation is one of the main causes of the PEMFC lifetime decay, which leads to several consequences such as carbon support corrosion, cell reversal and output performance degradation [61]. This will damage the the membrane electrode assembly in an irreversible way, which will damage the whole FC and cause breakdown [40, 62].

Roughly half of the energy produced by the electrochemical reactions in PEMFC power generation is heat. Thermal management plays a crucial role in prolonging its service lifetime and performance and is worthy of more attention. Maintaining an optimum electrochemical reaction demands control of operating stack temperatures. The reaction rate, evaporation, and condensation of water in the cell can depreciate. The FC system performs better at higher temperatures due to faster electrochemical reactions. However, too high temperatures can degrade the membrane in the form of dehydration, shrinking, wrinkles or ruptures. This causes higher ohmic resistance, followed by a lower output voltage. Furthermore, harmed membranes can also lead to flooding of the electrodes, where degradation of the FC is a consequence. Hence, an efficient thermal management subsystem is of great importance to maintain a uniform temperature distribution throughout the stack [35, 59].

2.7 Hydrogen Production

Hydrogen can not be found in a pure form on earth, it has to be separated from other molecules. There are two common methods for this process; steam reforming and electrolysis. Based on the production technique, hydrogen can be categorised as grey, blue or green. Currently hydrogen production is highly carbon-intensive, and about 96 % of global hydrogen production is based on fossil fuels. Steam reforming is mainly used, and this production runs on natural gas, oil and coal. The outcome is categorized as grey hydrogen, and is currently the cheapest type of hydrogen [63, 64].

Similar to grey hydrogen, production of blue hydrogen also include steam reforming and use of fossil fuels. However, blue hydrogen in principle has no emissions due to carbon capture and storage (CCS). In the production process CO_2 gets separated, transported and stored, and the outcome is clean hydrogen. Currently this method is more expensive than producing grey hydrogen because of high cost of CCS systems, but a technology development will likely cause the price to decrease [63]. Green hydrogen is a result of using water electrolysis powered by renewable energy. About 4 % of hydrogen used globally is classified as green [51]. With electrolysis, electricity and water is the input, and hydrogen and oxygen is the output [65].

2.7.1 Hydrogen production in Norway

According to a report from the classification society DNV, the hydrogen demand in the maritime sector will be 7 % in 2030 [31]. In addition to the ZeroKyst project, there are several initiatives in Norway to meet this need.

Recently the Norwegian hydrogen electrolysis company Nel opened a large scale hydrogen production at Herøya. With fully automated electrolyser production facilities, it is first of its kind worldwide. Currently the alkaline electrolysis plant can deliver 500 MW yearly, but a scale up to 2 GW is within reach with additionally investment. A goal for Nel is to deliver green hydrogen at 1.5 USD/kg [66].

An other example is the collaboration between Greenstat and Everfuel, planning a hydrogen production plant with a 20 MW electrolyser producing around 8 tonnes of green hydrogen each day. An expansion to a 60 MW production system within 2027 is planned. The plant location in Kristiansand makes it suitable for both maritime and land-based transport supplies. Moreover, the bi-products of hydrogen production, heat and oxygen, could also be utilized by local companies to ensure efficient energy use in all value streams [67].

2.7.2 Type of Water Electrolysis

A way to produce hydrogen is to use electricity to split water into hydrogen and oxygen. The only inputs are electrical energy and water, as shown in Equation 2.9. Electricity is applied for the chemical reaction to occur. Granted that the electricity comes from a renewable source, the hydrogen can be labeled as green hydrogen. The outcome deliverers high purity gas of H_2 and O_2. The by-product O_2 can be used in several processes which requires high purity O_2.

$$Energy + H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{2.9}$$

There are two common ways of operating electrolysis; alkaline water electrolysis (AWE) and polymer electrolyte membrane water electrolysis (PEMWE). These are often refereed to as low-temperature electrolysis. A lot of research has also been done on the possibility to use high temperature electrolysis, a so called solid oxide electrolyzer cell (SOEC). With minimal alterations, both PEM and SOEC can be used in reverse as a FC. A comparisons of different types of electrolyzers are given in Table 2.2.

Table 2.2: *Comparison of electrolysis technology*

	AWE	PEMWE	SOEC	Source
Maturity	Mature	Commercial	Demonstration	[63]
Lifetime [thousand hours]	60	50-80	<20	[63]
Temperature [°C]	70-90	50-80	700-950	[63]
Efficiency [%]	63-70	56-67	90 [1]	[31, 68]

[1] With a CHP system applied

Generally, the working principles of water electrolysis is very similar to that of a FC, with the exception of the reversed polarity and directions of every reaction. In this respect, the working principles are given in Section 2.6.2.

Alkaline Water Electrolysis

AWE is a relative mature technology, and has been around for about 100 years. The energy company Norsk Hydro started using it in the 1920's. The technology is cheapest in terms of investments compared to alternative electrolysis. This is mainly because of avoidance of precious materials [31, 45].

Like AFC, the core of the AWE system consists of an anode and cathode submerged in an alkaline solution. This system works in a similar but reverse way to AFC, as seen in Figure 2.13. The hydroxide ions move through a diaphragm to the anode side [51, 69]. As well as separating the electrodes, the diaphragms main function is to prevent mixture of the hydrogen and oxygen gases. It also functions as transport of water and hydroxyl ions between the anode and cathode. For a long time asbestos was used as the porous diaphragm. Due to toxicity and possibility of lung cancer, it was replaced by polymer-based composite materials. The diaphragm can also be a porous sintered material of for example sintered alumina, porcelain, glass or concrete [69].

There are some disadvantages with AWE. It can only operate with low pressure and high cell voltages. It also has low current density, which makes it sensitive to swift fluctuations in input power from for example wind power. A consequence could be a transfer of gas molecules through the diaphragm [69].

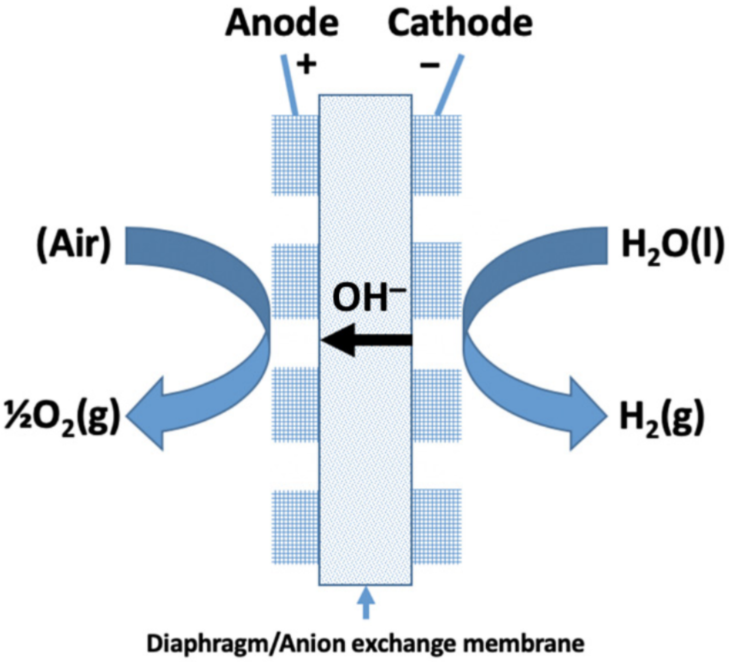

Figure 2.13: *Scheme of an AWE [45].*

Proton Exchange Membrane Water Electrolysis

PEMWE is a common method for electrolysis, and has been around since the 1960's. Alkaline and PEM electrolysis have approximately the same operating temperature, but today PEM electrolysis has a slightly lower energy efficiency. However, PEMWE may have a greater potential for increasing efficiency and reducing costs than alkaline electrolysis. An improvement to an efficiency of 62-74 % is predicted within 2030 [31]. The system requires high-purity water as input, but the result is hydrogen gas of high purity. In addition, PEMWE is a preferred process over AWE because of its flexibility concerning running with low-electrical input. This favors utilization with renewable energy networks [45].

Solid Oxide Electrolyzer Cell

SOEC is similar to the technology of SOFC. However, their operation as an electrolyzer adds some specific challenges concerning the materials used. An example of this is corrosion at the anode caused by oxygen evolution due to high operating temperatures. The degradation process can be further accelerated by corrosion of structural components. A highly corrosive environment, mechanical constraints, and thermal constraints are responsible for most performance losses, and further research and development are required [45].

2.8 Hydrogen Storage

The storage of hydrogen can be challenging because of the low volumetric density. There are strict requirements for material selection and design of storage tanks. Hydrogen can be stored compressed, liquefied or bonded to other elements [70].

2.8.1 Compressed hydrogen

Compressed hydrogen can be stored in tanks at different pressures. For small amounts of hydrogen, less than 100 kg, compressed hydrogen is generally considered the best way to store it. Compressed hydrogen is often pressurized to 250-700 bar. The compression increases the volumetric energy density, but increasing pressure has a consequence of higher energy losses [15].

To do simplified calculations of the volume of hydrogen at a specific pressure and temperature, the ideal gas law can be used. Even though, hydrogen is not ideal. The ideal gas law is shown in Equation 2.10 [71].

$$pV_N = n_m RT \tag{2.10}$$

Pressure is p, volume is V_N, number of moles is n, R is the molar gas constant and T is temperature. The value of the gas constant varies with the unit for pressure. When the unit for pressure is bar, volume is liter, and temperature is in kelvin, the molar gas constant is 0.083144 $\frac{L \cdot bar}{mol \cdot K}$ [71]. To use the ideal gas law, the number of moles is necessary. This is possible to calculate with Equation 2.11, where M is molar mass and m is mass.

$$n_m = \frac{m}{M} \tag{2.11}$$

2.8.2 Liquid hydrogen

Liquid hydrogen has higher energy density than compressed hydrogen. To get liquid hydrogen, the gas needs to be cooled down to under the evaporation pressure, $\sim$-253 °C. Compared with compressed hydrogen, cooling requires 25-35 % of the original energy content. Liquid hydrogen can achieve 2360 $\mathrm{kWh/m^3}$. For comparison, compressed hydrogen at 700 bar contains 1400 $\mathrm{kWh/m^3}$ [70]. Due to the large energy losses in the cooling process of hydrogen, liquid hydrogen is more advantageous for large-scale production. Liquefaction plants are complex and expensive, and this increases the selling price for costumers. Liquid hydrogen as energy carrier is currently most relevant for large ships, such as ferries [15].

2.8.3 Ammonia

Ammonia is an energy carrier considered suitable for the maritime sector. Due to high energy density it allows longer sailing distance, making it more suitable for cargo vessels and supply ships. Ammonia is commonly used in agriculture as a fertilizer. Like hydrogen, ammonia is categorized into different colors; brown, blue or green [72]. The chemical formula of ammonia is NH_3. Compared to liquid hydrogen, it contains approximately 50 % more energy per m^3 at 25 °C and 10 bar pressure. Challenges with ammonia are that it is toxic, has extra investment costs and reduced energy efficiency [70]. As more vessels are planned with hydrogen, the construction of more ships to be operated on ammonia is also planned. Currently the offshore supply ship *Viking Energy* is being reconstructed. *Viking Energy* was the worlds first LNG supply vessel, as seen in Figure 2.14, and now it will be the first ammonia supply ship [21].

Figure 2.14: *The worlds first LNG supply ship Viking Energy now being rebuilt into the worlds first ammonia supply ship [73].*

2.9 Health, safety and environment with hydrogen

Hydrogen as a fuel has to be handled with more care than diesel. The knowledge of risk and safety of using hydrogen may not be the same as with conventional fuel. Hydrogen gas has some safety-related properties and behaviors that must be taken into account when used as an energy carrier. This is such as hydrogen's low density, low ignition energy, wide flammability range and the potential to self-ignite. Additionally, hydrogen is an odorless gas, and it can be difficult to detect a leakage [74].

The combination of hydrogen's properties creates challenges for use as fuel for propulsion in fishing vessels. The use of hydrogen in the maritime sector has a promising potential, but needs a better and wider safety system than other gas fuels. Since the regulations and rules for hydrogen storage on vessels are incomplete, there are still some uncertainties on the safest solutions [70].

2.9.1 Transfer from land-based to maritime

Experiences from accidents with hydrogen in land-based vehicles, space industry and submarines can help with safely storing and fuelling ships. An example is the explosion in hydrogen tanks at Uno-x in Sandvika in 2019. The explosion was caused by a leakage due to a mounting error. A gas cloud built up and eventually exploded. The explosion resulted in minor human injuries, while the hydrogen industry learned from the incident. The main challenge is to make it more suitable for the maritime environment and utilization. However, the solutions from land-based industries can not directly be transferred to fishing vessels. There are other safety features that need to be adapted. A fishing vessel out in the field is mostly self-reliant and can not easily find help if an accident occurs. There is not any safe places to escape from a vessel as from a vehicle with hydrogen [74].

2.9.2 Storage

Hydrogen is stored in cylindrical tanks of steel, fiberglass or composite materials [70]. With storage in high-pressure tanks, there are some risks of leakage. Because of the small molecules, the leak does not need to be very large for the danger of explosion to increase significantly. In respect to today's regulations for a vessels, the high-pressure tanks must be stored in the open, above deck, to minimize the danger of a potential leakage. Leakage within confined walls can build up the gas and increase the severity of an explosion. However, when tanks are stored above deck, the detecting of a gas leaks can be more difficult. The hydrogen tanks are also more exposed to sea weather and damage from the outside. In the event of a leakage in closed room, sufficient ventilation is necessary. This can prevent congestion of gas and a possible explosion [74].

2.9.3 Bunkering

Bunkering of hydrogen is a critical process where the chances of leakage is increased. Unlike conventional fuel, hydrogen needs a larger safety zone while bunkering. Bunkering facilities at sites should be placed where the distance to housing and buildings is safe in relation to a possible explosion. SINTEF has done a quantitative risk analysis of safety zones for bunkering at different harbors in northern Norway. This is made in accordance with the regulations for major accidents (Storulykkesforskriftene), which is intended to limit the consequences of major accidents where hazardous chemicals occur. Among the harbors in SINTEF's analysis are Ramberg and Fredvang, which both are located in Flakstad municipality [15].

Figure 2.15 shows the safety evaluation at Ramberg harbor, and Figure 2.16 shows the safety evaluation at Fredvang harbor. The cross in the middle of the circles represent a vessel at the bunkering facility. The red circle represent the inner zone. This area should only have short-time passing, such as hiking paths. The yellow circle is the middle zone and has fewer regulations. This zone may contain public road, railway and quay, but should not have accommodation or housing. The green circle is the outer zone, which can be used by the general population, including stores and smaller accommodations. The exact size of the safety zones is dependent of many thing, including the storage volume of hydrogen. From this analysis, the safety zones for hydrogen bunkering facilities in Ramberg and Fredvang is affordable [15].

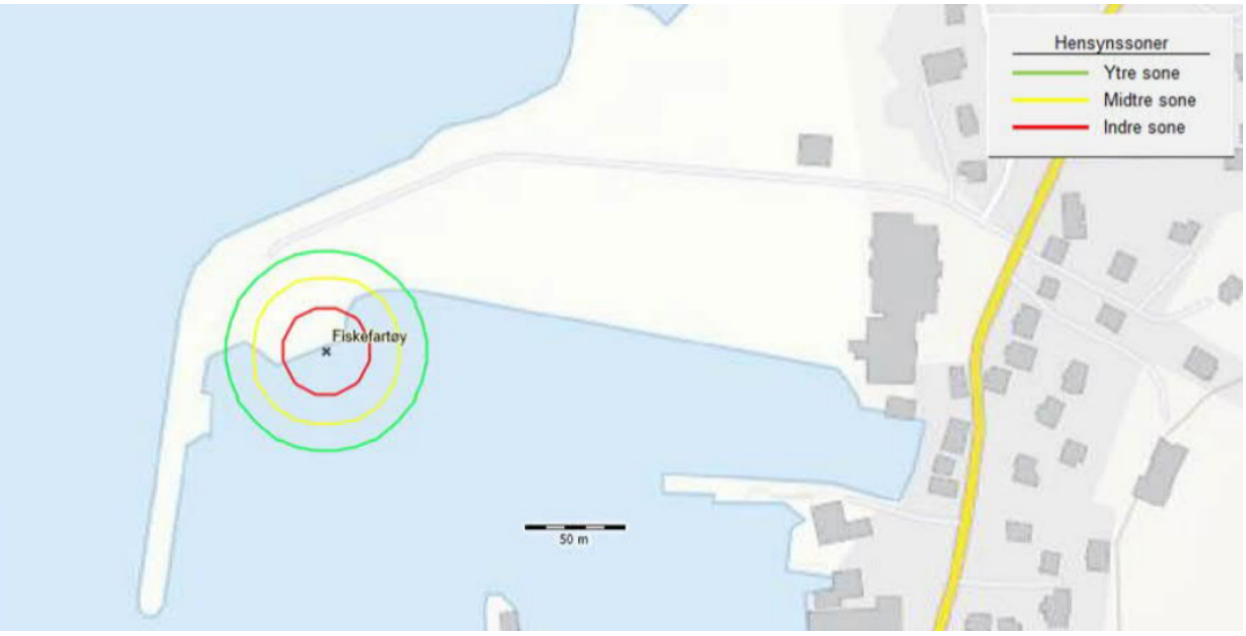

Figure 2.15: *Safety zones for hydrogen bunkering in Ramberg [15].*

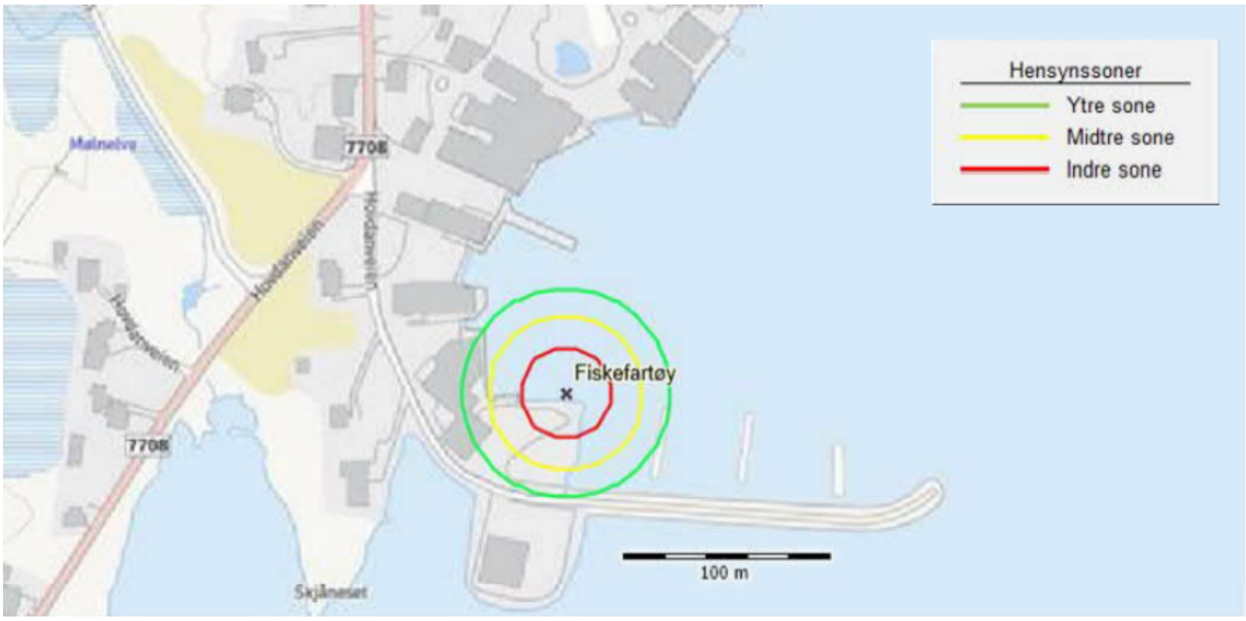

Figure 2.16: *Safety zones for hydrogen bunkering in Fredvang. Figure modified from [15].*

2.10 Lithium-ion batteries

Lithium-ion batteries (LIB) have a combination of high energy and power density. These properties make LIB widely used in portable electronic appliances, power tools, and electric vehicles (EV). The transport sector benefits from LIBs with high energy and power density because of the space limitation. LIBs can be part of the reduction of GHG emissions if it is charged with energy from renewable energy sources [75].

LIBs consist of four main components; anode, cathode, electrolyte and separator. Figure 2.17 illustrates how the LIB works with the four components. The anode is often based on carbon material, which is easily oxidized. Oxidation with respect of electrons means that the material emits electrons. The cathode is made of metal oxide, which easily absorb electrons. When a material receive electrons, it is called reduction of electrons. In a battery, the oxidation and the reduction happens simultaneously [76].

The separator is made of a porous material, and is the only inactive component of the LIB cell. It separates the anode from the cathode to prevent an internal short circuit, and provides a path for the ions to move through the liquid electrolyte. The electrolyte varies from the type of battery, but has the same properties; to transport ions between the anode and cathode [36, 77].

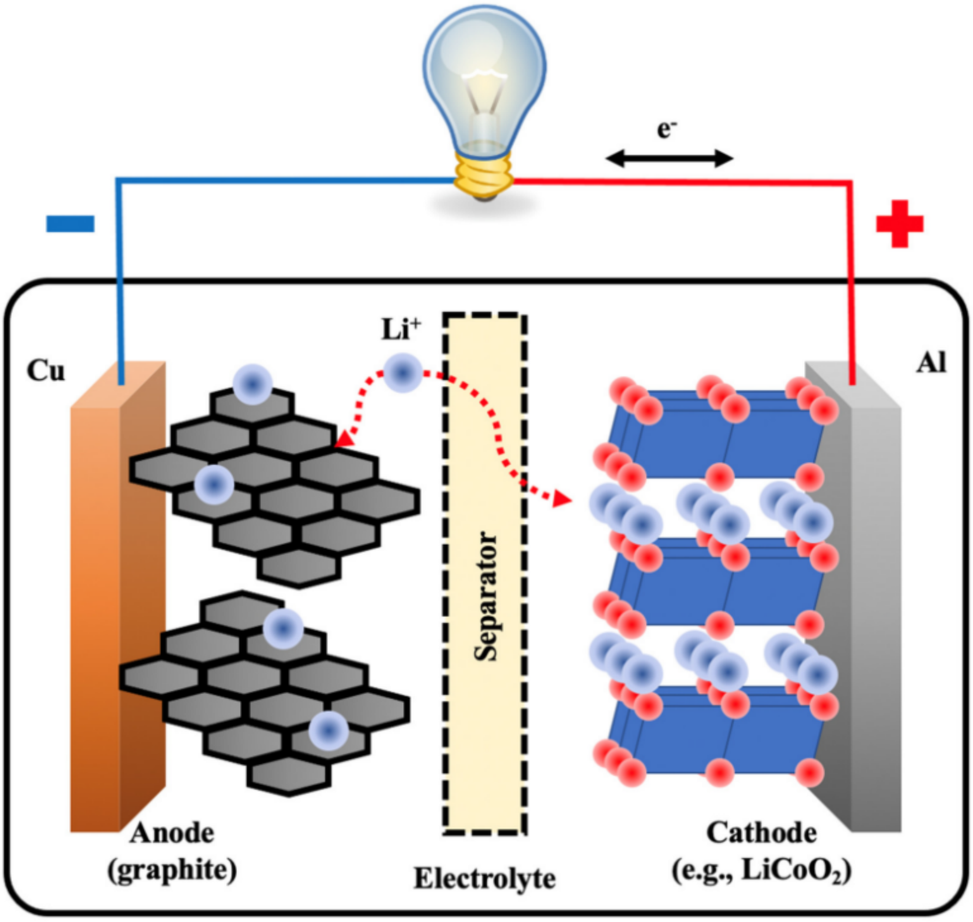

Figure 2.17: *Illustration of how a LIB work. Electrons are moving through an external circuit from anode to cathode while discharged, and from cathode to anode while charged [78].*

When the battery is connected to a load and discharged, the electrons move from the anode side to the cathode side through a outer circuit. At the same time, ions moves through the electrolyte from the negative electrode to the positive electrode [76]. When the battery is charged, electric load is connected and forces the electrons from the cathode side and back to the negative anode. While charging the lithium ions moves through the separator.

Equation 2.12 is the chemical reaction of a lithium nickel manganese cobalt oxide (NMC) battery. This battery uses graphite (C_6) as anode material and $NiMnCoO_2$ as cathode material. The chemical reaction in Equation 2.12 shows how the anode emits the electrons, and the cathode receives the electrons [79].

$$\begin{aligned} LiC_6 &\longleftrightarrow C_6 + Li^+ + e^- && Anode \\ NiMnCoO_2 + Li^+ + e^- &\longleftrightarrow LiNiMnCoO_2 && Cathode \\ LiCoO2 + C_6 &\longleftrightarrow LiC_6 + CoO_2 && Total\ reaction \end{aligned} \tag{2.12}$$

2.10.1 Production

The production of LIBs requires extraction of minerals and large amounts of energy, leading to large emission and acidification to the surrounding environment. What matters most is whether it is green electricity that charges the battery. With renewable energy, LIBs can be categorized as a green energy storage system [36].

2.10.2 State of Charge

State of Charge (SoC) indicates the charge level of a battery. One full cycle is charging from 0 % SoC to 100 % SoC. The C-rate is a measure of the rate at which a battery is charged and discharged. For example, 1 C is equivalent to charging one full cycle in one hour. If a battery uses half an hour charging one full cycle, it is 2 C. This is the same for a battery charging from 30 % SoC to 80 % SoC in 15 minutes. Figure 2.18 illustrate the SoC for a LIB [36].

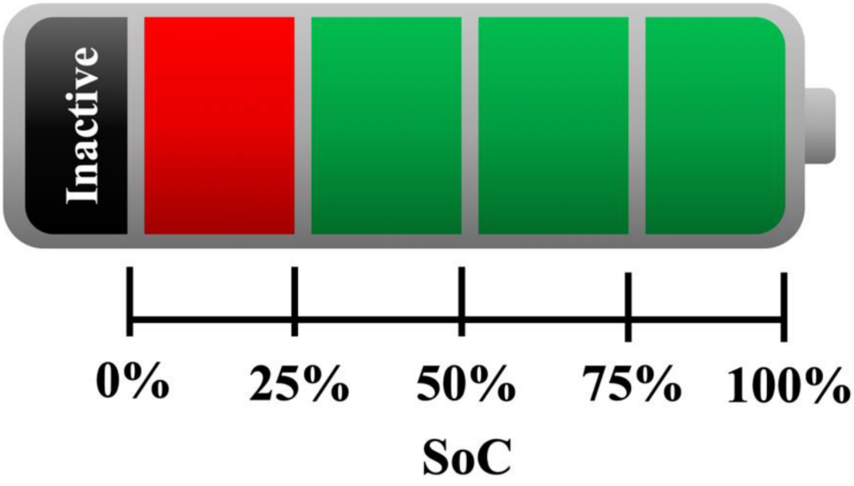

Figure 2.18: *Illustration status for SoC in a battery [80].*

For a LIB, it is recommended to never discharge under 20 % SoC and never charge over 90 % SoC. This SoC window only utilizes 70 % of the available energy. However, by doing this, the factors related to aging are affected. Batteries can only undergo several charging cycles before the capacity decreases considerably. The LIB can therefore be used longer if the SoC window is respected [36].

2.10.3 State of Health

State of Health (SoH) is a measure of how much capacity the battery have lost. To maintain the SoH of a battery for as long as possible it is beneficial not to exceed or fall below the recommended SoC [36].

Degradation of LIBs is the same as aging, and this happens for various reasons. Battery ageing can be dissociated into two parts, calendar ageing and cycle ageing. Each term defines the consequences due to different uses of the battery. The calendar ageing corresponds to the phenomena and the consequences of battery storage over periods of time. Cycle ageing is associated with charging and discharging. It is a direct consequence related to how the battery is used in addition to external factors. Ageing during cycle and calendaring is both affected by temperature and SoC [81].

2.10.4 Charging

The optimal LIB. The charging stages are shown in Figure 2.19. Stage 1 starts with a constant current, while the voltage rises quickly. At Stage 2, the voltage peaks, the current decreases and constant voltage starts. The capacity increases until the battery is fully charged. At Stage 3 the battery is fully charged and the voltage drops. Some chargers add a topping charge as Stage 4. LIB's can not absorb overcharge, and this can cause instability and increase stress on the battery [82].

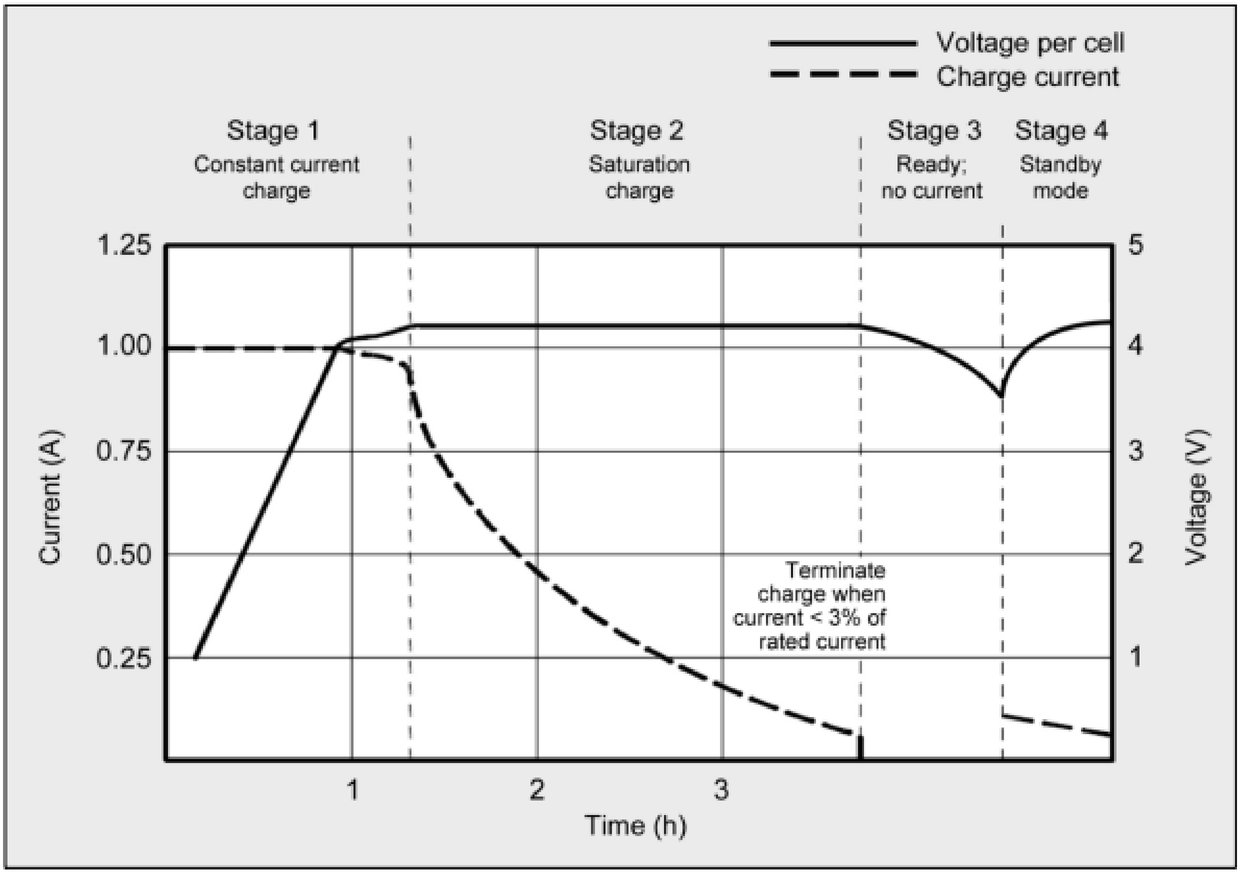

Figure 2.19: *Four charge stages of LIB [82].*

The charging time for EVs can be a large limitation compared to fossil fuel driven vehicles, where filling only takes minutes. This has made the development of fast charging an important part of making electricity driven propulsion more competitive. Fast charging a LIB can be very practical, but has some disadvantages. Increased stress on the battery can happen when rapidly fast charged. Stress and frequent use accelerated the ageing process. Fast charger is also affected by temperature. Low temperatures slow chemical reactions, as a result, charging takes longer [83].

Charging capabilities are important for hybrid fishing vessels. Power access is not always adequate at some ports, which makes simultaneous charging of large battery packs untenable. Small fishing vessels can charge like an EV with AC power. This only provides around 10 kW but requires a low investment. In the case of large fishing vessels, their energy requirements tend to be higher and they may need several days to recharge with this charger. Consequently, fast charging with DC power is often necessary. In addition, to relieve the power grid of the new loads, a buffer battery can be used on the quay. This battery can be continuously charged from the power grid and quickly discharged when necessary [15].

2.10.5 Maritime use

For electric and hybrid vessels, LIBs are most commonly used batteries. It is used in an increasing amount of vessels which are including batteries in the propulsion system. Vessels have a limited storage space, and therefore, it is advantageous to use a battery with high energy and power density. The fast development of the LIB technology and the decreasing costs makes LIBs a good energy carrier for vessels [84].

There are several reasons why batteries can not cover the entire energy demands of hybrid fishing vessels. Batteries range high in price, and increase the investment cost of the fishing vessel. In addition, they are large and heavy, which takes up load capacity, increases energy requirements and reduces buoyancy. On short distances, such as over a fjord where a ferry is running, battery propulsion is possible. However, when vessels have a longer sailing distance, as a fishing vessel often has, other energy carriers might be needed in addition. Fishing vessel needs to have storage space for the catch, and therefore large battery packs could be disadvantageous [15].

2.10.6 Health, Safety and Environment

For larger battery systems, extensive cooling is required to avoid overheating. Overheating and hot spots should be avoided to preserve the batteries lifetime and for safety reasons. Ships and vessels need a more comprehensive battery pack than electric vehicles. With this comes more safety challenges and risks to be aware of [85].

For developing LIBs, one of the most important challenges is to maintain its original stability under normal and irregular circumstances. High temperature increase can cause cell damage and lead to combustion or worst case an explosion. To avoid excess heat, from charge/discharge or related to a short circuit, it is essential to operate the battery during a healthy operating range. This is affected by the voltage, temperature, and current [78].

Thermal runaway may appear under misuse or inadequate cooling, leading to flames or explosions. When the cell has achieved a self-heating rate that is larger than or equal to the cooling rate, the reaction becomes exothermic. From this point, the temperature rises quickly and the reaction can propagate to other cells. In this case the reaction can be challenging to stop. Fishing vessels has variation in operating conditions, as the weather and workday varies. It can be demanding for batteries to handle significant temperature changes [78, 86].

3 Methodology

This Chapter presents the methods used to achieve the results that is presented in the thesis. This thesis aims to investigate whether a hydrogen-electric fishing vessel can be competitive with existing technology. If new technology is to be introduced, it must be competitive in terms of operating costs, range and safety. To estimate fuel consumption under different operating conditions, simulations in Simulink MATLAB were used. Further, to calculate the operating costs, calculations in Microsoft EXCEL were done. For additional necessary information to conduct the survey, it was searched in the literature, in addition to information from the industrial supervisor and their partners.

An already pre-made simulation model is used in the simulations. However, due to confidentiality, the simulation could not be performed with the battery model or FC efficiency from the supplier in of the actual vessel. Therefore, this had to be re-programmed. For the simulation and calculations of the hydrogen-electric vessel, it is assumed a 12 hours working profile. The fishers in Lofoten usually operate with a workday longer than 12 hours. Therefore, such operating profile is not entirely realistic, but gives a minimum requirement for what the emission-free propulsion system must be able to deliver. In addition, it is investigated what the energy requirement could be for an operating profile such as corresponds to how fishing in Lofoten is actually carried out [15].

3.1 Simulation

The software used to perform the simulation in this thesis is MATLAB and Simulink. MATLAB is a programming and numeric computing platform. The version 2019b was used, and the MATLAB script can be found in Appendix A.

3.1.1 Simulink

Simulink is a MATLAB-based graphical programming environment for modeling, simulating and analyzing multidomain dynamical systems. Simulink makes it possible to simulate systems before moving to hardware. This program makes it possible to create models without writing code. In this project Simulink is used to simulate fuel consumption, and how much fuel must be bunkered for the vessel to be able to operate in the fishing field for an entire workday [87].

3.1.2 Model

The industrial supervisor for this bachelor at Siemens Energy provided a simulation model in Simulink. This model is made to simulate the driveline of the hydrogen-electric fishing vessel. The simulation model shows the energy consumption of hotel load, energy consumption from the battery and hydrogen tank, the work of the FC, and when energy is pulled from the battery. The model makes it possible to get an estimation on how much energy the vessel will consume under different types of fishery during a 12-hour working day. The purpose of the simulation model is to simulate the progress of the fishing vessel and how much energy the vessel requires from the battery and hydrogen, and when it will be necessary to turn on the generator.

3.2 Operating profile

Several different scenarios are simulated and analyzed to determine whether this vessel can replace and be competitive with traditional fishing vessels. The challenge with the simulation is that it is difficult to find data on the daily diesel consumption of a fishing vessel. It is easy to access the information of the yearly fuel consumption of a fishing vessel, but not the fisher's active working days. When the fisher bunker with fuel, they tops the tank, and there can be many factors that make them use as much fuel as they does each day. Therefore, several assumptions have been made.

3.2.1 Assumptions

The simulation has a 12-hour operating profile. However, the final hour of the work day, the vessel is connected to a charger at port. It is assumed that the work day last for 12 hours but the vessel returns to port after 11 hours. The final hour is assumed to be cleaning after the day, in addition to preparation for the next work day.

It is challenging to find exact figures on fuel consumption. Therefore, a number of assumptions have been made to examine different operating patterns. The same fuel consumption is assumed every day. In addition, the number of days in port is assumed to be the same for all operating profiles. Fuel consumption varies with the weather, but this is difficult to calculate it is not known how much fuel the fishing vessel consumes on a daily basis. Also, it varies every year how many days the vessel is at port. The group assumed that an average fishing vessel is operating 200 days a year.

No fishing vessel has the exact same fuel consumption. Therefore, the main challenge is to assume realistic values and data on energy consumption for the simulation of the vessel. Because of this, the consumption that has been reported to GFF, which is an administrative body under the Ministry of Trade and Industry, is taken into consideration when creating the operating profiles.

Further assumtions

- Every simulation uses the same amount of time to get to the fishing field.
- The simulation do not account for charging and/or bunkering at the fishery.
- The simulation model does not include a diesel generator as the actual vessel will have.
- The vessel is connected to the charger when it returns to port.
- Net fishing and pulling crab pots has the same load.
- Bow thrusters are included parameters for them in the MATLAB code, but they are constantly set to zero because it assumes that they do not consume a significant amount of energy. It also depend a lot on the sailing conditions, such as weather, how much the fisherman uses the thrusters. Therefore they are neglected in the simulation.

3.2.2 Profiles

- **Case 1: Net fishing.**
  This is a modified operating profile provided by Siemens Energy. Therefore it is based on numbers from Siemens Energy and the hybrid vessel *Karoline*. Net fishing is a common type of fishing in coastal fishing, and is therefore considered a realistic scenario.
- **Case 2: Low demand.**
  This operating profile is based on a lower power demand than *Net fishing*. This profile has a power demand that equals a 50% load on the motor during piloting. As the fishermen do not know the demand on the different type fishing, this is an assumed low demand profile.
- **Case 3: Varying weather.**
  This profile is based on the calm sea in the morning, which gives less resistance to the engine. There is a higher power demand on the way home due to harsh weather. In any case, this is considered a realistic scenario as they encounter want varying weather. In addition, the vessel usually weights more on the way from the fishing field to the fish reception, due to the catch.
- **Case 4: Trawling**.
  This profile has a significant higher power demand than the others. It is based on a type of fishing called trawling. According to the fisher that the group has been in contact with, *Trawling* is the most energy-consuming type of fishing that a coastal fisher operates with (Bent Gabrielsen, Personal communication, 30/03/22). Trawling is a fishing gear that consists of a bottom tow net with two wings and a large bag in the middle. This type of fishing is used especially for flat fish [88].

3.2.3 Parameters

The same Simulink model has been used for every simulation, however the parameters in the MATLAB code have been changed. As one of the challenges with a hydrogen-electric fishing vessel is knowing how much energy is used, simulations with different energy consumption have been run. Therefore, to simulate different operating profiles, a few parameters have been changed for each simulation.

To collect data, several methods have been used. There has been research in literature, the group has consulted with fishermen, Siemens Energy and organizations related to coastal fishing to create as realistic variables for the operating profile as possible. Below in Table 3.1 the parameters changed in the different simulated cases are listed. It is assumed that the workday starts at 06:00 in the morning, and end at 18:00 in the afternoon. The **FirstStage** is between 06:00 and 08:00, sailing. **SecondStage** is between 08:00 and 15:00, fishing. **ThirdStage** is between 15:00 and 17:00, sailing. **AtPort** is the rest of the day, but it is not included in the graphs in the results. Assuming the fisher stays at the vessel one hour after arriving at port, makes it in total a 12-hour day.

Table 3.1: *Parameters used in the simulation*

Stage	Value for:	Case 1	Case 2	Case 3	Case 4
FirstStage	Pshipnet [kW]	10	10	10	10
FirstStage	Pmotor [kW]	100	60	80	80
SecondStage	Pshipnet [kW]	5	5	5	5
SecondStage	Pmotor [kW]	10	10	10	40
SecondStage	Phydraulics [kW]	10	10	10	20
ThirdStage	Pshipnet [kW]	10	10	10	10
ThirdStage	Pmotor [kW]	100	60	100	180
AtPort	Pshipnet [kW]	10	10	10	10
AtPort	Pmotor [kW]	0	0	0	0

Listed below is information provided by *Siemens Energy* (Unn Marit Forbregd, Personal communication, 22/04/22).:

- The motor in the vessel is 120 kW/1500 rpm (propeller 500 rpm)
- The FC can produce 100 kW of electricity.
- The battery in the simulation is a 330 kWh LIB. The ideal SoC for the battery is between 80 % and 20 %.
- The vessel has 45 kW hydraulics. The hydraulics run during fishing, the power demand depends on the type of fishing.
- The load in the pilothouse is 230 V, 13 kW, in the simulation it is never run above 10 kW.
- The vessel has two 15 kWh bow thrusters.

The diesel 110 kW generator mentioned in Section 2.4 is not included in the simulation model. This is because it is desirable that the diesel generator should only function as a backup (Unn Marit Forbregd, Personal communication, 22/04/22).

Battery model

In order to get the simulation model to run, it is necessary to implement some factors in the battery model within the simulation model. A simplified battery is used in the simulation process. The values used in the battery model are listed in Table 3.2.

Table 3.2: *Battery data, (Steffen Vinzenz Schmitt, Personal communication, 16/03/22)*

Battery	
Technology	Li-Ion NMC
Capacity	500 Ah
Energy	330 kWh
Voltage (max.)	756 V
Voltage (min.)	540 V

To maintain the battery's health, in a real scenario the battery should run with a SoC between 20 % and 80 %. However, the different scenarios were run with a fully charged battery, in addition to 80 %, due to the probability of the fisher charging the battery fully up.

Fuel Cell

The FC in the simulation model is based on a 100 kW FC delivered from PowerCell. The efficiency and fuel consumption to this FC are shown in Figure 3.1. The curve is provided by Siemens Energy.

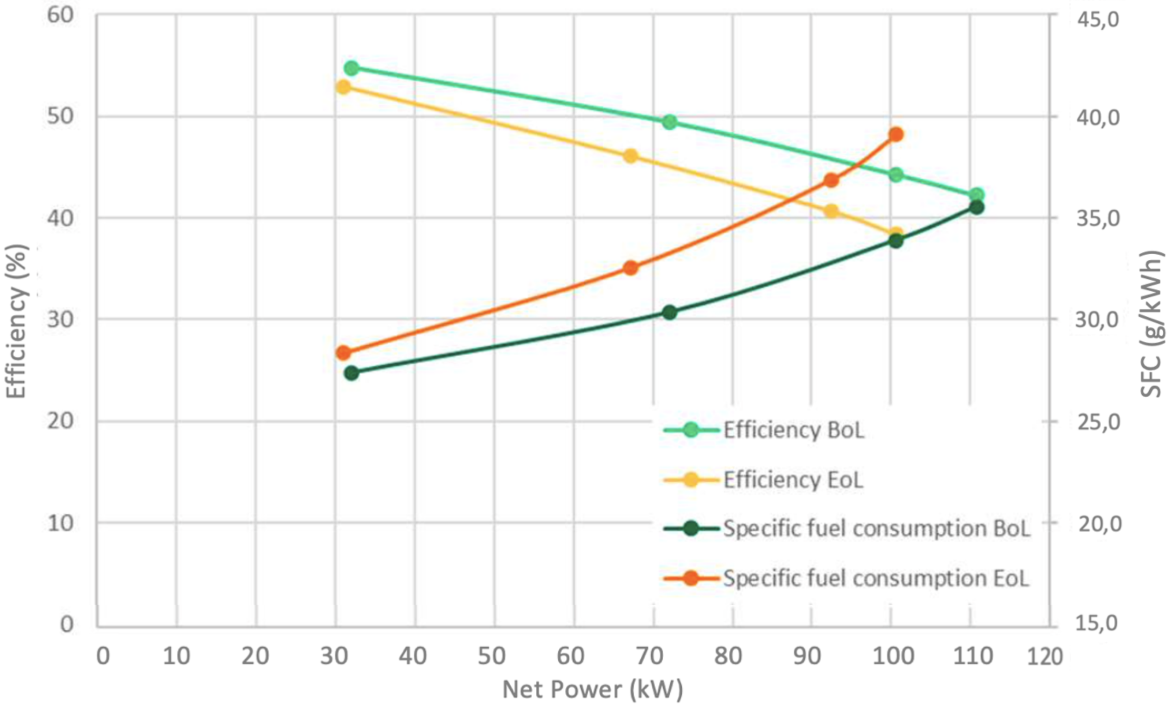

Figure 3.1: *Efficiency and fuel consumption curve for a 100 kW FC [89].*

For the purpose of the simulation, an estimated efficiency curve based on the curve from PowerCell is implemented. This is illustrated in Figure 3.2, and the yellow line is used for consideration of the performance of the FC at End-of-Life (EoL). As seen in the figure, the efficiency drops significantly at low power. It is undesirable to run the FC in that region in terms of fuel economy, hence why the operating region is chosen to be between 15 kW and 100 kW. The FC is assumed to be operating through the whole operating profiles, as long as the FC load demand is above 15 kW and there is enough hydrogen available. Otherwise, it will be shut down. This is to avoid FC starvation that leads to degradation, and voltage losses mentioned in Section 2.6.3.

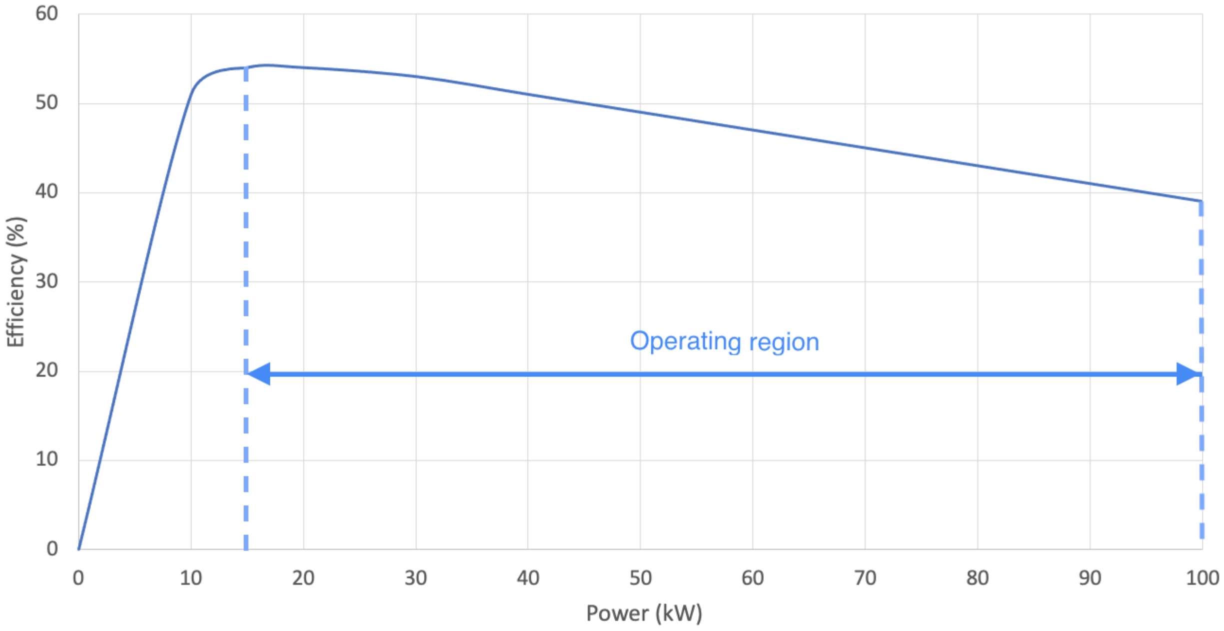

Figure 3.2: *Efficiency curve for the FC with operating region.*

3.3 Energy Management Strategy

In order to have better control of the energy available and enhance the overall efficieny, as well as service life of power sources, a simplified energy management strategy (EMS) is applied to the simulations. The vessel is provided with energy from a battery and a FC. The FC will cover the power loads, with help from the battery during high power demands. During rapid change of voltage, the battery is the preferred energy source due to the slow reaction time of the FC. Such situations can be starting the vessel, or rapid alteration of the speed [35].

With a high battery energy level and a relatively low energy demand, the vessel can run solely on batteries. To maintain a high energy level for the battery, the desired optimal SoC is stated as 60 %. The FC will be able to supply power to the battery when the SoC is approaching 60 %, allowing the battery to recharge to an upper level of 80 %.

Figure 3.3 shows how the FC adapts with the energy supply in relation to the battery's SoC in Simulink. Status of the battery's SoC, C-rate, and voltage are sent to the FC, as well as state of hydrogen (SoH2). Dependent on these factors, the FC will deliverer power to the battery if recharging is necessary.

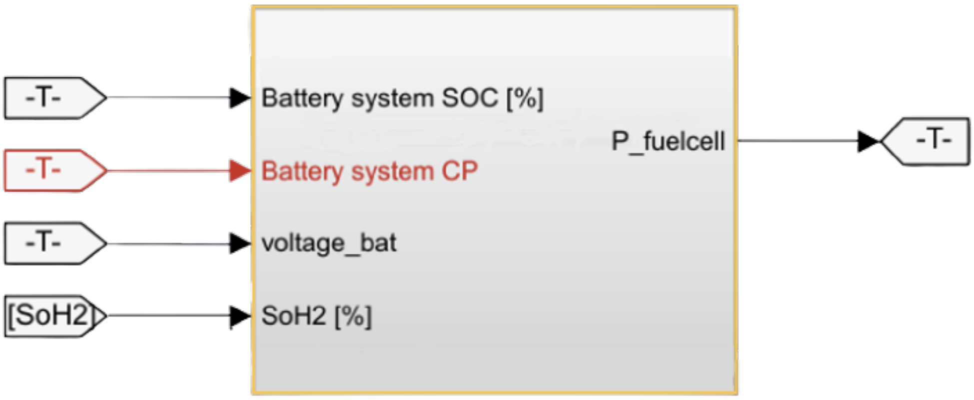

Figure 3.3: *FC control system in Simulink.*

How the power and propulsion system of the system is configured is given by Figure 3.4. The system consists of a PEMFC connected to a unidirectional DC-DC boost converter as the primary power source. Using a DC-DC converter, the output voltage can be modified to match the power density and load transient demands. Electrical energy losses between the FC and the DC-DC converter is assumed to be 3 %. Further, to regulate the charge/discharge power, a bidirectional DC-DC converter is coupled to the battery pack with the DC bus. The battery supplies the remainder of power through the bidirectional DC-DC converter if the load power exceeds the FC's output power. The extra power from the FC recharges the battery if the load power is less than the FC output power. The electrical motor is a constant power source, and determines the current to be drawn based on DC voltage and desired power set-point. The battery determines the voltage. The battery is favored to operate in charge sustaining mode, hence why SoC alteration is wanted at a minimum throughout the driving cycle. Degradation of service life and preserving the SoH of the battery is the main reason for this. Moreover, one of the main arguments to charge the battery with the FC and always keep the battery charged is due to FC starvation [35, 61].

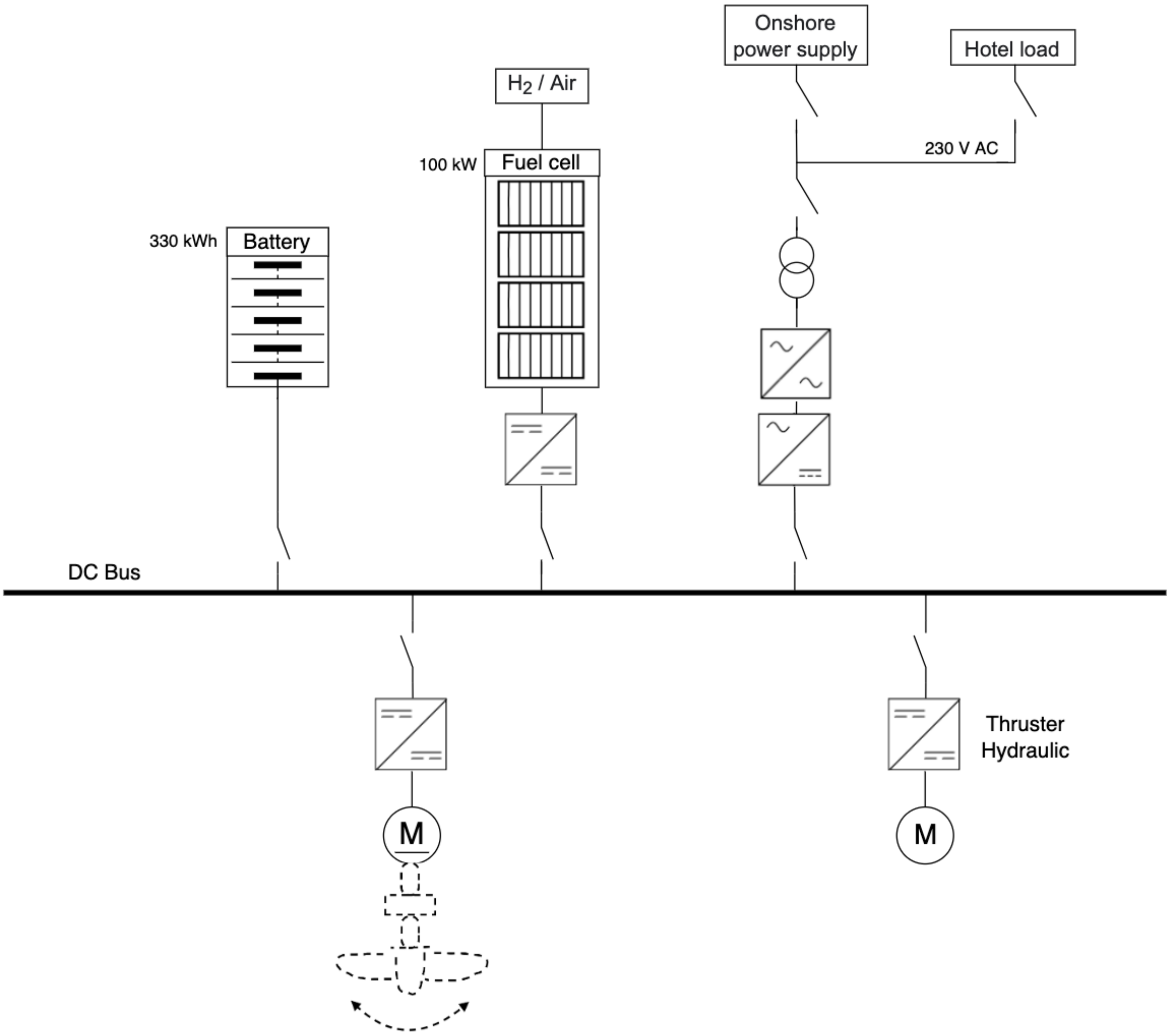

Figure 3.4: *Power and propulsion system of the vessel.*

3.4 Operational costs

This Section will go through the main operating expenses of the hydrogen-electric fishing vessel. These expenses will be compared with the operating costs of diesel and diesel hybrid fishing vessels. There will also be substantial installation and maintenance costs, but this is not included in the economic assessment. Microsoft EXCEL has been used to calculate and illustrate the operational costs and compare the different propulsion systems. Efficiency in the FC and diesel engine are not taken into account when a operational costs.

3.4.1 Fuel prices

Hydrogen pricing is influenced by a multitude of factors, which can lead to variations. Based on a report published by SINTEF the hydrogen price is assumed to be 50 NOK/kg [15]. This assumption will help give an basis for comparison with diesel. Table 3.3 exhibits an overview of the prices used in analyzing fuel prices. The diesel price is assumed to be what fishers in Norway pay after the refund of the CO_2 tax, also based on SINTEFs report [15].

Table 3.3: *Fuel prices used in calculations*

Fuel	NOK/kWh	NOK/kg	Source
Diesel	0.665	7.9	[15]
Hydrogen	1.52	50	[15]

When calculating the price per energy output for diesel and compressed hydrogen, the estimated price in NOK/kg is divided by their specific energy density from Table 3.4. The specific energy density for hydrogen is based on LHV.

Table 3.4: *Specific energy density values used in the calculations*

Fuel	Specific energy density	Source
Diesel	12.67 kWh/kg	[47]
Hydrogen	33.30 kWh/kg	[31]

The amount of energy used in the calculations is 1255.3 kWh, and corresponds to the energy from 31.75 kg hydrogen and a 330 kWh battery. The amount of energy in 31.75 kg hydrogen is calculated in Equation 3.1. This is to estimate how much diesel a regular fishing vessel would need for the same energy output.

$$33.3\ kWh/kg \cdot 31.75\ kg = 1057.3\ kWh \tag{3.1}$$

The battery used when calculating the charging costs has the same capacity as in the simulations, 330 kWh. To maintain the battery's SoH, as explained in Section 2.10.3, the LIB is only charged between 20 % and 80 % SoC. This is equivalent to storing energy of 198 kWh. The electricity price in Flakstad is used to estimate the cost of charging the battery in the hydrogen-electric and the diesel hybrid vessel. Flakstad municipality is located in northern Norway in the price range NO4. The price ranges in Norway is described in Section 2.5. The average electricity price in Flakstad in 2021 was 0.36 NOK/kWh [34]. With an estimated grid rent of 0.40 NOK/kWh, the electricity price is estimated to be 0.76 NOK/kWh. This is used when calculating the price for charging in Flakstad.

Table 3.5: *Energy composition in the different vessels*

Energy carrier	Hydrogen-electric vessel	Diesel hybrid vessel	Diesel vessel
Hydrogen	1057.3 kWh	–	–
Diesel	–	1057.3 kWh	1255.3 kWh
Battery	198 kWh	198 kWh	–
Total	1255.3 kWh	1255.3 kWh	1255.3 kWh

Table 3.5 shows an overview of the energy composition in the three different vessels. The same battery with 198 kWh available at 80 % SoC, is used in both hybrid vessels. The diesel vessel covers the energy demand with diesel. As can be seen from the total, the same amount of energy has been used in the calculation with all three vessels.

3.5 Volume

Fishing vessels are designed to carry large quantities of catch and benefit from utilizing the available space efficiently. Compressed hydrogen has a considerably lower volumetric density compared to diesel [70]. Comparing the required space of the different energy carriers is necessary to discuss whether the hydrogen-electric fishing vessel is competitive. The volume of diesel is compared with the volume of compressed hydrogen at 250 bar. Battery energy storage is commonly used as a energy carrier in vessels, the volume analysis in this thesis therefore has the main focus on hydrogen.

The volumetric density of hydrogen at 250 bar is calculated by using the ideal gas law, presented and explained in Section 2.8. Equation 3.2 calculates the number of moles in 31.75 kg compressed hydrogen. Further, the ideal gas law is used in Equation 3.3 to calculate the volume at 298.15 K (25 °C). The volumetric energy density is calculated in Equation 3.4.

$$n_m = \frac{m}{M} = \frac{31750\ g}{2.016\ g/mol} = 15749\ mol \tag{3.2}$$

$$V_N = \frac{nRT}{p} = \frac{15749\ mol \cdot 0.083144\ \frac{liter\cdot\ bar}{mol\cdot K} \cdot 298.15\ K}{250\ bar} = 1561.6\ liter \tag{3.3}$$

$$Volumetric\ energy\ density = \frac{1057.3\ kWh}{1561.6\ liter} = 0.68\ kWh/liter \tag{3.4}$$

4 Results and discussion

In this Chapter, the results from the study will be presented and discussed. The study is a combination of simulation, cost calculation, volume analysis and literature study. The methods used to find the results are presented in Chapter 3. The results consist of two main parts, energy demand/consumption and cost-and volume calculations. This thesis examines the hydrogen-electric fishing vessel's energy consumption using Simulink. Further, the operational costs and whether a hydrogen-electric fishing vessel can compete with diesel is analyzed using Microsoft EXCEL. Lastly, the different challenges and opportunities investigated and analyzed with the help of supporting literature are discussed.

4.1 Simulation

The simulation model in Simulink is explained in detail in Section 3.1. The group has used a reference operating profile provided by Siemens Energy. This is based on net fishing and on the energy consumption of the fishing vessel *Karoline*, which is a diesel hybrid. *Karoline* is described more in detail in Section 2.2.4. This is the only fishing vessel from which it is possible to extract exact figures on energy consumption. In every case, the FC charges the battery to maintain a optimal SoC of 60%. This is to prevent degradation in the battery and extend the lifetime and preserve the battery.

For the different operating profiles, some parameters were changed in the MATLAB script. This causes different operating profiles to come out. However, some loads in the vessel are the same for each simulation. In every case, the load in the pilothouse, called **P_shipnet** has the same load. The load is 10 kW during **FirstStage** and **ThirdStage**, and 5 kW during **SecondStage**, as shown in Figure 4.1.

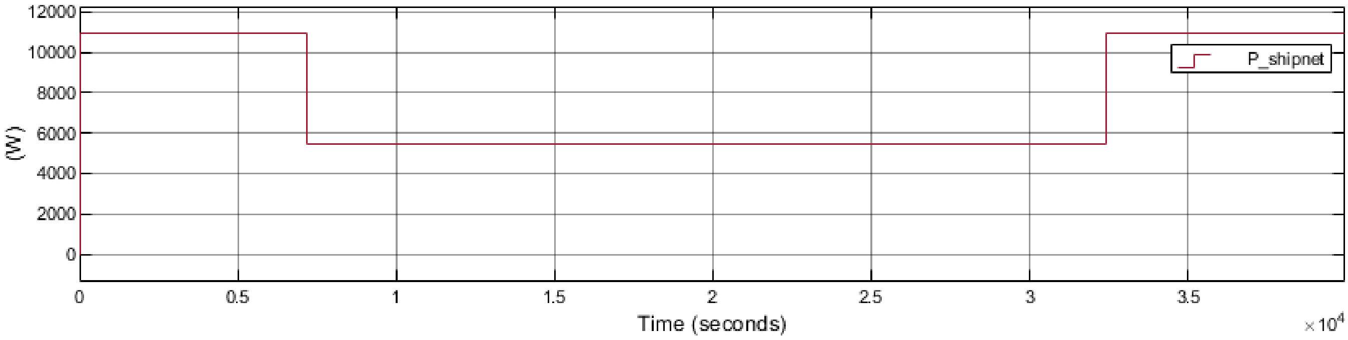

Figure 4.1: *The load on the pilothouse, similar in every simulation.*

The simulation is performed with four different operating profiles, which are explained in Section 3.2. The parameters that are changed for each simulation are listed in Table 3.1. For the figures showing the fuel consumption the label **Battery SoC** indicates the state of charge of the battery. Further, the label **SoH2** indicates how much hydrogen is left on the tank.

4.1.1 Case 1: Net fishing

The operating profile in Case 1 is simulating net fishing. The energy consumption is based on the operating profile of the diesel electric fishing vessel *Karoline* during net fishing. This operating profile is therefore the first one to run in the Simulink model, as a reference, and a starting point in fuel consumption. As shown in Figure 4.2, the propulsion system stops when it runs out of hydrogen at ~10 hours and 50 minutes and the battery reaches ~20% SoC.

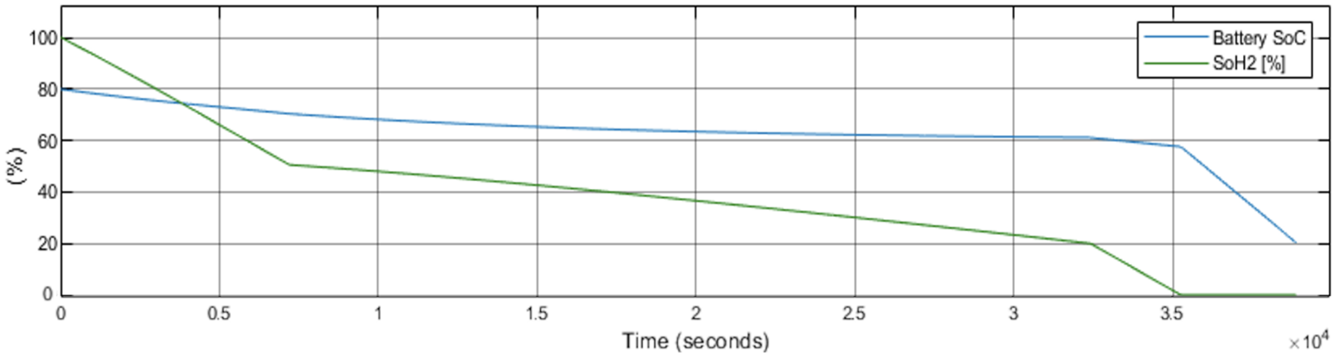

Figure 4.2: *Operating profile Net fishing and running on SoC between 80-20 %.*

In this case, the propulsion would have to be run by the diesel generator at the end to save the battery and not go below 20 % SoC. It is not sufficient with just zero-emission fuel for this operating profile. However, if one turns of the limitation for the battery and goes below the recommended SoC, it is possible to arrive at port with this operating profile with the zero-emission system as demonstrated in Figure 4.3.

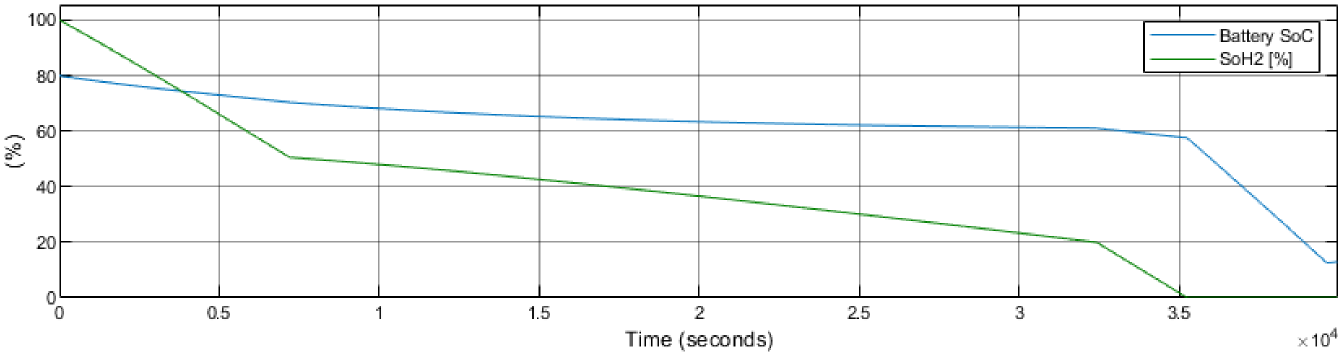

Figure 4.3: *Operating profile Net fishing, initial SoC at 80 %, without limitation on the battery.*

As shown in Figure 4.4, the vessel will return with ~35 % SoC if the vessel leave port with 100 % SoC. However, if the fisher fully charged or discharged the battery, this would lead to faster degradation of the battery over time, and would not be reasonable. The results do give an indication on how large the battery capacity should be, to be able to handle the load in Case 1. With a larger battery it is likely that the vessel could run on only zero-emission energy.

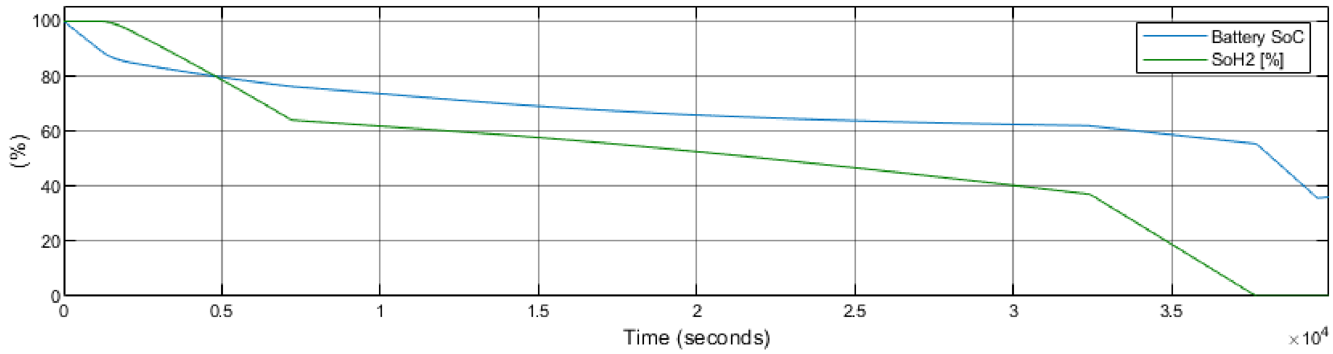

Figure 4.4: *Operating profile Net fishing with initial SoC of 100 % and no limitation.*

4.1.2 Case 2: Low demand

In this case it is assumed that the vessel run with a smaller load, and will still be able to maintain a speed that is possible to work with. The fuel consumption is shown in Figure 4.5. This simulation demonstrates that with a lower load while sailing, you will have a good safety margin, with a satisfactory range at 12 hours of operation. This operating profile presupposes that the fisher either sail very slowly or at the normal speed, in a shorter distance to the fishing field than in Case 1. During fishing it is the same load as *Net fishing*, and during sailing the load is smaller.

In this case, as demonstrated in Figure 4.5, the vessel return with ∼10 % hydrogen left in the tank. In addition, the vessel arrives at port with a battery with 60 % SoC, this is considered a satisfactory safety margin.

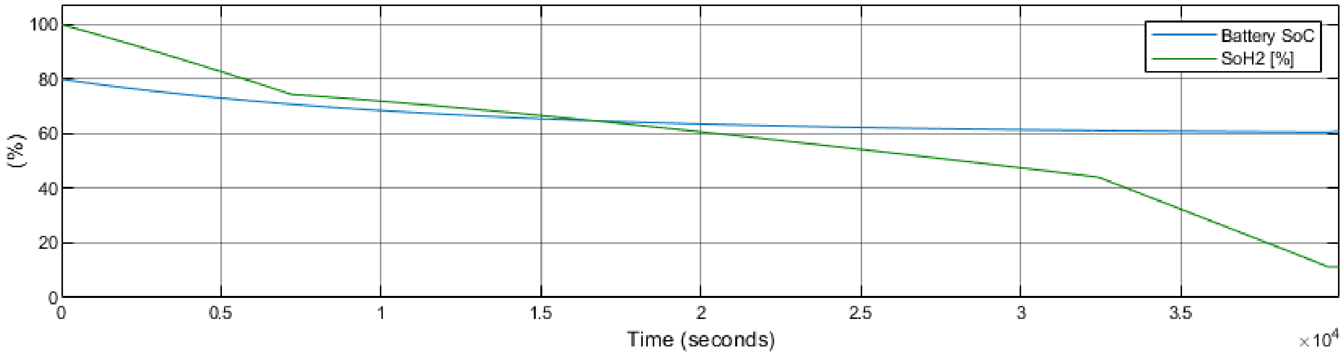

Figure 4.5: *Operating profile Low demand with initial SoC of 80 %.*

In Figure 4.6, where the initial SoC is 100 %, the system had ∼27 % hydrogen left on the tank upon arrival to port. However, the vessel arrives to the port with a battery with SoC of 60 %, which is a satisfying safety margin.

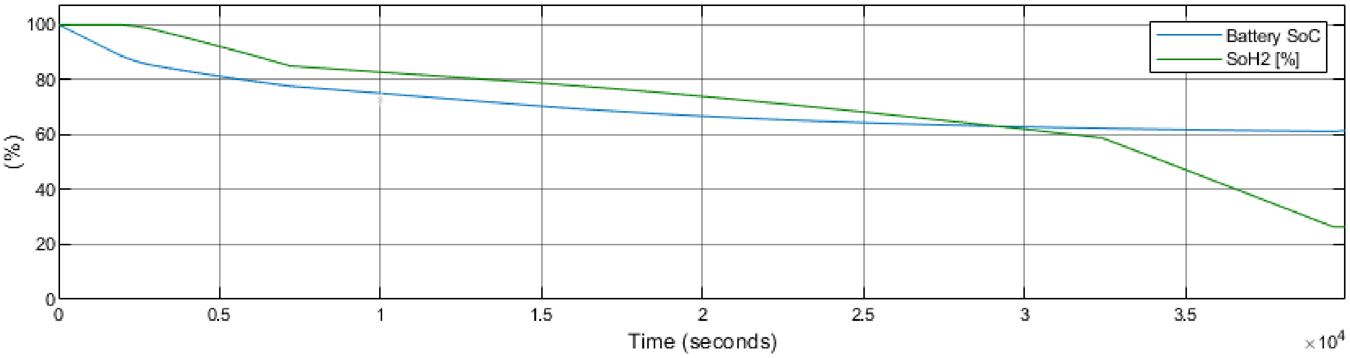

Figure 4.6: *Operating profile Low demand with initial SoC of 100 %.*

As demonstrated in both Figure 4.5 and Figure 4.6 this operating has sufficient amount of fuel in relation to the power demand.

4.1.3 Case 3: Variation of load

In this case, the purpose is to simulate different weather conditions on the exit and entrance to the fishing field. On the way out, the engine load is 80 kW and on the entrance it is 100 kW. During fishing, the total load demand is 25 kW. As seen in Figure 4.8, it is ∼50 % battery capacity left on arrival, while the hydrogen supply at initial 31.75 kg is all consumed. Starting with a SoC of 80 % on the battery, the vessel returned successfully with a remaining SoC level of ∼30 %, as seen in Figure 4.7.

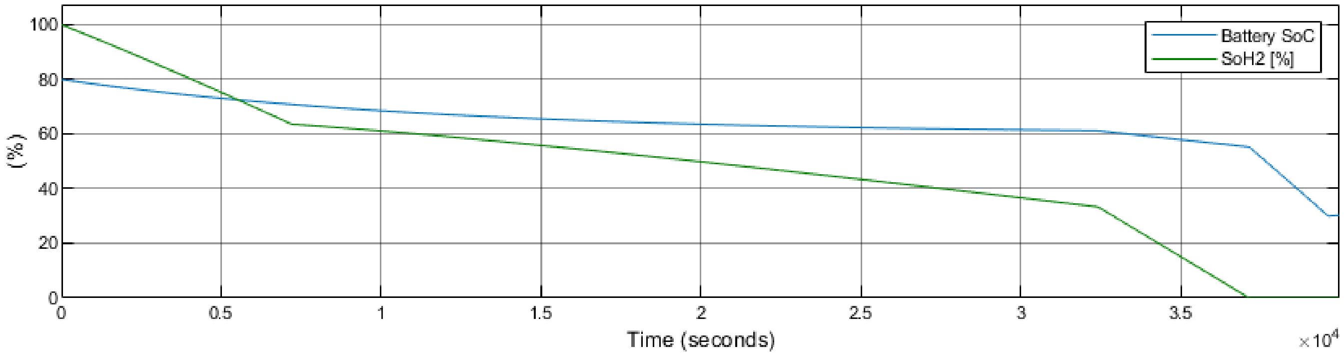

Figure 4.7: *Operating profile Variation of load with initial SoC of 80 %.*

In Figure 4.8 the vessel starts sailing with a fully charged battery. The figure shows the simulation demonstrating an operating profile arriving with ∼ 50% SoC on the battery.

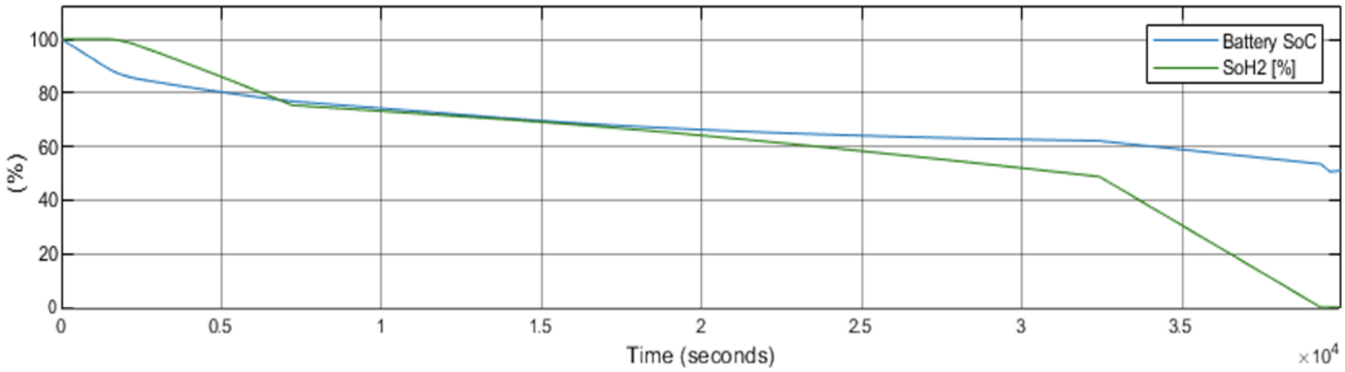

Figure 4.8: *Operating profile Variation of load with initial SoC of 100 %.*

In both cases the vessel returned without any hydrogen left, and hydrogen refuelling is necessary. Nevertheless, Figure 4.8 and 4.7 shows that the operating profile is achievable. There is still a possibility that some fishers think it is too short range, considering the small amount energy left when the hydrogen tank is empty and the battery is not fully charged.

4.1.4 Case 4: Trawling

Trawling is assumed to be the most energy-consuming type of fishing, as mentioned in Section 3.2.2. The first simulation shown in Figure 4.9 is a simulation running with the battery charged between 80 % and 20 %.

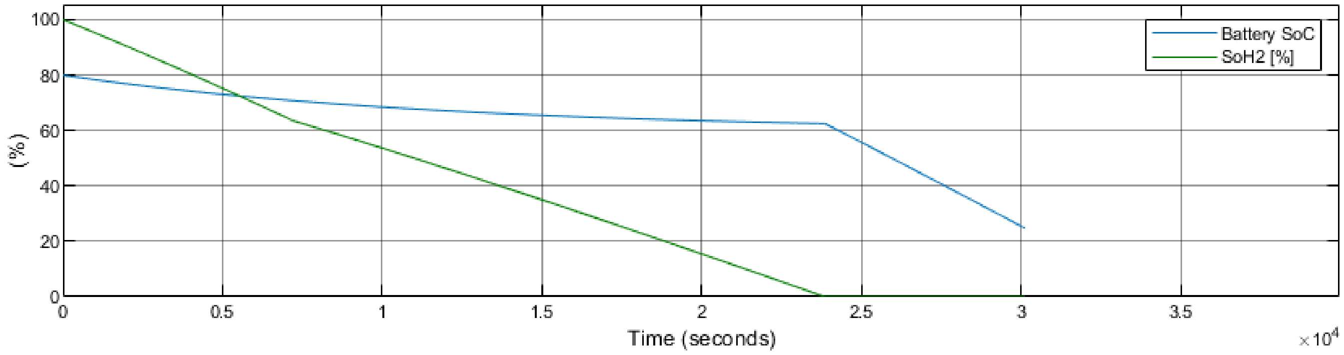

Figure 4.9: *Operating profile Trawling with SoC between 80 % and 20 %.*

The simulation demonstrated in Figure 4.10 has an initial SoC of 100 %. This is a case with heavier load than the other cases demonstrated in this study. The system runs out of energy after ∼8.5 hours. In this case, a diesel generator would be absolutely necessary. Nevertheless, the fisher will be able to operate large parts of the working day with only zero-emission fuel, and be able to enjoy the silence hydrogen and battery energy storage operation entails, compared to the diesel engine.

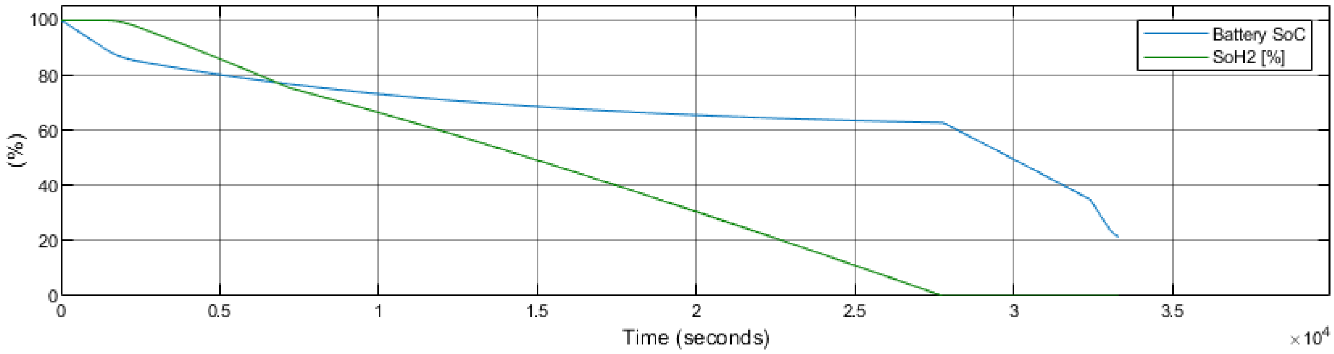

Figure 4.10: *Operating profile Trawling with 100 % SoC.*

Trawling is a common type of fishing according to the fisher the group has been in contact with. Therefore, a simulation was run with an increased amount of hydrogen to investigate whether it would be possible to run with trawling if the amount of hydrogen increased. The amount of hydrogen was doubled to 63.5 kg, which equals to 2114.6 kWh. The simulation is shown in Figure 4.11.

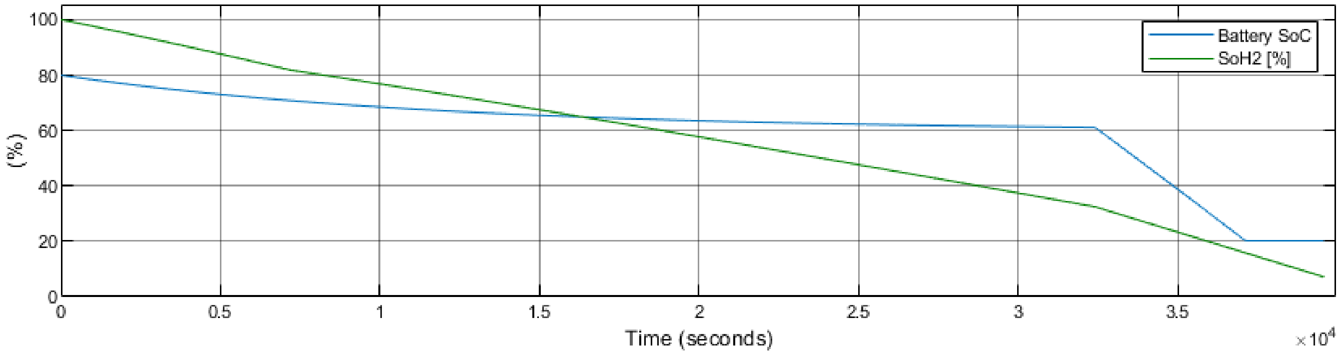

Figure 4.11: *Operating profile Trawling with 80 % SoC and double amount of hydrogen.*

As Figure 4.11 shows, even with double the amount of hydrogen, it is not sufficient. This operating profile has too high power demands. The vessel was close to returning to port, but the FC had to cover the low loads since the battery reached its minimal SoC. As the FC was ruled not to operate below 15 kW, this could explain why the vessel stops right before arriving at the port. Moreover, this amount of hydrogen will require more space on the vessel, which may not be possible without extending it.

As can be seen in the four different simulations, it is possible to carry out a 12-hour operating profile at certain loads. However, with more energy-intensive operating profiles, hydrogen and battery will not be enough, and the fisher will have to depend on the diesel generator.

The technology in this vessel will not be able to compensate for a traditional diesel vessel with range. A diesel vessel has a longer range, in addition to the safety of being able to receive fuel from nearby vessels. Due to large variations, it is challenging to create operating profiles for fishing vessels. The fishers often lives at different distances from the fishing field and have diverse lengths of the workday. In addition, fishers use assorted gear when fishing, which varies the load on the hydraulics. There is a significant difference in the load between net fishing, pulling crab pots and trawling. However, based on assumptions made in Section 3.2.1, it can be seen that Case 1-3 can be carried out with 100 % zero-emission fuel. Nevertheless, it would be necessary to charge above or below recommended charging window in Case 1. This would lead to increased battery degradation. In that case, the best solution in the long run would be to use the diesel generator, when considering the health of the battery.

For all cases, hydrogen refueling is not included, as well as recharging of the battery. It is only assumed that refueling/recharging occurs at the returning point after 12 hours of sailing. With more available refueling stations, the fishers could get more energy from hydrogen to extend the fishing period or operate with higher demand. The same goes for recharging the battery from an onshore power supply. Alternatively, mobile refueling infrastructure could be a good solution for providing more energy. Case 4 is an example of a operating profile that could be feasible with refueling and recharging available. Both land-based and mobile hydrogen bunkering is included in ZeroKyst's Sub-project 3, as mentioned in Section 1.1. Such measures make the hydrogen-electric fishing vessel more appealing and user-friendly.

The simulation model of the drive-line is a simplified version. The FC and battery are simplified as well as the EMS. Further focus on the auxiliary system could be added to control the desired temperature within different parts of the system. Optimization processes could have been done with the simulation model for an even more realistic result, but this is out of the scope of this thesis.

The simulations were performed without considering wasted heat. Current heat recovery solutions for FCs are mainly based on the CHP solution and waste heat power generation combined with a cooling system. The vessel operates with a PEMFC, which is categorized as a low temperature FC, and the waste heat is generally of low quality. Therefore, a CHP system would not be a good alternative. However, by altering the cooling system, the excess heat could be used to cover some of the hotel load by heating the pilothouse with excess heat.

An operating range is set for the FC for better fuel consumption. The FC efficiency curve is based on today's performances, but there is a lot of research and development on this technology. Several factors contribute to better efficiency, such as water management and temperature management within each cell, as described in Section 2.6.3. Water management needs to prevent flooding inside the FC and keep the membrane adequately hydrated. Higher temperature can result in improved efficiencies but also faster degradation of the membrane. In the future, designing the FC differently and using diverse materials could improve the performance. Alternatively, a scale-up of the FC system could contribute to better voltage efficiency and power performances for the given operating profiles. However, this will cause increased weight, volume, and costs of the system. Thus, there are several trade-offs between efficiency, power output, practical and economic aspects.

4.2 Operational costs assessment

To evaluate whether the hydrogen-electric vessel can compete with the existing technology, an operational cost assessment was conducted. To assess this, the operational costs for hydrogen-electric propulsion are compared with diesel and diesel hybrid propulsion. The operational costs include the price for hydrogen, diesel and charging the battery.

4.2.1 Comparing fuel prices

Fuel prices are compared to review the competitiveness in terms of the economics of the hydrogen-electric vessel. Figure 4.12 illustrates the hydrogen price compared to the price per energy output. The dark blue line is the hydrogen price which increases linearly with the price per energy output (NOK/kWh). The grey dotted line shows the current diesel price for fishers in Flakstad, 0.62 NOK/kWh equal to 7.9 NOK/kg [15]. The turquoise dotted line shows a scenario if the energy price of diesel was equal to the assumed hydrogen price of 50 NOK/kg. The points where energy price for hydrogen and diesel are equal is illustrated with the green dots on the graph. Diesel is stated in energy price (NOK/kWh) to get a realistic comparison due to the different energy densities.

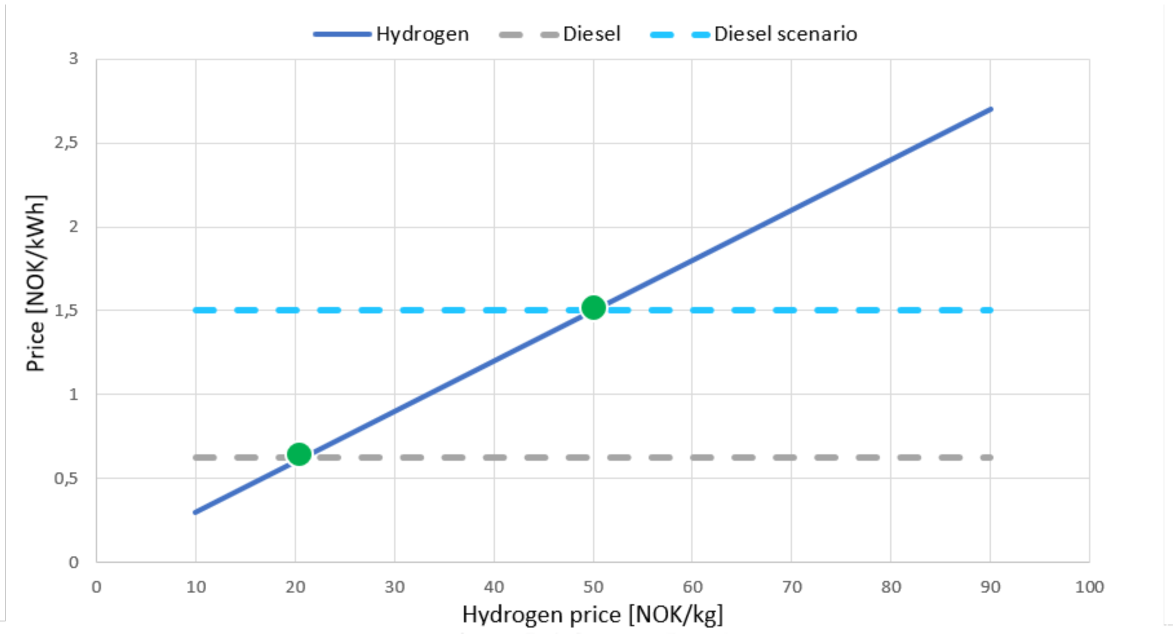

Figure 4.12: *Hydrogen price compared to diesel prices in NOK/kWh and NOK/kg.*

Figure 4.12 indicates that if the diesel price is 7.9 NOK/kg, the hydrogen price must be lower than 20.8 NOK/kg to be competitive with diesel. If the hydrogen price is 50 NOK/kg, diesel prices have to increase to 1.52 NOK/kWh, equivalent to 19 NOK/kg. This is more than double today's price for diesel for fisher. However, if fishers lose their compensation, it will be more expensive for fishers to use diesel as fuel. Nevertheless, the actual price increase for diesel is difficult to predict.

4.2.2 Bunkering and charging

Figure 4.13 shows the costs for bunkering and charging for a vessel with energy equivalent to 1255.3 kWh. This is based on the potential available energy on the hydrogen-electric vessel which is described in Section 2.4. The costs are calculated from data in Table 3.5 and the specific energy density from Table 3.4 in Chapter 3. In Figure 4.13, the battery is assumed to be charged in Flakstad using the electricity price from Section 3.4, which is 0.76 NOK/kWh. To bunker and charge the hydrogen-electric vessel, the total cost is estimated to be 1737.5 NOK. The calculated cost for bunkering and charging a diesel hybrid and a diesel vessel is 809.2 NOK and 782.7 NOK, respectively.

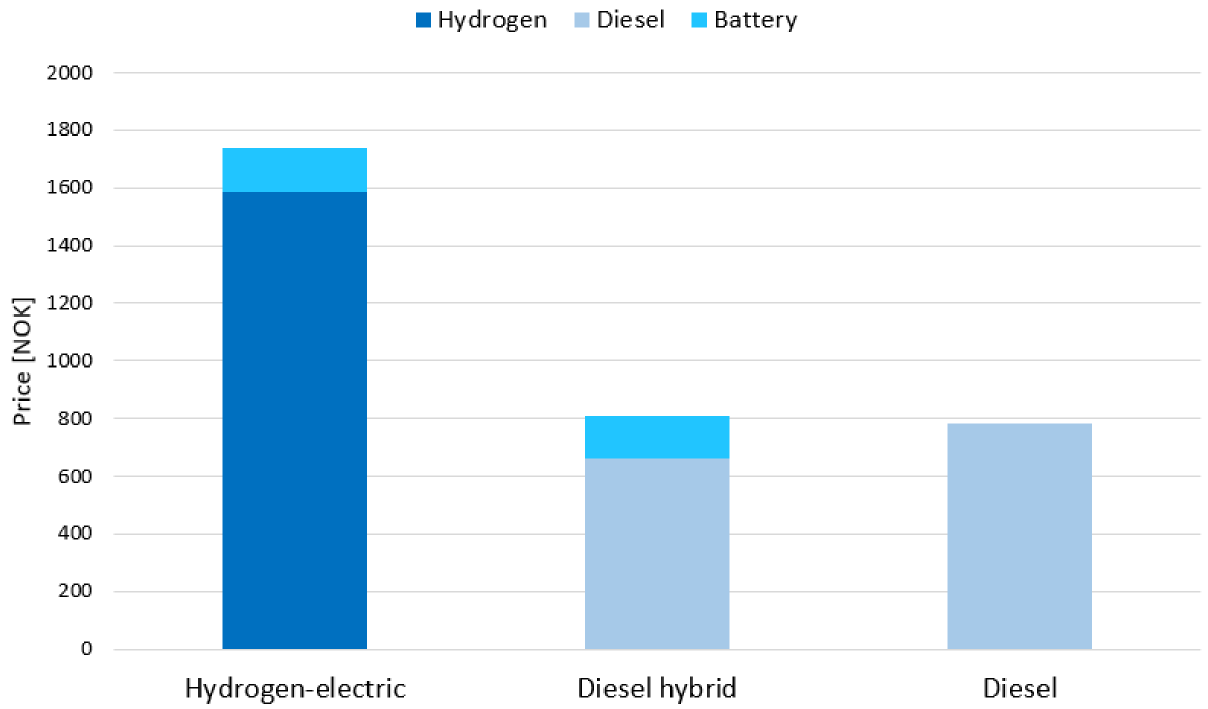

Figure 4.13: *Comparison of costs for fuel equivalent to 1255.3 kWh for different vessels.*

Based on Figure 4.13, the hydrogen-electric propulsion is the superiorly most expensive to operate. The diesel and diesel-hybrid vessel have quite similar expenditure. Charging the battery is a small part of the cost due to the low electricity price in Flakstad. However, there are some uncertainties associated with this due to the fact that the electricity price varies with season, location and from year to year. Figure 4.13 can indicate that the operation of a hydrogen-electric vessel is not yet competitive with existing technology.

4.3 Volume analysis

For a 11 m long fishing vessel the storage capacity is limited. Hydrogen is stored above deck, and therefore takes up space for the fishing gear and the fisher's working area. Figure 4.14 shows the volume of compressed hydrogen at 250 bar and diesel, as a function of energy. The fuels have different relation with volume and energy, as is demonstrated in the figure. Another observation is that hydrogen's volume increases faster with increased energy content than diesel. This indicates that the benefit of using diesel increases with the amount of energy stored, as hydrogen has lower volumetric energy density.

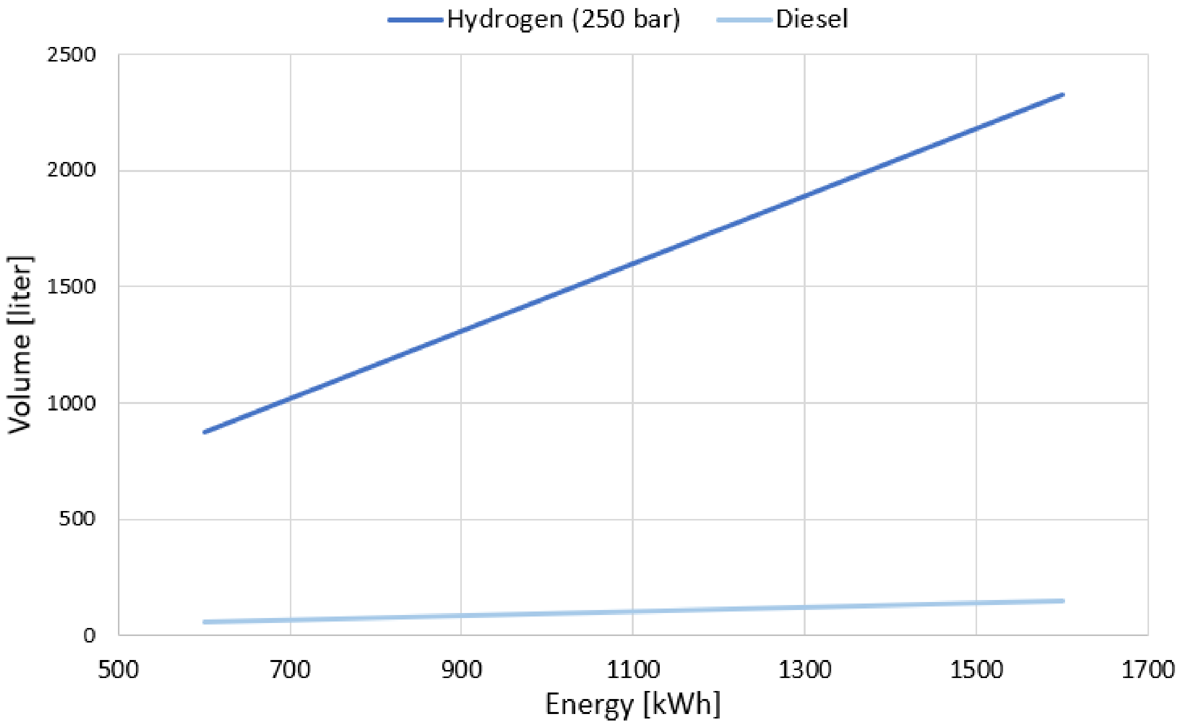

Figure 4.14: *Volumetric comparison of compressed hydrogen and diesel.*

For the hydrogen-electric fishing vessel the vessel can store 1057.3 kWh of hydrogen, this is equal to a volume of 1561 liter. This is considered a volume that can be stored on a 11 meter long vessel. Since larger vessels often sail for longer distances, Figure 4.14 shows that large vessels may have trouble operating on compressed hydrogen due to the volume, particularly if it is being stored above deck. They may benefit from using liquid hydrogen or ammonia in comparison to compressed hydrogen, as they have higher volumetric energy density.

Despite being an decent fuel for fishing vessels of 11 meters, hydrogen has its drawbacks. It goes at the expense of volume and working area. A solution to this could be to extend the vessel. However, due to current regulations described in Section 2.3, fishing vessels are forced to expand in width to accommodate their catch. This makes it difficult for fishers to extend the storage capacity without buying larger quotas or building the vessels bulky and energy inefficient. By developing rules that allow fishers with zero-emission vessels to buy the same quota for longer vessels, it may be possible to build them more energy efficient. Then, vessels can use less fuel and accommodate more compressed hydrogen storage. However, Section explain 2.3.2 how previous regulatory changes have taken a long time, this may be the case with hydrogen as well.

4.3.1 Energy system

Although hydrogen is a relatively new fuel, there are rules for the placement of hydrogen tanks on vessels. Because of safety reasons presented in Section 2.9, the hydrogen tanks must be stored above deck. This takes up the working area. If rules and safety are developed for hydrogen propulsion, the tanks can be stored in other, more practical places. This may lead to the vessel having room for more hydrogen, and the fisher getting a more extensive working area.

The use of hydrogen as fuel implies, as described in Section 2.9, several safety considerations. Experience from vehicles can make it easier to implement hydrogen as fuel in fishing vessels. The explosion in Sandvika is an example of incident which can reduce the popularity of hydrogen as a fuel. Even though it was a human error, it does not mean that it can not happen again. However, accidents like this can provide the hydrogen industry more experience in terms of safety. Due to hydrogen being an odorless gas, and hydrogen having to be placed above deck, a leakage can be problematic to detect. By being aware of the risks and taking precautions, hydrogen can be safely stored and used.

With a battery energy storage of 330 kWh, the energy available with a charging window between 80-20 % is 198 kWh. Charging with AC takes a long time, therefore fast charging with DC is an alternative. In addition, with enough fast chargers spread over various ports and fish receptions, the fishers can manage to recharge during the 12-hour assumed working day to extending the range. However, as mentioned in the Section 2.10.4, fast charging can contribute to increased stress on the batteries, leading to faster degradation.

Degradation of the energy system is a challenge with this fishing vessel. The battery will start degrading after a certain number of charging cycles, degree of charge and discharge affect this. In addition, the membrane in the FC will also degrade. As the FC does not operate below 15 %, it is ideal to use the hydrogen to charge the battery at sea, as the battery can take the low loads. It would mean more risk for the fisher if there was no energy left on the battery, as opposed to running out of hydrogen.

4.3.2 Adapted infrastructure and bunkering

The infrastructure, regarding bunkering facilities and available charging capacity, is essential for fishers who consider buying a hydrogen-electric fishing vessel. As established in Section 2.4.1, lack of infrastructure is one of the challenges with the new technology. The development of infrastructure must be built for the future demand. It only makes sense to expand the charging and bunkering options if it will be used.

Bunkering compressed hydrogen takes less time compared to charging batteries. However, there are other challenges associated with this. Due to the risks of leakage, bunkering has to take place in surroundings adapted for the purpose. The safety zones described in Section 2.9, should be considered when deciding on the location of bunkering facilities. The investment costs for a new hydrogen plant may affect the selling price of hydrogen. However, the vessel investment costs and the infrastructure investment are not a part of this project.

4.3.3 Why choose the hydrogen-electric vessel?

In order for hydrogen-electric fishing vessels to be competitive with existing diesel vessels, it must provide the same opportunities at a reasonable price compared. This includes price, fuel availability, range, safety, and storage space. As explained in Section 2.3, the government in Norway is substituting the transition into hydrogen and other zero-emission fuels. In addition, they have started to cut of the substitute for diesel, while the taxes and prices on diesel is becoming higher for the fishers. As mentioned in Section 2.3, transition to a zero-emission fishing vessel might be easier for some fishers if there was a economical reward for choosing it. However, as mentioned in Section 2.1.2 climate challenges are affecting fishers job, and this could also be a motivation to change technology.

5 Conclusion

The objective of this thesis is to investigate whether a hydrogen-electric fishing vessel is competitive with traditional fishing vessels. This includes an assessment of fuel consumption in various operating conditions, operational costs, and safety aspects.

In the simulation, the results were generated from four different cases with a 12-hour operating profile, created and demonstrated in the simulation model. The different cases had different theoretical operating profiles for the fishing vessels. Additionally, each case was run with altered initial SoCs.

Case 1, showed a simulation depending on the diesel generator if the battery had a charging window between 80 and 20 % SoC. This simulation showed that it is sufficient with the hydrogen-electric propulsion system if the battery is fully charged. Case 2 showed that there is more than enough fuel, and that with this load, the fisher will return to port with more than enough battery. However, it is uncertain whether this low-demand operating profile is realistic. Further, Case 3 showed that with varying loads, the fisher will have enough fuel with a satisfactory safety margin. With sailing and fishing under these conditions, the fisher would not have to turn on the diesel generator. Case 4 showed that this type of fishing, which is very energy-intensive, will not be able to be carried out with only zero-emission fuel. In this case, the vessel will be dependent on a diesel generator or refilling/recharging opportunities. Nevertheless, it is better to use a diesel unit on a zero-emission vessel than to only operate on diesel, in terms of emissions.

Operational costs assessment demonstrated that the zero-emission vessel had higher operational costs than vessels with diesel propulsion. For the operation of the hydrogen-electric fishing vessel to be competitive with other propulsion systems, the hydrogen price must be at the same level as, or lower, than diesel per kWh. In addition, competitiveness is also depended of regulations and compensation schemes to favor zero-emission fishing vessels.

Whether the hydrogen-electric fishing vessel is competitive with existing technology or not is decided by the fisher, and the extent to which the solution meets the fisher's needs. The simulation shows that it is possible to sail on zero-emission energy for an entire workday at specific operating profiles. However, it is highly dependent on the usage of the fisher if the technology is sufficient. A backup solution with a diesel generator can lower the barrier to transition and further development of bunkering and charging infrastructure eases the changeover. This again is favored by lower hydrogen prices and collaboration between the government, companies, and private initiatives.

In conclusion, the opportunities with the hydrogen-electric fishing vessel surpasses the challenges. In some types of fishery the fisher would have to depend on the diesel generator. In any case, replacing a traditional diesel propulsion system with a hydrogen-electric system can significantly reduce emissions and ocean acidification. Additionally, it may be more affordable in the long run. Regardless, a zero-emission vessel will provide a quieter working environment, and the environmental benefits of using the technology could be a decisive factors for some fishers.

5.1 Further work and recommendations

In this section suggestions for further work and recommendations are presented. In order to reduce the emissions both in the maritime and other sectors. The world is dependent on new zero-emission technology. Both private persons and companies needs to invest to make a change. The world is in the starting phase of a developing time within low-emission or emission free technology. This thesis has been written over a small period of time, and with this comes a lot of limitations of the boundaries of the thesis. Given more time, the thesis would have included more topics.

The simulations were performed with little / no variation in battery and hydrogen content. Further work would include calculations with a larger battery and more hydrogen, in order to have a broader basis for comparison.

Due to limited available information and neglect of investment costs in hydrogen production, further work would include more comprehensive calculation of the price of hydrogen. In this way, more realistic calculations would have been performed, which could be compared to the operational price of existing technology.

Battery

In this thesis, an NMC battery configuration is used for the simulation purpose. LIBs work well onboard vessels, but new and improved battery technologies are researched and developed with the increasing demand for energy storage. Therefore, it could be interesting to look into for example solid-state batteries as a replacer of the NMC battery [90].

As mentioned earlier in the discussion, higher power loads can be covered by discharging the battery below the optimal range. Further, it is enlightened that this can degrade the battery's health and that a diesel generator can therefore be used to cover these loads. It would be interesting to examine what would lead to the most emissions: Use a diesel generator in addition or use the battery with no regulation of operating SoC and then replace it with a new one. In the latter case, the hydrogen stored onboard could be used for propulsion instead of recharging the battery, and a higher power demand could be covered.

Infrastructure

In order to be able to use the vessel as it is today, the infrastructure for charging and bunkering must be adapted so that the fisher can bunker or charge during the day. This can for example be a fleet as mentioned in sub-project 3. An other option could be fast charging at the fishery, then the fisher could charge the vessel while offloading the fish. This will give a better range to the fisher. In addition, it will provide an extra safety margin on the type of operation that has already covered its fuel needs.

Hydrogen

One downside with the FC technology is that it has a lot of losses, in addition to losses associated with hydrogen production. A way to increase the efficiency of the FC is to use a high temperature FC, such as a SOFC. The excess heat can be used in a CHP system to increase efficiency. It could therefore be interesting to look into use of SOFC with CHP system instead of a PEMFC. In addition, a SOFC configuration with ammonia could be interesting to implement and compare with hydrogen. Ammonia has a higher volumetric energy density than compressed hydrogen and could improve the range for the vessel, but this is a expensive solution.

Liquid Hydrogen

LH_2 does have higher energy density than compressed hydrogen, therefore compressed is more cost efficient. Due to space problems, compressed hydrogen will not be an option for larger ships that sail long distances. With a smaller energy demand, LH_2 is not cost efficient as the tanks for LH_2 are expensive. LH_2 requires large production sites and volume. The development of liquefaction technology could in the future bring the cost down. The same shipping company that built the first electric ferry *Ampere* is now in the process of rebuilding the ferry *Hydra*. Which is planned to run on liquid hydrogen [27].

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Appendix

A: Matlab

```
%% Init_system

%% Simulation settings;
Ts_sim=2.4*2e-4; % Algorithm simulation time step
Ts_simpower = Ts_sim; % Power circuit simulation time step

%% Select scenarios
enable_fuelcell=1;
enable_battery=1;

%% Voltage references
v_ref_dc = 630;
v_ref_ac=230;
v_dc_init = 756;

%% Fuel Cell data
fuelcell.Pmax = 100e3;
fuelcell.Pmin = 0.15*fuelcell.Pmax;
fuelcell.I = fuelcell.Pmax/v_ref_dc;
fuelcell.L = 1e-6;
fuelcell.R = 0.1e-3;
fuelcell.C = 3e-3;
fuelcell.controlKp =1; % set this equal zero to disable SoC optimalization
fuelcell.H2_energy = 33.3*31.75e3; %Wh
fuelcell.DCDCefficiency = 0.97; % 3% electrical losses
fuelcell.H2_ini = 1; % 1 = 100% (0-1)

%% Battery data
battery.energy = 330e3; %Wh
Rbat_internal = 350e-5;
battery.L = 1e-7; %cable inductance
battery.R = 0.01e-3; %cable resistance
battery.optimalSOC = 0.6; %satt som optimal SoC for batteriet
battery.lower_SOC_limit = 0.2;
battery.upper_SOC_limit = 0.8;
```

```

% SOC values when start limitng
battery.lower_SOC_Startlimit = 0.25;
battery.upper_SOC_Startlimit = 0.85;
battery.SOC_limitation_range_lower =
    battery.lower_SOC_Startlimit - battery.lower_SOC_limit;
battery.SOC_limitation_range_upper =
    battery.upper_SOC_limit - battery.upper_SOC_Startlimit;

SOC_ini = 0.8;

battery.maxCP_discharge = 2;
battery.maxCP_charge = -2;
battery.CP_discharge_Startlimit = 1.9;
battery.CP_charge_Startlimit = -1.9;
battery.CP_limitation_range_discharge =
    battery.maxCP_discharge-battery.CP_discharge_Startlimit;
battery.CP_limitation_range_charge =
    battery.CP_charge_Startlimit-battery.maxCP_charge;

battery.max_voltage = 688;
battery.min_voltage = 520;
battery.max_voltage_startlimit = 680;
battery.min_voltage_startlimit = 537;
battery.voltage_limitation_range_upper =
    battery.max_voltage-battery.max_voltage_startlimit;
battery.voltage_limitation_range_lower =
    battery.min_voltage_startlimit-...battery.min_voltage;

battery.charge_solution = 400; %charge solution 230 V vs. 400 V
if battery.charge_solution > 230
    battery.charge_power = 22e3;
else
    battery.charge_power = 11e3;
end

%% Motor 120 kW data
Motor120.Pnom = 120e3;
Motor120.WavePower = 2e3;
Motor120.WaveFrequency = 1/1; %1/10;
```

```
Motor120.Ploss = 0.03;
% Motor120.Padjustable = 40e3;
%% Hydraulix 45 kW data
Hydraulic.Pnom = 45e3;
Hydraulic.Ploss = 0.03;
%% Port side thruster 14 kW data
PortSideThruster.Pnom = 14e3;
PortSideThruster.Ploss = 0.03;
%% Starboard side thruster 14 kW data
StarboardSideThruster.Pnom = 14e3;
StarboardSideThruster.Ploss = 0.03;
%% Shipnet 13-20 kW data
Shipnetload1.Pnom = 13e3;%6e3
Shipnetload2.Pnom = 4e3;
Shipnetload3.Pnom = 3e3;
Shipnetloss.P = 0.03*3; %2 converter + 1 transformer, 3% each



%% Load Profile Garn
% clear all;
%% 0600-0800
FirstStage.TimeDuration = 2*60*60; %[s]
FirstStage.Pshipnet = 10e3/Shipnetload1.Pnom; %[%]
FirstStage.Pmotor = 100e3/Motor120.Pnom; %[%]
FirstStage.Phydraulic = 0; %[%]
FirstStage.PportSideThruster  = 0; %[%]  left side of the ship
FirstStage.PstarboardSideThruster = 0; %[%]  right side of the ship

%% 0800-1500
SecondStage.TimeDuration = 7*60*60; %[s]
SecondStage.Pshipnet = 5e3/Shipnetload1.Pnom; %[%]
SecondStage.Pmotor = 10e3/Motor120.Pnom; %[%]
SecondStage.Phydraulic = 10e3/Hydraulic.Pnom; %[%]
SecondStage.PportSideThruster  = 0; %[%]  left side of the ship
SecondStage.PstarboardSideThruster = 0; %[%]  right side of the ship

%% 1500-1700
ThirdStage.TimeDuration = 2*60*60; % [s]
ThirdStage.Pshipnet = 10e3/Shipnetload1.Pnom; %[%]
```

```
ThirdStage.Pmotor = 100e3/Motor120.Pnom; %[%]
ThirdStage.Phydraulic = 0; %[%]
ThirdStage.PportSideThruster  = 0; %[%]  left side of the ship
ThirdStage.PstarboardSideThruster = 0; %[%]  right side of the ship

%% At port, including charge of battery
AtPort.TimeDuration = 24*60*60- FirstStage.TimeDuration -
SecondStage.TimeDuration  - ThirdStage.TimeDuration; %[s]
AtPort.Pshipnet = 10e3/Shipnetload1.Pnom; %[%]
AtPort.Pmotor = 0; %[%]
AtPort.Phydraulic = 0; %[%]
AtPort.PportSideThruster  = 0; %[%]  left side of the ship
AtPort.PstarboardSideThruster = 0; %[%]  right side of the ship

%% Concentrate the data/load profile
t1 = FirstStage.TimeDuration;
t2 = t1 + SecondStage.TimeDuration;
t3 = t2 + ThirdStage.TimeDuration;
t4 = t3 + AtPort.TimeDuration;

LoadProfileVec.T = [0 t1 t1 t2 t2 t3 t3 t4];

LoadProfileVec.Pmotor = [FirstStage.Pmotor FirstStage.Pmotor
    SecondStage.Pmotor SecondStage.Pmotor ThirdStage.Pmotor
    ThirdStage.Pmotor AtPort.Pmotor AtPort.Pmotor];

LoadProfileVec.Pshipnet = [FirstStage.Pshipnet FirstStage.Pshipnet
    SecondStage.Pshipnet SecondStage.Pshipnet ThirdStage.Pshipnet
    ThirdStage.Pshipnet AtPort.Pshipnet AtPort.Pshipnet];

LoadProfileVec.Phydraulic = [FirstStage.Phydraulic FirstStage.Phydraulic
    SecondStage.Phydraulic SecondStage.Phydraulic  ThirdStage.Phydraulic
    ThirdStage.Phydraulic AtPort.Phydraulic AtPort.Phydraulic];

LoadProfileVec.PportSideThruster = [FirstStage.PportSideThruster
    FirstStage.PportSideThruster SecondStage.PportSideThruster
    SecondStage.PportSideThruster ThirdStage.PportSideThruster
    ThirdStage.PportSideThruster  AtPort.PportSideThruster
    AtPort.PportSideThruster];

```

```
LoadProfileVec.PstarboardSideThruster = [FirstStage.PstarboardSideThruster
    FirstStage.PstarboardSideThrusterSecondStage.PstarboardSideThruster
    SecondStage.PstarboardSideThruster ThirdStage.PstarboardSideThruster
    ThirdStage.PstarboardSideThruster AtPort.PstarboardSideThruster
    AtPort.PstarboardSideThruster];

%% Save to .matfile
% create dataset
LoadProfile_ds = Simulink.SimulationData.Dataset;

%convert data to timeseries
ShipnetData = timeseries(LoadProfileVec.Pshipnet',LoadProfileVec.T);
MotorData = timeseries(LoadProfileVec.Pmotor',LoadProfileVec.T);
HydraulicData = timeseries(LoadProfileVec.Phydraulic',LoadProfileVec.T);
PortSideThrusterData = timeseries(LoadProfileVec.PportSideThruster',LoadProfileVec.T);
StarboardSideThrusterData = timeseries(LoadProfileVec.PstarboardSideThruster',
    LoadProfileVec.T);
%add timeseries to dataset
LoadProfile_ds = addElement(LoadProfile_ds,ShipnetData,'Shipnet');
LoadProfile_ds = addElement(LoadProfile_ds,MotorData,'Motor');
LoadProfile_ds = addElement(LoadProfile_ds,HydraulicData,'Hydraulic');
LoadProfile_ds = addElement(LoadProfile_ds,PortSideThrusterData,'PortSideThruster');
LoadProfile_ds = addElement(LoadProfile_ds,StarboardSideThrusterData,
    'StarboardSideThruster');

% save dataset to .mat file (readable for simulink model)
save('LoadProfile.mat', 'LoadProfile_ds')



%% Init
clear all;
%% Add path for subfolders
run('init_system');
run('LoadProfile_Garn_Karoline');
%% Default parameters
Ts_sim_new = 24*60*60-12.9*60*60;
```

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