Bachelor's thesis

Mai 2019

NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Design

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Preface

This Bachelor's Thesis is written during the last semester of a three-year bachelor degree program in Renewable Energy Engineering at NTNU (Norges teknisk-naturvitenskaplige universitet). Contact between group members and NVES (Nasjonalt Vindenergisenter) were established during a Renewable Energy Conference at NTNU Trondheim in the autumn of 2018. The assignment were put forth by the CEO of NVES, Thomas Bjørdal during this meeting. The objective were to investigate the possibility to replace a traditional diesel engine system on board the service vessel Fosna Orion, with a pure hydrogen fuel cell system. In addition to this, review the possible dimensions and range of battery fuel cell hybrid system, and economical aspects of the zero emission system.

This thesis is the work of four students with the help of our supervisor, Professor Bruno G. Pollet. It has been a educational working process. Working in a group of four has been challenging, but also very helpful considering the different perspectives and reflections of each individual. All group members contributed to the arrangement of the thesis, structure and the scope of project. Tasks were assigned in order to work as efficient as possible.

Acknowledgements

We would first like to thank our supervisor Professor Bruno G. Pollet at the Department of Energy and Process Engineering for great help, guidance and expertise through our thesis. A Professor that was truly committed to guide us through the assignment with quick response and open reflections.

We would also give a special thanks to our external supervisor from NVES, Thomas Bjørdal, for his guidance and valuable information throughout the semester. He put us in contact with Bjarne Ytterøy, Quality Manager in Abyss. We are also grateful for the opportunity to work on such a exciting task.

As of this, we give a special thank you to the quality manager in Abyss Aqua, Bjarn Ytterøy, whom gave us the opportunity to use real life engine data from the Sky Nordic data logger gathered from their vessel, Fosna Orion, and access to valuable technical specifications.

Furthermore, we would like to thank Trym Sandblost from Selfa Arctic and Stephen Merricks from Abyss for the great technical advisement in regard to our calculations on the diesel propulsion system and electrical system.

We are also grateful for the valuable information regarding market values, which Anders Ødegård and Edel Sheridan from Sintef and Bernhard Kvaal from TrønderEnergi supplied us with.

A big thank you to everyone that has supported and helped us during this project.

Thesis statement

As of this, we hereby declare that our thesis is our own work. The theory and information used to create a foundation for our calculations and analysis is not fabricated or manipulated. All cited sources are collected with a critical mind to secure that the values are valid, and content of gathered theory has been quoted or rephrased.

Sammendrag

Denne bacheloroppgaven har tatt sikte på å sammenligne et hydrogen-brenselscellesystem, et batterisystem, og en kombinasjon av de to til å drifte en servicekatamaran, med navn Fosna Orion. Fosna Orion brukes i den norske oppdrettsnæringen. Vår oppgave var å utforske muligheten for å erstatte det nåværende dieselmotor-systemet med et nullutslipps-system. De forskjellige systemene blir sammenlignet ved hjelp av maksimal rekkevidde, innvesterings-, drifts- og drivstoffkostnad og virkningsgrad, som tar hensyn til et sett vekt- og volumbegrensninger, mot det eksisterende dieselsystemet ombord på båten.

Noen av systemene er teknologisk kapable til å utføre hovedoppgavene til servicebåten, men på grunn av vekt- og volumbegrensningene er verken hydrogen-brenselscellesystemet eller noen av de andre systemene i stand til å oppnå rekkevidden til dieselsystemet, selv om de andre systemene har en vesentlig høyere kostnad. Til tross for dette legges det vekt på trusselen som klimaforandringer forårsaker, og det er stort behov for å møte disse utfordringene. Den maritime industrien har et stort potensial til å kutte utslippene sine, og med økonomisk støtte fra statlige programmer, vil det være en redusert økonomisk risiko for investorer for grønne løsninger som enda ikke er lønnsomme. Det er også mulig det blir innført en karbonskatt i fremtiden, noe som vil gjøre det mer kostbart å bruke fossilt brensel. Basert på dette, og mer, er det anbefalt med et rent hydrogen-brenselscellesystem.

Abstract

This bachelor's thesis aims at comparing a hydrogen fuel cell system, a battery system, and combinations of the two technologies to power a service catamaran, named Fosna Orion. Fosna Orion is used in the Norwegian fish farming industry. Our objective is to explore the possibility of replacing the current diesel engine system with a zero emission system. The different systems are compared in terms of maximum range, capital expenditure, operational expenditure, efficiency and fuel costs, with a set of weight and volume limitations, against the existing diesel system on board the ship.

Some of the systems are technologically able to cover the main tasks of the service vessel, but due to the weight and volume limitations, neither the hydrogen fuel cell system or any of the other systems could achieve the range of the diesel system, even though the other systems cost considerably more. Despite of this, since we are faced with climate change, there is a dire need for to drastically reduce our emissions. The maritime industry has a great potential with regard to reducing their emissions, and with economic support from governmental programs, the economic risk is lowered for the investors of green solutions which are not yet profitable. There is also a possibility for a carbon tax in the future, which will make it more expensive to operate on fossil fuels. Based on these notes, among other, a pure hydrogen fuel cell powered system is recommended.

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Abbreviations

AFC Alkaline Fuel Cell

AIS Automatic Identification System

AWE Alkaline Water Electrolyser

CAPEX Capital expenditure

CCS Carbon Capture and Storage

CHP Combined Heat and Power

SSB Statistisk Sentralbyrå

DoD Depth of Discharge

ECU Engine Control Unit

ESS Energy Storage System

EV Electrical vehicles

GHG Green house Gas

ICE Internal combustion engine

IMO International Maritime Organization

IPCC Intergovernmental Panel of Climate Change

LH2 Liquid hydrogen

LIB Lithium Ion Battery

LNG Liquid natural gas

Mt Megatonne

MCEC Molten Carbonate Electrolysis Cell

MCFC Molten Carbonate Fuel Cell

NCS Net Cleaning System

NTNU Norwegian teknisk-naturvitenskaplige universitet

NVES Nasjonalt vindenergisenter

OCV Open Circuit Voltage

OPEX Operational expenditure

PAFC Phosphoric Acid Fuel Cell

PHEV Plug-in hybrid electric vehicles

PEME Polymer Electrolyte Membrane Electroliser

PEMFC Proton Exchanger Mambrane Fuel Cell

PW Power to Weight

SLI Starting, Lightning and Ignition

SFC Specific fuel consumption

SOFC Solid Oxide Fuel Cell

SoC State of Charge

SoD State of Discharge

SoH State of Health

SLI Starting, Lightning and Ignition

SOWE Solid Oxide Water Electrolysis

TtW Tank to Wave

US DOE United States Department of Energy

UN United Nations

WtW Well to Waves

wt% Weight percent

1 Introduction

One of the great challenges in the maritime industry is the emission of greenhouse gasses and local pollution from shipping. Due to political regulations, changes might be headed for the maritime industry. The goal is to apply zero or low emission propulsion system in a vessel to meet the upcoming requirements, and create a cleaner environment than today.

Nasjonalt Vindenergisenter (NVES) is located in close proximity to Smøla wind farm, and their goal is to increase the demand and knowledge of wind power. NVES are currently working towards establishing a local hydrogen economy, by producing hydrogen via electrical power from the wind turbines. The fish-farming industry is one of the largest industries in Norway and is one of the bigger consumers in Norway of marine diesel. According to Statistisk Sentralbyrå (SSB), in 2018, maritime transportation consumed 314.5 million litres of marine gas oil of the Norwegian shores. 12 million of these was consumed in the area of Trønderlag.[1] This study attempts to estimate the energy expenditure of a single service vessel operating around the island of Smøla, and use this to examine the possibility of using hydrogen as an energy carrier for all or some of the operations of the boat. Smøla is the location for a mid-sized wind farm and is in a good position to produce hydrogen, and in this way create a localised hydrogen economy. This is the long term goal of NVES, and this bachelor's thesis is a piece in this puzzle.

1.1 Structure of the Thesis

This thesis starts off with an introduction to hydrogen energy, where theory about various production methods, storage solutions and compression types for hydrogen are introduced and explained, before an overview of the workings of different fuel cell types are given. In this chapter, the fuel cell technology for the rest of the thesis is chosen.

Next follows a chapter about batteries. Here are primary and secondary batteries introduced, before an explanation of lead-acid and lithium-ion batteries follows. Further, some battery specifications are explained. This chapter ends with an exploration of suitable batteries for marine applications.

The fourth chapter is a brief explanation of the most important aspects of internal combustion engines, before chapter five gives an overview of the current cost of energy storage devices. In this chapter, target cost and lifetime values from the US Department of Energy (US DOE) are compared against both current and target values for cost and lifetime of fuel cell systems from other sources. The cost of hydrogen, storage and batteries are all briefly explained before moving on to the next chapter.

The sixth chapter starts by focusing on global emissions, before narrowing it down to emissions from the maritime sector, and further narrowed down to look at emissions from the Norwegian fleet. After this, various Norwegian maritime technologies are explored. The chapter is concluded by introducing the service catamaran that is the main focus of this thesis.

Chapter seven contains all the assumptions made, along with calculations and methods used in this thesis. The results and discussion is summarised in chapter 8. The chapter is split into sections where the systems first is explained one by one and assessed with regard to their maximum range, given a set of weight and volume limitations. Further, the systems are compared in terms of range, economy, and performance. A summary of the results are presented and a discussion of these results follows. The chapter ends in a recommendation of a technology for the vessel.

Finally, in chapter nine, a conclusion of the findings are presented. Following this, chapter ten presents some possible future work for those who would like to pursue this path further.

1.2 Main Tasks

The main objective of this thesis was to investigate the possibilities and options for implementing a zero-emission drive system in a short- to medium-range marine service vessel used by the Norwegian fish farming industry. The main task was to collect and calculate consumption data and use this to estimate the energy demand and climate gas emissions of the ship. This consumption estimate made it possible to uncover which solutions are feasible and if it is technologically possible and economically viable in today's market to replace diesel as the prime mover in this class of ships.

1.3 Motivation for the Thesis

The impact of human civilisation on the global climate has become alarmingly apparent, and it is vital to reduce greenhouse gas emissions to avoid the most drastic climate changes. One of the considerable contributors to these emissions is the marine industry, as it uses primarily marine diesel to fuel their ships. In order to migrate away from fossil fuels, the implementation of zero-emission systems is required. The team will study this potential, the available technologies, and if the technology is ready for implementation in marine environments.

2 Introduction to Hydrogen Energy

Hydrogen (H_2) is the lightest element in the periodic table at 1.008 g/mol. 70 % of the earth's surface is water, making hydrogen an abundant element with 0.9 Wt% is present at all time in the air, and it can only be found in combination with other elements such as in water (H_2O). Hydrogen has no colour, odour or taste. Pure hydrogen does not have any environmental impact. It is environmentally friendly, does not pollute the ground and groundwater, or creates any harmful emissions when used right, and it reacts readily with other elements. This makes hydrogen an interesting element as a fuel from an environmental perspective. When referring to hydrogen it is usually in its gaseous state, but at sufficiently low temperatures it exists in both liquid and solid states. In table 1, the different states are listed with its temperatures and densities [2][3][4, p. 378].

State	Temperature [K]	Density [kg/m^3]
Gas ($\mathbf{H_{2(g)}}$)	273	0.0899
Liquid ($\mathbf{H_{2(l)}}$)	20.4	71
Solid ($\mathbf{H_{2(s)}}$)	4.2	89

Table 1: Showing the different states of hydrogen [2]

2.1 Hydrogen Production

There are several methods available for producing hydrogen. As mentioned previously, hydrogen does not occur in a pure state, but in combination with other elements. It is necessary to separate the constituting parts of water to produce it. This makes hydrogen regarded as an energy carrier, as it must be produced from other sources of energy. Several types of energy sources, like nuclear power, fossil fuels or renewable energy can be used for this production [3].

Hydrogen can, under the right conditions, be considered a clean energy alternative to today's carbon industry. It is possible to use hydrogen to generate electrical energy, but the power used to obtain the hydrogen must be clean for it to make any sense to use it as a replacement for fossil fuels. The process can not result in any climate gas emissions for it make sense from an environmental perspective. There are three main methods for extracting hydrogen used today, and they are known as brown, blue and green hydrogen [3].

2.1.1 Brown Hydrogen

Gasification is a process of producing hydrogen. A carbonaceous material like oil, coal or biomass is dried, and heated to above 700 °C without combusting. This is done by reacting carbonaceous material with oxygen and steam. The products of this process are carbon monoxide, carbon dioxide and hydrogen, as shown in equation 1.

$$\text{Carbonaceous material} + O_2(g) + H_2O(g) \longrightarrow CO(g) + CO_2(g) + H_2(g) + \text{other species} \tag{1}$$

In order to increase the production of hydrogen, a water-gas shift reaction is used. From equation 2, one can see that when reacting carbon monoxide with steam, carbon dioxide and hydrogen are produced, and the total yield of hydrogen is increased [3][5].

$$CO(g) + H_2O(g) \longrightarrow CO_2(g) + H_2(g) + \text{Heat} \tag{2}$$

Gas Reformation

The gas reforming method uses natural gas, biogas or liquid-petroleum gas, to produce hydrogen. Natural gas steam reforming is the most widespread method of obtaining hydrogen today. Natural gas mainly consists of methane (CH_4). Equation 3 shows that when methane and steam reacts, pure hydrogen gas and carbon monoxide (CO) are produced.

$$CH_4(g) + H_2O(g) \longrightarrow CO(g) + 3H_2(g) \tag{3}$$

The carbon monoxide is then reacted through the same water gas shift process with carbon dioxide and hydrogen as products, as shown in equation 4.

$$CO(g) + H_2O(g) \longrightarrow CO_2(g) + H_2(g) \tag{4}$$

For every four moles of hydrogen, one mole of carbon dioxide is created. The molecular weight of hydrogen is 1.008 g/mol, and carbon dioxide has a per mole weight of approximately 44 g/mol. This equates to a weight ratio of about 11. This means that for every kg of hydrogen, about 11 kg of CO_2 is created [5].

2.1.2 Blue Hydrogen

Hydrogen produced from gas reforming or gasification with carbon capture and storage (CCS) is called blue hydrogen. CCS is a method used to store CO_2 long term to reduce climate gas emissions. As an example, in Norway, Equinor is capturing and storing CO_2 from steam reforming using CCS on the Sleipner field by storing CO_2 one kilometre under the sea bed in a salt reservoir. There are several other ways to use CCS, but this is beyond the scope of this project [3][6].

2.1.3 Green Hydrogen

Hydrogen produced with electrolysis is called green hydrogen. An electrolyser uses an electrical current to split water into hydrogen and oxygen. Regarding the electrical power mix used in the electrolyser, there are no international standards that states that for the hydrogen to be green it has to come from renewable energy sources. There are two mature methods used today, Alkaline Water Electrolysis (AWE) and Polymer Electrolyte Membrane Electrolysis (PEME). Two other options are Solid Oxide Electrolysis Cell (SOEC) and Molten Carbonate Electrolysis Cells (MCEC), but they are under development. Figure 1 shows how the elements behave in AWE and PEME [3][7, p. 164].

2.2 Water Electrolysis

2.2.1 Alkaline Water Electrolysis

This hydrogen production method gives a high purity for hydrogen of 99,7 % and operates between 60-200 °C, with energy efficiencies from 55-69 %. The alkaline water electrolyte used has a pH level higher than 7, and the liquid solution contains potassium hydroxide or sodium hydroxide. A diaphragm is used to separate the two electrodes. The diaphragm has several impacts on the system, but one of the qualities is that it works as an ionic current barrier. Water is split on the cathode, where the products are hydrogen gas and hydroxide anions. The loaded hydroxide moves through the diaphragm to the anode side where the electrons are absorbed. The hydroxide ions are oxidised and the products are water and oxygen gas. These reactions, and the rest of the reactions mentioned further down in this sub-chapter are show in table 2. Figure 1 illustrates the internal chemical reactions going on inside an alkaline water electrolysis cell [3][7, p. 156][8, p. 116-117].

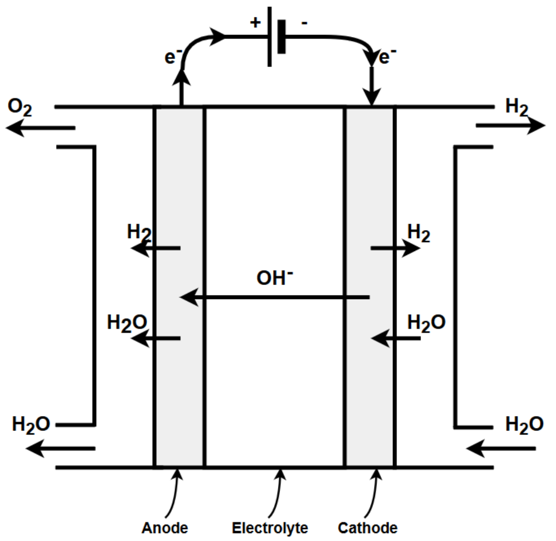

Figure 1: Illustration of Alkaline Water Electrolysis, adapted from the following source [9]

2.2.2 Polymer Electrolyte Membrane Water Electrolysis

Figure 2 shows a Polymer Electrolyte Membrane (PEM) water electrolysis cell.

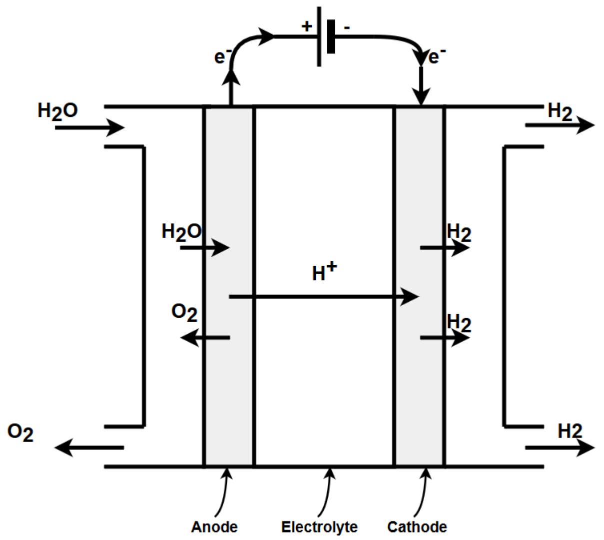

Figure 2: Illustration of Proton Exchange Membrane water electrolysis cell, adapted from the following source [9]

PEM water electrolysis uses a solid acidic electrolyte membrane to split water and produce pure hydrogen with a bit lower purity rate than from AWE. Nafion membrane is a commonly used membrane. It is called Proton Exchange Membrane electrolysis (PEME) because the membrane transports hydrogen protons from the anode to the cathode. The efficiency of a PEM electrolyser depends on the temperature within the electrolyser. It has efficiencies between 55-66 % when the temperatures are 25-80 °C. When reversing the process of the electrolyser it can be used as a fuel cell. Liquid water separates on the anode and the reaction result in oxygen and hydrogen protons and electrons. The hydrogen proton goes through the membrane and reacts with the electron producing hydrogen [3][7, p. 159][8, p. 121-122].

2.2.3 Solid Oxide Water Electrolysis

Figure 3 shows that the Solid Oxide water electrolysis (SOWE) cell has two gas channels where one transports steam and hydrogen gas to the cathode, and the other transports air to the anode. The solid electrolyte in the middle is made of a ceramic material that can handle high temperatures and transport oxygen ions. The electrolyte often consists of yttrium-stabilised zirconium (YSZ) and can operate above 700 °C. One of the big challenges is developing materials that can handle such high temperatures.

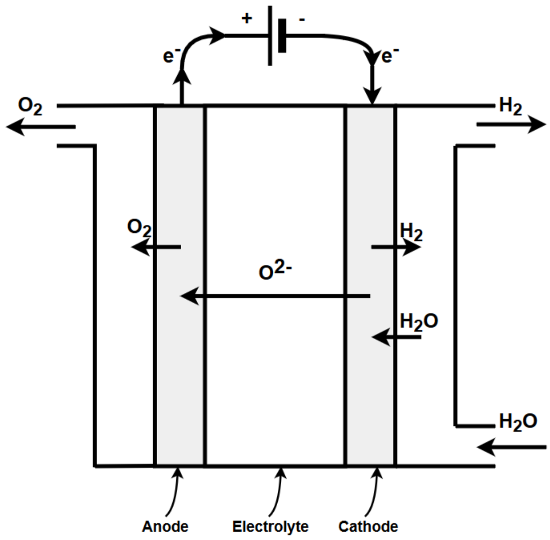

Figure 3: Illustration of Solid Oxide Water Electrolysis Cell, adapted from the following source [9]

In table 2 under SOWE, it shows that steam is split on the cathode, into hydrogen gas and oxygen ions. On the anode side, the oxygen ions react with the anode, producing oxygen gas and electrons [7, p. 162][8, p. 129-130].

2.2.4 Molten Carbonate Water Electrolysis

Molten Carbonate Electrolysis Cell (MCEC) is another high-temperature electrolyser. It operates between 100- 500 °C. It can also be used as a fuel cell by reversing the electrolyser process. On the cathode side, steam and carbon dioxide react and produce hydrogen gas and carbonate ions, which can be seen in figure 4.

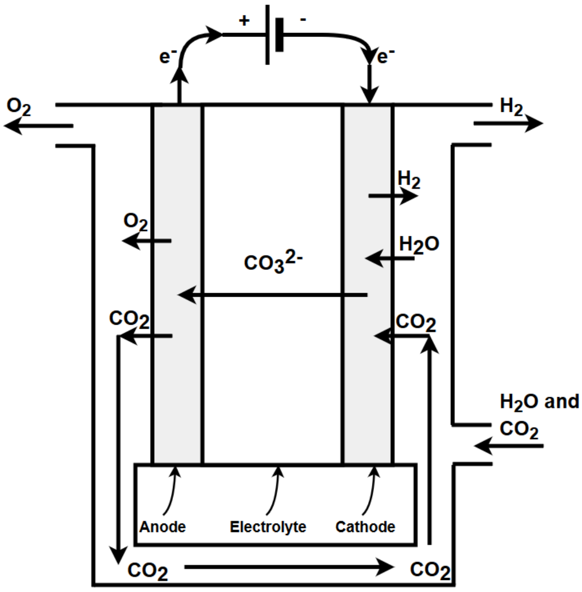

Figure 4: Illustration of Molten Carbonate Water Electrolysis Cell, adapted from the following source [9]

The carbonate ions are transferred through a solid alkaline membrane to the anode. The products on the anode side are carbon dioxide and oxygen gas [7, p. 164, 186]. These reactions, along with the rest of the reactions mentioned for the other electrolysis reactions, are gathered below in table 2.

Fuel Cell	**Anode Reaction**	**Charge Carrier**	**Cathode Reaction**
PEMWE	$2\,OH^- \longrightarrow H_2O + \frac{1}{2}O_2 + 2\,e^-$	H^+	$2\,H^+ + e^- \longrightarrow H_2$
AWE	$2\,OH^- \longrightarrow H_2O + \frac{1}{2}O_2 + 2\,e^-$	OH^-	$2\,H_2O + 2\,e^- \longrightarrow H_2 + 2\,OH^-$
MCWE	${CO_3}^{2-} \longrightarrow \frac{1}{2}O_2 + CO_2 + 2\,e^-$	${CO_3}^{2-}$	$H_2O + CO_2 + 2\,e^- \longrightarrow H_2 + {CO_3}^{2-}$
SOWE	$2\,O^{2-} \longrightarrow O_2 + 4\,e^-$	${O_2}^-$	$H_2O + 2\,e^- \longrightarrow H_2 + {O_2}^-$

Table 2: A summary of the internal reactions of the mentioned water electrolysis cells. Adapted from [7]

2.3 Hydrogen Storage

Hydrogen has the highest energy per mass of any fuel available today, but it has a low energy per volume at a higher temperature and atmospheric pressure. This can be seen in figure 5. This means that one of the main challenges in the application of hydrogen as a fuel is storing it in a compact, convenient, safe and affordable way. Hydrogen can be stored in either compressed, liquid, in solids or metal hydrides. It is also possible to store it in a chemically bonded organic liquid, such as methanol. In this thesis, we will focus mainly on compression storage. [10]

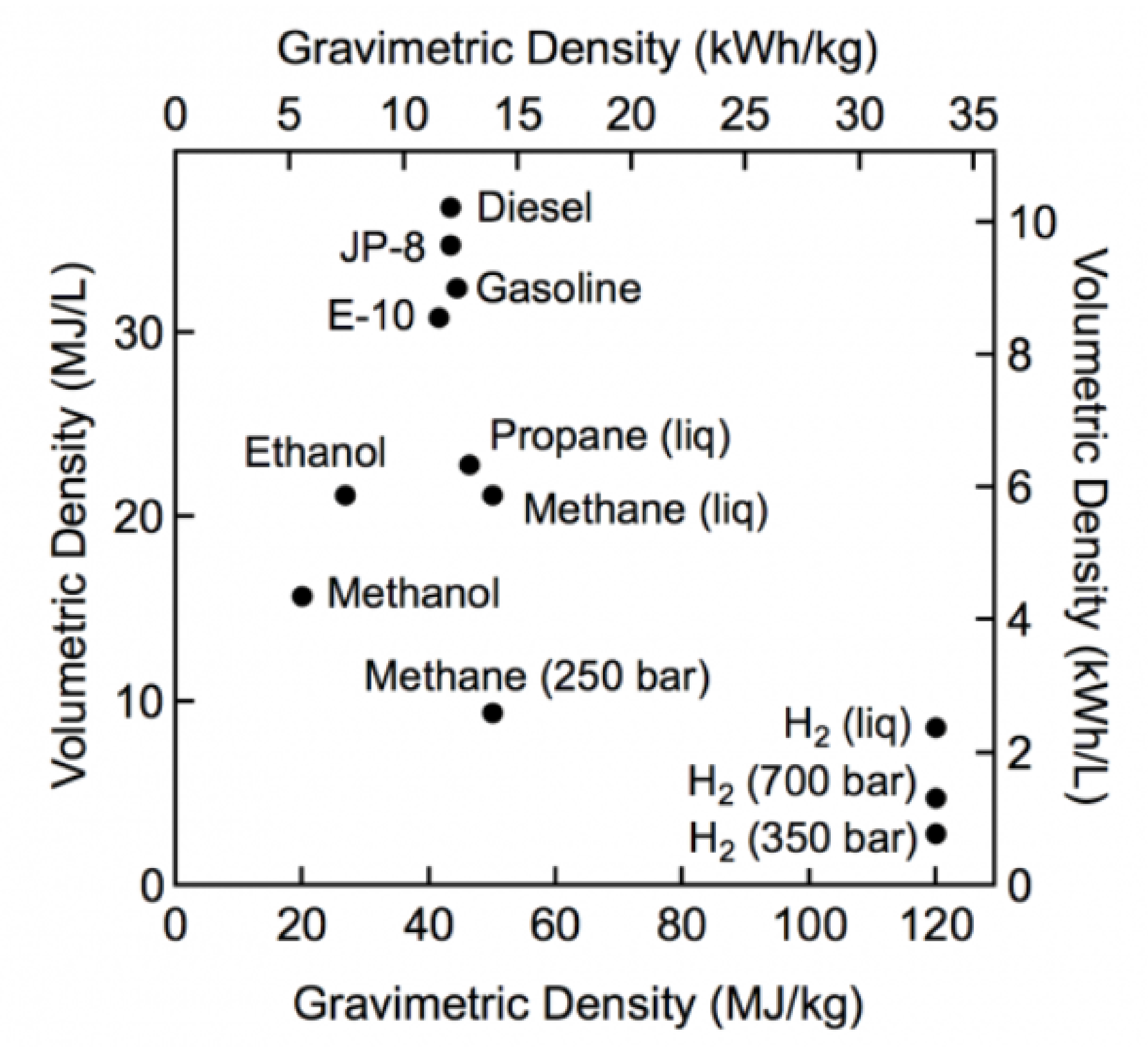

Figure 5: Volumetric and gravivmetric density of different fuels [10]

2.3.1 Liquid Cryogenic Storage

Cryogenic hydrogen (LH2) uses a device to cool the hydrogen. As seen in table 1, hydrogen is in liquid form at 20.4 K (-253 °C) at atmospheric pressure. Cooling the hydrogen to these temperatures turns the hydrogen into a liquid that can be stored at low pressures (below 10 bars) in a highly insulated container.

This increases the energy density, but the cooling process demands 30-40 % of the total energy. There is also some hydrogen lost to evaporation in a process known as boil-off. This lowers the efficiency of the storage, as hydrogen turns to gas that is lost to the atmosphere with the current methods of transferring and storing LH2 [11, p. 19]. The capacity of LH2 is currently in the range of 5-7 Wt%, as seen in figure 6.

USDOE targets for liquid storage

- 1.5 kWh/kg system (4.5 Wt% hydrogen)
- 1.0 kWh/l system (0.030 kg H_2/l)
- $10/kWh ($333/kg stored hydrogen)

2.3.2 Compression Storage

The most common forms of hydrogen storage for transportation today is to compress the gas to 350 and 700 bar. 700 bar is mostly used in smaller vehicles, such as cars where space is a limiting factor for the size of the tank, while 350 bar is common in larger applications, such as busses and trailers where space is less of an issue. There are several different types of storage vessels for compressed gas on the market today. This is divided into four categories with different qualities shown in table 3. The current capacity of compressed hydrogen is in the range of 3-4 Wt% for 350 bar, and 2.5 - 4.5 Wt% for 700 bar, as seen in figure 6. Table 3 shows the approximate weight relation of the type of tank for each kg of hydrogen it can safely contain, along with some of the main advantages and disadvantages for the tanks.

	Material	**kg/kg$_H2$**	**Advantage**	**Disadvantage**
Type 1	Solid steel	~80	- Cheap	- Heavy
Type 2	Thinner solid steel with wire wrapping in key areas	~50	- bigger capacity - lower weight	- Price
Type 3	Aluminium composit core wraped in carbon fiber	~20	- bigger capacity - lower weight	- Price
Type 4	Plastic bladder wrapped in carbon fiber, and covered in resin	~13	- Extremely light - High volumetric density	- Price

Table 3: Different classes of gas storage tanks

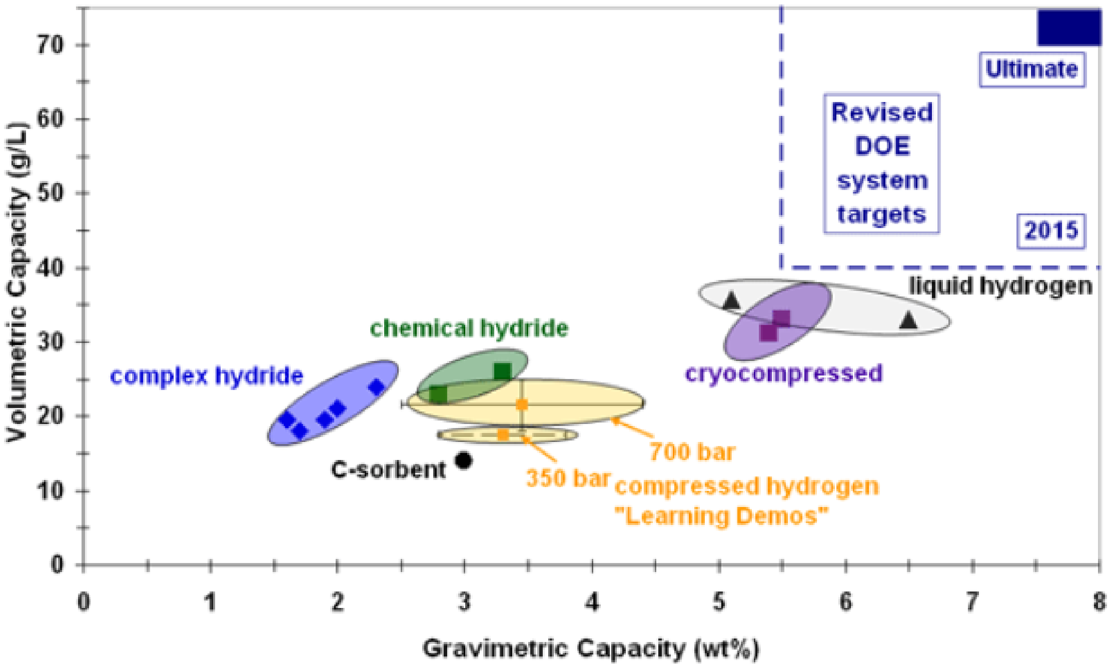

Figure 6: USDOE's current capacity of hydrogen storage solutions [10]

2.4 Hydrogen Compression

When the gas is compressed it takes up less space. This increases the volumetric density of the gas and allows for more energy to be stored in a given volume. The compression-ratio of hydrogen is somewhat proportional (1:1) at lower pressures(below 100 bar), but decreases at increased pressures. Doubling the pressure from 100 to 200 bar at 25°C increases volumetric density with a factor of 1.4. The equation that governs the states of the hydrogen is given by equation 5 [2, p. 98].

$$(p+\frac{\alpha \cdot n^2}{V^2}) \cdot (V - n \cdot b) = n \cdot R \cdot T \tag{5}$$

Where:

- p = Gas pressure [Pa]
- α = Inter-molecular force H2(g) = 24.7170 $[L^2 \cdot kPa \cdot mol^{-2}]$
- V = Volume $[m^3]$
- R = Individual Gas constant = 4124 $[J \cdot K^{-1} \cdot Kg^{-1}]$
- T = Temperature [K]
- n = Number of moles
- b = Molar volume of hydrogen = 0.0270 [L/mol]

2.4.1 Mechanical Compressors

A compressor is a device that allows work to be translated to pressure. This kind of equipment can be roughly divided into two categories, mechanical and non-mechanical. Mechanical compressors are devices that increase the pressure of a gas by decreasing the volume by inputting mechanical power. There are several types available. The most widespread compressor is the piston compressor. It uses a the same mechanism as a gasoline engine, but in reverse. it accepts power via a crankshaft and compresses the medium in the cylinder via a piston at a constant ratio. These can work up to around 100 bar. Figure 7 illustrates the key components of a general mechanical compressor [2, p. 101].

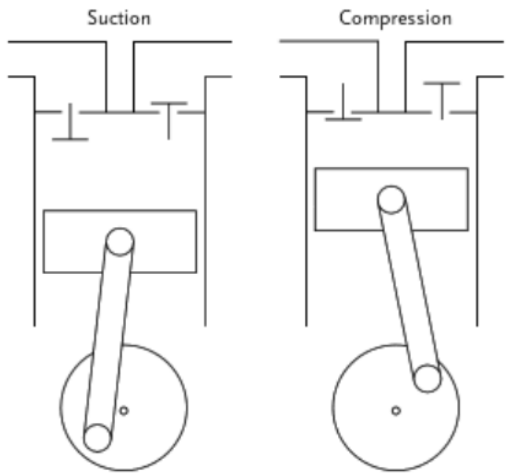

Figure 7: Piston Compressor [2]

Another type is the diaphragm compressor, which is shown in figure 8. This works on the same concepts as a piston compressor, but it adds a membrane made from a suitable materials. This membrane is driven by the piston via a hydraulic fluid. This removes the need for lubrication, and because of this, it is often used where contamination is a problem [2, p. 101].

2.4.2 Non-Mechanical Compressors

These are devices that work without any moving parts and can use thermal energy as the work input. These have big advantages over mechanical compressors, as they are smaller, lighter, and does not need to convert electrical energy to mechanical via motors.[2].

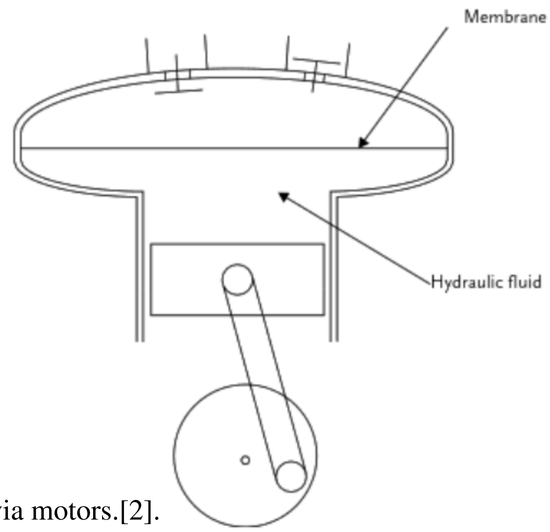

Figure 8: Diaphragm Compressor [2]

2.4.3 Metal Hydride Compressors

These use a thermally driven adsorption and desorption-process. This process works as follows:

1. Adsorption at low temperature and pressure.
2. Heating to high temperature and pressure by heat source.
3. Desorption at high temperature and pressure
4. Cooling to low temperature.

This process is batch driven, as it takes in a given amount of gas, and compresses it. Several units can run in parallel and out of phase, to produce a semi-continuous stream of high-pressure gas. The advantages of this type of compressor are that even though the efficiency is lower than a mechanical unit, it is possible to lower the price as the input energy can come from waste energy or other sources of heat. [2].

2.4.4 Electrochemical Compressor

This is based on the Proton Exchange Membrane. It oxidises hydrogen on the anode, and because of the energy supplied, the hydrogen is transported to the cathode, where the gas will be available at a higher pressure. This is basically running a fuel cell in reverse [2].

2.4.5 Work Required to Compress Gas

When storing energy in the form of compressed hydrogen, work has to be put in to increase the pressure. To calculate the energy input, there are two idealised cases to consider. Firstly, one looks at the case where the compression gives no thermal energy to the environment. This is known as an adiabatic compression, and can be calculated by equation 6. Secondly one has to consider the ideal case of a compression that occurs at a defined constant temperature. This is known as isothermal compression and can be calculated from equation 7 [2].

$$W = \frac{\gamma}{\gamma - 1} \cdot R \cdot T \cdot \left(\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \tag{6}$$

$$W = n \cdot R \cdot T \cdot ln \frac{p_1}{p_2} \tag{7}$$

Where:

- p = Gas pressure [Pa]
- n = number of moles
- V = Volume $[m^3]$
- R = Ideal Gas constant = 8.3145 $[J \cdot K^{-1} \cdot mol^{-1}]$
- T = Temperature [K]
- γ = Specific heat ratio = $\frac{c_p}{c_v}$

2.4.6 Purification

To be able to store hydrogen reliably in a container, the gas has to be virtually free from impurities. For a system that uses compression, 5 parts per million (PPM) is the upper limit before clogging starts to occur, while for LH2, the limit is 1 PPM. The most common process in industrial applications is the Pressure Swing, adsorption. This process is based on the fact that pressurised gases tend to be attracted to solid surfaces (adsorption). Different gases have different tendencies to adsorb to different materials. By applying this principle, it is possible to separate hydrogen from a stream of mixed gas, by applying pressure to the stream, through a stack of materials that adsorb the impurities. When the filtering stack is out of capacity, the pressure can be lowered, releasing the adsorbed molecules, and the process can start over [2, p. 97].

2.5 Introduction to Fuel Cells

A fuel cell is an electrochemical energy-conversion device that directly converts the chemical potential energy stored in a fuel such as hydrogen gas (h_2), and an oxidant such as oxygen gas (O_2) or air, in the presence of a catalyst into electricity, heat and water through an electrochemical process [12][13]. The waste products can also contain other components, such as carbon dioxide (CO_2), depending on the fuel used.

In some ways, a fuel cell resembles a chemical battery, as both consists of two electrodes and they both produce a current as a product. However, in contrast to most chemical batteries, the reactants of a fuel cell are not stored within the fuel cell itself, but is continuously delivered to the fuel cell during standard operation [14].

The voltage produced by a fuel cell depends upon the fuel used and the reaction taking place. An ideal hydrogen fuel cell produces 1.23 V, but due to irreversible losses, this number will realistically be a little lower [15]. Fuel cells can, however, be stacked together to deliver a higher voltage, which means that they can be scaled to better match the energy and power demand of a given application. This scalability makes them versatile and readily applicable for several different areas of use, such as for transport, power stations, and portable devices [16][17]. A set of fuel cells that are stacked together is called a fuel cell stack, and the size of the fuel cell stack is most commonly given in kilowatts (kW).

Compared to a typical internal combustion engine, a typical fuel cell is often more than two times as effective, depending on the type of fuel cell and if the heat product of the fuel cell process is utilised or not [16][18]. Such a system is called a combined heat and power system (CHP).

A fuel cell can, in theory, use any oxidisable species as a fuel, but hydrogen, with its high theoretical power density, is the fuel that is most commonly used. Hydrogen is also easily catalysed, and when hydrogen reacts with oxygen, for example from the air, the waste products are just heat and water, as shown in 5 and is therefore considered a zero-emission fuel [19][20].

There are no combustion processes involved in the use of fuel cells, and as long as a carbon-free fuel is used, there are no CO_2 emissions related to the day-to-day operation of a fuel cell. The clean waste products and hydrogen's high theoretical power density, make hydrogen an excellent fuel for a fuel cell [19].

There are several different types of fuel cells, each with certain membranes, electrolytes, electrodes and fuels. Due to this, they also have their own advantages and disadvantages which governs their areas of application. Due to the scope of this thesis, hydrogen fuel will be the main focus of the rest of the chapter. In table 4, some of the fuel cell technologies that are available on the market today are mentioned, along with some information about each of them.

Technology	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEMFC)	Perfluorosulfonic acid	<120°C	<1 kW - 100 kW	60% direct H2, 40% reformed fuel	Backup power, Portable power, Distributed generation, Transportation, Specialty vehicles	Solid electrolyte reduces corrosion and electrolyte management problems; Low temperature; Quick start-up and load following	Expensivecatalysts; Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassiumhydroxide soaked in a porous matrix, or alkaline polymermembrane	<100°C	1 kW - 100 kW	60%	Military, Space, Backup power, Transportation	Wider range of stablematerials allows lower cost components; Low temperature; Quick start-up	Sensitive to CO2 in fuel and air; Electrolyte management (aqueous); Electrolyte conductivity (polymer);
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150°C - 200°C	5 kW - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymermembrane)	40%	Distributed generation	Suitable for CHP; Increased tolerance to fuel impurities	Expensive catalysts; Long start-up time; Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600°C - 700°C	300 kW - 3 MW, 300 kW module	50%	Electric utility, Distributed generation	High efficiency; Fuel flexibility; Suitable for CHP; Hybrid/gas turbine cycle	High-temperature corrosion and breakdown of cell components; Long start-up time; Low power density;
Solid Oxide (SOFC)	Yttria stabilized zirconia	500°C - 1000°C	1 kW - 2 MW	60%	Auxiliary power, Electric utility, Distributed generation	High efficiency; Fuel flexibility; Solid electrolyte; Suitable for CHP; Hybrid/gas turbine cycle	High temperature corrosion and breakdown of cell components; Long start-up time; Limited number of shutdowns;

Table 4: A summary of key figures and factors of some of the most promising hydrogen fuel cell technologies on the market [16]

To compare fuel cells against each other to find out which technology is better suited for a task, one must take into account the set of criterion for the given situation. In this thesis, the fuel cell system faces numerous restrictions as its purpose is to power a small maritime vessel. Phosphoric Acid fuel cells (PAFC), Molten Carbonate fuel cells (MCFC) and Solid Oxide fuel cells (SOFC), all have their strengths in stationary applications where they can function as combined heat and power (CHP) systems, which will be beneficial for the electrical efficiency of the system. MCFC and SOFC can also be used in maritime transport, but is better suited for very large ships where the need for a constant electrical power supply is crucial. Further, due to Alkaline fuel cell's (AFC) need for a pure supply of oxygen, which triggers the need for a second tank and thus require a far greater volume for the total fuel cell system, Proton Exchange Membrane fuel cells (PEMFC) is what seems to be the most suitable fuel cell technology for this project.

2.5.1 Proton Exchange Membrane Fuel Cell

Below in figure 9, a basic sketch of the most important workings of a Proton Exchange Membrane fuel cell (PEMFC) is shown.

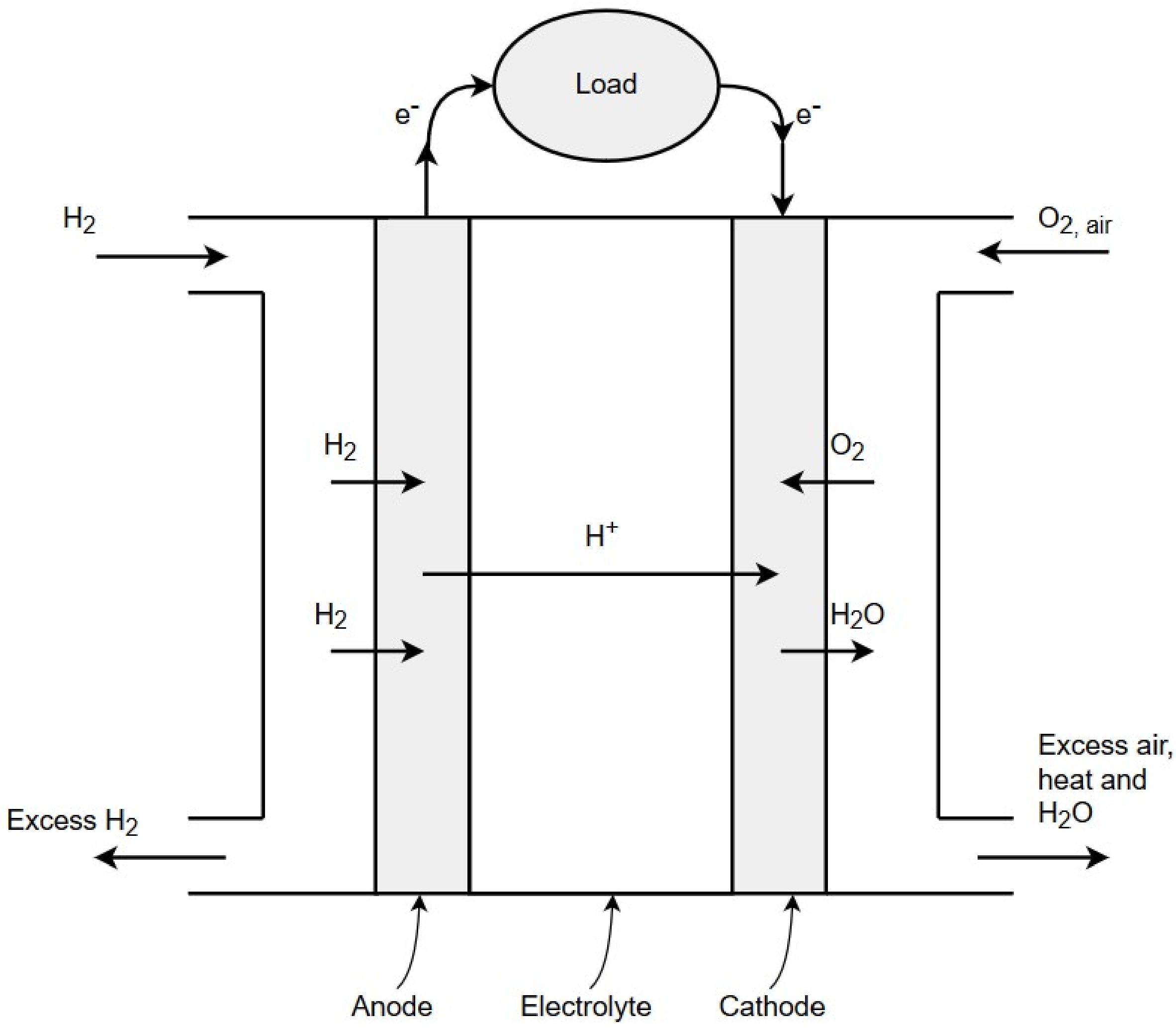

Figure 9: Illustration of Proton Exchange Membrane Fuel Cell, adapted from the following source [9]

The Proton Exchange Membrane Fuel Cell (PEMFC) is considered to be the most mature fuel cell technology, and it has a wide spectrum of areas of application [7]. It was invented in 1960 and was originally intended for NASA's Gemini spacecraft. Since then, the overall cost has been drastically reduced by improving the electrode and membrane configurations and reducing the amount of platinum used for the catalyst [21], and today, the PEMFC is the leading fuel cell technology in the transportation sector [22]. PEM can also stand for polymer electrolyte membrane, but in this thesis proton exchange membrane is meant when PEM is mentioned [7].

The PEMFC consists of porous electrodes coated with a catalyst of platinum. The catalyst is present at both the PEMFC's anode and cathode to facilitate the redox reactions, namely oxidation of hydrogen at the anode and reduction of oxygen at the cathode [23][22]. Hydrogen gas entering the anode side is split apart and oxidised, leaving two electrons and two protons per hydrogen gas molecule. The protons diffuse through the electrolyte membrane to the cathode side, while the electrons travel through an outer circuit to the cathode side. At the cathode side, oxygen gas is split apart and reduced. Finally, the protons and the reduced oxygen combine to form water. These reactions are shown in figure 9 and equation 5. This process generates, in addition to electricity, a substantial amount of heat. This heat, which is a waste product when the fuel cell is designed to generate electricity, can, among others, be used as an extra source of heating in stationary applications where heating is required, such as in buildings.

2.5.2 Alkaline Fuel Cell

Similarly to the PEMFC, the Alkaline Fuel Cell (AFC) was also used by NASA. The alkaline fuel cell was first developed in 1960 and was used by the Apollo space program to supply the spacecraft with water and the electric power needed for onboard applications. It has now become one of the most efficient fuel cell technologies. This type of fuel cell has not had its development affected as much by costs as some of the other fuel cell technologies, as it has often been used for remote power applications in space, military and undersea industries, where the economic aspect not necessarily is the primary concern. To be a viable option in the commercial markets, however, there has been an increased focus on lowering the cost of this technology by looking at cheaper alternatives for various components, such as the electrodes [24].

The electrolyte in an alkaline fuel cell consists of an aqueous solution of potassium hydroxide (KOH), which transfers hydroxide ions (OH^-) between the electrodes while the electric current goes through an outer circuit. Alkaline fuel cells are prone to carbon dioxide poisoning, which occurs due to the solidification of alkaline carbonates in the electrolyte when carbon dioxide is present in the cell. To avoid carbon dioxide from entering the cell, the AFC need a supply of pure oxygen, as carbon dioxide is present in the air. This raises a need for a second tank, one with hydrogen and one with pure oxygen [25]. An illustration of an Alkaline fuel cell can be found below in figure 10.

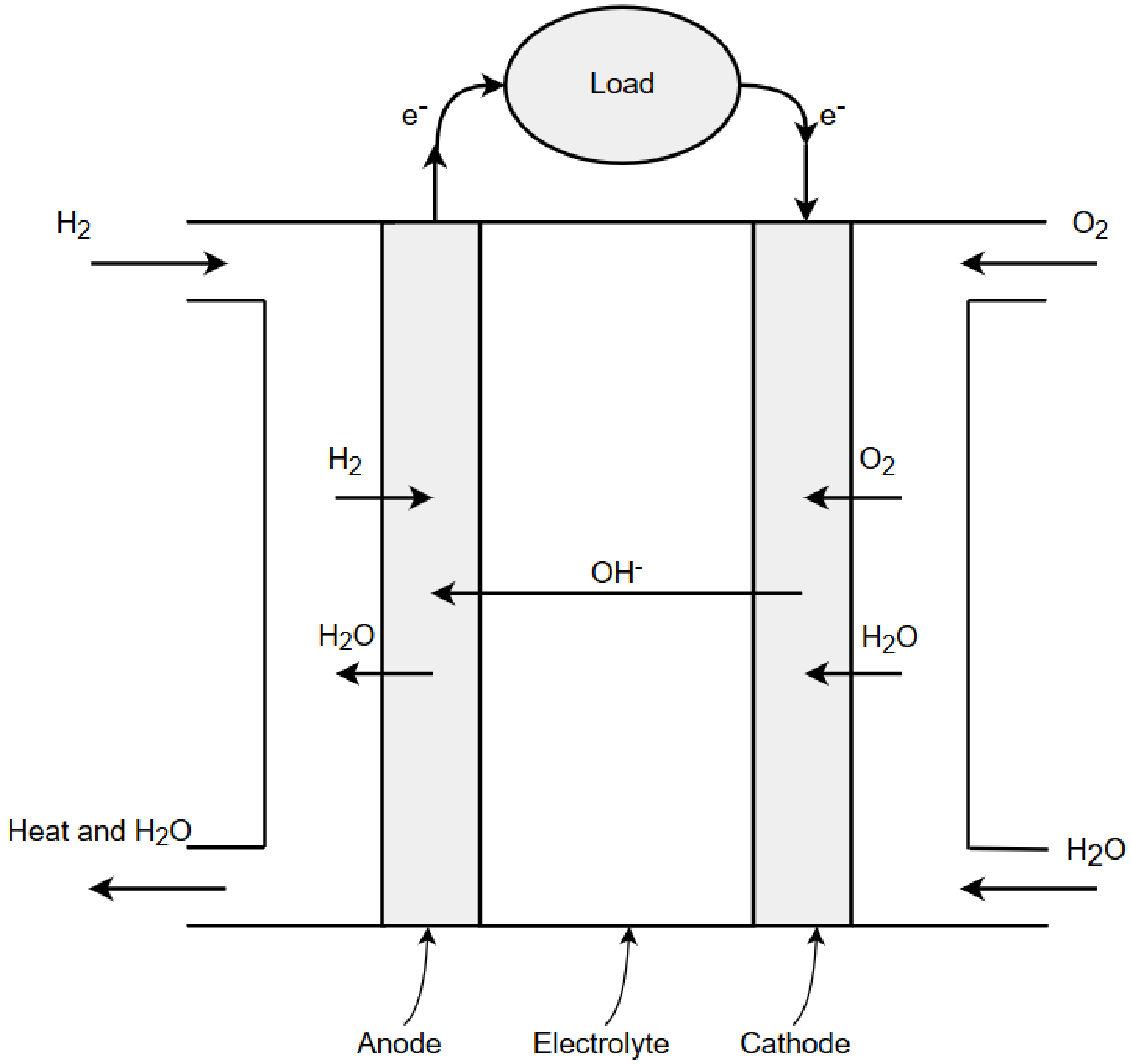

Figure 10: Illustration of Alkaline Fuel Cell, adapted from the following source [9]

2.5.3 Phosphoric Acid Fuel Cell

The Phosphoric Acid Fuel Cell (PAFC) is not as prone to impurities in its fuel as the AFC, which eliminates the need for an extra tank for pure oxygen. However, it requires an expensive platinum catalyst, and due to the acidic environment within the fuel cell, corrosion resistant materials. These limitations, along with a few others, have caused some experts to lose faith in this technology. The workings of a PAFC is similar to the PEMFC, except that the electrolyte in a PAFC consists of a liquid phosphoric acid [26].

2.5.4 Molten Carbonate Fuel Cell

This is a high-temperature fuel cell, with a working temperature of 600 °C to 700 °C. Due to this high temperature, the Molten Carbonate Fuel Cell (MCFC) can convert various types of fuels to hydrogen through internal reformation, thus taking advantage of the excess heat which makes cooling less of a challenge [27]. MCFCs are not prone to carbon dioxide poisoning, on the contrary, it needs carbon dioxide supplied at the cathode [28]. Figure 11 shows the reactions and the cycling of the carbon dioxde from the anode and back to the cathode.

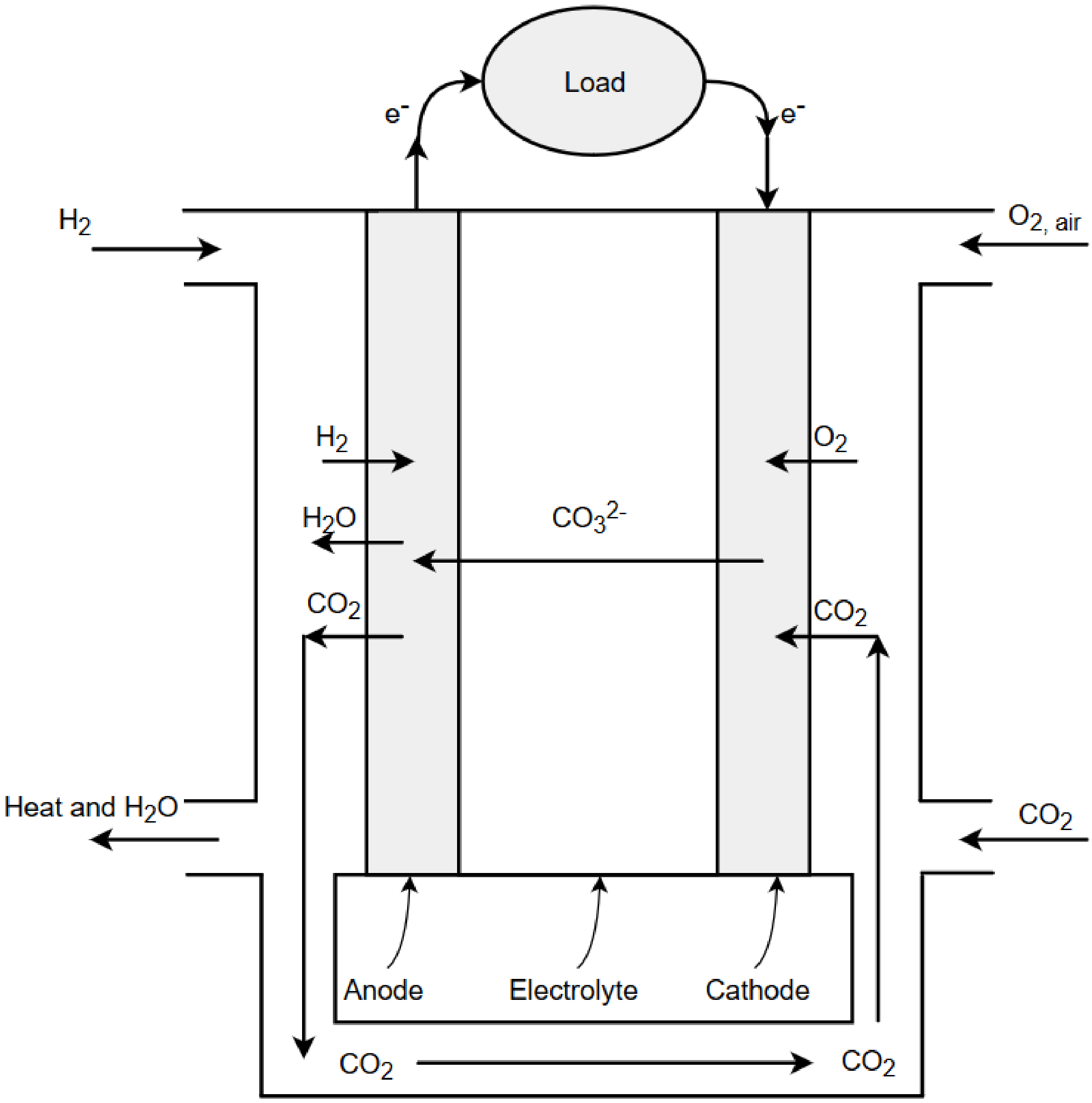

Figure 11: Illustration of Molten Carbonate Fuel Cell, adapted from the following source [9]

The alkali metal carbonates, which the electrolyte is made up of, are solid at room temperature. However, once the cell approaches its temperature of operation, the carbonates become molten, allowing carbonate ions (CO_3^{-2}) to travel through the electrolyte from the cathode to the anode, while the electrons travel through an outer circuit. To get a clearer picture of the reactions of the MCFC, table 5 might be of help.

2.5.5 Solid Oxide Fuel Cells

As the name suggests, this fuel cell uses a solid ceramic electrolyte to transfer ions from the anode to the cathode. Solid Oxide Fuel Cells (SOFC) are being tested and used for a broad spectrum of applications, ranging from small scale (<5 kW) distributed generation to large scale (100 kW to 1 MW) power generation [29]. The SOFC is one of the most efficient technologies for converting chemical fuels into electricity with possible efficiencies above 60 % [30]. When harnessing the heat produced for use in combined heat and power (CHP) systems, the efficiency can be above 80 % [31]. The extra heat can also be used for internal reforming, which opens up for a wider range of possible fuels while reducing the cooling requirements due to the endothermic nature of the reformation process [32]. Below follows figure 12 and a description of the chemical reactions taking place in this kind of fuel cell.

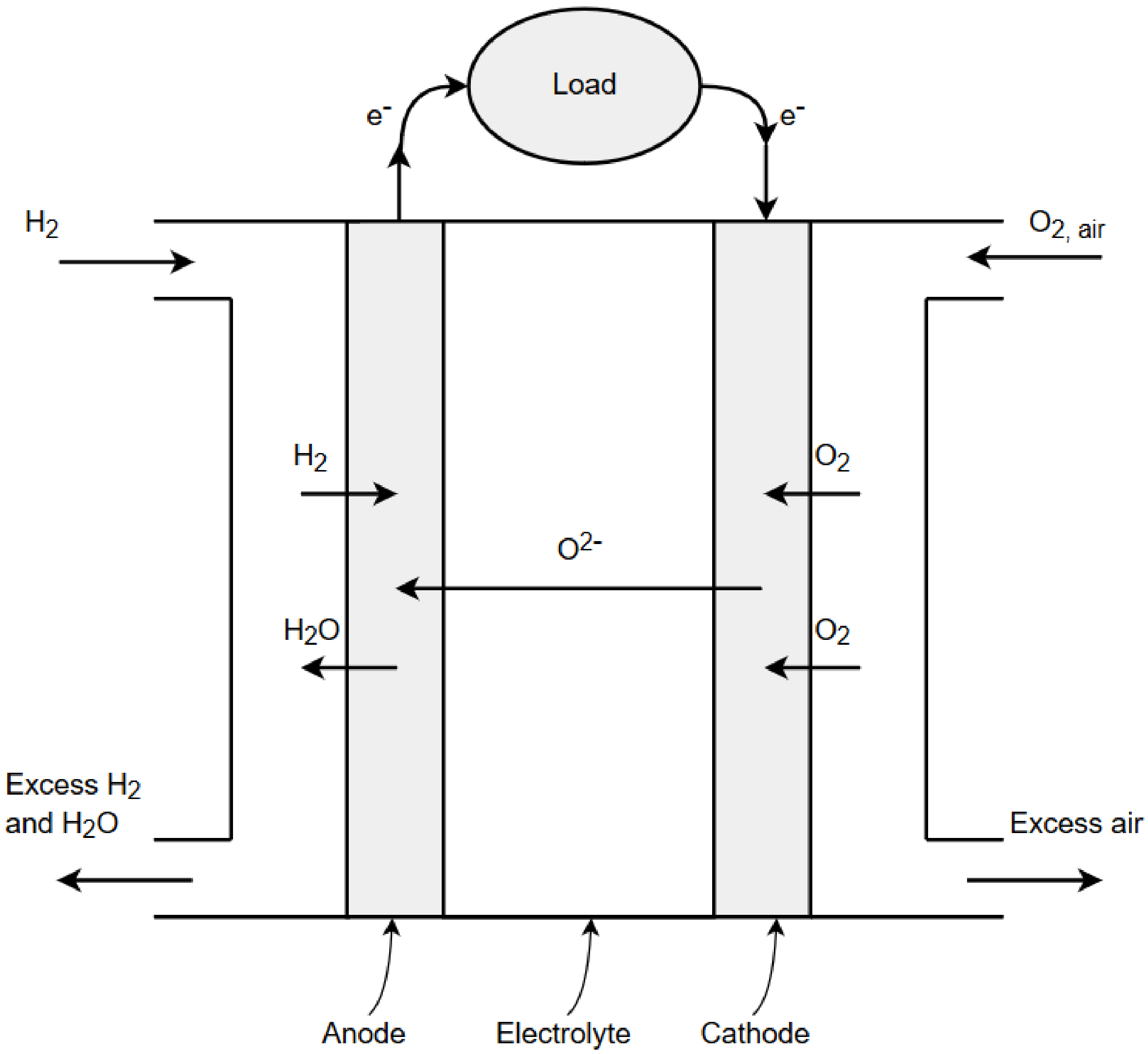

Figure 12: Illustration of Solid Oxide Fuel Cell, adapted from the following source [9]

The charge carrier in a hydrogen SOFC is the oxygen(-2)anion (O^{2-}), which is transferred through the solid ceramic electrolyte between the electrodes, while the electrons travel in an outer circuit, supplying a current to connected external loads. Table 5 summarises the fuel cell reactions explained in this sub-chapter.

Below, in table 5, follows a summary of the reactions for the hydrogen fuel cells mentioned above.

Fuel Cell	Anode Reaction	Charge Carrier	Cathode Reaction
PEMFC	$H_2 \longrightarrow 2H^+ + 2e^-$	H^+	$\frac{1}{2}O_{2(air)} + 2H^+ + 2e^- \longrightarrow H_2O$
AFC	$H_2 + 2OH^- \longrightarrow 2H_2O + 2e^-$	H^+	$\frac{1}{2}O_2 + H_2O + 2e^- \longrightarrow 2OH^-$
PAFC	$H_2 \longrightarrow 2H^+ + 2e^-$	H^+	$\frac{1}{2}O_2(air) + 2H^+ + 2e^- \longrightarrow H_2O$
MCFC	$H_2{}^+CO_3{}^{2-} \longrightarrow H_2O + CO_2 + 2e^-$	$CO_3{}^{2-}$	$\frac{1}{2}O_2(air) + CO_2 + 2e^- \longrightarrow CO_3{}^{2-}$
SOFC	$2H_2 + 2O^{2-} \longrightarrow 2H_2O + 4e^-$	$O_2{}^-$	$O_2\,(air) + 4e^- \longrightarrow 2O_2{}^-$

Table 5: A summary of the internal reactions of the mentioned hydrogen fuel cells [7]

2.5.6 Balance of Plant for Energy Systems

A Balance of Plant (BoP) refers to all the components making up the workings of the system and what is needed to deliver energy except the part that is directly producing the main product of the system, which in the case of a fuel cell system is the actual fuel cell stack. The BoP may contain components or parts such as the heat exchangers, pumps, compressors, intercoolers, valves, tanks, sensors, power electronics, air preheaters and more [33].

3 Introduction to Batteries

A battery is a device that stores electrical energy in a form of chemical energy and used as a portable source of power. A rapid technological development have increased the performance and life expectancy of batteries, making them more competitive and less expensive. A battery system can be designed for different purposes. One advantage of using batteries is that it can supply electrical energy when needed. Battery system technology already exists in electrical vehicles (EV) and plug-in hybrid electric vehicles (PHEV). Battery systems can provide a high power output to to electric motors replace completely, or to assist the main engine through peak loads, allowing the engine to operate more efficiently. This opens up many possibilities for fuel consumption reduction, as well as CO_2 and NOx gas emission, with an added benefit of reducing maintenance cost. Implementing battery systems in the marine and offshore industry can have a large impact, in the same way reducing fuel cost, maintenance, greenhouse gases, and local pollution.

There are two main categories of batteries. The single-use primary battery, and the rechargeable secondary battery. [34]

3.1 Primary Batteries

A primary battery has a high energy density during moderate loads. They are often used for powering small electronical devices, such as remote control, calculator, flashlight, hearing-aids etc. They come in various voltages and sizes, as seen in figure 13. Primary batteries are intended as a reliable power supply, but unfortunately, they have a high internal resistance which limits the current flow. When a primary battery is used in a power demanding devices, heat is produced, resulting, in the worst case, a thermal breakdown of the battery [36].

Figure 13: Illustration of Primary batteries [35]

3.2 Secondary Batteries

Secondary batteries, on the other hand, has the ability to be recharged and this makes them more flexible in use. Unfortunately, they have a lower energy density compared to the primary battery. In the later years, the technological development of secondary batteries has accelerated, mostly due to the boom in the sales of electric vehicles. This has led to developing new ways to improve the energy density, methods of charging and lifetime improvement, making them more reliable. Using the battery for energy storage has become a useful tool in the automotive industry. Implementing battery systems in traditional fuel engine systems has increased system efficiency. [34, p. 10]

A secondary battery consists of three main components, two electrodes and one electrolyte. The two electrodes are called the anode and cathode. They are made of different materials, usually metals immersed in a corresponding solution, and separated by an electrolyte. The battery works as a galvanic cell while discharging, and as an electrolytic cell during charging.

An illustration of a galvanic cell and an electrolytic cell is shown in figure 14 and 15, respectively. Both the galvanic cell and the electrolytic cell is an electrochemical cell which contains two electrodes and an electrolyte. When the two electrodes are connected to a load, energy is released by a spontaneous redox reaction, causing the battery to discharge. This reaction can later be reversed by applying a current.

During the redox reaction, one electrode is reduced and the other is oxidised. Electrons released from the oxidation reaction side will be transferred through the circuit and the positively charged ions go into the corresponding solution. At the same time, the other electrode receives electrons, which sticks to the surface of the metal, making the corresponding solution more negative. To maintain equilibrium in each solution, an electrolyte is connecting the corresponding solutions of anode and cathode, that allow the positive and negative charged ions to move freely. In a Galvanic cell a, spontaneous reaction occur, the oxidation reaction occurs on the anode, while the reduction reaction occurs on the cathode [38]. In an Electrolytic cell, a non-spontaneous reaction occurs. The reaction requires electrical energy to induce the reaction. In that case, the anode is positive and cathode negative, and the reaction is reversed [39].

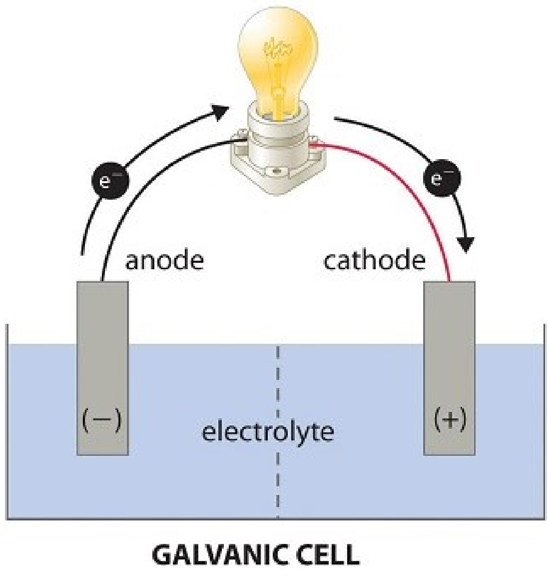

Figure 14: Illustration of Galvanic cell [37]

The voltage across the conductor depends on the types of materials used as electrodes. Each chemical used as electrode has different a standard chemical potential and the potential differences between the positive and negative terminal determines the voltage. A battery module consists of several battery cells connected in series or parallel to increase the system voltage potential. In a galvanic cell, the discharge will continue until the electrodes are at equilibrium, or is disconnected. The rechargeable batteries used in high energy demanding systems is mainly based on lithium-ion and Lead Acid batteries. This is because of their high potential cell voltage and charge/discharge characteristics [40].

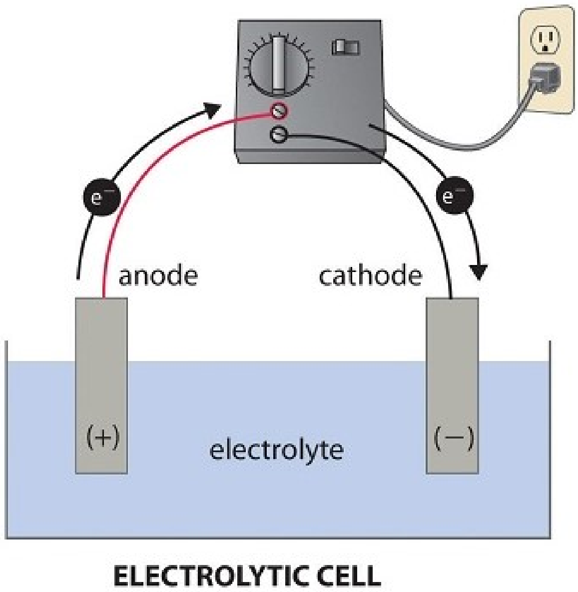

Figure 15: Illustration of Electrolytic cell [37]

3.2.1 Lead Acid Batteries

The Lead Acid battery was invented in 1859 by Raymond Gaston Planté and was the first type of rechargeable battery for commercial use. These types of batteries are cost-efficient, dependable and robust, with the ability to provide high surge current. This is today mainly used for starting engines in non-electrical vehicles, scooters, ships, and backup powers for critical systems. Key specifications are listed in figure 16.

A battery is made from several cells. In lead-acid batteries, a cell is often comprised of interleaved plates made from a lead alloy. The reason for this is that pure lead is too soft and can not support itself. It is necessary to ad small quantities of other metal to add strength and improve the electrical properties of the lead. The additional metal is usually antimony, calcium, tin or selenium [41].

Lead Acid	
Spesific energy [Wh/kg]	20-40
Spesific power [W/kg]	2-200
Energy density [Wh/L]	80-90
Efficiency, η [%]	60-90
SOC [%]	0-100
OCV [V]	2,05
Temperature range [°C]	(-10) - 50

Figure 16: Key Figures Lead Acid [7, p. 117]

The lead-acid battery has the same general structure as the Lithium-ion battery, with two electrodes and an electrolyte. A single positive and negative plate has 2,05 Volt per cell. To increase the battery voltage, several plates can be stacked in a compact arrangement. That gives a higher voltage and greater capacity. Each cell is immersed in a dilute sulphuric acid solution and surrounded by a leak-proof casing and a wire that joins to cells. This results in a heavy and robust unit. [41].

A lead-acid batteries lifetime is compromised when it is close to completely discharged. This is known as deep cycling. This state puts a lot of strain on the battery and the plates start to corrodes and the electrolyte crystallises on the positive electrode. The extent of this corrosion depends on the material being used and the expansion of the material from operating temperatures and acceleration of discharge currents. Every time a lead acid battery is deep cycled, a fraction of the capacity is lost [41]. Figure 17 contains a more visual explanation of the discharge patterns of starter and deep-cycle batteries.

To optimise and improve the function of the battery with regards to the application, two main types of lead-acid batteries have been developed. One type for start motor application, and one type for deep cycle duty. A starter battery also is known as a Starting, Lightning and Ignition battery (SLI). An SLI battery provides maximum power for a brief duration, often needed to start an engine, while a deep cycle battery is optimised to provide continues power, often used in marine applications, industrial equipment and heavy transport vehicles. The chemical composition is similar, but the design varies.

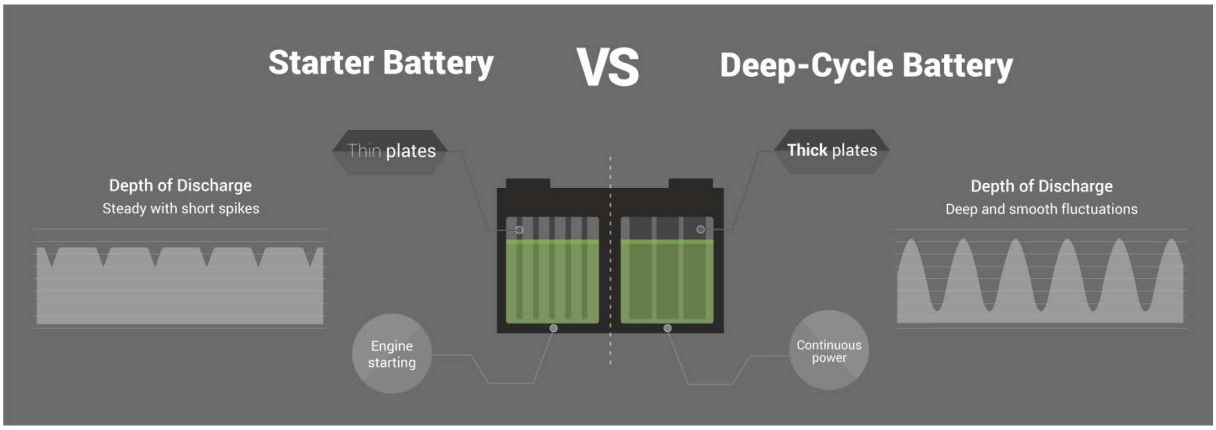

Figure 17: Starter battery and Deep cycle battery [42]

The main difference between a deep cycle battery and an SLI battery is the thickness of the plates within the cells. This is illustrated in figure 17. Thick plates improve the deep cycle abilities, while having many thin plates in parallel achieves low resistance with high surface area, resulting in a higher current capacity. The thickness of the plate varies in regards to what use it is intended for. It is possible to achieve a compromise between an SLI and deep cycle battery. This is often used in buses, trucks and other transport vehicles [41].

The battery life also varies with the depth of discharge. Figure 17 shows the cycle performance of a Deep cycle and SLI battery during full discharge, half discharge and moderate discharge. The performance is quantified by the number of cycles before the capacity is reduced.

3.2.2 Lithium-Ion batteries

Lithium is the lightest solid metal in the periodic table. A Lithium-ion battery (LIB) can have a cell potential up to 4.2 Volt. This gives it a high energy density and capacity compared to other battery technologies. A LIB has a low self-discharge rate, and this makes it flexible in use. Key figures for lithium-ion batteries are listed in figure 18 .

Lithium Ion	
Spesific energy [Wh/kg]	150-250
Spesific power [W/kg]	100-500
Cycles life 10^3	1-20
Energy efficiency η [%]	90-98
SOC [%]	20-90
OCV [V]	3-4,2
Temperature range [°C]	(-20) - 50

Figure 18: Key figures lithium-ion battery [7, p. 117]

LIB technology has become a fast-growing market. Tesla and Sonnen are both one of the leading developers and supplier of a commercial Lithium-ion battery system. These rechargeable batteries are often used in portable applications, such as phone, laptops, electrical tools, as well in electric vehicles. They are also becoming utilised for energy storage in power production from solar and wind power.

One of the major challenges with batteries is to increase energy density and life span. When a battery ages, the capacity degrades. The storage temperature can also have an impact on lifetime. These parameters are important when implementing the battery system in vehicles and other transportation vessels with a long life expectancy. The cycle life is defined as the number of full discharge and charge cycles that the battery can go through before the cell capacity start to degrade. This means at the end of the cycle life, the capacity has changed a fraction, but still has a significant number of discharge and charge cycles left. To maximise the lifetime of the battery system, Tesla Motors has decided to charge the cells to 4.15 Volts which represents a charge of 95% and a lower limit of discharge at 3.0 Volt per cell. In addition to this, Tesla has been developing Lithium-ion chemistry that has achieved better chemical combinations to expand the cycle life and to maintain high capacity and energy density than earlier battery technologies [43].

Lithium-ion battery consists of two electrodes and an electrolyte. Lithium is the anode side, and there are many different composites of the cathode. Most common is Manganese oxide($LiMn_2O_4$), cobalt oxide($LiCoO_2$) and iron phosphate ($LiFePO_4$). These are regarded as disposable. NMC uses nickel-manganese-cobalt as the cathode material [34][39].

Standard Lithium-cobalt oxide battery (LCO) battery discharge reaction. Table 6 shows the characteristics of different type of cathode material in i Lithium-ion battery, while table 7 gives a indication of pricing [7, p 131]. All batteries have a life expectancy. The decomposition process is influenced by recharging cycles, storage temperature, causing a limited lifetime.

Specifications Chemistry	**Li-Cobalt** $LiCoO_2$	**Li-Manganese** $LiMn_2O_4$	**Li-Phosphate** $LiFePO_4$	**NMC** $LiNi\,0.5\,Mn\,0.5\,CoO_4$
Cell voltage [V]	3.8-4.4	3.8-4.1	3.2-3.5	3.8-4.0
Charge limit [V]	4.20	4.20	3.60	4.20
Cycle life	500	500-1,000	1,000-2,000	1,000-2,000
Specific energy $[Wh/kg]$	190	150	160	160
Energy density $[Wh/L]$	560	418	260	260
Thermal runaway °**C**	150	250	270	210

Table 6: Cathode material for Lithium-ion batteries [7, p 131]

Specifications Chemistry	**Li-Cobalt** $LiCoO_2$	**Li-Manganese** $LiMn_2O_4$	**Li-Phosphate** $LiFePO_4$	**NMC** $LiNi\,0.5\,Mn\,0.5\,CoO_4$
Cost (2015/16)				
$[NOK/Wh]$	1.5	1.3	1.2	1.9
$[USD/Wh]$	0.2	0.17	0.16	0.25
Cycle cost				
$[ore/kWh]$	13-134	11-114	11-117	17-167
$[cent/kWh]$	2-18	2 - 15	1 -14	2-22

Table 7: Single cycle costs based on 20 - 90 % SoC lifetime, and 2,000-20,000 cycles [7, p 131]

3.3 Battery Specifications

In this, section some battery specifications will be introduced.

State of charge (SoC) is an expression of a battery's current capacity and is often referred to in a percentage of maximum capacity. When a battery is discharged the term Depth of Discharge (DoD) states how many per cent the battery capacity has been discharged. Equation 8 shows the relationship between SoC and DoD.

$$SoC = 100\% - DoD \tag{8}$$

The C-rate is an expression of discharge and charges current relative to maximum capacity. 1C refers to a charge time of one hour form 0 % SoC to 100 % SoC, which is a full cycle. As the battery capacity goes down with age the term State of Health (SoH) refers to how much charge in coulombs is available for use in the battery at a given C-rate relative to maximum capacity. Ah is a measure of electric charge. The measurement of a battery without load is called Open Circuit Voltage (OCV) [7, p. 111-113].

3.4 Battery for Marine Applications

3.4.1 AKAZEM

A company called ZEM has developed an electrical drive line suggestion for hybrid and purely electrical vessels with a required power demand between 40 - 450 kW. The ZEM driveline consists of AKAZEM battery system, propulsion engine, converter, ZEM controller and can deliverer 230 V or 400 V three-phase power for hydraulic and other power-demanding equipment. The components are adapted to the maritime use and meet the requirements of DNV GL and the Norwegian maritime administration.

The battery system AKAZEM 15 OEM battery is specifically designed for service vessels in the aquaculture industry and fishing vessels, similar to the AKASOL 15 OEM battery system. It as an autonomous IP 67-compliant liquid cooled modular system, making it suitable for vessels with limited space and power requirements up to a 2C power range. It consists of 15 sub-modules connected in series with a waterproof controller unit. Each stack has a capacity of 24.4 kWh, and weighs 253 kg per unit, and can deliver a voltage between 540 - 756 V. The volume of the pack is 1700 x 700 x 150 [mm]. It is possible for the pack to deliverer 150 kW power for 10 seconds and 50 kW continues power delivery. The AKAZEM battery module can be connected in parallel to increase the power and charging capacity. [44] [45]

4 Internal Combustion Engine

One of the most common uses of fossil fuels today is as a fuel source for the four-stroke internal combustion engine (ICE). This type of engine creates works by compressing and burning a mix of air and ignitable fuel to supply energy, which is converted to mechanical motion by a cylinder, piston and crankshaft mechanism. There are two main categories of fuel commonly used; Gasoline and Diesel. The main difference between these engines is the method of igniting the Air/fuel-mix. While the gasoline-engines uses high voltage to create a spark, the diesel engine relies on the conservation of energy by squashing air to 1/30 of the volume. This drastically increases the temperature in the cylinder, which ignites the fuel to produce work via the same piston-cylinder-crankshaft-mechanism as the gasoline engine. In this paper, we will focus on the diesel engine, as it is the prime mover of choice in marine vessels, due to its high torque output at lower RPM. [46]

4.1 Efficiency

The efficiency of a Diesel ICE is in the ideal case 55-60 %. In a real engine, there are several losses, such as friction from bearings, parasitic power used by water and oil pumps, and heat loss in the exhaust. Most modern diesel engines today use a turbocharger that extracts energy from the exhaust stream that would otherwise be lost to the environment. This increases efficiency. To visualise this, it is common to us a Stankey-diagram as seen in figure 19. The efficiency of an ICE is dependant on the state of all components, but it generally lies in the 20-40 % interval. [46]

4.2 Break Specific Fuel Consumption

BSFC is a measurement that can represent the efficiency of a combustion engine. The term break is related to the use of an electrical brake applied to the output shaft to measure the torque of the engine. As previously mentioned, an ICE burns fuel and air to produce rotational power, this power can be calculated from equation 9. The break specific fuel consumption and efficiency can be calculated using equations 10 and 11, respectively.

Mass flow is commonly measured in kg/s, the engine power in kW which gives the brake specific fuel consumption in g/kWh. The mechanical output power is possible to calculate by using angular velocity, ω and Torque, T on the shaft.

After combustion, approximately 30 % of the energy is lost as heat, around 30 % loss in exhaust gases. That gives approximately 40 % of the remaining energy mechanical conversion. In general ICE, the mechanical conversion would have friction loss and pumping losses, this is depending on the engine type and quality. The overall efficiency is expected to be in the area of 25 % - 40 %.

It is possible to calculate the efficiency by a function of the brake specific fuel consumption and the lower heating value (LHV) of the fuel.

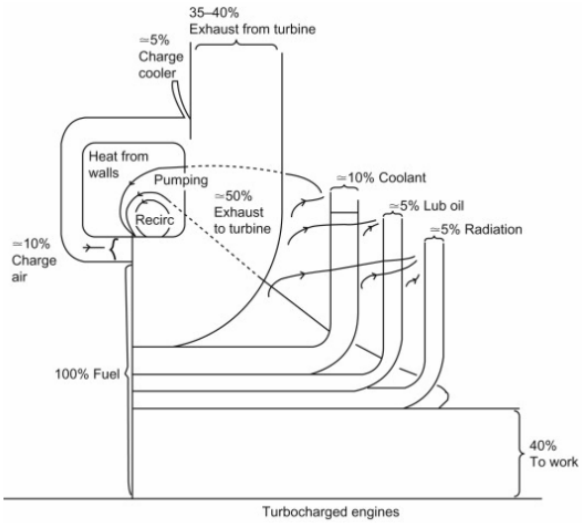

Figure 19: A *Stankey diagram* [46]

$$P_{out} = \omega \cdot T = \frac{\pi \cdot n \cdot T}{30} \quad (9)$$

$$BSFC = \frac{m_f}{P_{out}} \quad (10)$$

$$\eta_f = \frac{1}{BSFC \cdot Q_{LHV}} \quad (11)$$

Where:

- $\dot{m}_f$=fuel mass flow rate - [kg/s]
- P_{out}=effective (break) engine power [kW]
- T_e=effective (brake) engine torque [Nm]
- ω_e=angular velocity [rad/s]
- n_f=fuel conversion efficiency [%]
- BSFC=brake specific fuel consumption [g/kWh]
- Q_{LHV} [kWh/g]

5 Current Cost of Energy Storage Devices

The following section provides an overview of the economic aspects of a fuel cell system including the price mechanisms of hydrogen.

5.1 US Department of Energy Targets

The US Department of Energy (US DOE) has set some target values for various aspects of the hydrogen economy, such as the cost of hydrogen from electrolysis and the cost and lifetime of hydrogen fuel cells for transportation. These targets are by many considered the benchmarks for the industry.

When it comes to the hydrogen from water electrolysis, the US DOE's 2020 target cost for distributed hydrogen production is less than \$2.30/gge, where gge stands for a gallon of gasoline equivalent. As the energy content of a kilogram of hydrogen is approximately equal to a gallon of gas, the target is less than \$2.30/kg_{H2}. Further, their target cost for compressed and dispensed hydrogen at 700 bar in 2020 is less than \$4.00/kg hydrogen, which equates to about 25 NOK/kg and 43 NOK/kg, respectively, when calculated from the 2007\$ used by the US DOE in their report, to 2019\$. This is assuming no taxation of the hydrogen [47]. For comparison, the pump price of hydrogen in Norway from Uno-X is currently about 90 NOK/kg [48].

The US DOE's target value for the durability of hydrogen fuel cells for transportation, are set to be 5,000 hours for 2020, with an ultimate target of 8,000 hours [49]. For comparison of the durability, an analysis performed for single PEM cells tested under automotive load cycling using two different estimation methods and a time-upscaling methodology, found that the lifetime of a cell based on the output voltage, and thus also the lifetime of the fuel cell stack, lied in the range of 436-441 hours of operation for one of the estimation methods and between 508-515 hours for the other estimation method [50]. This is well below the lifetime of a fuel cell stack, as reported in an assessment of fuel cell buses which is already in use in public transport. In the assessment, the expected lifetime of a fuel cell stack is 12,000 hours for the current generation of fuel cells. One of the stacks in the study had exceeded 22,000 hours of operation at the time of the study. The expected lifetime for future generations of fuel cell stacks according to the assessment is in the range of 20,000-25,000 hours of operation [51].

For the cost targets of mass-produced fuel cell systems, the numbers have been gathered from a report contracted by the US DOE, so the values mentioned closely reflects the DOE's targets of 40 \$/kW by 2020, with an ultimate goal of reducing the cost to 30 \$/kW, while also including targets for 2025 [49]. It should be noted that the capacity for mass-producing fuel cell systems does not yet exist, and it will take several years to get to a point where the manufacturing rate of fuel cell systems listed further down is possible [52]. Thus, the costs mentioned are based upon the cost of components and services needed to build a fuel cell system, along with an estimated cost reduction caused by mass production. It is also important to differentiate between the net and gross electric power, which will affect the price per kW of the fuel cell system. The difference between the two is that the gross electric power accounts for the whole fuel cell system, while the net electric power takes into account the electric power that the fuel cell will have to supply to the BoP components for the system to work. This means that the net electric power is the power that the fuel cell system is capable of delivering to auxiliary systems outside of the fuel cell system [53]. The relationship between the net electric power and the gross electric power is given from equation 12, where P is the electric power, and peripheral refers to the BoP components that draw electric power from the fuel cell.

$$P_{net} = P_{gross} - P_{peripheral}[53] \tag{12}$$

The fuel cell prices will depend on the number of units produced. An increased production amount will lower the price of the individual fuel cells, and therefore also the fuel cell system. To account for this, three price estimates will be given, a low, a medium and a high price estimate. In table 8, the price estimates for PEM fuel cells for 2017, along with predictions for the price of PEM fuel cells in 2020 and 2025. Please note that the high price estimates given in the table, corresponds to a low production amount, and the low price estimates, corresponds to a high production amount. Further, in table 9, the estimated prices for a full Proton Exchange Membrane Fuel Cell (PEMFC) system, that is the fuel cell stack and the rest of the components that make up the BoP are given, along with predictions for the price of the PEMFC systems for 2020 and 2025. The last row in table 9 contains information about how large of a portion of the full system price the BoP cost is estimated and predicted to account for. As can be seen from the table, the BoP cost accounts for a higher percentage of the full system when the production amount increases. This is likely due to the fact that the price of the fuel cells decreases as the production amount increases, causing the fuel cells to account for a lower percentage of the total system costs. The OPEX of the fuel cell system will be assumed to be 20 % of the capital expenditure (CAPEX) per annum. This assumption is based upon information from an e-mail conversation with a professor at NTNU that the OPEX of fuel cell systems lies between 10-30 % (Professor Pollet BG 2019, e-mail communication, 27th of April).

Year	**2017**			**2020**			**2025**		
Estimate	High	Medium	Low	High	Medium	Low	High	Medium	Low
$\$/kW_{net}$	118	28	19	112	26	18	96	18	12
$\$/kW_{gross}$	107	25	17	102	24	16	88	16	10

Table 8: Fuel cell stack prices in US Dollars per kW [52]

Year	2017			2020			2025		
Estimate	High	Medium	Low	High	Medium	Low	High	Medium	Low
$\$/kW_{net}$	179	59	45	173	56	43	155	47	36
$\$/kW_{gross}$	163	53	41	157	51	39	141	43	33
BoP [%]	33	51	55	34	52	56	37	62	67

Table 9: Fuel cell system prices [52]

To also get a comparison for the PEMFC system target costs mentioned above, the SF-BREEZE, a high-speed, zero-emission hydrogen fuel cell passenger ferry will be used. The estimated PEMFC CAPEX for the SF-BREEZE, were in the range of $2,500/kW to $1,800/kW [54]. This cost discrepancy between the SF-BREEZE's and the US DOE's PEMFC system CAPEX, can in part be explained by the difference in the assumed manufacturing volume. For the US DOE targets, an assumed production volume between 1,000 to 500,000 PEMFC systems was used for the upper and lower cost ranges respectively [52], while for the SF-BREEZE it is a one time order of a novel system [54]. Due to the large gap between these values, the cost used further in this report will $1,268/kW, which is the mean value between the maximum value of $2,500/kW and the minimum value of $36/kW for the net systems.

5.2 Hydrogen Cost Targets in Norway

Due to a competitive market, exact prices will not be made publicly available, and the prices listed below will not necessarily be completely accurate. However, they should be precise enough to compare the operational expenditures (OPEX) of different energy systems.

Due to the reasons listed above, and based upon a meeting with a representative from TrønderEnergi, we assume a price range of 30 NOK/kg to 50 NOK/kg of hydrogen in Norway in 2019 for compressed hydrogen at 300 bar to 350 bar, from a supplier's point of view (Kvaal B 2019, oral communication, 3rd of April). As mentioned earlier, Uno-X prices their hydrogen at around 90 NOK/kg, but this is the consumer price [48]. The price of hydrogen is vulnerable to several factors, such as if the hydrogen is produced at the location where it will be supplied to the consumer, known as on-site production, or if it needs to be transported from the production facilities and out to the consumers. The hydrogen production price is also dependent on the prices and the various taxes and duties on electricity in a given country. The United States Department of Energy has set their target price for distributed hydrogen in 2020 to \$2.30/kg_{H_2} [55] [56].

In Norway, production from electrolysis is exempt the tax on electricity that the normal consumers experience [57]. So where a consumer in May 2019 would have to pay 0.552 NOK/kWh, not including various grid taxes, the price for electrolysis would be 0.325 NOK/kWh, which is only about 58 % of the original price [58]. This, along with the low price for electricity in Norway makes it cheaper to produce hydrogen from electrolysis in Norway compared to many other countries [59]. A further reduction in cost might be achieved by selling the oxygen, which is a byproduct of the electrolysis process, to industries such as fish farms where the oxygen can be used to in closed fish tanks to oxygenate the fish [60].

Some of the other factors that affect the production cost, and therefore also the price of hydrogen are, among other, the capital expenditure of all the parts for production, the production method and the hydrogen electrolyser technology used, the operational costs of the electrolyser, if the hydrogen is cooled down to a liquid or if the hydrogen is delivered in a compressed state, and if so then to which pressure it has been compressed.

5.3 Hydrogen Storage Cost

Due to a competitive market, there is not a standard price of hydrogen tanks. Table 10 shows a range and an approximate price per kilogram hydrogen gas stored in the tanks. The prices are collected from the report Bærekraftig verdikjede hydrogen has not specified pressurised prices, but (the prices from a meeting with Trønderenergi 03.04.2019) are specified. These prices are specified with an ability to store 395 kg H2 with 300 bar, and 1500 kg H2 with 700 bar. These storage systems are delivered in 38 m^3 container system that is meant for a stationary land-based construction. The price for the 300 bar container system is 2.295 million NOK and for a 700 bar container system have a cost range of 3.680-3.460 million NOK. In table 10 the composite 300 bar container system price will be used as a reference further in this thesis.

Hydrogen storage tanks	Price range (NOK/kg_{H2})	Price range (\$/kg_{H2})
Steel [a]	~1700	~196
Fiberglass [a]	~4000	~462
Composite (300 bar) [b]	5810	632.9
Composite (700 bar) [c]	2453.3	283.3

Table 10: Price overview of hydrogen tanks.

a: Prices are found in the report Bærekraftig verdikjede hydrogen [61].
b: Prices of 300 bar tanks of 395 $kg_{H2(g)}$ delivered in a 38 m^3 container system.
c: Prices of 700 bar tanks of 1500 $kg_{H2(g)}$ delivered in a 38 m^3 container system.

5.4 Batteries Cost

From 2010 - 2018 there has been a 85 % price drop on Li-ion battery packages and cells. Figure 20 shows the price fall with a percentage year to year overview and an average price per kWh. In 2018 the average price was \$176/kWh which is around 1540 NOK/kWh. By using the average prices the prices can be higher or lower in reality. The prices are expected to continue to fall to $94/kWh in 2024 and to 62 $/kWh in 2030 as the demand of Li-ion batteries gets higher [62].

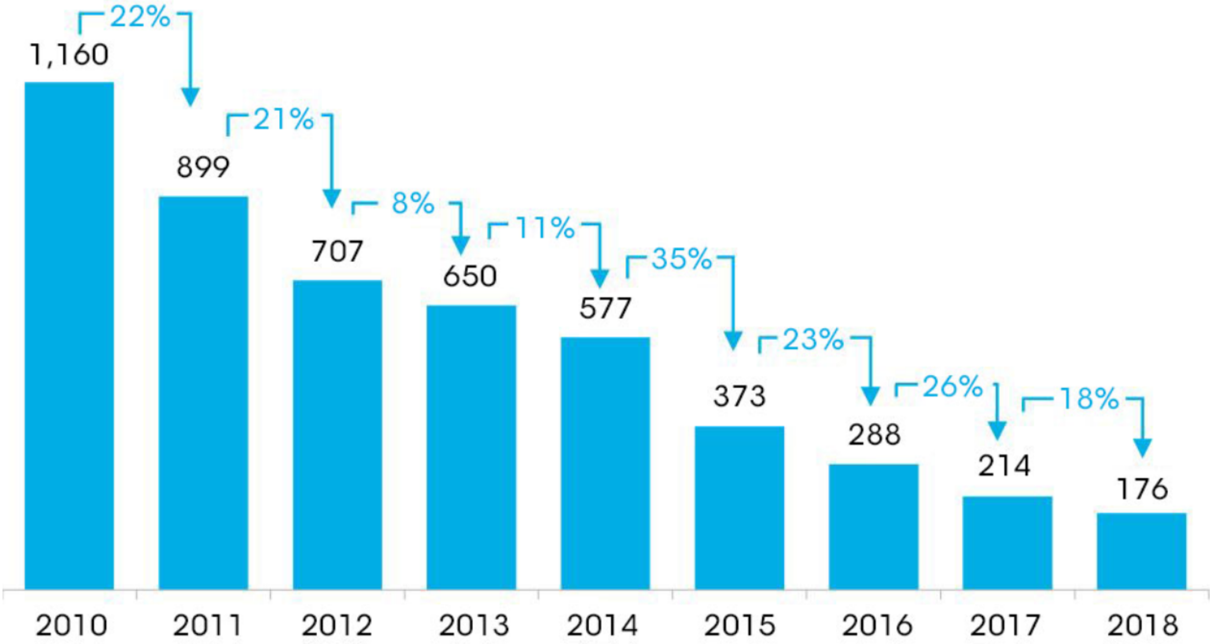

Figure 20: Li-ion battery back average price from 2010-2018 [62]

6 Greenhouse Gas Emissions

6.1 Global Emissions

The average temperature of the earth's climate system is rising and this causes the climate to change. The Earths climate may in general change seemingly randomly by itself, but the long term changes are caused by external forces, as an example the change in compositions of the atmosphere. In this case, the greenhouse effect appears. The greenhouse effect is a natural process where the greenhouse-gasses in the atmosphere absorb and reflect the heat from the sun, and increase the temperature of the earth. The natural greenhouse effect is a requirement for life on earth. An increased composition of greenhouse gasses in the atmosphere would contribute to raising the global temperature on earth.

The Intergovernmental Panel on Climate Change (IPCC) is an international institution founded by United Nations compile existing knowledge of the climate changes. In their latest report form 2014, it is stated that *"Human influence on the climate system is clear, and recent anthropogenic emission of greenhouse gases are the highest recorded in history. Recent climate changes have had a widespread impact on human and natural system."* It is also stated that *"both atmosphere and ocean have warmed, the amount of snow and ice have diminished and sea level has risen."*[63, p 2] Since the beginning of the industrial era, caused by economic and population growth, increase in emission of greenhouse gas (GHG) such as carbon dioxide(CO_2), methane(CH_4) and nitrous oxide(N_2O). In order to compare different gasses ability to heat up the atmosphere, each gas is converted into CO_2-equivalents using Global Warming Potential (GWP), thus making them directly comparable. Figure 21 shows the total annual anthropogenic GHG emissions in gigatonne(Gt) of CO_2-equivalent per year ($GtCO_2 - eq/yr$) of emission from 1970 to 2010. It is shown that the emissions from fossil fuel and industrial processes contributes to a great amount of the total emission per year. A graph showing the increase in GHG emissions from 1970 until 2010 can be seen in figure 21.

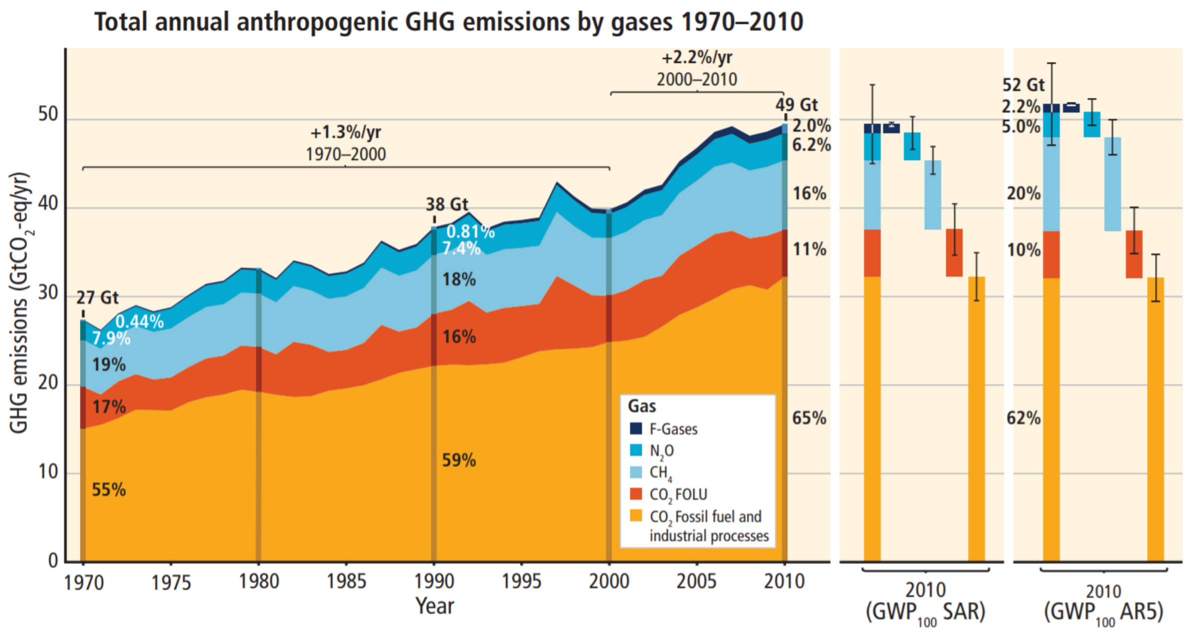

Figure 21: Greenhouse gas emissions from 1970 to 2010 [63, p 5]

The IPCCs fifth report 2014, has also stated that humans are *"extremely likely"* to have been the dominated cause of climate changes [63, p 4]. The large growth in population and industry, demanding community and a change in lifestyle is in one way contributing to emission and local pollution, causing a ripple effect on the climate. Global warming and climate changes have become a large problem. Therefore political measures have been taken, with the United Nations (UN) is in the lead. The Paris agreement was set in 2016, committing all the signed countries to reduce the emissions of GHG. Each country is obligated to form a plan to reduce emission, work together and help each other to achieve this goal. It also specifies that the global temperature should not exceed 2 °C [64].

In 2017 UN published the 9th edition of the UN Environment Emission Gap Report [65]. The report shows the latest scientific findings on current emissions and the estimated future emissions. Prominent findings were the global greenhouse gas emission in 2017, which reached a record of 53,5 $GtCO_2eq$, and an increase of 0,7 $GtCO_2eq$ compared to the previous year. In order to reach the 2 °C goal set by the Paris agreement, the GHG emissions need to be reduced by approximately 25 % within the year 2030 [65]. A way to analyse the green house gas emissions, energy efficiency and the industrial cost of the fuel used in the automotive industry and the marine industry are the Well-to-Wheels analyses. This analysis also includes the Tank-to-Wheels analysis. In this report these analysis methods will be referred to as Well to Waves (WtW) and Tank to Waves (TtW). The WtW analysis calculate the total energy required and green house gas emitted to transport the fuel from production to the usage of the fuel. Figure 22 shows the pathway analysis area from WtW including the area of the TtW of the fuel. An analysis that includes energy and CO_2 emissions form the building of the facilities and the vessels, and the destruction these are the Life Cycle Analysis (LCA) [66]. Figure 22 shows a graphical description of well-to-tank and tank-to-wheels (tank-to-waves in this thesis).

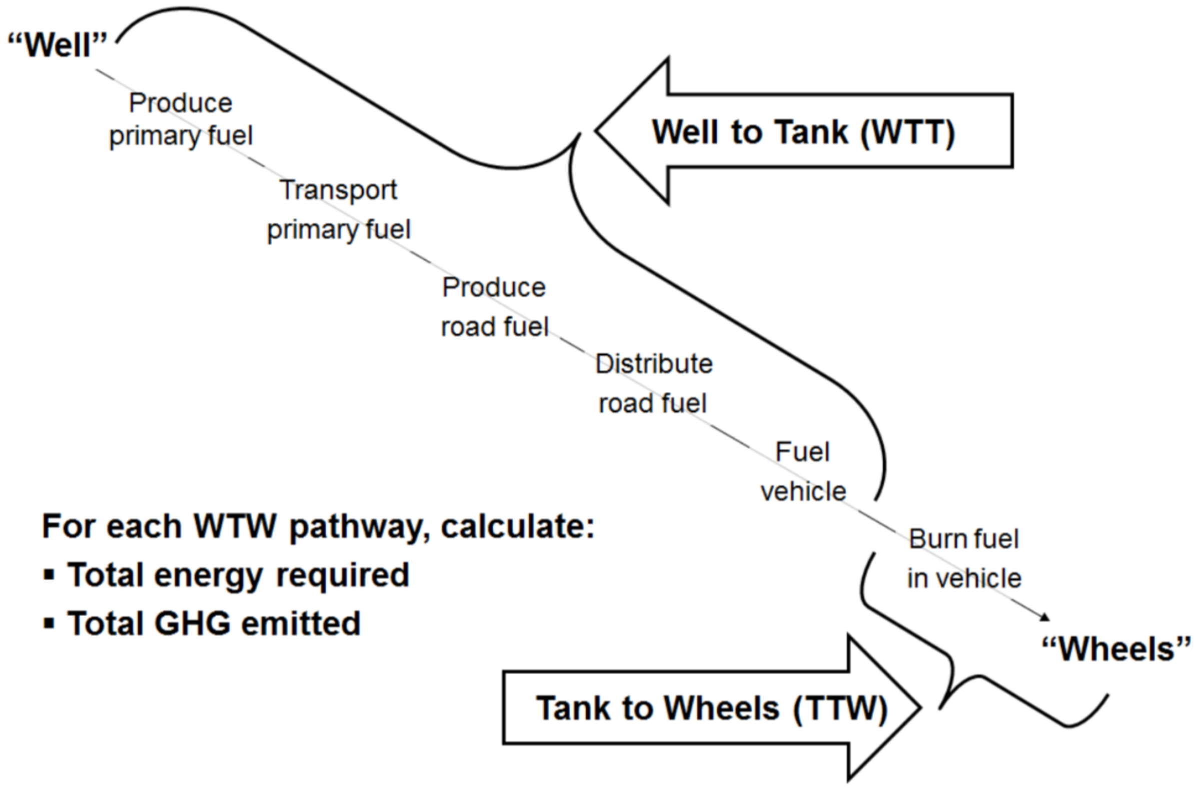

Figure 22: An overview of the WtW analysis roadmap [66]

6.2 Global Emissions from the Maritime Sector

One of the great challenges in the maritime transport sector is to reduce the emission of greenhouse gas. The International Maritime Organisation (IMO) was founded by the United Nations in 1948 to maintain safety, security, and efficiency of ships larger than 500 tonnes, as well as prevent pollution in the marine environment. IMO is specialised in developing international legislation and regulation for the international fleet of 100 000 ships.

In addition to this, IMO estimate the greenhouse gasses (GHG) emitted from the from shipping and conducted a study to map the largest contributors of GHG emissions. The 3rd IMO GHG study was released in 2014. Some of the key findings were table 11 that shows emission from shipping compared to the global GHG emission. The $CO_{2,eq}$ emission values are in million tonnes in table 11 [67, ch. 1.1].

Year	**Global $CO_{2,eq}$**	**Total Shipping**	**% of global**	**International shipping**	**% of global**
2007	34,881	1,121	3.2 %	885	2.6 %
2008	35,677	1,157	3.2 %	921	2.6 %
2009	35,519	998	2.8 %	855	2.5 %
2010	37,085	935	2.5 %	771	2.1 %
2011	38,196	1,045	2.7 %	850	2.3 %
2012	39,113	961	2.5 %	796	2.1 %
Average	**36,745**	**1,036**	**2.8 %**	**846**	**2.4 %**

Table 11: Shipping GHGs(in CO_2e) compared with global GHGs (values in million tonnes $CO_{2,eq}$)

Exhaust from the engines is the primary source of emission from ships, in which carbon dioxide is the dominant factor for air pollution. Chemical and oil spill contribute in large quantities to the pollution to the marine environment. In 2018 the quantity of oil spill reached a record of an estimated 116 000 tonnes. The main reasons for spillage are caused by collision within vessels and groundings. [68, p. 7]

6.3 Emissions from the Norwegian Fleet

The Norwegian fleet is one of the worlds largest fleets in tonnage and the need for marine transport is expected to increase. It also contributes to a significant amount of air pollution and greenhouse gasses such as Nox, SOx, particles and CO_2 both domestic and international. Today, domestic shipping has an emission of 3,4 million tonnes (Mt) CO_2, which contributes to 9 per cent of the total emission in Norway. In 2040, DNV GL has calculated the emission in line with considerable growth of the marine transport sector. They have also assumed that the technologies, type of fuel and operational during ship handling stay the same. Due to these assumptions, it is estimated emission of 5,2 Mt CO_2. If newly built ships meet the energy requirements, it is estimated to 4,7 Mt CO_2 [69].

The Norwegian authorities have ambitious goals to reduce greenhouse emissions, with a commitment of reducing at least 40 per cent from non-quota applicable sector and the marine transport sector. To reach the goal, a large restructuring in the sector is necessary, by implementing new technologies and upgrading existing ships [69].

In Norway, the development of climate-friendly technology for maritime applications has increased the past few years due to a forward-looking market and strict environmental requirements. The growth technology development has given Norway a solid foundation of competence and the possibility to create a complete zero emission value chain, with production utilising renewable sources or fossil energy sources with carbon capturing, infrastructure and access to low emission technologies. Some example of these type of technologies are the pure battery powered vessel, Future of the Fjords, shown in figure 24, and Viking Energy that run on liquid natural gas, shown in figure 23. Figure 25 shows a model of a hydrogen fast ferry under construction by Brødrene Aa [70].

6.4 Green maritime Transport in Norway

Norway has good conditions for adopting new technologies in the marine industry. Based on a well-developed grid, a solid knowledge of electric power, material and process technologies it is possible to produce low emission technology such as batteries, fuel cell and electrolysis with coherent infrastructure. Norway has a stable access to green energy sources and materials for production, and support from the authorities making investment possible.

Norway's maritime fleet is a well developed and has the possibility to be exemplary for tests and demonstrations of new technologies and solutions before commercialising and export to the international market. It is supported by a strong maritime cluster that focuses on environmental challenges and explores the possibility to utilise new technologies that reduce emission [71].

6.5 Liquid Natural Gas

Norway possesses a significant amount of natural gas (NG) resources and has world-leading competence of extraction and converting fuel. Liquid natural gas (LNG) is a fossil natural gas condensed and cooled. LNG is applicable when pipeline investments are not suitable. Depending on the technologies, it is possible to reduce the greenhouse emissions by 25 %, given that leakage of methane CH_4 is not present. Utilising LNG would reduce NOx pollution by 90 % and SOx and other particles almost completely eliminated [72, p 17].

Several companies have already taken positions in the Norwegian and international marked by phasing in liquid natural gas (LNG) as fuel in shipping. Viking Energy can be seen in figure 23 when it was launched in 2003, it was the first LNG powered offshore vessel. In 2016 an energy storage system at 653 kWh/1600 kW were installed to reduce the fuel consumption further. The battery is charged with a stable generator load, makes it capable to handle peak demands on the vessel. The batteries are used for peak shaving and contributes to responsive power during power demanding operations and avoid fluctuating engine power with batteries as a steady energy supplier. As a result, the average fuel consumption was reduced by 16-17 %. In addition to this, by utilising a dynamic positioning (DP) system using a battery system has lowered the fuel consumption by 28 % in DP mode [73][70].

Figure 23: Viking Energy: Offshore supply ship [74]

6.6 Battery

The advantages of surplus power, grid, low electrical prices, secure power supply through reservoirs and international cable connection substantiates the reason for using electricity for propulsion on ships. Several Norwegian companies have the competence of charging infrastructure, as an example, Cavotec has the delivered solutions for the charging system, while Corvus energy deliver energy storage system for maritime applications [75]. The battery industry has strong growth and an increase of demands for batteries used in electric vehicles and battery modules as energy storage in a solar power plant. This causes a drop in battery price and opens the possibility of batteries in marine applications, makes it more profitable. Batteries on ships with short crossings can be cost efficient and reduce greenhouse gasses and local pollution. Pure battery propulsion is still not possible for heavy vessels because of the limited range, even though the battery development is continually improving the capacity. Among Sintef and NTNU, the science and research environment have a strong initiative in battery technologies and great competence in material, electrochemistry, lifetime expectancy, module design, and safety. This provides great opportunities for industries such as Siemens to build a battery module production area for maritime applications in Trondheim.

During the past decade, battery systems has been utilised more often in the maritime sector, due to the advantages of fuel consumption reduction and reasonable electrical power pricing. One of the leading companies when implementing new technologies in ships is the company Brødrene Åå. Due to a strong cluster and suppliers delivering new technological solutions, making it possible to build the Vision of The Fjords, a diesel electrical passenger vessel in 2016 and the fully electrical passenger catamaran, Future of The Fjords in 2018. It has two 450 kW permanent magnet engine for propulsion and two battery packs at 900 kWh each (1,8 MWh from ZEM Energy) [76].

Figure 24: Electric Fast ferry, Future of The Fjords [76]

Traditionally, battery systems were not designed to work as a high power supply system in large scale for ships and offshore installations. These were mainly installed for emergency system and backup devices that could deliver a high amount of energy in a short period of time. A ship needs a continuously uninterrupted power supply, and traditionally batteries could not meet their demands and therefore not used for such applications. The recent development of technology has opened up the possibility for vessels and offshore installations to utilised batteries in large scale for propulsion, increasing system efficiency, lower maintenance costs, by allowing the engine to operate at its most beneficial. [77]

Figure 25: Hydrogen fast ferry [78]

6.7 Hydrogen

Norway has a long history of hydrogen production from natural gas combined with carbon capture. The Norwegian hydrogen cluster has taken an initiative to lead suppliers, shipowners, shipyards, port owners, and other stakeholders to renew the infrastructure and to implement new technologies in the marine industry. Based on the good conditions for hydrogen production in Norway, with low electricity prices, renewable energy, access to cutting edge technology and custom ships design puts Norway in a good position to be competitive in the future hydrogen economy.

Utilising hydrogen as an energy carrier for propulsion is suitable for vessels with high energy consumption, and also beneficial when there is limited access of charging, low grid capacity, or where pure battery propulsion solutions cause weight-related challenges. One of the leading shipyard when it comes to utilising new technologies in ships is the engineering company Brødrene Aa, unveiling a new Hydrogen-powered fast ferry for passenger transport [78]. In addition, one of Norway's largest ferry and express boat operators, Norled AS, are in the process of planning and building two ferries using hydrogen fuel cells and batteries for propulsion [79][80].

Hydrogen vessel at sea requires a well-developed refuelling infrastructure. The county of Sør-Trøndelag is forward leaning and innovative, and has already presented a study for Hydrogen fueling stations in Trøndelag, in preparations for the upcoming hydrogen vessels. The study reviews the possibility to produce and deliver locally produced hydrogen at existing docks and reveal probable obstacles [81].

One of the great motivations for the hydrogen project is to reduce local emission and marine pollution. A restructuring is necessary to meet the requirements of zero-emission vessels before 2022. Hydrogen solutions can make it possible, as long as the product is produced from renewable sources. Some of the target production areas/filling stations are startpoint at Trondheim City to Brekstad, Sanstad, Kjørsvikbugen, Edøy and Ringholmen with a final destination at Kristiansund City. Sintef has estimated a distance of 92.5 nautical miles, with an energy demand of approximately 6000 kWh, from start to the final destination, depending on the vessel type. When assumed that one kilogram of hydrogen in a fuel cell gives 15 kWh, the transit would have a hydrogen demand of 400 kg. This would fluctuate with regard to weather conditions and route deviations. An additional 50 kilo of hydrogen will be taken into account to cover possible deviations [81, p. 4].

Possible local production areas for hydrogen are the coast of Trøndelag and Nord-Møre. Hydrogen can be produced from surplus power from wind farms, such as Smøla wind farm or can be supplied from surplus hydrogen from Equinor at Tjelbergodden [81, p. 4]. Production costs are essential for utilising hydrogen as a fuel, as well as investment costs and operational costs. Target costs for hydrogen in Norway would be approximately 40 NOK/kg [81, p. 21].

6.8 Hybrid Marine Vessels

Hybrid solutions for propulsion is a possibility for energy demanding vessels. A hybrid solution with battery modules allows the machinery to operate on its most optimum. As a result, it is possible to reduce fuel, local pollution, operating damages and the need for maintenance.

Hydrogen and fuel cell as a propulsion system is assumed to vary in distance with respect to storage pressure and volume availability. By combining the hydrogen and fuel cell system with a battery module, will increase range and reduce the amount of fuel. To utilise this type of system, it is necessary to facilitate charging stations and refuelling stations. As mentioned, hydrogen cluster and stakeholders are researching the possibility of locally produced hydrogen for infrastructure and alternatives for transport of hydrogen to remote destinations.

The Norwegian marine transport sector is evolving and can be leading in marine low and zero-emission solutions. There are large resources and competence for production and development of key components for storage and utilize hydrogen and system integration in ships. Several companies are already involved in a hydrogen community, where technologies are being tested and further developed to improve quality and safety when implementing new systems. It is assumed that Norway will become a great supplier of well-developed energy efficient solutions for maritime applications in the future. Furthermore, supplier of key components for such systems as tanks, fuel cell, batteries, filling and charging stations, ship design, material and fuel [77].

6.9 Fosna Orion

Fosna Orion is a 15 meters long and 10 meters wide catamaran service vessel build by Moen Marine and owned by Abyss Aqua AS. Fosna Orions main port is in the city of Kristiansund. The main tasks of this ship are to carry equipment, crew, and to maintain and clean nets used in the fish farming industry. This is a typical vessel used in the aforementioned industry. It is powered by two large diesel engines that put out a maximum of 882 kW. It has 24 tons of cargo capacity on deck. This is an interesting vessel for converting to locally produced hydrogen, as it operates in and around the wind farms of Smøla, it has a limited range of travel, and it is a big consumer of marine diesel. As this is a common ship used in Norway, it is an interesting subject for implementation of zero-emission technology, since it operates in areas where green power is available for hydrogen production. Fosna Orion is shown in the two pictures in figure 26.

Figure 26: Pictures of Fosna Orion [82]

7 Calculations and Methods for Fosna Orion

To realise a vessel that runs on hydrogen, one of the main question is; how much power is required to operate the vessel in basic conditions. In the following section, one approach to arrive at these numbers will be described. The first section gives an overview of the assumptions. Secondly the energy demanding systems on board the vessel will be accounted for, and thirdly the calculation, methods and results are presented and summarised. The parasitic power in the battery system is assumed to be negligible.

7.1 Summary of Assumptions

A summary of results is shown below in table 12.

Assumptions	Assumed value	Clarifications
Diesel engines	Full load	
Diesel generator	(25 % and 75 % load)	Transit and operations
Weight of propulsion-systems	Equal	Electric and ICE
Electrical Motor efficiency	98 %	
Marine diesel volumetric density	10 kWh/liter	
Marine diesel price	6.5 NOK/liter	
Hydrogen Gravimetric density	33.32 kWh/kg	
Hydrogen wt% storage @ 350 bar	4 %	Hexagon type 4 tanks
Hydrogen 350 bar price	40 NOK	Averaged value
H350 bar volumetric density	577 kWh/m3	Averaged value Hexagon
FC gravimetric density	0.26 kW/kg	Ballard VeloCity-HD
FC volumetric density	137 kW_{FC}/m^3	Ballard VeloCity-HD
Efficiency FC	60 %	
BoP parasitic power	10 %	
Lithium battery efficiency	94 %	Average value
Lead acid battery efficiency	75 %	Average value
Fully charged battery	100%	

Table 12: List of assumptions

7.2 Fuel Consuming Equipment

Fosna Orion is driven by two diesel engines for propulsion and one diesel generator for power supply. The vessel has a tank that can store around 8 000 litres of marine diesel fuel. A mobile net-washer system is used to wash the fishing nets. Figure 27 shows a visual overview of the basic energy demanding systems on-board Fosna Orion, with the maximum power output of the energy demanding components.

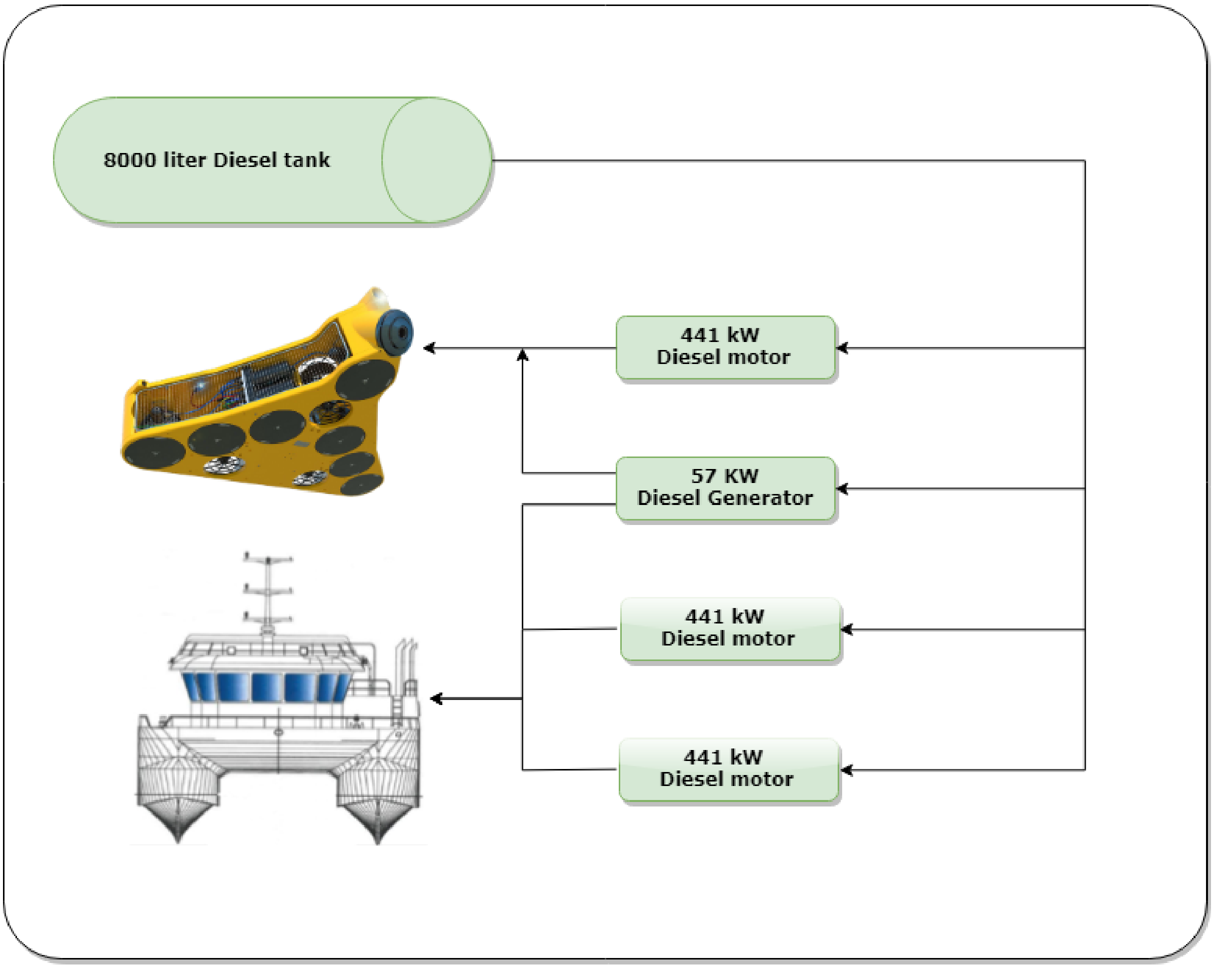

Figure 27: Fosna Orions basic system overview

Table 18 shows the weight of different components on Fosna Orion. When replacing diesel demanding equipment, weight is a variable needs to be considered when comparing the different system solutions. With a higher weight, a higher energy demand. The Net cleaning system includes the container the system is stored in, a Scania DI13 072M diesel engine, a Hammelman HDP 252 High-Pressure Pump, and the Stealth Cleaner MK2. In this system and the propulsion system, the diesel engines will be replaced with electric motors.

7.2.1 Diesel Propulsion

Fosna Orion uses two diesel engines of the type shown in figure 28 for propulsion. These have a total max output of 882 kW. Connected on each engine is a gearbox that have a power take-off (PTO) system that drives one hydraulic pump each. The hydraulic system drives among other things a crane used for general work.

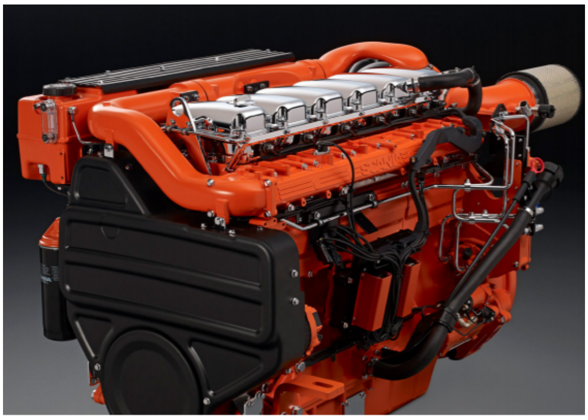

Figure 28: The diesel engine used on board Fosna Orion [83]

7.2.2 Diesel Generator

A John Deere diesel generator, like the one shown in figure 29, delivers 57 kW electric power to the boat. This is used for supplying the electricity needed for the entire vessel. According to the engineer, it runs at 75 % load when the net washer is running, and at around 25 % load when only supplying power to the vessel.

Figure 29: The diesel-generator on board the vessel [84]

7.2.3 Auxiliary Equipment

To clean the nets of the fish-cages, Fosna Orion uses the Stealth cleaner MK2. This is a device used to clean the growth on the fish-cages. The net cleaner system (NCS) is built as a semi-portable platform that can be transferred between vessels as needed. The picture in figure 30 shows the containers that house the NCS. It uses a high-pressure pump to push seawater through nozzles of the remotely operated vehicle. This pump is powered by the same type of engine as the main drive. The pump and the engine are installed in a 28 m^3 container. The ROV is powered by 3-phase power supplied by the onboard generator. Using the crane, the cleaner is placed in the cage. The stealth cleaner is controlled by an operator on deck.

Figure 30: The containers that house the net cleaner system and the control room

7.3 Fuel Consumption Calculations

This section will describe how the information regarding fuel consumption and energy requirements was collected, and the process of achieving a fuel consumption estimate. The generalisations and assumptions will be accounted for. The flowchart in figure 31 shows the algorithm for calculating the energy estimates

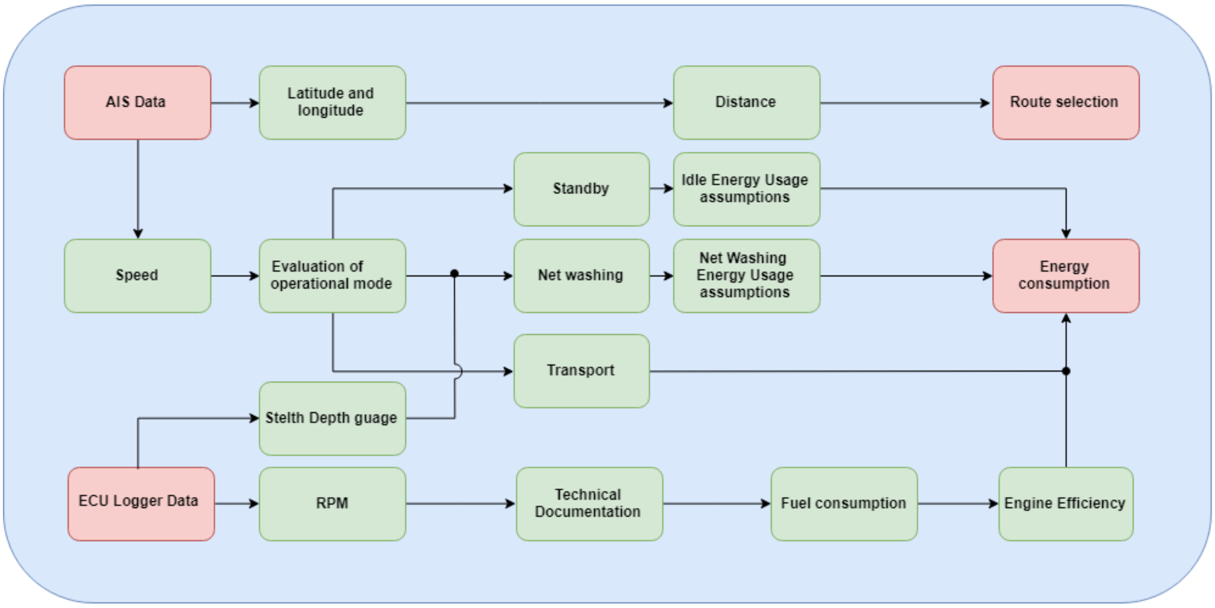

Figure 31: Fuel consumption calculation flowchart

7.3.1 AIS Data Calculations

AIS (Automatic Identification System) is a service that tracks all vessels over a certain size. It tracks the ID of the vessel, its heading, course, speed, and position in the form of latitude and longitude degrees. MarineTraffic is one of several providers of this sort of ship tracking and maritime intelligence. This service supplied historical information from the vessels AIS. The team acquired data for the time interval we had corresponding engine data. This information was used to visualise the movements of the vessel, and to calculate the common distances it traverses.

The distance of the routes was calculated from latitude and longitude data, using the equation found in the appendix D [85]. This was summed up to give the distances travelled each day. The team evaluated the different travel routes the vessel had traversed and found a viable trip for our analysis.

7.3.2 ECU Data Logger Calculations

A data logger was installed on the engines ECU. This device logs the real-time data from the vessel's engines, providing among several other parameters the RPM and throttle-information at a given timestamp. The thermal nature of the ICU makes it a challenging task to estimate the mechanical power output precisely. Because of this, the team chose to look at the vessel running at full load. Figure 32 shows the manufacturer supplied ideal case Specific Fuel Consumption (SFC) for a range of RPM [83]. Using the information given here, an estimate of the power output of the motor was calculated by pairing RPM-values with corresponding full load power output. This was multiplied by the time-frame of each sample interval. This gave an estimate of the energy output of the motor, which can be calculated using the following formula $E_{output} = P_{output} \cdot t$.

The power output needed from a fuel cell would be dictated from the maximum output from the diesel engines, as a drop in performance is unwanted. Going with the same assumptions as previously mentioned, the power output was plotted as a function of RPM, using the power output supplied by Scania. From the plot in figure 32, the maximum power produced by the motor was around 400 kW.

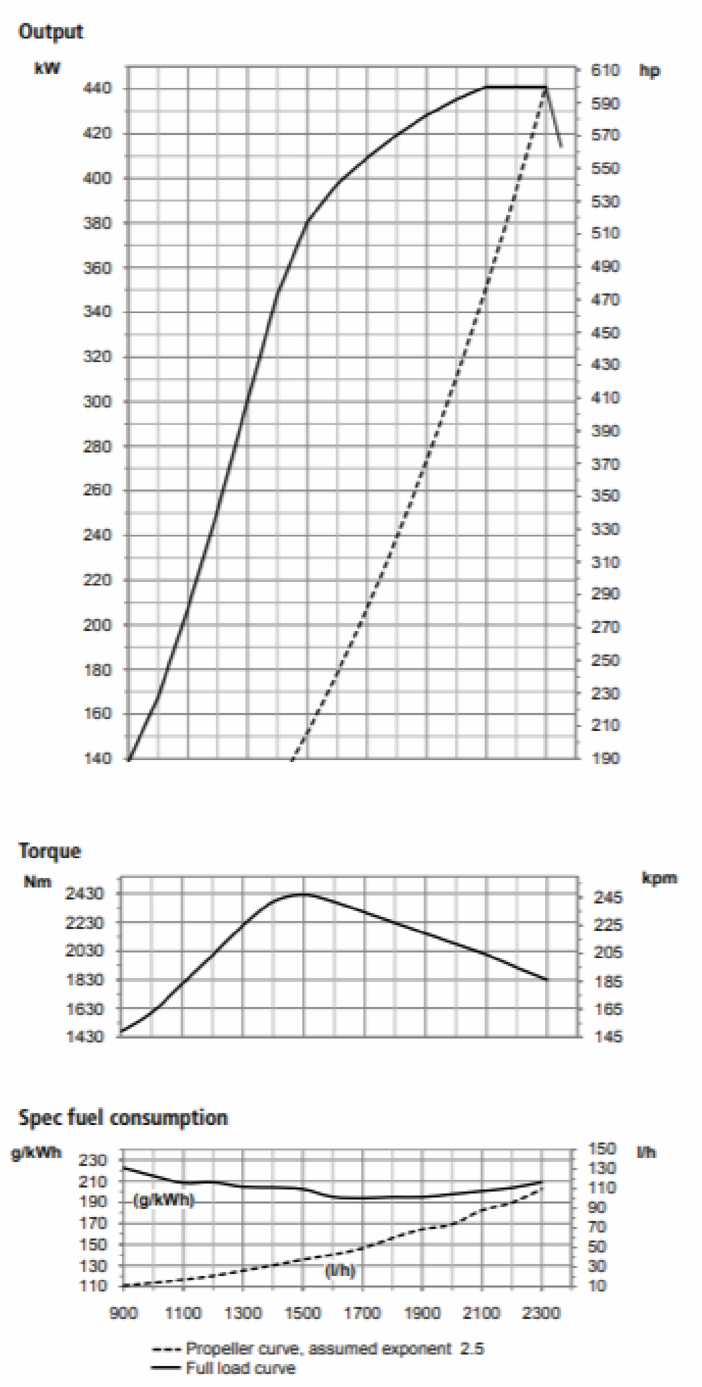

Figure 32: Full load power output [83]

7.3.3 Fuel Consumption for the Net Cleaner System

The NCS is equipped with a sensor that gives a readout of the depth of the ROV. This data was used to determine the average time spent on a single cage. As no data were available on the actual motors (generator and pump motor) that runs the systems, the team consulted with the main engineer, that could report that the pump runs on 1800 rpm if it is driven by an electrical engine, while it runs on 2150 rpm on the diesel motor. The pump deliverers a water flow of 818 l/min with the possibility of two outputs on the stealth cleaner. The high-pressure pump will mainly be operated at 150 bar. The pressure could be regulated, and if needed it can operate on 200 bar. From the datasheet in figure 33, the pump would require between 250-300 kW at under these conditions. Appendix A shows an electric motor unit that can be used for an electric powered system.

7.3.4 Energy Demand for Auxiliary Power

The power needed to run the electrical equipment onboard the vessel comes from the generator. It supplies the power needed to run all the electric equipment onboard the vessel. The generator runs continuously at 25% load and 75 % when the NCS is running. The diesel consumption of the generator under these conditions are respectively 4,3 litres per hour, and 10,6 litres per hour. Using marine diesel which is rated at around 10 kW per hour, this would equate to 43 and 103 kWh per hour. Assuming an efficiency of 40 %, this equates to a power output of 17,2 kWh per hour at transit, and 42.4 kWh per hour when washing cages.

Q [l/min]	Required power rating [kW]					
	110	132	160	200	250	300
	Operating pressure [bar]					
569	100	120	150	190	230	
683	90	100	120	160	190	230
818	70	90	100	130	160	200
744	80	95	115	145	170	
892	65	80	95	120	150	170
1069	55	65	80	100	125	150

Figure 33: NCS Pump Specs [86]

7.3.5 Emissions from the Diesel Fuel

Diesel is a fuel consisting of chains of hydrocarbons. The composition can vary from different types of diesel but assuming that the diesel used on Fosna Orion is comprised of the molecule $C_{12}H_{23}$. From communications with the owners, an estimate of 100.000 litres of diesel was consumed each year by the vessel. Applying the calculations in table 13, the vessel puts out 265 tonnes of CO_2 each year.

	Molar weight
Carbon	12 [g/mol]
Hydrogen	1 [g/mol]
Oxygen	16 [g/mol]
$C_{12}H_{23}$	167 [g/mol]
CO_2	48 [g/mol]
Balanced equation	$4\,C_{12}H_{23} + 71\,O_2 \longrightarrow 46\,H_2O + 48\,CO_2$
Ratio	$C_{12}H_{23}$ = 12 CO_2 = (12 ·48) / 167) = 3.45 [kg CO_2/kg diesel]
Diesel density	0.840 [kg/liter] Appendix C
Diesel emission	$3.45 \cdot 0.840 = 2.65$ [kg CO_2/liter diesel]

Table 13: Calculating CO_2 emissions from diesel fuel

7.4 Calculation Results

The team chose two categories to analyse the vessel; Transit, and Operation. The travelling route of Fosna Orion has been analysed over the period of the past year. Figure 34 illustrates the frequency of travel distances. Note that this information only shows distances, not the mode the vessel operates in.

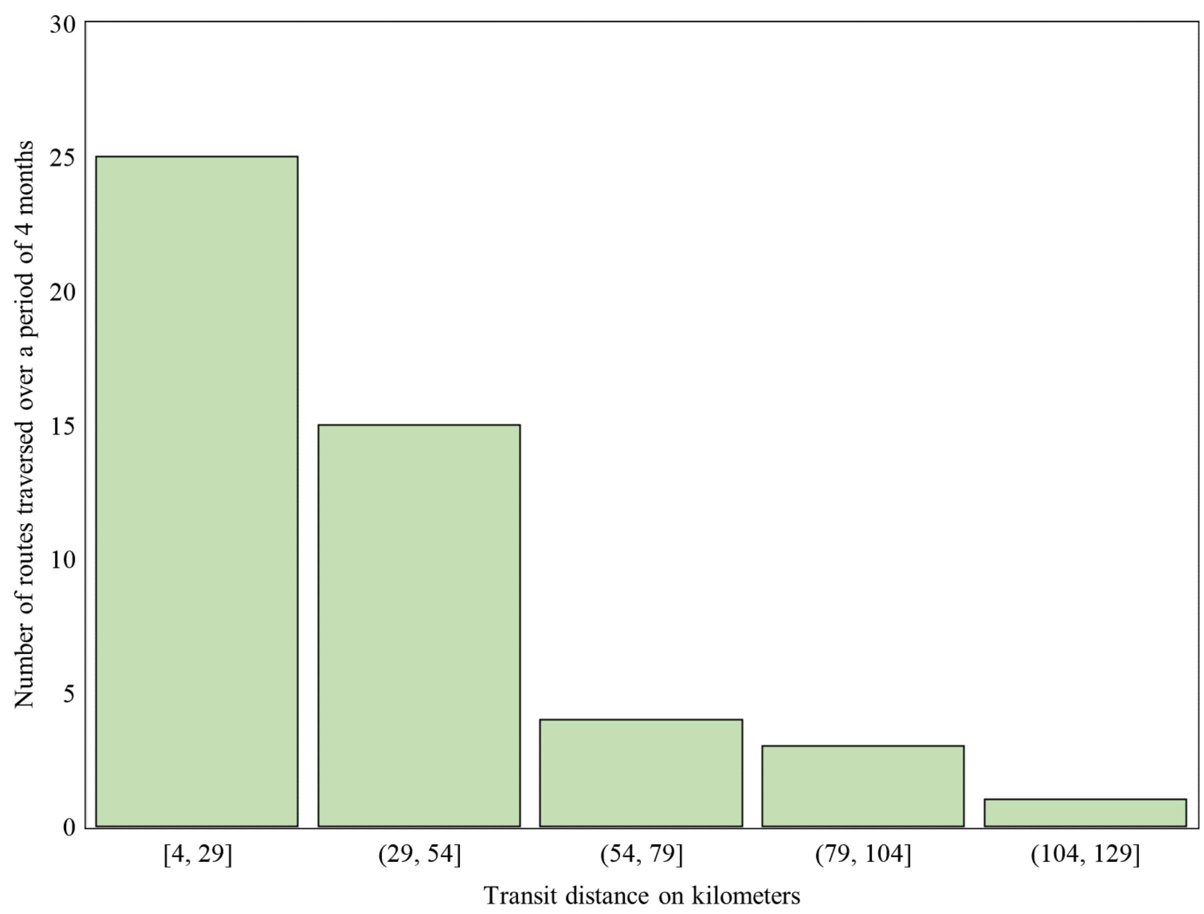

Figure 34: Shows the distribution of travel distances over 4 months.

The past year, missions have taken place at the coast of Nordmøre, where the vessel has been doing operations with net washing for the fish farming industry. It was preferable to assume that the vessel would operate around the island of Smøla, close to potential hydrogen production areas and filling stations, and have the possibility to take on assignments near the archipelago of Frøya and Hitra.

When the team received overlapping data from marine traffic and Sky Nordic data logger were left with three missions to analyse. The routes were chosen with regard to distance of transits and duration. Figure 35 shows the sea route for the overlapping period of different data sources.

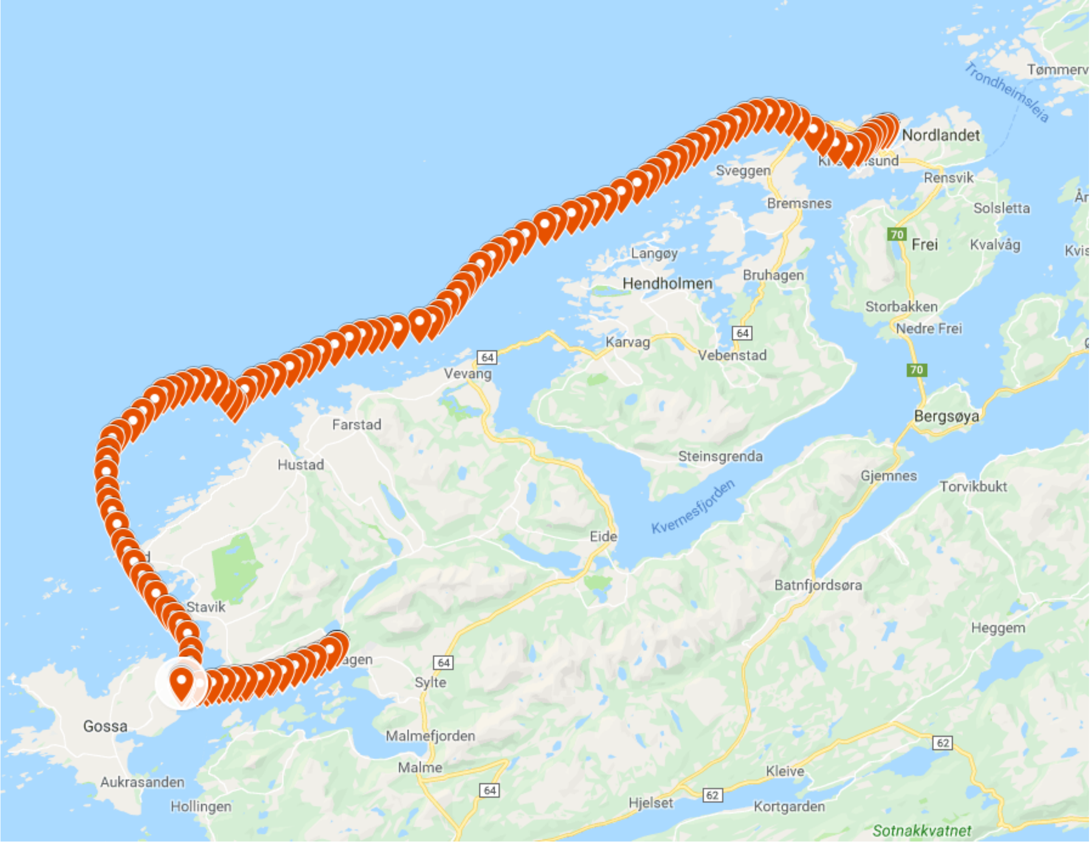

Figure 35: A map showing route 1

7.4.1 Route 1

This is a summary of Fosna Orion's activities during the day where route 1 were tracked.. The calculations presented in table 14 gives an overview of the activities and energy requirements of a propulsion engine, generator and net cleaning system, along with the CO_2 emissions based on the fuel consumption in table 14 and the calculations in table 13.

As seen in the map in figure 35, Fosna Orion travelled from the city of Kristiansund to Aukra for net cleaning operations at fish farming-nets. Fosna Orion traversed a distance of 88 km with an average transit velocity at 16.2 km/h. The propulsion engines were calculated to have a total energy output of approximately 5000 kWh. After arriving on the location, the vessel cleaned cages for 3 hours. This would equate to energy consumption at 1269 kWh and includes the net cleaners required energy and the output energy of the generator at 75 %. Total energy consumption for this operation with cages was estimated to approximately 1650 kWh. After the operation, the vessel was headed to shore to bunker before the travelled back to the fish farming fleet for the night. The total energy consumption for transit on this day was estimated to 4915 kWh with a distance travelled at 86 km gives an energy consumption rate at 57.2 kWh/km.

The total energy consumption during this day with both transit and operations is estimated to 6561.4 kWh. The net cleaner operation contributes a great deal to the total consumption during operation mode. The total CO_2 emission calculated from this trip was at 4346 kg CO_2.

Route 1		
Total distance traveled	88 km	47.5 nm
Transit duration		7.5 hours
Average speed transit	16.2 km/h	8.75 knots
Average speed operation	2.1 km/h	1.13 knots
Peak power per engine	410 kW	549.8 hp

Transit energy output (Mode 1)		
Distance	86 km	46,4 nm
Propulsion		4795 kWh
Generator 25 % load		120 kWh
Total transit energy output		4915 kWh
Energy output per distance	57.2 kWh/km	106 kWh/nm

Operation energy output (Mode 2)		
Distance	2 km	1.07 nm
Propulsion		350 kWh
Generator (75% load)		169 kWh
Generator (25 % load)		28 kWh
NCS		1100 kWh
Operation duration		3.0 hours
Total operation energy output		1646 kWh
Energy output per hour		549 kWh/h

Energy summary	**Fuel in [l]**	**Energy out [kWh]**
Propulsion	1286.3	5145
Generator 25 % load	37	148
Generator 75 % load	42	169
NCS	275	1100
Total	1640 l	6562 kWh
CO_2 emissions	4346 kg CO_2	
CO_2 emissions per kilometres	49 kgCO_2/km	

Table 14: Summary of calculations from Route 1

7.4.2 Route 2

Route 2 describes Fosna Orion's activities on 6. April 2019, and the summary of this trip is presented in table 15. This was a transit route of 157 km, from the base port in Kristiansund to the island Frøya. The transit had a duration of 7 hours, with an average speed at 15.5 km/h. During transit, the generator had a load at 25 % while the propulsion engines operated on full load, and peak power output was recorded at 400 kW. It was estimated that a total energy output of 7715 kWh, which gave an energy consumption of 49.3 kWh/km. The CO_2 emissions on the trip was around 5000 kg CO_2.

Route 2		
Total distance traveled	156.6 km	84.5 nm
Transit duration		7.0 hours
Average speed transit	15.5 km/h	8.34 knots
Peak power per engine	400 kW	543.8 hp
CO_2 emissions per kilometers		33 kg CO_2/km
CO_2 emissions		$\sim$5100 kg CO_2

Transit energy output (Mode 1)	**Fuel in [l]**	**Energy out[kWh]**
Propulsion	1904	7616
Generator 25% load	25	99 kWh
Total energy output	1929	7715 kWh
Energy output per distance	49.3 kWh/km	91.3 kWh/nm

Table 15: Summary of calculations from Route 2

7.4.3 Route 3

Route 3 represents a summary of Fosna Orion's activities on 8. April 2019 and is presented in table 16. During this day, Fosna Orion had three transits distances that give a total distance of 39.5 km with an average speed at 11.4 km/h. The total energy consumption for transit was estimated at 2150 kWh, which equates to 54.4 kWh/km. From the depth gauge onboard the NCS it was found that the system operated for three hours between first and second transit. During this time, the generator operates on 75 % load, and at 25 % when moving between cages. The propulsion engines delivered 570 kWh and the NCS put out 825 kWh. The total output energy sums up to 3741.5 kWh. The total CO_2 emissions for this trip was $\sim$2500 kgCO_2.

Route 3		
Total distance traveled	40.5 km	21.9 nm
Operation duration		3.0 hours
Average speed transit	11.4 km/h	6.16 knots
Average speed operation	1.9 km/h	1.03 knots
Peak power per engine	380 kW	516.6 hp

Transit (Mode 1)		
Distance	39.5 km	21.3 nm
Propulsion		2100 kWh
Generator 25% load		49 kWh
Total transit energy output		2150
Energy output per distance	54 kWh/km	101 kWh/nm

Operation (Mode 2)		
Distance	1 km	0.54 nm
Transit duration		3.5 hours
Propulsion		570 kWh
Generator (75% load)		127 kWh
Generator (25 % load)		71 kWh
NCS		825 kWh
Total energy output		1592 kWh
Energy output per hour		455 kWh/h

Energy summary	**Fuel in [l]**	**Energy out [kWh]**
Propulsion	668	2670
Generator 25 % load	30	120
Generator 75 % load	31	127
NCS	206	825
Total energy	936 l	3742 kWh
CO_2 emissions		$\sim$2500 kg CO_2
CO_2 emissions per kilometers		61 kg CO_2/km

Table 16: Summary of calculations from Route 3

7.4.4 Summary

The information from the 3 routes was calculated, and the pattern of usage was charted. The team categorised two modes of usage; Operation and Transit. The derived energy-information in the previous sub-chapters was distributed into these two categories, and the mean of the 3 routes resulted in two conversion-factors presented in table 17. Note that total energy is not the sum of these two modes, as the mode 2 includes some transit. These two factors was the basis for the calculations in the energy-systems in the following chapters.

Transit	Mode 1	54 kWh/km
Operation	Mode 2	540 kWh/h

Table 17: Averaged conversion factors for Transit and Operations

8 Results and Discussion

This chapter will comprise of reviews of several energy systems for the vessel. The team chose to investigate four basic setups for replacing the current diesel drive system. Firstly, a Plugin battery drive, secondly, a pure Hydrogen PEMFC-system, and finally two versions of a Hydrogen PEMFC battery plugin drive. In the hybrid solutions, the goal is to investigate the distribution of energy regards of the fuel cell and the battery system. The two hybrid variations that were reviewed are a 50/50 and 70/30 power and capacity split. Common for both these systems is the power electronics, which includes converters and distribution systems that deliver energy to the propulsion system, hydraulics motor, NCS and auxiliary power. A overview of the four systems can be seen in figures 37, 40 and 43.

Fosna Orion weighs 57,4 tonnes. This means that it has a power to weight ratio of around 14 kW per tonnes. From the power output analysis in chapter 7, it is clear that the engines usually run at an output of 80-90 % when traversing. As a drop in performance is unwanted due to the nature of the industry, the systems presented will use this ratio to represent the performance of the vessel. As a limit the team decided that the zero-emission solutions have to manage 50 % of the range of the trips in figure 34 to be concidered technically viable. The team chose to assume an electric motor power output of 1 MW. The team assumed that the weight of the electric motors and the corresponding BoP is equal in weight to the diesel motors system.

When looking at the available cargo capacity on the vessel, it is specified to have a loading capacity limit on deck set at 24 tonnes given by the stability documentation. When removing the diesel system, the weight of the diesel accounts for 7 tonnes. This weight is assumed to be made available. In this case, we chose to use 75 % of the deck cargo weight capacity plus the weight of the diesel as the upper weight limit of equipment onboard the vessel. The pie chart in figure 36 shows the distribution of this available weight. The owners of the boat reported that 80 m^2 of space was available on deck. The team chose to set the area limitation at a one-meter high box 50 % of this, totalling to 40 m^3

The central results from the system analysis done in the following chapters mainly focus on volumetric and gravimetric limitations, inquiring which of these aspects would prove to be the limiting factor in each case. A rough estimate of the CAPEX and OPEX for the different systems will also be presented and discussed, based on the general assumptions presented in table 12 at the beginning of chapter 7. The lifetime of the various technologies is not taken into account for the cost or recommendations as the battery lifetime is highly dependent on the amount of charging cycles and load characteristics. investigations into the load characteristics and optimisation for each system will be neglected, and we will assume that the systems are capable of producing the rated continuous power in the given loads. In other words, this chapter will consist of unit-based calculations from the assumptions, limitations, and results of chapter 7. Table 36 lists some of the equipment on board Fosna Orion and how much it weighs.

Relevant equiptment on Fosna Orion	Number of units	Weight per unit (kg)
Diesel tank	1x	7000
Scania DI13 072M Propulsion Engines (excluding oil and coolant)	2 x	1285
Oil and coolant (5% of engine weight)	2 x	64
John Deere 4047TFM50 Diesel Generator	1 x	462
Net-cleaner system	1 x	4069
Load capacity on deck		24 000

Table 18: Weight overview of relevant energy demanding systems

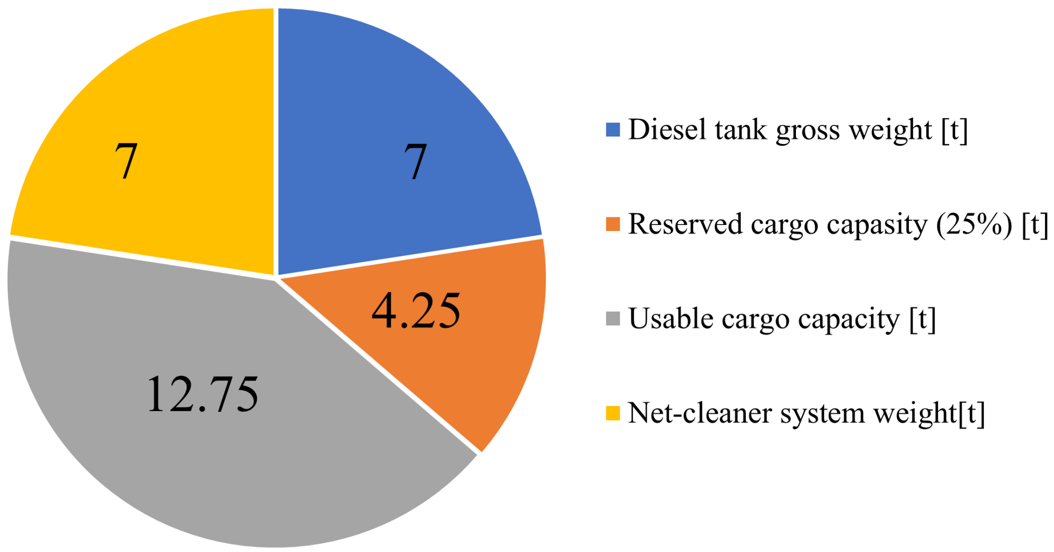

Figure 36: The distribution of weight capacity on-board Orion

In regard to former calculations of the vessel Fosna Orion, it was concluded to use the average energy consumption during transit and operation mode respectively. Mode 1 (Transit) had an energy consumption of 54 kWh per kilometres, while Mode 2 (Operation) has an average energy consumption of 540 kWh per hour during net cleaning. In order to do a proper analysis, it was assumed that the electric propulsion engine has an efficiency of 100 %, which means that the battery systems output energy would be equivalent to the mode values. It was decided to look at 3 hours of effective net cleaning duty and estimate the required energy stored relative to the distance travelled and energy required for the net cleaning duty.

8.1 Plug-In Battery Drive

In this part, we will look at using a battery system as the primary power supply on the vessel. Figure 37 shows an overview of the Plug-in Battery drive system, where the battery pack are charged at the dock, and the batteries supply power for the propulsion engines, hydraulics and the auxiliary power on-board. It is important to apply technology intended for maritime use. These batteries are specifically designed to operate in a fluctuating environment where movement, water, dust, corrosion, and more are most likely to be an issue. Using batteries for energy-capacity and power supply on ships contributes to a more responsive vessel because of the torque characteristics of the electric motor. It will improve performance and open up possibilities for engine optimisation. Utilising a battery system can also lower maintenance cost, give a significant reduction of fuel consumption, emissions and local pollution.

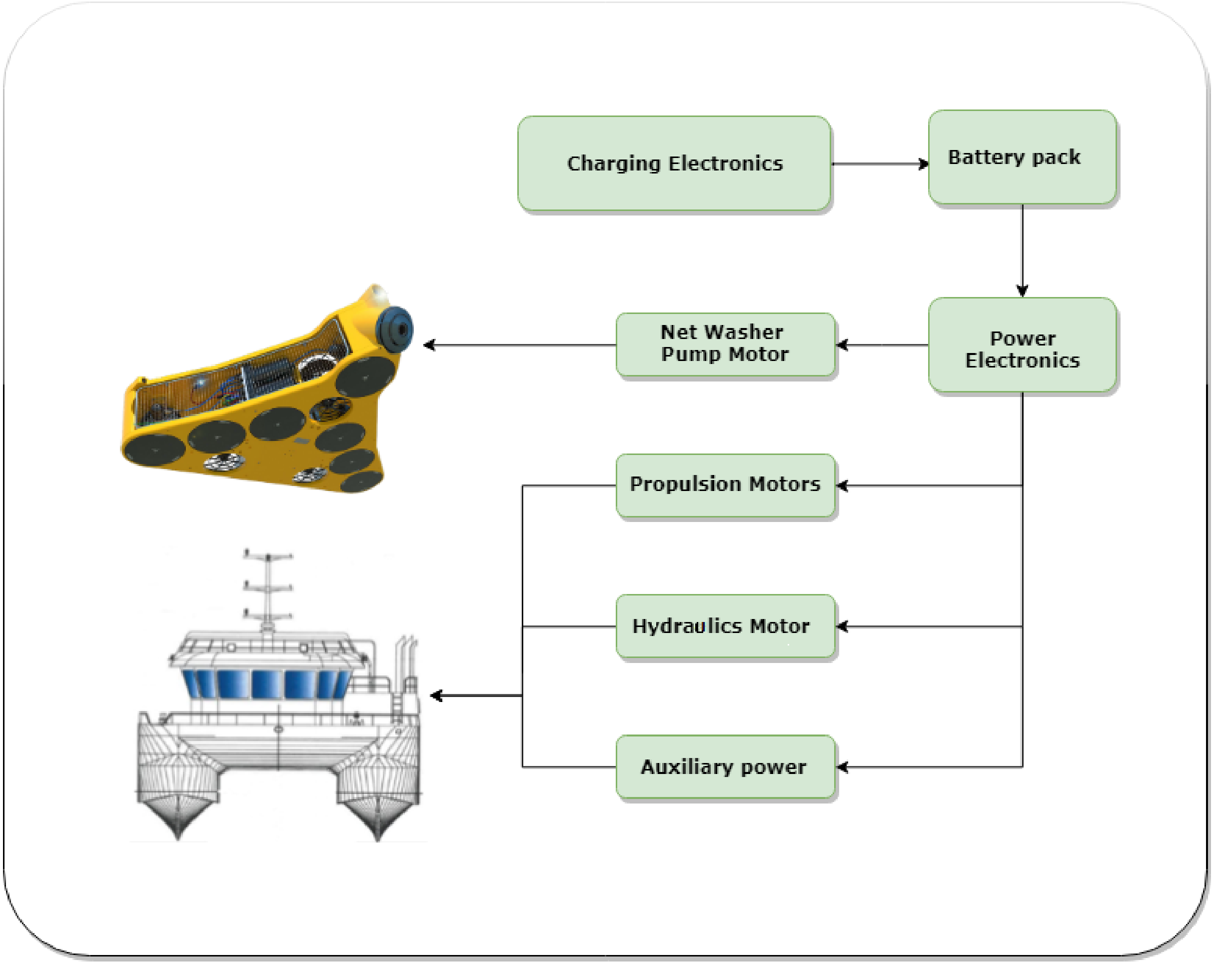

Figure 37: Plug-in Battery drive system overview.

8.2 Evaluation of Battery types

Lead Acid is a mature and reliable battery technology with a low cost of 90$ per kWh 24 compared to other battery technologies. PbA-batteries are traditionally used in shipping for continues power supply because it is capable of handling a high discharge rate. Depending on the structure of the plates within the battery, it can be used for either deep cycling, SLI a compromise of the two.

When implementing a battery system based on Lead Acid, it is important to consider the operating state the batteries would be experiencing. If the battery system is going to supply propulsion engine, auxiliary power, and the net cleaning system it is reasonable to assume the batteries to be fully discharged on a regular basis. because of this, it is preferable to look at a deep cycle battery.

As previously mentioned, the deep cycle battery has at most 200 cycles when fully discharged, and 500 cycles at half discharge before the nominal capacity is reduced. The capacity of the battery is also affected by the storage condition when it is not being used.

To add to this, a Lead acid battery has a gravimetric energy-density (40 Wh/kg) (figure 16). This limits the usefulness on ships, as large amounts of energy are required for the propulsion. When exchanging the diesel system with a Lead Acid battery pack, the power to weight ratio is reduced significantly. To compensate for this, the power of the engines need to be scaled up. To produce the same range, the energy storage muse again be increased. A Lead Acid battery has 2.6 times higher weight to energy ration compared to Lithium-ion battery when delivering the same amount of energy. As seen from figure 39 showing the range with lithium-ion batteries, it is reasonable to conclude that the range will be short to non-existent on a system like this based on lead-acid batteries. Volume is not an issue as the weight will limit the range, as seen by the longer range in figure 38. Due to weight limitations on the vessel, a battery with gravimetric energy-density would be required. This makes the lead acid battery a bad alternative for this application and would be more suitable for a low powered vessel, or stationary onshore installations. A Li-ion battery can provide large currents within the set charge limits and it has a high volumetric and gravimetric energy density compared to lead acid. Because of this, the team chose to focus on Lithium-ion batteries.

8.2.1 Weight and Volume

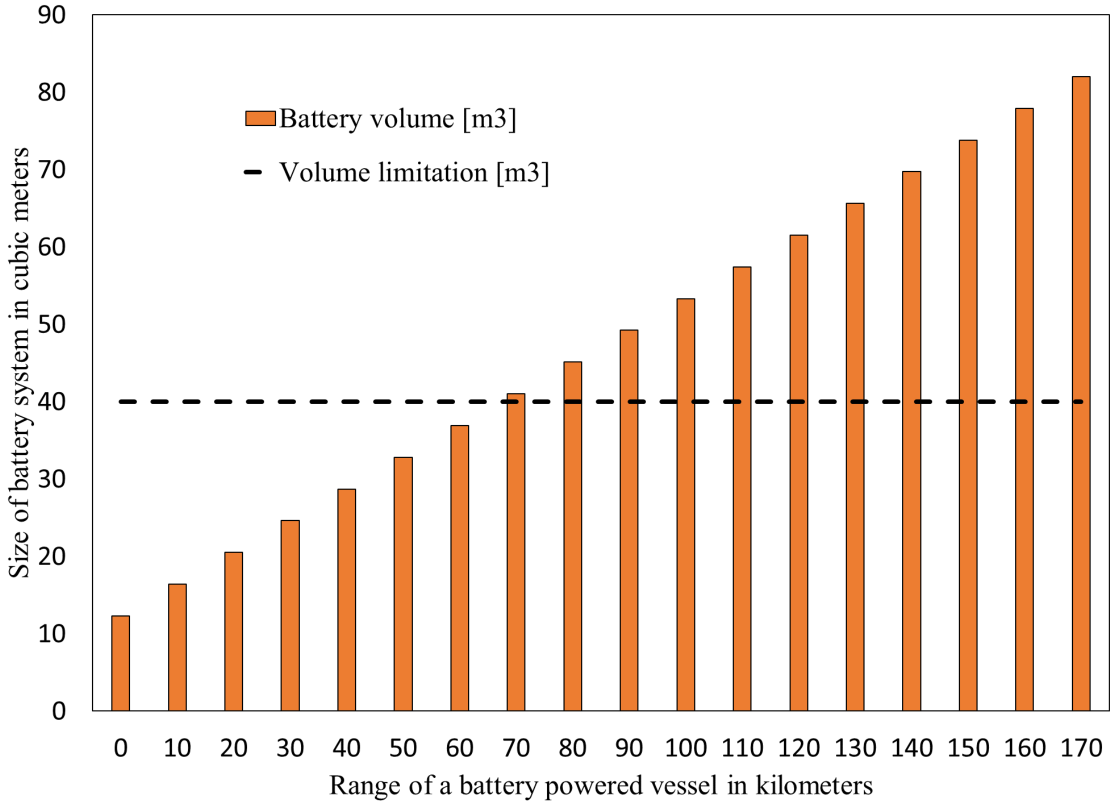

Figure 38: Volume of Li-ion battery system for specific range.

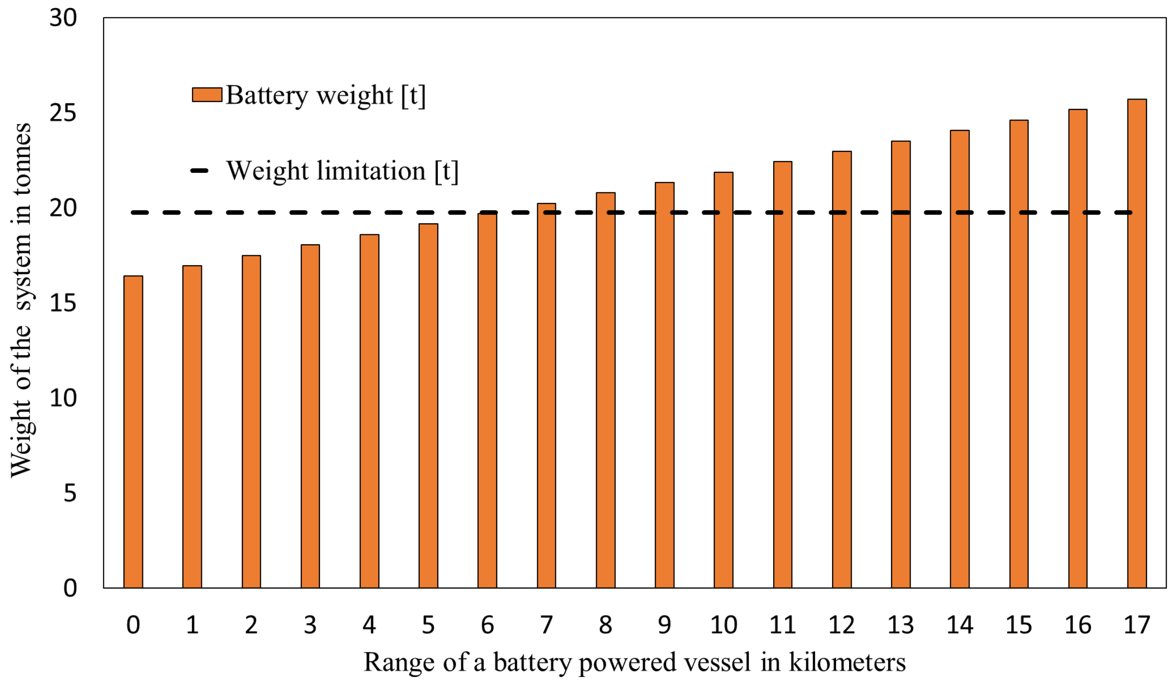

Figure 39: Gravimetric overview of the Lithium-ion battery system

The AKASOL 15 OEM battery module was chosen as the reference system for weight and volume. For larger battery packs, a cooling system is required. In this module, the cooling system and the rest of BoP are included, and will not be further evaluated. The price of the system is assumed to be approximately 176$ per kWh. With this, it was possible to calculate the weight and volume of the battery system with regard to the range. The plot in figure 38 and 39 shows the estimated volume and weight of the battery system with regard to distance. It also shows the volume limitation at 40 m^3 and the limitation of 75 % of available weight loading capacity.

From this, it can be seen that the weight of the batteries was the limiting factor. The system is only capable of a 6 km transit. A range of 6 km corresponds to a system volume of 12 m^3. It is important to note that 0 km represents the energy requirement of the 3-hour net-cleaning duty. The calculations are based on three hours of net cleaning duty. Removing this duty would result in 30 km extended range.

8.2.2 Lithium-Ion Battery Efficiency

When evaluating the required capacity of Lithium-ion battery efficiency need to be taken into account. This battery types have an efficiency ranging from 90 - 98 %. In this case, the team assumed in following calculations that the energy storage system has an average efficiency of 94 %. The parasitic power-drain from the BoP is neglected.

8.2.3 Summary

From this evaluation, it is clear that this system will not meet the range requirements, and will only cover a small percentage of the recorded trips in figure 34.

8.3 Proton Exchange Membrane Fuel Cell Drive

In this section, we will look into using a pure PEMFC-setup to supply the power demand. Figure 40 shows a basic system layout. The system consists of hydrogen storage tanks and fuel cells, with a buffer battery to reduce the energy peaks. The chosen storage option was hydrogen gas at 350 bar, due to indications from the industry in the area that this will be the favoured format. By using the power requirement for the diesel combustion engine and generator of Fosna Orion calculated in the previous chapter, the dimensions of the fuel cell was determined. The energy input from hydrogen was calculated to find the volume and weight of the hydrogen system required to power the vessel with regards to the range. The fuel cell setup is shown in 40.

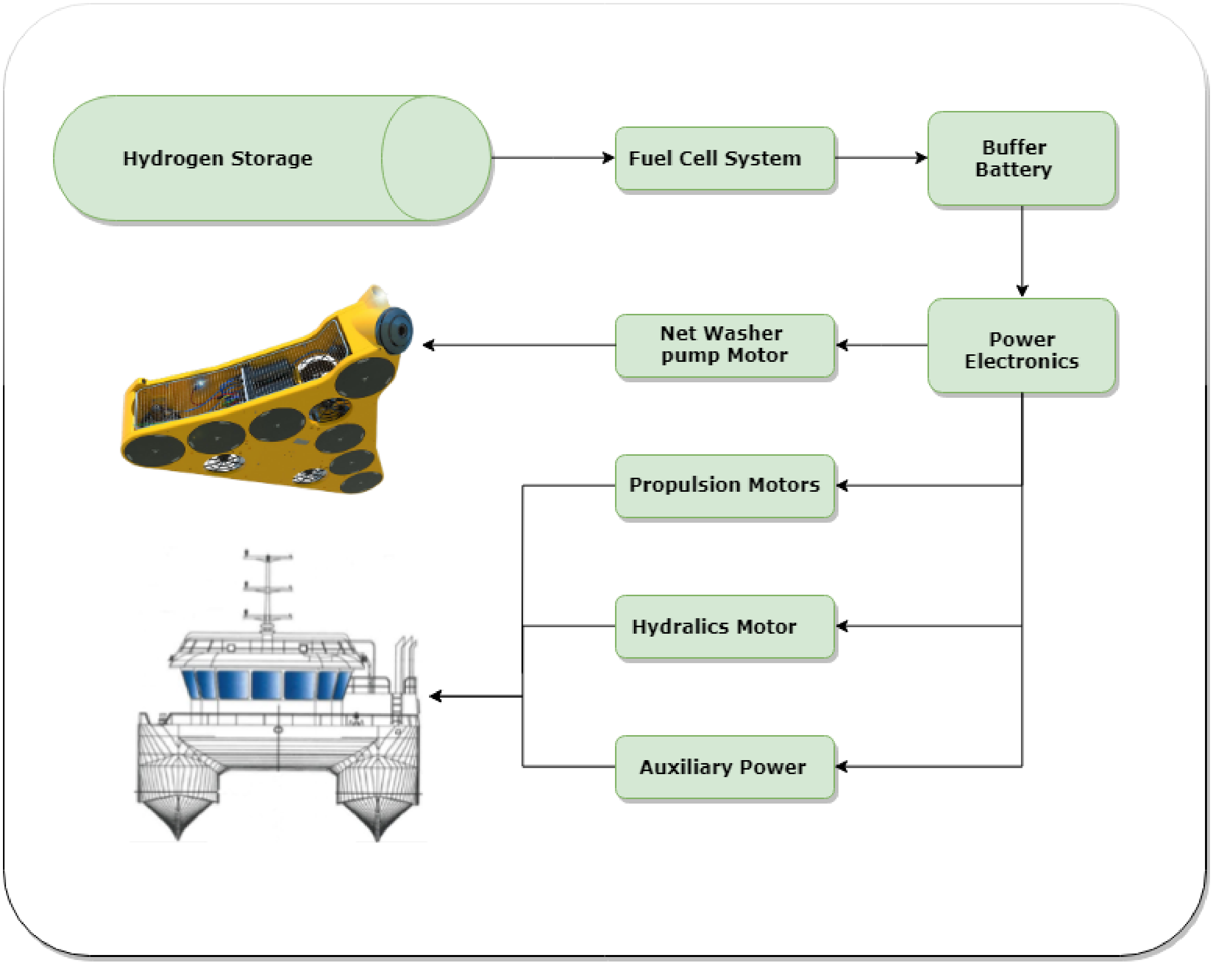

Figure 40: Fuel Cell system overview

8.3.1 System Volume and Weight

For this setup, the Ballard VeloCity-HD was chosen as the reference system. This can be found in appendix F. 10 units of 100 kW were needed to deliver the right amount of power. This system weighs 390 kg per 100 kW, including the BoP. This means that the FC system will weigh 3.9 tonnes. Hexagon type 4 tanks were chosen as references for the tank specifications. The plot in figure 42 shows how the total weight increases for the different storage methods as the range of the vessel increases. This including an NCS workload of 3 hours as previously mentioned. This is illustrated as the capacity requirement for 0 km in figure 42 and 41

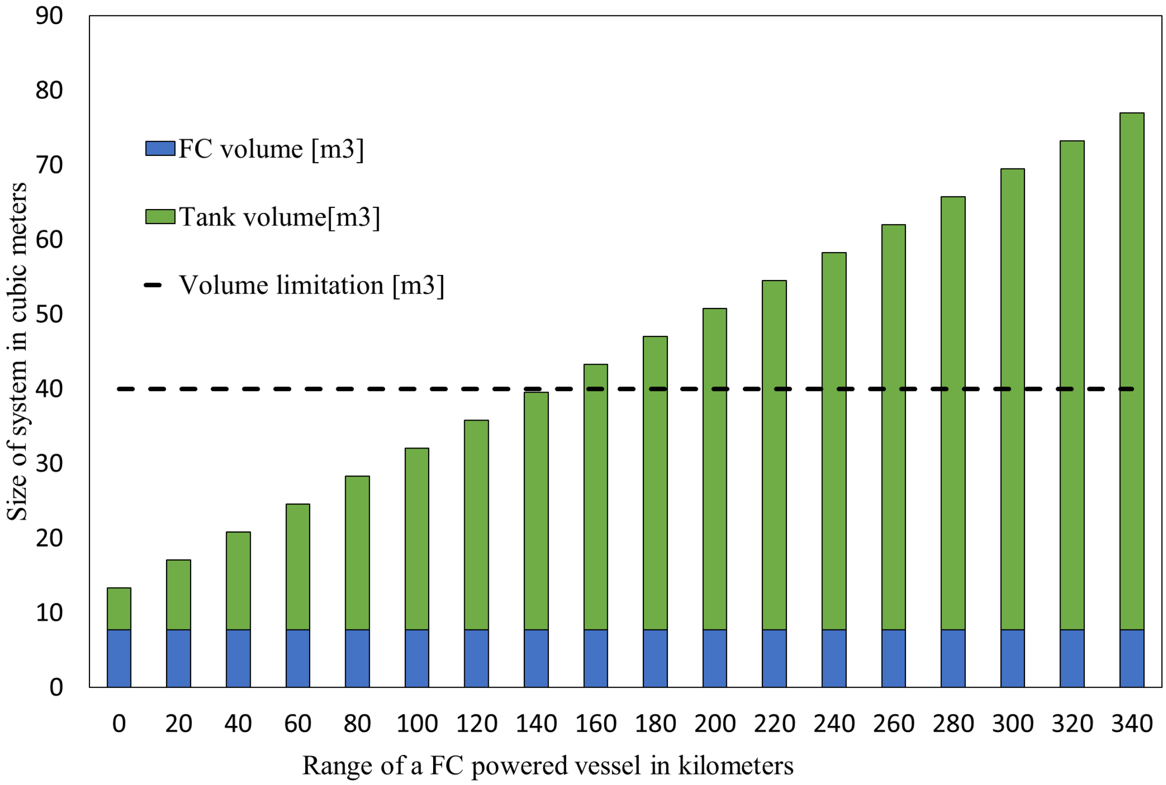

Figure 41: Volumetric overview of the fuel cell system

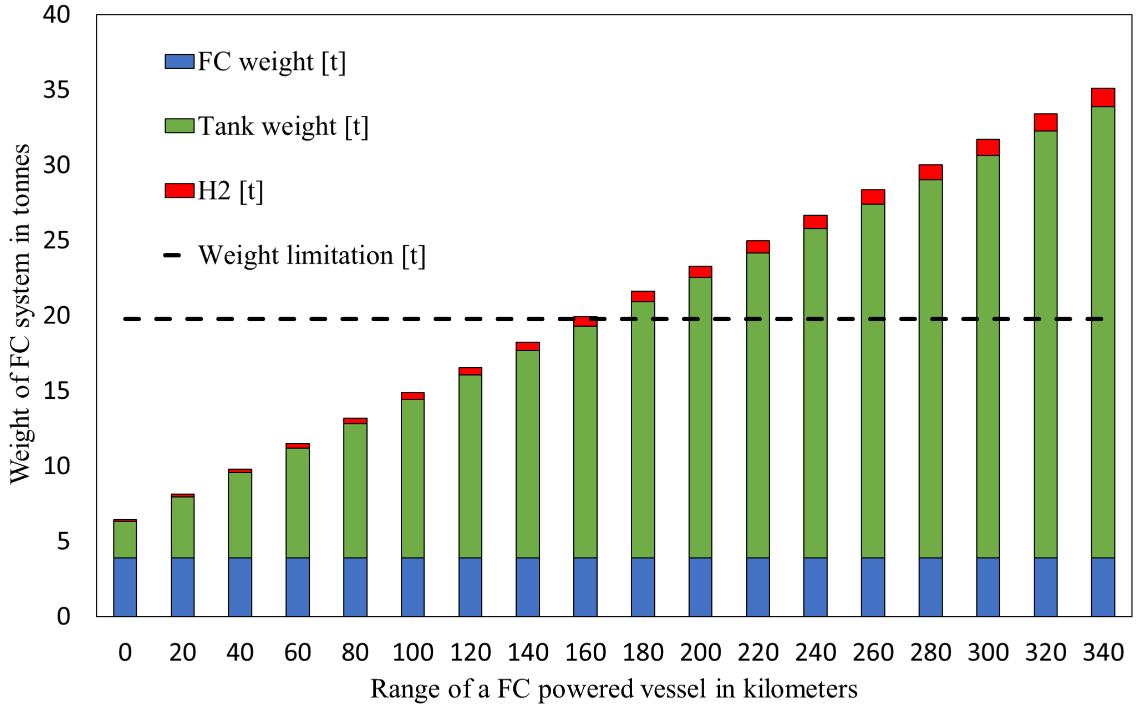

Figure 42: Gravimetric overview of the hydrogen fuel cell system

Looking at this graph, it can be seen that the limiting aspect when converting to a hydrogen system on this vessel is the physical size of the system by a small margin. The graph in figure 42 shows that the range for the gravimetric limitation will be in the range of 140-160 km, while the plot in figure 41 shows that the volumetric limitation is in the range of 120-140 km.

8.3.2 Efficiency

The efficiency of fuel cells is assumed to be 60 % in best cases. Including 10 % parasitic power from the BOP, this puts the efficiency estimate at 50 %. with an efficiency of electrolysis at 50 %, the efficiency of this system would be around 25 % on a Well-to-Waves(WtW) basis, and 50 % on a Tank-to-Waves(TtW) basis

8.3.3 Summary

From this section, it was clear that the weight and volume would not pose a problem. From the graph in figure 34 it can be seen that the range of this system covers 100% of the routes the vessel traversed in the analysed time-interval. This is a technically feasible solution.

8.4 Battery Fuel Cell Hybrid Systems

The hybrid system consists of a battery pack and a Hydrogen fuel cell system. An overview of the prioritised energy demanding systems onboard are shown in figure 43. The fuel cell system consisting of the fuel cell system running in parallel with the battery system. The power electronics system controls the flow of energy throughout the vessel, and the main goal of this is to distribute the required energy needed on the boat as effective as possible. In this project, we discussed both a 50/50-ratio distribution of the power and energy and a 70/30-ratio distribution of the power and energy.

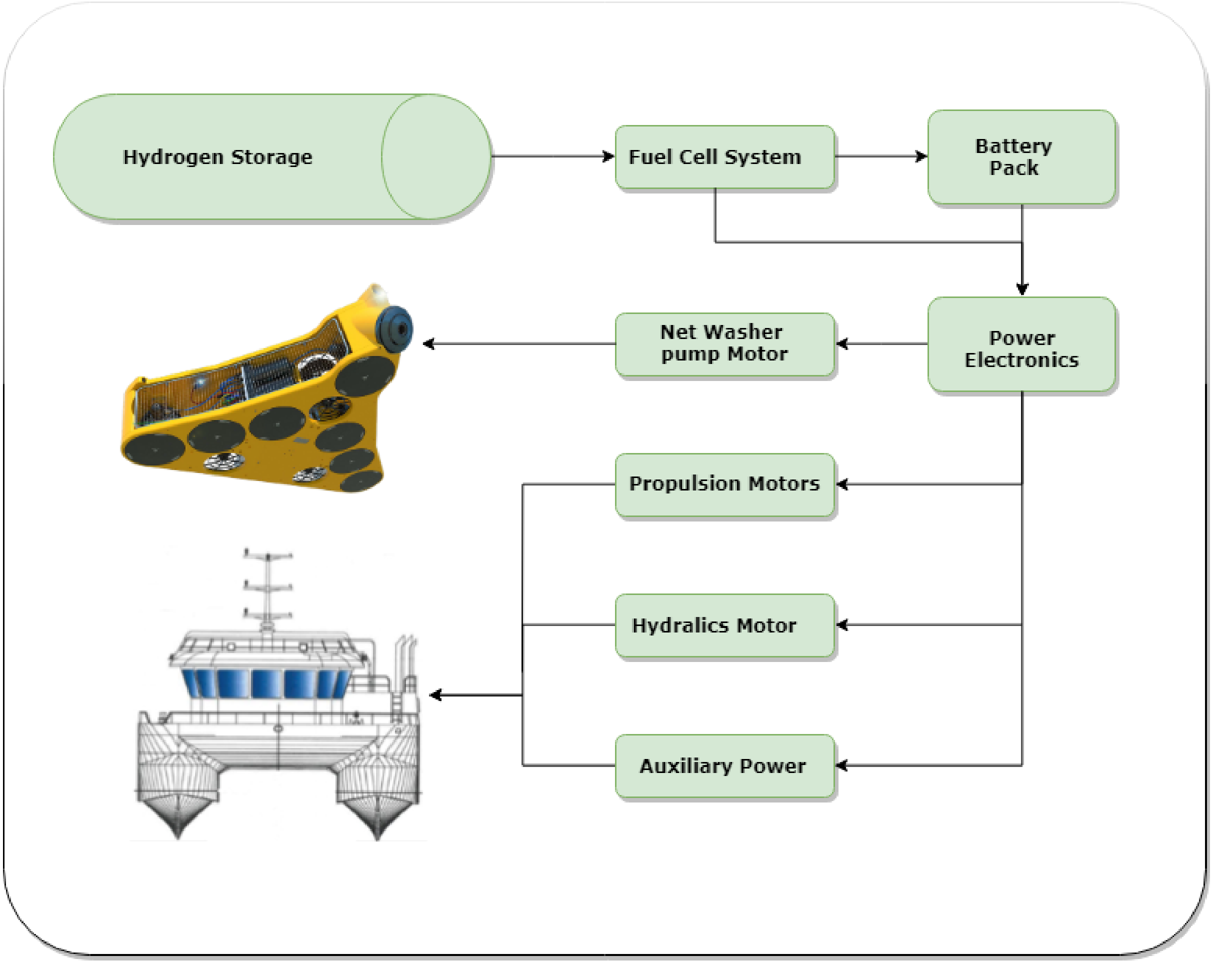

Figure 43: Fuel Cell Battery Hybrid system overview

Combining fuel cell with a fraction of plug-in batteries will introduce some of the required energy at a higher efficiency. Charging a battery has an assumed efficiency of 94 %. The efficiency of the fuel cell is assumed to be 60 % in best cases. Including 10 % parasitic power from the BOP, this puts the efficiency estimate at 50 %. With an efficiency of electrolysis at 50 %, the efficiency of this system would be around 25 % on WtW basis, and 50 % on a TtW basis. Including a fraction of batteries will, in theory, increase the system efficiency and lower the consumption of hydrogen.

One of the challenges of designing the boat is the weight and volume requirements of the hydrogen storage system, the fuel cell and the battery packs. From the battery system calculations, it became clear that lead-acid batteries are too heavy, so the team chose to use the same lithium-ion battery module in the hybrid system.

8.5 Fuel Cell Battery Hybrid Drive 50/50 Ratio

This fuel cell battery hybrid drive will have a 50/50 ratio, meaning that the fuel cell and the battery systems will deliver 50 % power and energy each.

8.5.1 System Weight and Volume

Figure 44 shows the total volume of the hybrid system with regard to the range in kilometres. The volume limitation, set to 40 m^3, is reached at 90 km, but like in the previous chapters, the weight is the key limiting factor. Figure 45 shows the total weight of the system including H_2 fuel in tonnes with regard to the range in kilometres. The weight limitation was stil set at19.7 tonnes. This is reached at around 26 km. This system is lacking in range for any of the routes described in chapter 7, but is adequate for 48% of the trips described in figure 34. This is 23 of 48 trips in 4 months.

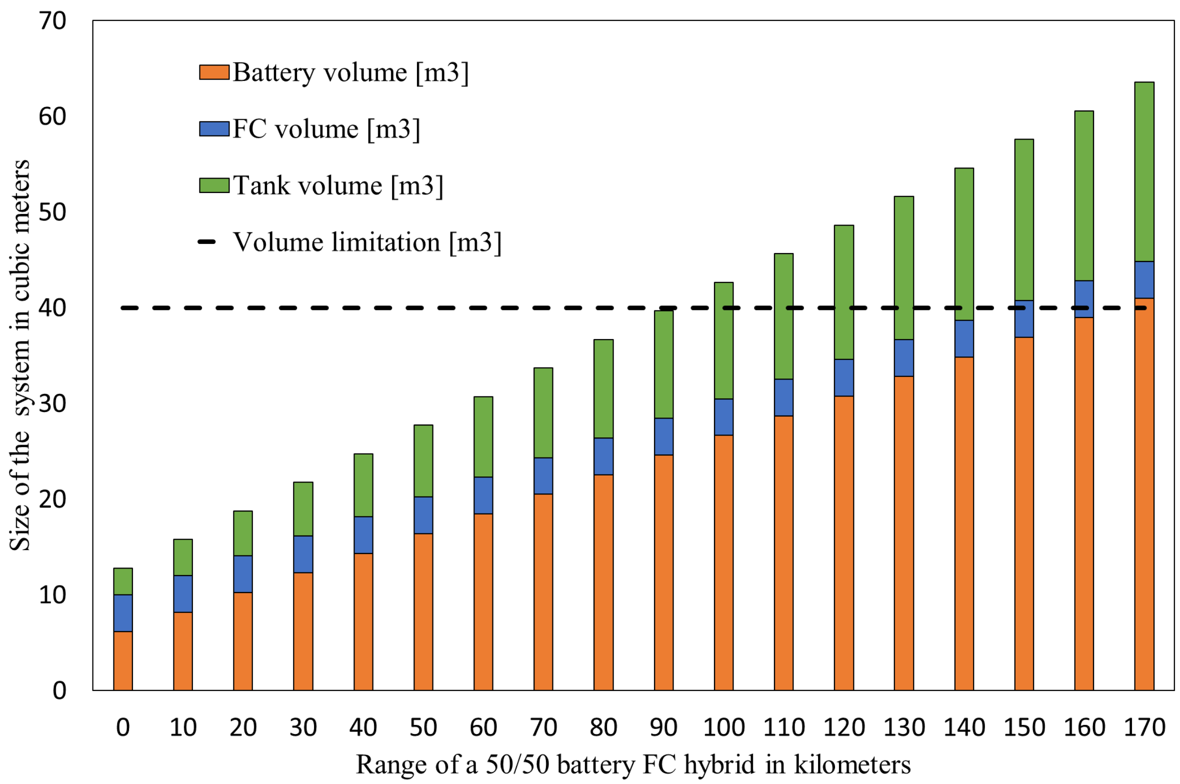

Figure 44: Volumetric overview of the hybrid system

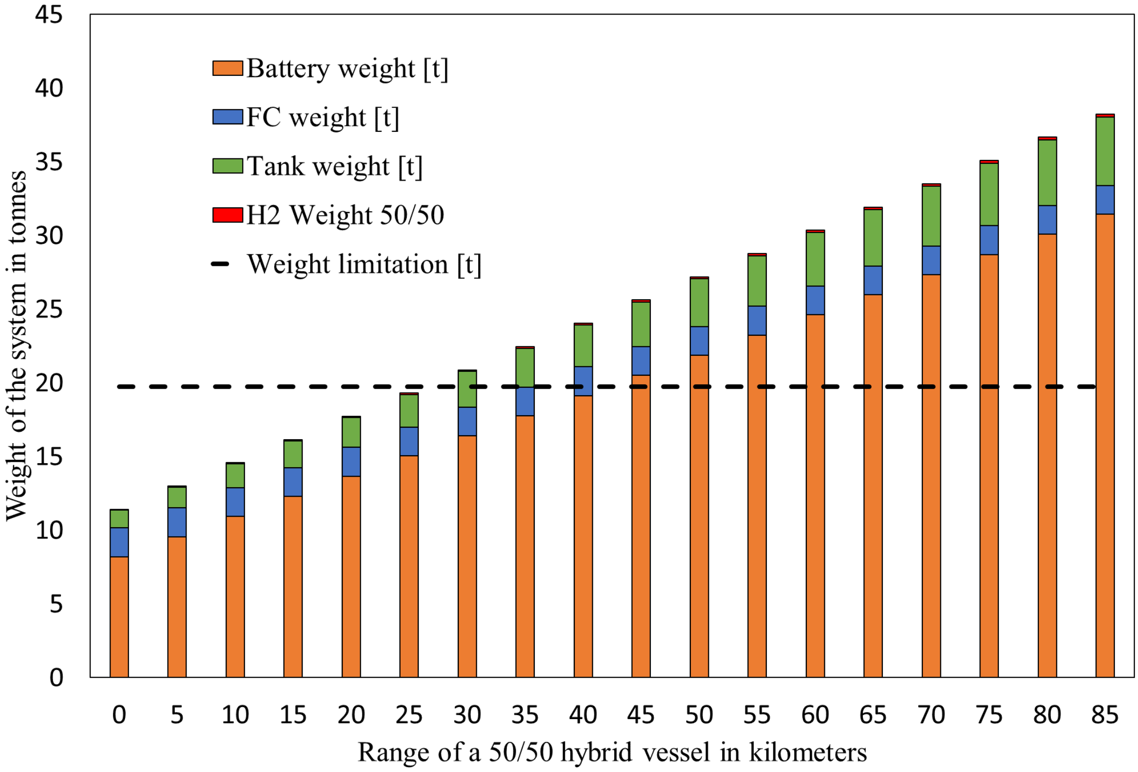

Figure 45: Gravimetric overview of the hybrid system

8.5.2 Efficiency

As this system includes batteries and FC, each delivering 50 % power and energy. The battery is assumed to have an efficiency of 94 %, the FC is assumed to be 50 %, and the electrolyser at 50 %. This means the Well-to-Waves efficiency equates to $0.5 \cdot 0.94 + 0.5^3 = 59.5\%$ and the Tank-to-Wave efficiency calculates to $0.5 \cdot 0.94 + 0.5^2 = 72\%$.

8.5.3 Summary

In this chapter, it is clear that the 50/50 hybrid solution has its problems according to the weight. With a distance of around 26 km, the boat covers 48 % of the distances travelled in figure 34 in chapter 7.

8.6 Fuel Cell Battery Hybrid Drive 70/30 Ratio

As can be seen in figures 44 and 45 in the Fuel Cell Battery Hybrid Drive 50/50 Ratio sub-chapter, the battery system has the largest impact on both the volume and, especially, the weight as the maximum range is increased. Due to this, a hydrogen PEMFC battery hybrid system where the fuel cell system contributes 70 % of both the energy capacity and power requirements, and the battery system contributes the last 30 % of both the energy capacity and power requirements were explored. With this system ratio, the maximum range increases by approximately 23 km, from around 26 km to 49 km, without exceeding the weight and volume limitations assumed at the beginning of chapter 8.

8.6.1 System Weight And Volume

While considering this system ratio in figures 46 and 47, it became clear that the battery weight would still be the limiting factor in terms of the vessel's maximum range. However, the maximum range is nearly doubled compared to the 50/50-ratio system. By achieving a maximum range of close to 50 kilometres, including three hours of operation for the net washer, 81 % of the trips mentioned in figure 34 in subchapter 7.4 are within the range limitations. With this being said, the vessel would be required to refuel about once a day and recharge the batteries each night for this to be accurate, which realistically rules out the possibility to anchor up for the night at a fish farm without a refuelling station or an electrical output nearby.

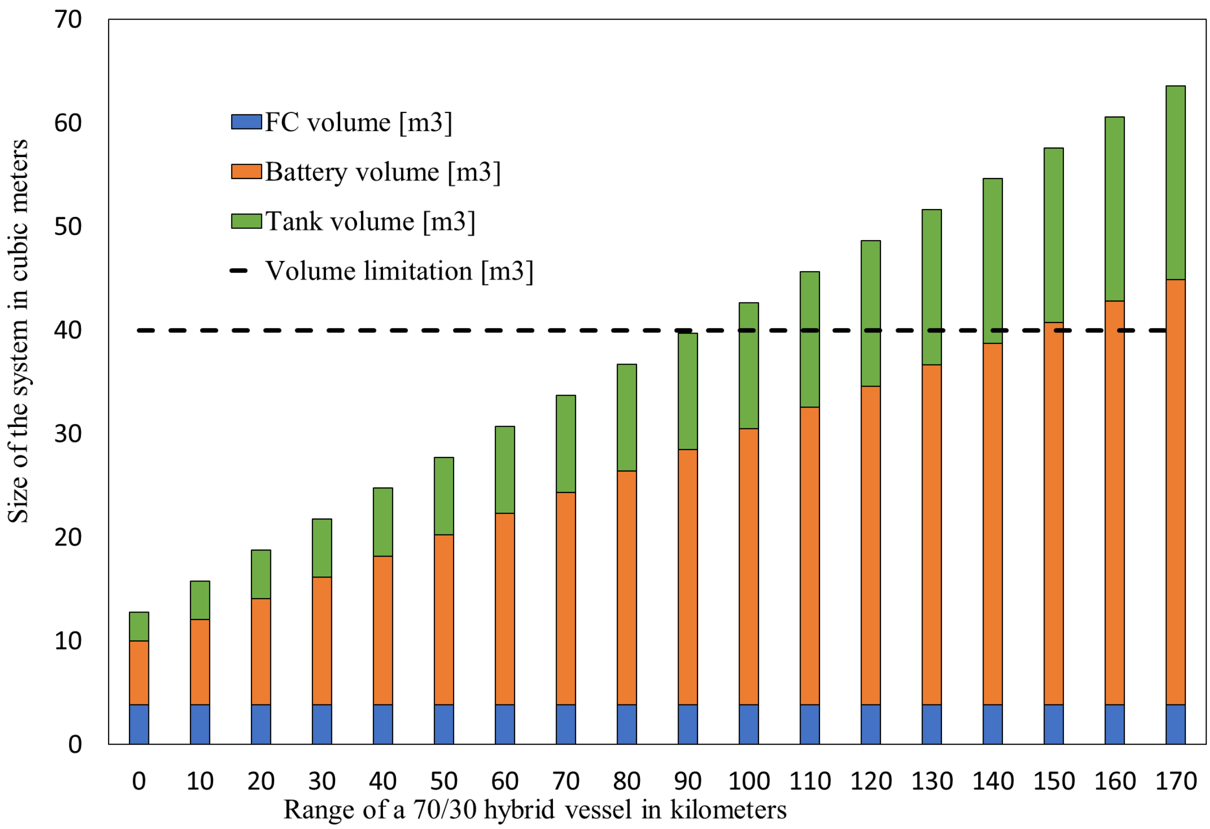

Figure 46: Volumetric overview of the hybrid 70/30 system

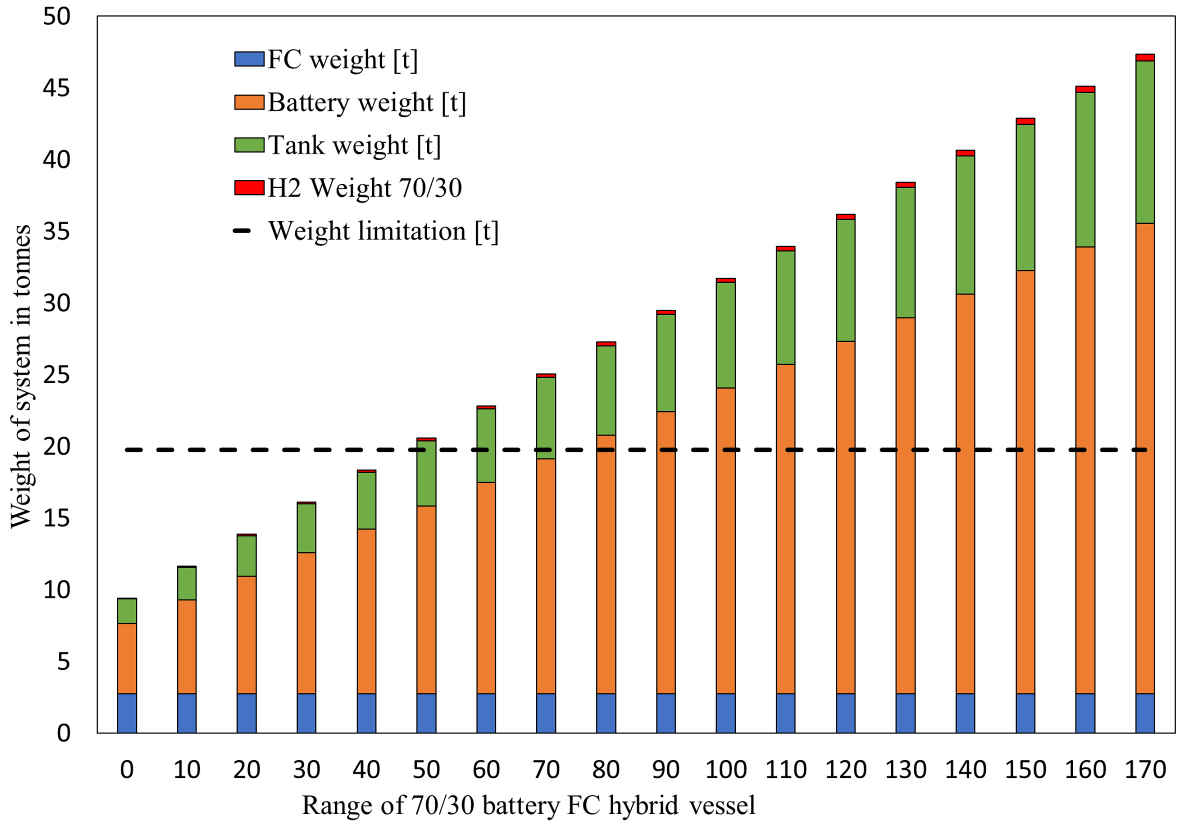

Figure 47: Gravimetric overview of the hybrid 70/30 system

8.6.2 Efficiency

With the summation of the 70/30 system, the WtW efficiency is 45.7 % and the TtW efficiency is 63.2 %.

8.6.3 Summary

The weight is the limiting factor for the range of both the hybrid systems. However, the 70/30-hybrid system has a higher maximum range due to the high weight of the batteries compared to the fuel cell, but it has a lower total efficiency for both WtT and WtW compared to the 50/50-hybrid system.

8.7 Comparison of Systems

Table 19 is a collection of the ranges and efficiencies of the systems.

	Plug-in Battery drive	Fuel Cell drive	50/50 Hybrid	70/30 Hybrid
η_{WtW}		25 %	59.5 %	45.7 %
η_{TtW}		50 %	72 %	63.2 %
Transit range	6 km	140 km	∼26 km	∼49 km
Coverage of range	6 %	100 %	48 %	81 %

Table 19: Comparison of the different system analysed

As shown in table 19 the system with the highest efficiency is the 50/50 hybrid drive, with a WtW efficiency at 59.5 % and a TtW efficiency at 72 %, but the range was limited to around 26 km. Changing the energy contribution from 50/50 to a 70/30 solution the range was extended toaround 50 km, but the efficiencies dropped to 45.7 % WtW and 63.2 % TtW. The coverage of the trips taken in the four-month period shown in figure 34 also extended, from 48 % coverage to 81 % coverage. The solution with a 100 % coverage was the Fuel cell drive, as it has the longest range with a transit-range of 140 km (170 is the NCS-duty is carried out). The Fuel cell drive has an efficiency of 25 % WtW and 50 % TtW. Compared with the 50/50 hybrid solution is has lower efficiency, but have no range problem. The battery-powered vessel was the least viable option, At 0 kilometres, it is estimated three hours of duty would require approximately 1700 kWh, with a battery weight at 16 400 kg and a volume of 12 m^3. The propulsion and auxiliary power is depending on the travelled distance. Pure transit gives the battery-vessel a range of 35 kilometres. it is clear that a pure battery-powered vessel for these modes of operations is unobtainable at the current gravimetric densities.

With the new solutions disclosed we can assume that these solutions are CO_2 emission free from a TtW perspective. Compared with the CO_2 emissions for the diesel driven Fosna Orion used today, it can be assumed that this can remove the CO_2 emissions from route 1, 2 and 3 summarised in table 14, 15 and 16. Another way is an analysis of the CO_2 emissions from a WtW perspective or an LCA on both the diesel boat and the new disclosed solutions. These analyses would maybe have a different result but is out if the scope of this thesis.

8.8 Economy

A fuel cell powered vessel is a technically viable solution today for the ranges needed. The main drawbacks to this solution are the substantial price tag. As seen in figure 48 Figure 48 shows the CAPEX in NOK for the different system as a function of the range in kilometres. To illustrate the range of the different systems, the dotted lines are included in the graph. Estimates for the CAPEX and OPEX for the different systems are shown in table 20.

Systems	CAPEX [MNOK]	OPEX [MNOK]
Battery Plug-in	2.7	0.5
Fuel Cell Drive	13.3	2.8
50/50 Hybrid Drive	8	1.6
70/30 Hybrid Drive	10.2	2.1

Table 20: CAPEX and OPEX for the different systems

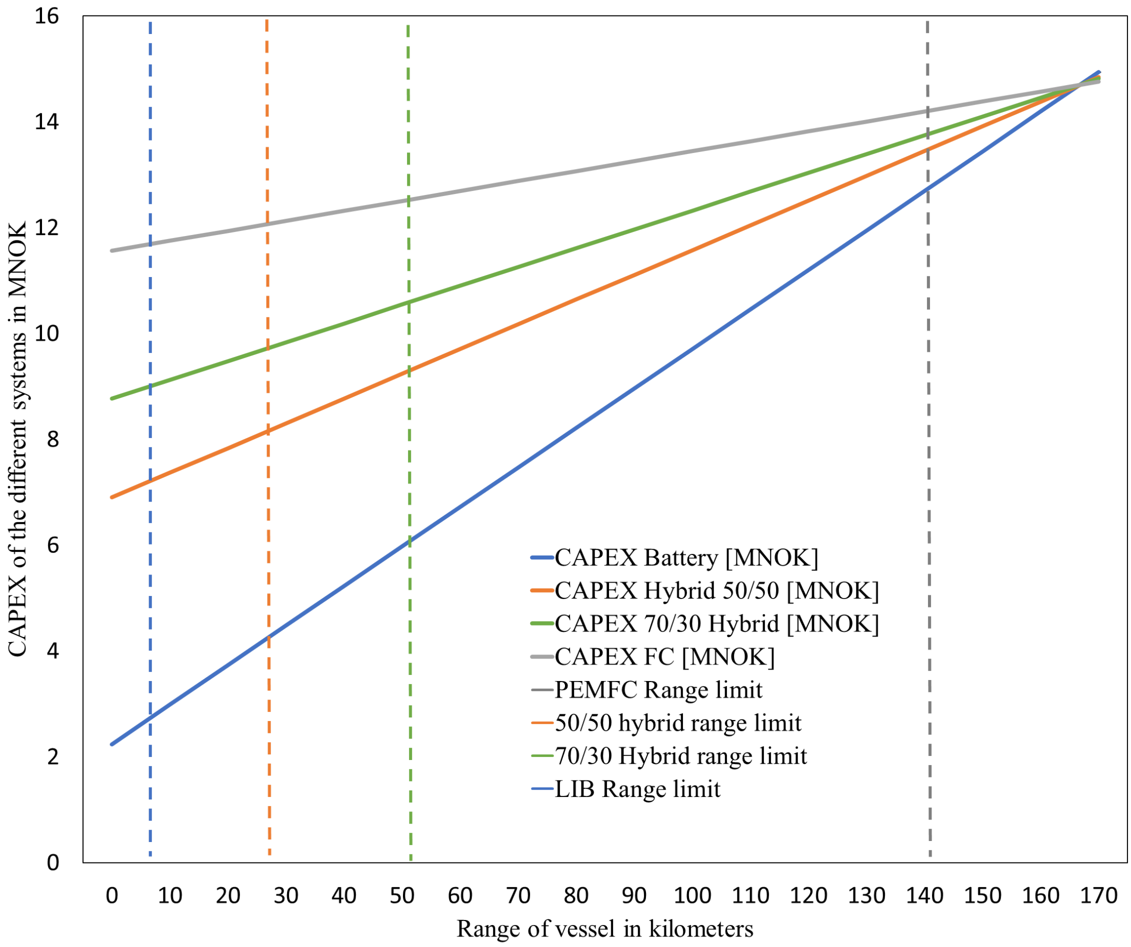

Figure 48: CAPEX of the different systems

On a yearly basis, the vessel Fosna Orion were analysed with regard of distance, travelling routes frequency of duty missions using Marine Traffic data. In this analyse, net cleaning duty is not included. It was estimated an average travelling distance at 5383 kilometres on a yearly basis. It was then interesting to look at the fuel consumption costs and investment costs to see how the economics would evolve. Lifetime expectancy and maintenance is not taken into account. The reason for this is that load of the battery in both the pure battery system and the hybrid systems are fluctuating and lifetime expectancy does vary in terms of cycle life.

It is taken into account the efficiency of the battery system, fuel cell and diesel engine is respectively 94, 50 and 40 %. With an average energy consumption of 54 kWh/km, and set values of hydrogen and electric costs, total fuel costs were estimated.

It is expected that the investment costs would decrease when the hydrogen marked increases due to strict emissions regulations. A large movement towards zero emission solutions is contributing to a lower market price, making it more valid in the future. Battery system for maritime applications has also a strong leed in today's market, making the system expenditures to be more achievable in the future.

Figure 49, an overview of the CAPEX of the battery system, fuel cell system, the two hybrid systems and the diesel system. CAPEX is shown as the level of expenditure at zero kilometres and increases by the yearly fuel costs of Diesel, hydrogen and electric energy in terms of each system. This figure also shows a crossing point as approximately 10 years, between battery and diesel. In this case, the long term basis diesel cost will exceed the battery system costs.

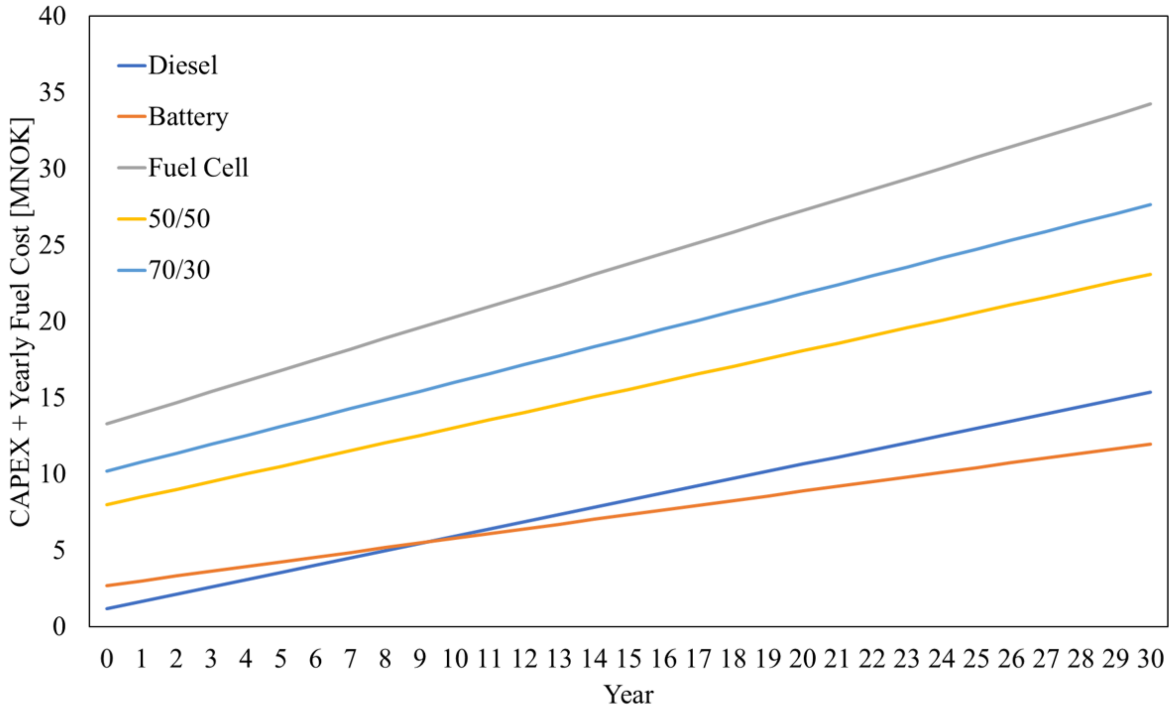

Figure 49: A comparison of the CAPEX, with the yearly fuel cost added per year

Table 21 shows the fuel cell costs for one-year duration. Diesel engine system was estimated with high efficiency of 40 %. It is clear that a propulsion engine system with a lower efficiency would have higher consumption and there for higher costs. In this specific case, the diesel costs are estimated to around 472 000 NOK/year, while the LIB-system has a significantly lower energy pricing at approximately 300 000 NOK/year. With a hydrogen pricing at 40 NOK/kg, is estimated that the fuel consumption on the pure hydrogen fuel cell system has a yearly cost of almost 700 000 NOK/year.

It is a significant difference in fuel costs of the LIB-system and a purely hydrogen driven vessel. When analysing the hybrid solution it is possible to lower the fuel consumption costs. The 50/50 hybrid fuel cell system is close to 500 000 NOK, which makes it more competitive to a diesel system.

8.9 Performance

As stated in the beginning of this chapter, the main variable in which the performance of the energy systems is evaluated in this thesis, is the power-to-weight ratio (PW). A lower PW would indicate poorer performance. The team chose early on to set the power output of the electrical engineering as a constant to reduce the scope of the project to the energy systems, but it is worth noting that this limits the possibilities to optimise the performance of the system. A low PW could be compensated for by increasing the power output, but this would, in turn, increase the power and energy demand, increasing weight and so on. This optimisation is a possibility for future work.

Figure 50 shows the Power-to-Weight (PW) ratio in terms of the range. From this, it is clear that the best performing systems under these conditions is the pure FC-system.

Fuel costs per year				
Average distance	5383 km			
System for propultion		**System efficiency**	**NOK**	**NOK/km**
Diesel		$\eta_{engine} = 40\%$	**472 358**	**87.7**
Full Electric		$\eta_{LIB} = 94\%$	**309 236**	**57.5**
Hydrogen Fuel Cell		$\eta_{FC} = 50\ \%$	**697 706**	**129.6**
	Distribution of energy	**Systems efficiency**	**NOK**	**NOK/km**
Hybrid 50/50	$50\%_{FC}$	$\eta_{FC} = 50\ \%$	348 853	64.8
	$50\%_{LIB}$	$\eta_{LIB} = 94\ \%$	154 618	28.7
	Total		**503 471**	**93.5**
Hybrid 70/30	$70\%_{FC}$	$\eta_{FC} = 50\ \%$	488 395	90.7
	$30\%_{LIB}$	$\eta_{LIB} = 94\ \%$	92 777	17.2
	Total		**581 164**	**107.9**

Table 21: Fuel cost estimate on a one year basis

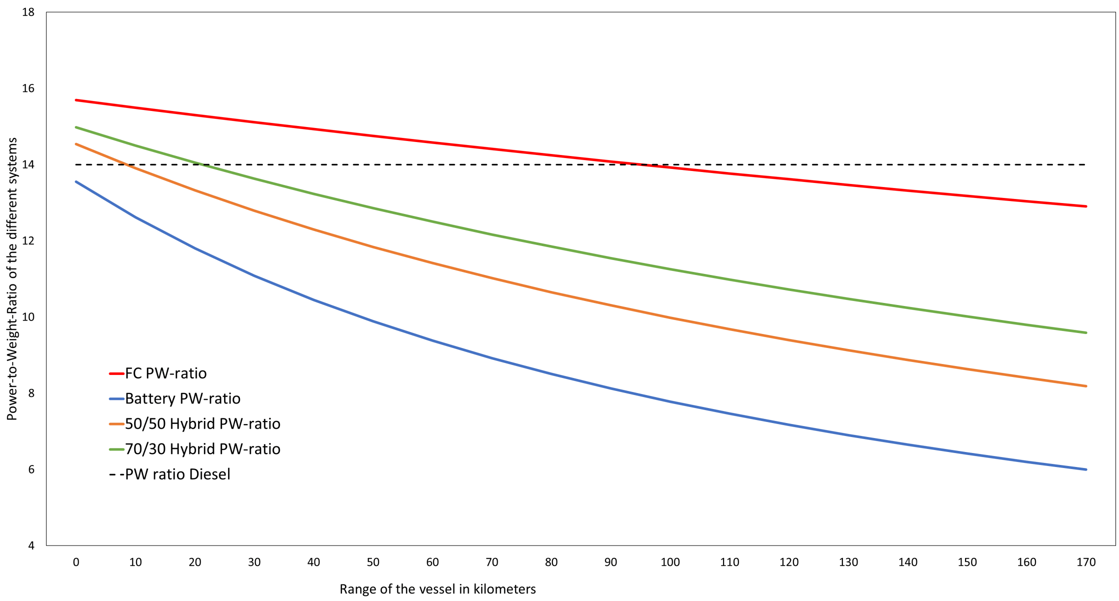

Figure 50: A graph showing the power-to-weight ratio of the different systems

8.10 Summary of Results

The best system in terms of maximum range is the diesel system with a maximum range of approximately 593 km, while the second-best system is the fuel cell system with a maximum range of 140 km. The fuel-cell system is the system with the highest CAPEX at 14 MNOK and is also the system with the highest OPEX at about 2.7 MNOK per year. In terms of the tank-to-wave efficiency, the battery system is on the top of the list with an efficiency of 95 %, followed by the 50/50-hybrid system with a 72 % tank-to-wave efficiency. All the key figures and most important results are listed in table 22.

System	**Range** [km]	**CAPEX** [MNOK]	**OPEX pr year** [MNOK]	**Fuel cost pr year** [MNOK]	η_{TtW} [%]
Diesel	593.0	1.8	0.85	0.47	40
Battery	6.0	2.7	0.54	0.31	94
Fuel Cell	140.0	13.3	2.7	0.70	50
50/50 Hybrid	26.0	8.0	1.6	0.50	72
70/30 Hybrid	49.0	10.2	2.0	0.58	63

Table 22: Key figures and the most important results

8.11 Discussion

As can be seen from the results in the previous chapters, the hydrogen fuel cell electric hybrid is not yet economically viable compared to the existing diesel engine system. However, there exist various programs in Norway that can help lower the economic risks. Investing in hydrogen technology will contribute to the demand-side of the novel hydrogen economy, and with demand comes supply. There are notable actions being taken on this front, with several different companies designing this sort of maritime transport and fuelling infrastructure. With more focus and support for this type of technology, it is probably just a matter of time before the economy of scale becomes noticeable on the fuel cell and tank pricing.

If Norway is to meet its commitment to the Paris agreement and the 1.5-degree target, it is quite clear that this is one of the more promising paths towards meeting the target. As mentioned earlier, this vessel releases in the area of 265 tonnes of CO_2 into the atmosphere each year. This is only one of many vessels of this size, so the potential for large CO_2-reductions in this class of ships is prominent. There have been some discussions regarding carbon taxation on the maritime industry. This will probably make a drive-system like the ones presented in this thesis more attractive for a profit-motivated industry.

The fish farming industry has the economic power to be a driver in a future hydrogen market. Fish farming requires oxygen in the production, and electrolysis of water produces both hydrogen and oxygen, making them a perfect consumer for the hydrogen economy.

A ship with a drive-system like this will probably need a different perspective on the ship as one tool for everything, towards more integrated design, and docking solutions into the fish farming industry. A diesel driven ship like the one in this paper would have 4-5 times the range of the hydrogen-powered vessel presented in the previous chapters. This means that a hydrogen-powered vessel would require local filling stations that are in the radius of the tasks at hand, as the tank would need to be filled every 1-2 working days. Different ships with different characteristics for different tasks could be a solution. For instance, the vessel in our calculations could do the tasks at hand, if the fish cages were in the radius of a little under half the available transit distance. This could be taken into consideration when discussing the location of future fishcage infrastructure.

The behaviour-patterns of the pilot on the ship would also need to be examined, as it is can be interpreted from the ECU-data, that fuel economy is not the primary focus on-board this vessel, as can be expected from a profiting viewpoint. A zero-emissions ship would probably benefit from a more careful approach to transit speed and load with regards to both fuel consumption, and system lifetime. However, this is just a qualitative observation and might not be the case, but an anecdote passed to the team by people in the industry comes to mind; A larger diesel-consumption than expected was noticed on a ship, it turned out the crew was running the larger diesel-engines at night to charge their phones because this engine had a lower noise-pollution than the generator, making it more comfortable to sleep. This was mended by introducing a simple battery for this specific purpose.

It is our understanding from the literature that this sort of system could be implemented with the current status of the technology. As mentioned there is a rather large economic hurdle towards this, but there are limited options for this type of transport. LNG and bio-diesel could be an option, but this poses its own disadvantages. These types of ships still produce local pollution, both in the form of emissions, but also in the form of noise. A ship driven by electric motors would probably contribute to a healthier working environment, both for the crew and the fish.

It is also worth mentioning that producing hydrogen could be a good economical solution to the problem of stochastic renewable power production. With the introduction of notable amounts of installed power coming from wind and solar, it could be beneficial to use the surplus power to produce hydrogen instead of exporting it at a low price. This be could also beneficial in areas with limited capacity in the grid.

8.12 Recommendations

Based on an assumption that economic support from a governmental program is given, we would recommend the pure fuel cell system as a zero-emission system on board Fosna Orion. Further, we would strongly recommend giving subsidies to establish a hydrogen infrastructure to stimulate to growth for a hydrogen market, for both the supply, and in this case, the demand side.

9 Conclusions

The 70/30-hybrid and pure fuel cell systems are technically viable in regard to performing the main tasks of today's version of Fosna Orion. The 50/50-hybrid and battery plug-in systems were considered suitable for the tasks required. The 70/30-hybrid and pure fuel cell systems are not economically viable. For such a solution to be economically viable, one can apply for economical support to lower the economic risk. A better hydrogen infrastructure is needed to increase the geographical range of the hydrogen systems.

10 Future Work

As this is a bachelor thesis, the scope of the rapport had to be narrowed. One of the big assumptions made was the volume limitations. The different systems were assumed to be placed on the deck of the vessel. Future work could be an evaluation of the actual placement possibilities, into possibly increase the volumetric limitation, as this was shown to be the key limiting factor for the range of the fuel cell system. A safety analysis on the placement of the battery and hydrogen systems would be helpful, as the team's only impression was that tanks had to be placed on deck, to make sure that gas would not gather in a confined space, and pose an explosive danger.

The algorithm for calculating the energy-demand has some room for improvement. The calculations were made on an assumption of full load, and this is definitely not the case. It became apparent to the team towards the end of the thesis, that it is possible to use the turbo-pressure sensor on the ICE as an indication of the load en the engines. This would increase the resolution of the calculations by a factor of 3, as the data-sheet supplied information regarding the consumption at 50, 75, and 100% load. The estimates for energy consumption would be improved by gathering more data. Because of technical issues with the equipment, the team had only overlapping data for two weeks. The owners of the vessel also have limited data on hand of the diesel consumption and actual distances for the vessel, and all the numbers used to estimate emissions was based on an average value from a bulk number for the entire fleet of 12 ships. With better data on the actual consumption, it would be possible to verify the calculations by some extent.

It would also be beneficial to make the calculations for energy-demand dynamic with regards to the increasing weight of the different system. This was not accounted for in the calculations. another aspect that could be improved is the semi-arbitrary ratio of batteries to fuel cells. Further investigations into load the characteristics of batteries, fuel cells, and the control system, would possibly yield an improved ratio.

Another aspect not regarded in this thesis, is the need for heat onboard the vessel. The waste heat from the ICE in the diesel system is utilized, but quantifying this need is challenging.

It would also have been interesting to look into the literature regarding health, environment and safety concerns when using electric motors compared with a diesel motor.

It would be useful to increase somehow increase the industry's willingness to share information regarding the economic aspects of hydrogen technology.

Appendices

A Hammelmann HDP 300 High Pressure Pump series

http://www.hammelmann.de/wAssets/docs/downloadcenter/en/hochdruckpumpen/HDP_300-en.pdf

B Stealth Cleaner MK2

https://www.ocein.no/uploads/oh0eU5Br/OceIn-MKIIStealthCleaner-Teknisksspesifikasjon.pdf

C Scania Marine Diesel Engine DI13 072M. 441 kW (600 hp)

https://www.scania.com/content/dam/scanianoe/market/master/products-and-services/engines/pdf/specs/marine/DI13072M_441kW.pdf

D Distance from Longitude and Latitude

$$acos(cos(\frac{\pi \cdot (90 - Lat1)}{180}) \cdot cos(\frac{\pi \cdot (90 - Lat2)}{180}) + sin(\frac{\pi \cdot (90 - Lat1)}{180}) \cdot sin(\frac{\pi \cdot (90 - Lat2)}{180}) \cdot cos(\frac{\pi \cdot (Long1 - Long2)}{180})) * 6371$$

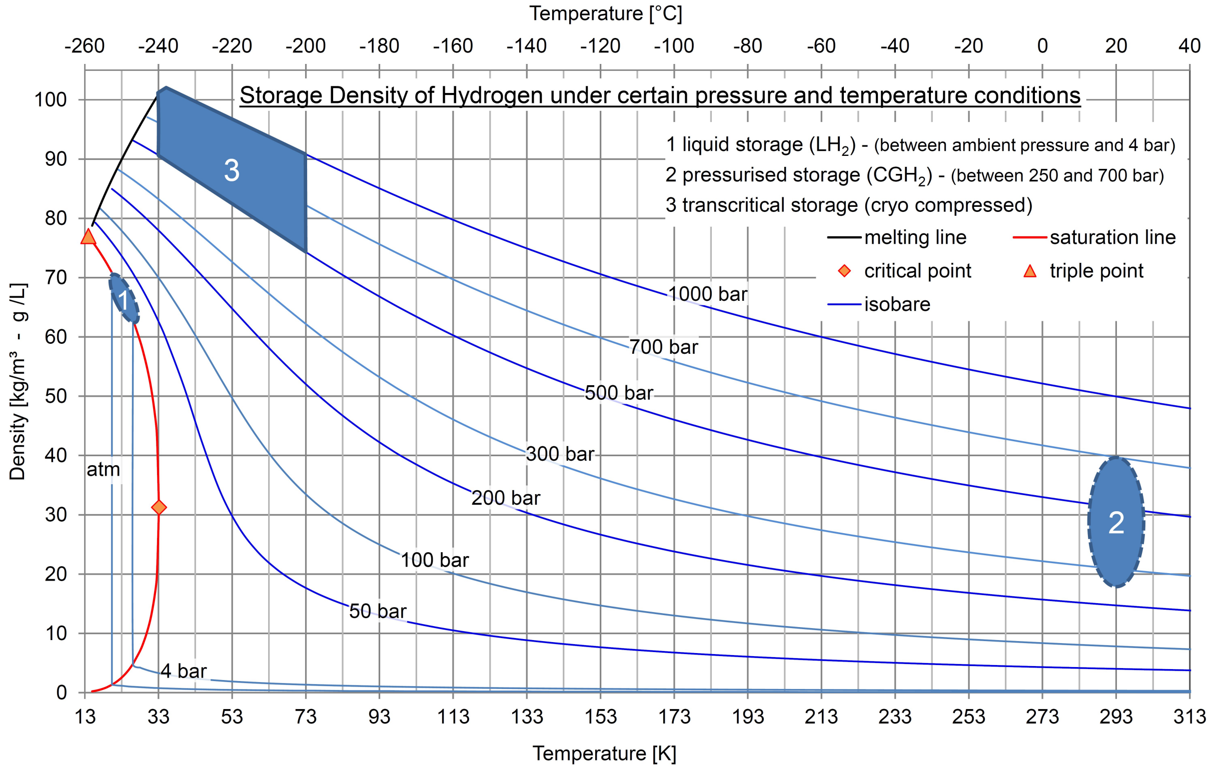

Figure 51: By ILK Dresden, Moritz Kuhn

E Hydrogen Storage

F BALLARD Velocity FC

BALLARD®
PUTTING FUEL CELLS TO WORK

FCveloCity®-HD

PRODUCT SPECIFICATIONS

	HD60	HD85	HD100
Performance			
Net power	60 kW	85 kW	100 kW
Operating voltage range	220 - 350 VDC	280 - 420 V	400 - 580 V
Rated net current	288 A	288 A	288 A
Idle power	3.3 kW	4 kW	6 kW
Physical			
Fuel cell module			
• *Dimensions (l x w x h) mm*	1130 x 869 x 506	1130 x 869 x 506	1200 x 869 x 506
• *Weight*	244 kg	256 kg	285 kg
Coolant Subsystem			
• *Dimensions (l x w x h) mm*	737 x 529 x 379		
• *Weight*	44 kg		
Air Subsystem			
• *Dimensions (l x w x h) mm*	676 x 418 x 352		
• *Weight*	61 kg		
Reactants and Coolant			
Type	Gaseous hydrogen		
Composition	As per SAE specification J2719		
Supply pressure	8 barg nominal		
Oxidant	Air		
Coolant	50/50 pure ethylene glycol and deionized water WEG 60° to 70°C		
Safety Compliance			
Certifications	ISO 6469-2:2009 [1] ISO 6469-3:2011 [1] ISO 23273:2013 [1]		
Enclosure	IP55		
Monitoring			
Control interface	CANbus		
Emissions			
Exhaust	Zero-emissions (no PM, NOx, SOx, CO or CO2)		

[1] Specific clauses within each standards

Sub-system

The FCveloCity®-HD includes separate air and coolant systems for simplified and flexible integration into the electric drive system. These two discrete modules have been designed, tested and validated for transit bus and light rail applications.

Coolant sub-system
Delivers a water/ethylene glycol (WEG) mixture at a prescribed flow rate to the fuel cell module. Sub-system includes coolant pump, piping, control valve and freeze protection.

Air sub-system
Delivers air at a prescribed flow rate to the fuel cell stack to support the electrochemical reaction. Sub-system includes motor, controller, air compressor and a mass flow sensor.

[87]

G Results from Calculations on the Fully Electrical Vessel

Three hours net cleaning duty included in the transit calculations.

H Calculations of the Hydrogen Fuel Cell system

Calculations for the hydrogen fuel cell system including 3 hours of net cleaning.

Transit Distance [km]	**Propulsion** req. energy [kWh]	**Li-ion η=94%** En. storage [kWh]	Weight [tonne]	Volume [m^3]	**PbA η=75%** En. storage [kWh]	Weight [tonne]	Volume [m^3]
5	270	287.2	1.4	0.7	360	9.0	4.2
10	540	574.5	2.7	1.4	720	18.0	8.5
15	810	861.7	4.1	2.1	1080	27.0	12.7
20	1 080	1 148.9	5.4	2.8	1 440	36.0	16.9
25	1 350	1 436.2	6.8	3.5	1 800	45.0	21.2
30	1 620	1 723.4	8.1	4.2	2 160	54.0	25.4
35	1 890	2 010.6	9.5	4.9	2 520	63.0	29.6
40	2 160	2 297.9	10.8	5.6	2 880	72.0	33.9
45	2 430	2 585.1	12.2	6.3	3 240	81.0	38.1
50	2 700	2 872.3	13.5	7.0	3 600	90.0	42.4
55	2 970	3 159.6	14.9	7.7	3 960	99.0	46.6
60	3 240	3 446.8	16.2	8.4	4 320	108.0	50.8
65	3 510	3 734.0	17.6	9.1	4 680	117.0	55.1
70	3 780	4 021.3	18.9	9.8	5 040	126.0	59.3
75	4 050	4 308.5	20.3	10.5	5 400	135.0	63.5
80	4 320	4 595.7	21.6	11.2	5 760	144.0	67.8

Table 23: Transit distance, propulsion output energy and energy storage of each battery type

Operation Eff. hours [h]	En. output [kWh]	**Li-ion η=94%** En. storage [kWh]	Weight [kg]	Volume [m^3]	**PbA η=75%** En. storage [kWh]	Weight [tonne]	Volume [m^3]
1	540	574.5	5 468.9	4.1	720	18 000	8.5
2	1 080	1 148.9	10 937.9	8.2	1 440	36 000	16.9
3	1 620	1 723.4	16 406.8	12.3	2 160	54 000	25.4
4	2 160	2 297.9	21 875.7	16.4	2 880	72 000	33.9
5	2 700	2 872.3	27 344.7	20.5	3 600	90 000	42.4
6	3 240	3 446.8	32 813.6	24.6	4 320	108 000	50.8
7	3 780	4 021.3	38 282.6	28.7	5 040	126 000	59.3
8	4 320	4 595.7	43 751.5	32.8	5 760	144 000	67.8

Table 24: Effective net cleaning duty in hours, output energy during net cleaning, and energy storage of battery type

I Hybrid Solution with Battery and Fuel Cell System

Distance	Energy output including 3 hours net cleaning duty	Li-ion η = 94 % En. storage	Weight	Volume	CAPEX	El. costs
[km]	[kWh]	[kWh]	[kg]	[m^3]	[NOK]	[NOK]
5	1 890	2 010.6	19 141.3	14.4	2 626 898.9	2 010.6
10	2 160	2 297.9	21 875.7	16.4	3 002 170.2	2 297.9
15	2 430	2 585.1	24 610.2	18.5	3 377 441.5	2 585.1
20	2 700	2 872.3	27 344.7	20.5	3 752 712.8	2 872.3
25	2 970	3 159.6	30 079.1	22.6	4 127 984.0	3 159.6
30	3 240	3 446.8	32 813.6	24.6	4 503 255.3	3 446.8
35	3 510	3 734.0	35 548.1	26.7	4 878 526.6	3 734.0
40	3 780	4 021.3	38 282.6	28.7	5 253 797.9	4 021.3
45	4 050	4 308.5	41 017.0	30.8	5 629 069.1	4 308.5
50	4 320	4 595.7	43 751.5	32.8	6 004 340.4	4 595.7
55	4 590	4 883.0	46 486.0	34.9	6 379 611.7	4 883.0
60	4 860	5 170.2	49 220.4	36.9	6 754 883.0	5 170.2
65	5 130	5 457.4	51 954.9	39.0	7 130 154.3	5 457.4
70	5 400	5 744.7	54 689.4	41.0	7 505 425.5	5 744.7
75	5 670	6 031.9	57 423.8	43.1	7 880 696.8	6 031.9
80	5 940	6 319.1	60 158.3	45.1	8 255 968.1	6 319.1

Table 25: Fully electrical system with 3 hours net cleaning duty

		Energy storage	Hydrogen	FC		Tank	
Distance	Energy out	Energy inn	Required	Volume	Weight	Volume	Weight
[km]	[kWh]	[kWh]	[tonne]	[m^3]	[tonne]	[m^3]	[tonne]
0	1 620	3 240	97.2	7.7	3 100	5.6	2 430.2
5	1 890	3 780	113.4	7.7	3 100	6.6	2 835.3
10	2 160	4 320	129.6	7.7	3 100	7.5	3 240.3
15	2 430	4 860	145.8	7.7	3 100	8.4	3 645.4
20	2 700	5 400	162.0	7.7	3 100	9.4	4 050.4
25	2 970	5 940	178.2	7.7	3 100	10.3	4 455.4
30	3 240	6 480	194.4	7.7	3 100	11.2	4 860.5
35	3 510	7 020	210.6	7.7	3 100	12.2	5 265.5
40	3 780	7 560	226.8	7.7	3 100	13.1	5 670.6
45	4 050	8 100	243.0	7.7	3 100	14.0	6 075.6
50	4 320	8 640	259.2	7.7	3 100	15.0	6 480.6
55	4 590	9 180	275.4	7.7	3 100	15.9	6 885.7
60	4 860	9 720	291.6	7.7	3 100	16.8	7 290.7
65	5 130	10 260	307.8	7.7	3 100	17.8	7 695.8
70	5 400	10 800	324.0	7.7	3 100	18.7	8 100.8
75	5 670	11 340	340.2	7.7	3 100	19.7	8 505.9
80	5 940	11 880	356.4	7.7	3 100	20.6	8 910.9
85	6 210	12 420	372.6	7.7	3 100	21.5	9 315.9

Table 26: Calculations of Hydrogen Fuel cell system

Distance	Total Energy output	50/50 Distribution	Battery 50 % Distribution			Hydrogen 50 % Distribution					
		Energy out	Energy in	Weight	Volume	Energy in	Hydrogen	Weight tank	Volume tank	Weight FC	Volume FC
[km]	[kWh]	[kWh]	[kg]	[kg]	[m^3]	[kWh]	[kg]	[kg]	[m^3]	[kg]	[m^3]
0	1 620	810	861.7	8 203.4	6.2	1 620	48.6	1 215.1	2.8	1 550	3.8
5	1 890	945	1 005.3	9 570.6	7.2	1 890	56.7	1 417.6	3.3	1 550	3.8
10	2 160	1 080	1 148.9	10 937.9	8.2	2 160	64.8	1 620.2	3.7	1 550	3.8
15	2 430	1 215	1 292.6	12 305.1	9.2	2 430	72.9	1 822.7	4.2	1 550	3.8
20	2 700	1 350	1 436.2	13 672.3	10.3	2 700	81.0	2 025.2	4.7	1 550	3.8
25	2 970	1 485	1 579.8	15 039.6	11.3	2 970	89.1	2 227.7	5.1	1 550	3.8
30	3 240	1 620	1 723.4	16 406.8	12.3	3 240	97.2	2 430.2	5.6	1 550	3.8
35	3 510	1 755	1 867.0	17 774.0	13.3	3 510	105.3	2 632.8	6.1	1 550	3.8
40	3 780	1 890	2 010.6	19 141.3	14.4	3 780	113.4	2 835.3	6.6	1 550	3.8
45	4 050	2 025	2 154.3	20 508.5	15.4	4 050	121.5	3 037.8	7.0	1 550	3.8
50	4 320	2 160	2 297.9	21 875.7	16.4	4 320	129.6	3 240.3	7.5	1 550	3.8
55	4 590	2 295	2 441.5	23 243.0	17.4	4 590	137.7	3 442.8	8.0	1 550	3.8
60	4 860	2 430	2 585.1	24 610.2	18.5	4 860	145.8	3 645.4	8.4	1 550	3.8
65	5 130	2 565	2 728.7	25 977.4	19.5	5 130	153.9	3 847.9	8.9	1 550	3.8
70	5 400	2 700	2 872.3	27 344.7	20.5	5 400	162.0	4 050.4	9.4	1 550	3.8
75	5 670	2 835	3 016.0	28 711.9	21.5	5 670	170,1	4 252.9	9.8	1 550	3.8
80	5 940	2 970	3 159.6	30 079.1	22.6	5 940	178,2	4 455.4	10.3	1 550	3.8
85	6 210	3 105	3 303.2	31 446.4	23.6	6 210	186,3	4 658.0	10.8	1 550	3.8

Table 27: 50/50 distribution of energy from battery and hydrogen fuel cell system

Distance	Total Energy output	Battery 30 % Distribution				Hydrogen 70 % Distribution						
		Energy out	Energy in	Weight	Volume	Energy out	Energy in	Hydrogen	Weight tank	Volume tank	Weight FC	Volume FC
[km]	[kWh]	[kWh]	[kWh]	[kg]	[m^3]	[kWh]	[kWh]	[kg]	[kg]	[m^3]	[kg]	[m^3]
0	1 620	486	517.0	4 626.7	3.7	1 134	2 268	68	1 701.2	3.9	2 170	5.4
5	1 890	567	603.2	5 397.8	4.3	1 323	2 646	79	1 984.7	4.6	2 170	5.4
10	2 160	648	689.4	6 169.0	4.9	1 512	3 024	91	2 268.2	5.2	2 170	5.4
15	2 430	729	775.5	6 940.1	55	1 701	3 402	102	2 551.8	5.9	2 170	5.4
20	2 700	810	861.7	7 711.2	6.2	1 890	3 780	113	2 835.3	6.6	2 170	5.4
25	2 970	891	947.9	8 482.3	6.8	2 079	4 158	125	3 118.8	7.2	2 170	5.4
30	3 240	972	1 034.0	9 253.4	7.4	2 268	4 536	136	3 402.3	7.9	2 170	5.4
35	3 510	1 053	1 120.2	10 024.6	8.0	2 457	4 914	147	3 685.9	8.5	2 170	5.4
40	3 780	1 134	1 206.4	10 795.7	8.6	2 646	5 292	159	3 969.4	9.2	2 170	5.4
45	4 050	1 215	1 292.6	11 566.8	9.2	2 835	5 670	170	4 252.9	9.8	2 170	5.4
50	4 320	1 296	1 378,7	12 337.9	9.8	3 024	6 048	181	4 536.5	10.5	2 170	5.4
55	4 590	1 377	1 464.9	13 109.0	10.5	3 213	6 426	193	4 820.0	11.1	2 170	5.4
60	4 860	1 458	1 551.1	13 880.2	11.1	3 402	6 804	204	5 103.5	11.8	2 170	5.4
65	5 130	1 539	1 637.2	14 651.3	11.7	3 591	7 182	215	5 387.0	12.4	2 170	5.4
70	5 400	1 620	1 723.4	15 422.4	12.3	3 780	7 560	227	5 670.6	13.1	2170	5.4
75	5 670	1 701	1 809.6	16 193.5	12.9	3 969	7 938	238	5 954.1	13,8	2 170	5.4
80	5 940	1 782	1 895.7	16 964.6	13.5	4 158	8 316	250	6 237.6	14.4	2 170	5.4
85	6 210	1 863	1 981.9	17 735.8	14.2	4 347	8 694	261	6 521.2	15.1	2 170	5.4

Table 28: 70/30 distribution from fuel cell and battery systems, respectively

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