Methanol based range extender for high-speed electric boats

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Preface

This bachelor thesis is written at the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS), for the program Energy Technology. The topic of this thesis is methanol based range extender for high-speed boats.

We would like to thank our supervisors, professor Velaug Myrseth Oltedal, and Trond Strømgren from Evoy, for their help and guidance through this project.

Abstract

The marine industry accounts for 3–4 % of annual global greenhouse gas emissions. Regulations and pressure from reputable international organisations are pushing forward the development of new low- and zero-emission technologies in vessels. Battery electric boats are one of the increasingly common solutions for decarbonisation. One of the main problems with battery electric boats is the limited range. This thesis investigates the possibility of using methanol based range extenders in electric boats with sizes from 20 up to 50 feet.

Methanol has several advantages over alternative fuels. It has a higher volumetric density than hydrogen, ammonia, and all kind of batteries. In addition, it is compatible with existing infrastructure, as it is easy to store, transport, and distribute. For methanol to provide a climate benefit, it is necessary to use green methanol. Green methanol is produced by hydrogen from electrolysis based on renewable energy and recycled carbon dioxide. In this way, methanol becomes carbon neutral. Green methanol is currently not available on the Norwegian market, but two facilities are planned in northern Norway.

This thesis investigates a range extender system for three boats that represent different boat sizes. Four driving distances are considered to provide a basis for the solution, 15 nm, 20 nm, 45 nm, and 50 nm. The distances are based on fish farming and tourism. All boats require a range extender for driving distances of 45 nm and up.

Goldfish X9 and Skarsvåg 799 represent the middle and smallest boat sizes. The range extender system for these boats will include a motor, two batteries and a high-temperature PEM fuel cell system. Goldfish X9 and Skarsvåg 799 will need seven and eight fuel cells respectively. The range extender system's total weight is approximately two metric tonnes and has an investment cost of NOK 3,993,000 and NOK 4,358,000 respectively.

Boat 1 is a codename for a real boat which represents the largest boat. As the boat has a high energy consumption, four different cases were considered. Cases 1 and 2 combine the range extender with the current electric motor system, and they have a speed of 25 and 18 knots respectively. Cases 3 and 4 reduce the number of motors and batteries in the electric motor system and have a speed of 25 and 10 knots respectively. Case 3 turns out to be the best solution. In this case, the range extender system will include a motor, four batteries and a high-temperature PEM fuel cell system with 15 fuel cells. The system's total weight is approximately four metric tonnes and has an investment cost of NOK 7,620,000.

Sammendrag

Den marine industrien står for 3–4 % av årlige globale klimagass utslippene. Reguleringer og press fra anerkjente internasjonale organisasjoner presser frem utviklingen av nye lav- og nullutslipps teknologier i fartøy. Batterielektriske båter er en av de økende løsningene på avkarbonisering. Et av hovedproblemene med batteri elektriske båter er begrenset rekkevidde. Denne oppgaven undersøker muligheten for bruk av metanol basert rekkevidde forlenger i elektriske båter med størrelse fra 20 opptil 50 fot.

Metanol har flere fordeler sammenlignet med alternative drivstoff. Den har høyere volumetrisk energitetthet enn hydrogen, ammoniakk og alle typer av batteri. I tillegg er den kompatibel med eksisterende infrastruktur, ettersom den er enkel å lagre, transportere og distrubere. For at metanol skal være en gevinst for miljøet er det nødvendig med bruk av grønn metanol. Grønn metanol produseres av hydrogen fra elektrolyse basert på fornybar energi og resirkulert karbondioksid. På denne måten blir metanol karbonnøytralt. Grønn metanol er midlertidig ikke tilgjengelig på det norske markedet, men to anlegg er planlagt i Nord-Norge.

Denne oppgaven undersøker rekkevidde forlenger system for tre båter som representerer ulike båtstørrelser. Fire kjøredistanser vurderes for å gi et grunnlag for løsningene, 15 nm, 20 nm, 45 nm og 50 nm. Distansene er basert på fiskeoppdrett og turisme. Alle båtene vil trenge en rekkevidde forlenger ved kjøredistanser fra 45 nm og oppover.

Goldfish X9 og Skarsvåg 799 representerer den mellomste og minste båt størrelsen. Rekkevidde forlenger systemet for båtene vil inneholde en motor, to batterier og en høy-temperatur PEM brenselcelle system. Goldfish X9 og Skarsvåg 799 vil trenge henholdsvis syv og åtte brenselceller. Rekkevidde forlenger systemets totale vekt ligger rundt to tonn og har en investeringskonstand på henholdsvis 3 993 000 kr og 4 358 000 kr.

Boat 1 er et kodenavn for en reell båt som representerer den største båten. Ettersom båten har en høy energiforbruk er fire caser vurdert. Case 1 og 2 kombinerer rekkevidde forlengeren med det eksisterende elektriske motor systemet, og har henholdsvis hastighetene 25 og 18 knop. Case 3 og 4 reduserer antall motorer og batterier i det elektriske motor systemet, og har henholdsvis hastighetene 25 og 10 knop. Case 3 viser å være den beste løsningen. I dette tilfellet inneholder rekkevidde systemet en motor, fire batterier og en høy temperature PEM brenselcelle system med 15 brenselceller. Systemets totale vekt ligger rundt fire tonn og har en investeringskostnad på 7 620 000 kr.

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Nomenclature

AFC	=	*Alkaline fuel cell*
DMFC	=	*Direct methanol fuel cell*
DNV	=	*The Norwegian Veritas*
DoD	=	*Depth of discharge, i.e., the discharge rate of the battery*
EMSA	=	*European Maritime Safety Agency*
HFO	=	*Heavy fuel oil*
HTPEM	=	*High-temperature proton-exchange membrane fuel cell*
IGF code	=	*International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels*
IMO	=	*International Marine Organization*
LH_2	=	*Liquid hydrogen*
LNG	=	*Liquified natural gas*
LSHFO	=	*Low sulphur heavy fuel oil*
MDO	=	*Marine diesel oil*
N.A.	=	*Not available*
nm	=	*Nautical miles*
PBI	=	*Polybenzimidazole*
PEM	=	*Proton-exchange membrane fuel cell*
PM	=	*Particulate matter*
POX	=	*Partial oxidation*
SI	=	*Spark ignition*
SOFC	=	*Solid oxide fuel cell*
SR	=	*Steam reforming*
UN	=	*United nations*
VLSFO	=	*Very low sulphur fuel oil*
η	=	*Efficiency*
ρ	=	*Density*

1. Introduction

The marine industry accounts for 3-4 % of the annual global greenhouse gas emissions. New regulations and pressure from reputable international organisations, force the maritime sector to decarbonise. Decarbonisation of the maritime industry requires a transition from traditional fuel technology to low- and zero-emission technology. Electrification of boats has become an increasingly common solution to this transition. Battery electric boats offer several advantages such as being quiet, having no direct emissions and requiring less maintenance. However, the challenge with electric boats is the limited range [1]. One way to combat this is by combining a range extender with the drive systems.

There are several green fuel options to be used in a range extender system. Among them, methanol has gained increasing interest and has several advantages compared to other green fuels. Methanol has a higher volumetric density than hydrogen, ammonia, and all kinds of batteries. In addition, it is compatible with existing infrastructure, as it is easy to store, transport, and distribute. It is necessary to use green methanol as a fuel for it to provide a climate benefit. Green methanol is produced by hydrogen from electrolysis based on renewable energy and recycled carbon dioxide. In this way, methanol is carbon neutral and will contribute to reducing greenhouse gas emissions [1].

This thesis is a feasibility study intended to investigate whether it is realizable to use methanol as a range extender in electric boats. Two alternatives are considered. Alternative A uses methanol directly in a fuel cell. Alternative B involves reforming methanol into hydrogen and then using it in a hydrogen fuel cell. The thesis uses three different boat sizes between 20 and 50 feet for examples of the four scenarios. The scenarios are based on fish farming and tourism, which are the most common uses of the chosen boats. The thesis investigates whether the technology is available and if such a solution will be realizable. In addition, it is considered whether it is financially profitable to invest in such a project.

2. Background

This chapter gives a background of Evoy's electric motor system and why a range extender is beneficial in electric boats. Further, methanol will be considered as a fuel candidate compared to other alternative fuels, as well as fuel cell technologies.

2.1 Evoy's electric motor system

Evoy was established in 2018 with its headquarters in Florø, Norway. The company's vision is to eliminate vessel emissions by supplying electric motor systems for commercial and leisure boats. Evoy offers plug-and-play inboard and outboard systems that can be integrated into new or existing boats between 20 and 50 feet. The electric motor system includes a charger, smartboard, batteries, and motor [2].

This thesis investigates three different boats with Evoy's inboard electric motor system. As the boats have different sizes and capacities, the range extender system solutions will be different. Evoy's motor system can be supplied with one to two motors, while the number of batteries varies from two to twelve. The number of these components depends on the boat size. Each battery has a capacity of 63 kWh and weighs 400 kg, while the motor has a continuous capacity of 300 kW and weighs 343 kg [3].

2.1.1 Boat 1

Boat 1, which is a codename because of anonymity, represents the largest boat and is 40 feet long. It has a length of 12 m, and a width of 3.3 m. Boat 1 has a capacity of transporting up to 6 persons on board and is mainly used for passenger transport, aquafarming, defence, rescue, and tourism [4]. The motor system in the boat includes two motors and eight batteries, which gives a range of 15–55 nautical miles (nm) depending on the speed [4]. Table 1 shows the weight of the components and the total weight of the motor system.

Table 1: The total weight of the electric motor system for Boat 1

Components	Weight [kg]
Battery (63 kWh)	8 x 400
Motor (Hurricane 300 kW)	2 x 343
Total	3 886

2.1.2 Goldfish X9 Explorer

Goldfish X9 Explorer represents the medium boat size and is 32 feet long. The boat has a length of 9.7 m, and a width of 3.1 m [5]. Like Boat 1, Goldfish X9 can transport up to 6 persons on board. The boat is a rigid inflatable boat (RIB) with a hull and a design that allows the boat to drive at a higher speed. [6]. The main uses of the boat are fish farming, tourism, and passenger transport [5]. Figure 1 shows a picture of Goldfish X9.

Figure 1: Goldfish X9 Explorer [5]

The motor system includes a motor and two batteries, which give a range of 20–30 nm [7]. Table 2 shows the total weight of the system.

Table 2: The total weight of the electric motor system for Goldfish X9

Components	Weight [kg]
Battery (63 kWh)	2 x 400
Motor (Hurricane 300 kW)	343
Total	1 143

2.1.3 Skarsvåg 799

Skarsvåg 799 represents the smallest boat size and is 26 feet long. The boat has a length of 8 m, and a width of 3.6 m. It has a transport capacity of 6 persons on board [8]. Skarsvåg 799 has a similar design and hull as Boat 1, and they are often used for the same areas [6]. Figure 2 illustrates Skarsvåg 799.

Figure 2: Skarsvåg 799 [8]

Like Goldfish X9, Skarsvåg's motor system includes one motor and two batteries. Table 3 shows the total weight of the system.

Table 3: The total weight of the electric motor system for Skarsvåg 799

Components	Weight [kg]
Battery (63 kWh)	2 x 400
Motor (Hurricane 300 kW)	343
Total	1 143

2.2 Range extender

Battery electric boats offer several advantages. They are quiet, have no direct emissions, and have low maintenance costs. However, there are several challenges associated with using batteries in boats. With the current battery technology, battery electric boats are used mainly for short distances, and therefore make a smaller percentage of seagoing vessels [1].

Batteries have both low volumetric and gravimetric energy densities. The consequence of this is a significantly limited range depending on the size of the battery. Increasing the size of the battery results in greater weight and will quickly exceed the boat's maximum carrying weight [1]. Additionally, higher speeds will require more energy from the battery reserves as the boat will be exposed to greater resistance from the waves. This contributes to a reduced range. By driving at a slower speed, it will be possible to achieve the optimal range. For some cases, the range will triple by reducing the speed from 9 to 5 knots. Speed reduction is a good measure to achieve a longer range. However, speed reduction will also result in longer time consumption, which can be a disadvantage in professional use. The short range of battery electric boats makes them best suited for shorter distances [9].

The lifetime of an electric motor is long and Evoy's motor lasts for 15 years. Evoy's batteries have a lifetime of 3000 charge cycles, but the capacity will decay over time [10]. If a boat is charged two times a day, it constitutes a four-year lifetime. After a while, the batteries will weaken, and there will be a need for more charges a day. In return, this will reduce the batteries' lifetime. Low temperatures, deep charging and discharging are factors that will lead to a faster weakening and determine the lifetime of the batteries [9]. Weakened batteries lead to a shorter range as the batteries discharge faster. To preserve a longer lifetime, less draining and charging of the batteries can be beneficial. The depth of discharge (DoD) means how much of the battery capacity can be discharged between each charge [11]. Evoy recommends a depth of discharge of 70 % to achieve 3000 charge cycles before the battery capacity reduces by 20 %, but a depth of discharge of 80 % is also within reasonable limits. Evoy’s battery has a capacity of 63 kWh, and with a depth of discharge of 70 %, only 44 kWh of the battery should be used each time before a new charging. In practice, this means that the batteries should stop charging at 90 % and not discharge below 20 % [12].

The current battery technology limits the range of battery electric boats. However, this problem can be solved by installing a range extender. In this way, electric boats can have the same range and driving pattern as traditional diesel boats. This thesis investigates a methanol based range extender in electric boats.

2.3 Methanol as an energy carrier

This section considers the environmental aspects of methanol as fuel and its current status. Further, the properties of methanol will also be compared to other alternative fuels.

2.3.1 Environmental aspects

Emission reduction potential, energy density, usability and costs are highest assessed when it comes to new alternative fuel solutions. There are several fuel options for decarbonisation such as batteries, biofuel, hydrogen and hydrogen carriers. Methanol is considered a fuel candidate in vessels to contribute to the reduction of greenhouse gas emissions [1]. This section considers methanol from an environmental aspect and compares it with alternative fuels.

Today, methanol is mainly produced from natural gas through a two-step catalytic process. The two-step process involves the gasification of carbonaceous feedstock which forms syngas, a gas mixture of carbon monoxide and hydrogen. Further, the syngas is converted into methanol. The most commonly used fossil feedstocks are coal and natural gas [13]. This production method, based on fossil feedstocks, produces what is called ‘grey’ methanol and accounts for 95 % of the total methanol used in the shipping industry [1]. The methanol facility at Tjeldbergodden is the largest in Europe and is owned by Equinor and ConocoPhillips. Here, methanol is produced on a large scale and can cover 20 % of Europe's needs. Annually, the production is 900,000 metric tonnes of methanol and is based on natural gas as feedstock. For every metric tonne of methanol produced, it produces 0.3 metric tonnes of CO_2 emissions. The production at the facility also emits 120 metric tonnes of nitrogen oxides (NO_x) per year [14].

When surveying greenhouse gas emissions from various fuels, it is important to assess the entire value chain, well-to-wake, from extraction and production to consumption, instead of only emissions from combustion [1]. Figure 3 illustrates two value chains, well-to-wake, for grey and green methanol.

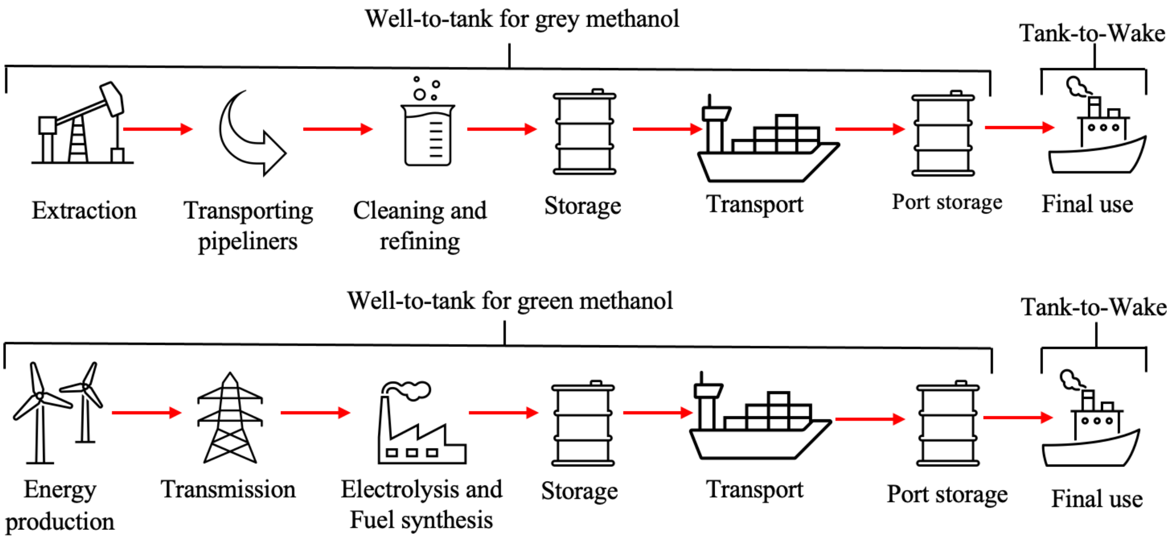

Figure 3: Illustrate two value chains, well-to-wake, for grey and green methanol based on source [1]

Currently, hydrogen and ammonia are mainly produced by natural gas, like methanol. Hydrogen is produced by steam methane reformation, which is energy-intensive and emits large amounts of carbon dioxide. Grey ammonia and grey hydrogen will therefore have a high well-to-wake emissions profile [1]. Figure 4 illustrates well-to-wake emissions from alternative fuels and traditional marine fuels. Fossil-powered boats with the size between 20 and 50 feet often use diesel EN590. The emission profile of diesel EN590 has not been found and thus is not discussed in this thesis. Grey hydrogen and grey ammonia only have water as a by-product of combustion. However, compared to very low sulphur fuel oil (VLSFO), grey hydrogen and ammonia will produce 64 % and 48 % more emissions well-to-wake. Grey methanol also has higher emissions than VLSFO, but grey hydrogen and ammonia have an even higher emissions profile. According to MAN Energy Solutions, the value chain of grey methanol gives 20 % less CO_2, 80 % less NO_x, 99 % less sulphur oxides (SO_x) and 95 % less Particulate Matter (PM) than heavy fuel oil (HFO) [1].

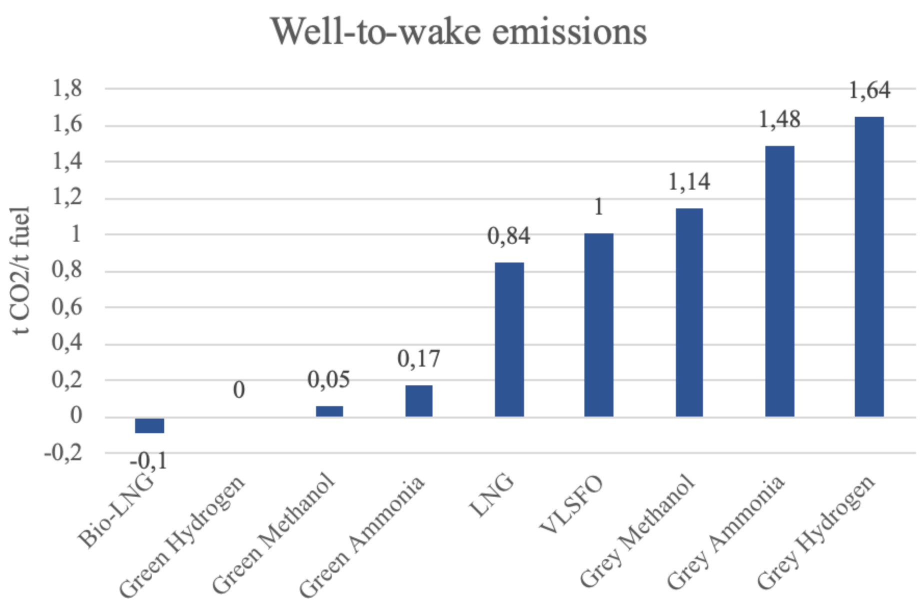

Figure 4: Well-to-wake emissions [1]

Methanol has pure complete combustion with only carbon dioxide and water as by-products. Table 4 shows the amount of emission the fuels have when combusted. When it comes to combustion only when using engines, methanol, liquid natural gas (LNG), marine diesel oil (MDO), and low sulphur heavy fuel oil (LSHFO) have approximately the same carbon dioxide emission profile. Methanol will produce 522 g CO_2/kWh, compared to LSHFO and MDO which produce 541 g CO_2/kWh and 524 g CO_2/kWh respectively. Hydrogen and ammonia, on the other hand, use fuel cells and do not produce CO_2 and SO_x gases. Hydrogen does not produce NO_x gas, and it is uncertain if ammonia produces NO_x and nitrous oxide (N_2O) emissions during combustion [13].

On 1 January 2020, the International Marine Organization (IMO) implemented the new rule «IMO 2020» which entails a new limit on sulphur content in marine fuels. Previously, the limit was 3.5 % sulphur content and has now been reduced to 0.5 % [1]. This rule contributes to better air quality, and protection of the environment and human health [15]. Like hydrogen and ammonia, methanol does not contain sulphur and it will not produce SO_x in fuel cells or internal combustion engines. In internal combustion engines, methanol will produce a negligible amount of PM and NO_x. Incomplete combustion, on the other hand, will produce carcinogenic formaldehyde. The formation of formaldehyde is a result of the engine's internal cracks, cold spots, and fuel leaks [1].

Table 4: Combustion emission profile of traditional and alternative fuels [13]

Fuel	**Operational Fuel Emission Factor [g/kWh]**					
	CO_2	**CH_4**	**N_2O**	**SO_x**	**NO_x**	**PM**
LSHFO	541	0.01	0.027	3.23	15.8	0.72
MDO	524	0.01	0.026	0.32	14.8	0.16
LNG	412	3	0.016	0.003	1.17	0.027
Methanol	522	0	0	0	3.05	0
LH_2	0	0	0	0	0	0
Ammonia	0	0	N.A.	0	N.A.	0

In addition to pure combustion, methanol is a biodegradable liquid, unlike several other fossil fuels. In the case of a methanol spill, the liquid will be decomposed in the air or groundwater as a result of a photochemical reaction or bacterial digestion. This means that a methanol spill will not lead to an increased carbon footprint or toxicity in the sea or nature [1].

For it to be appropriate to use methanol as a fuel and provide a climate benefit, green methanol must be used. Green methanol is produced by recycled carbon dioxide and hydrogen from electrolysis based on renewable sources, which makes it carbon neutral [1]. This means that the carbon dioxide sum from production to end-use will not increase the carbon dioxide content in the atmosphere. The amount of carbon dioxide released from the combustion of methanol is the same as it was in the atmosphere initially and will be recycled in a new cycle of green methanol [16]. In this way, our relationship with carbon dioxide changes, and the gas is used as a resource instead of waste. Therefore, methanol can contribute to a reduction in greenhouse gas emissions.

Today, there is no production of green methanol in Norway. However, Norway has great access to renewable energy which makes it possible to establish green methanol production. Like all sectors, the industry is also being pressured to switch to environmentally friendly methods. Two green methanol facilities are planned in Northern Norway at Mo i Rana and Finnfjord. Mo industrial park in Mo i Rana has a planned production of 100 million litres of green methanol per year, and at Finnfjord 100,000 metric tonnes of green methanol will be produced per year [17][18].

In 2021, DNV estimated that 99.5 % of the world's ships went on traditional fuels, while only 0.5 % went on alternative fuels where 0.013 % is methanol [19]. In 2015, Stena Germanica became the world's first methanol-powered ship. The ship is a ferry with a route from

Gothenburg to Kiel that previously went on diesel. The existing ship was converted to methanol and today the ship can use both methanol and diesel as fuel [20]. In 2016, the first two methanol-powered cargo ships in Norway, Lindanger and Mari Jone were launched. Lindanger is owned by Westfal-Larsen and is located in Bergen, while Mari Jone is owned by Marinvest and Waterfront Shipping which is located in Haugesund. All these ships use an engine [21]. More and more countries are catching up with developments such as Canada, the USA, Germany and Denmark. Thus, the Danish container ship group Maersk has ordered 12 new methanol-powered ships to be launched in 2024. From 2015 until today, the growth of methanol-powered ships has increased [22].

2.3.2 Properties of methanol

Properties of methanol as an energy carrier have several advantages, compared to other renewable energy carriers. Hydrogen, LNG and ammonia are gases at atmospheric pressure and room temperature. Therefore, these energy carriers are required to be compressed or liquefied during storage. Hydrogen requires high pressure for compression (350-700 bar) and low temperature (-253 °C) for liquefaction. LNG also requires a low temperature for liquefaction (-162 °C), while ammonia requires cooling to -34 °C for liquefaction or compressed at moderate pressure for compression. This is energy consuming and offers storage challenges. The transport, storage, and use of the energy carriers require expensive investments and the development of an infrastructure that does not currently exist. Methanol is a liquid at atmospheric pressure and room temperature that makes it compatible with the existing infrastructure. It is easy to transport, store, and distribute methanol in the same way as petrol and diesel [23].

Figure 5 is an overview of the volumetric energy density of several fuels. The volumetric energy density of methanol is lower than HFO, MDO, and diesel EN590. The volumetric energy density of methanol is 4.4 kWh/dm^3 which is half of HFO, MDO, and diesel EN590. To achieve the same range as HFO and MDO, larger storage tanks and amounts of methanol are needed onboard the boat. In addition, when using an engine, the engine's fuel system must be designed to accommodate higher fuel speeds so that it meets the need for more fuel. On the other hand, methanol has a higher volumetric energy density than batteries and gaseous fuels. The volumetric energy density of methanol is five times higher than batteries, three times higher than compressed hydrogen and twice as high as liquid hydrogen. The volumetric energy density of ammonia is slightly lower than of methanol. The gravimetric energy density, on the other hand, is much higher for hydrogen than methanol. This is an important factor where weight is limited [23].

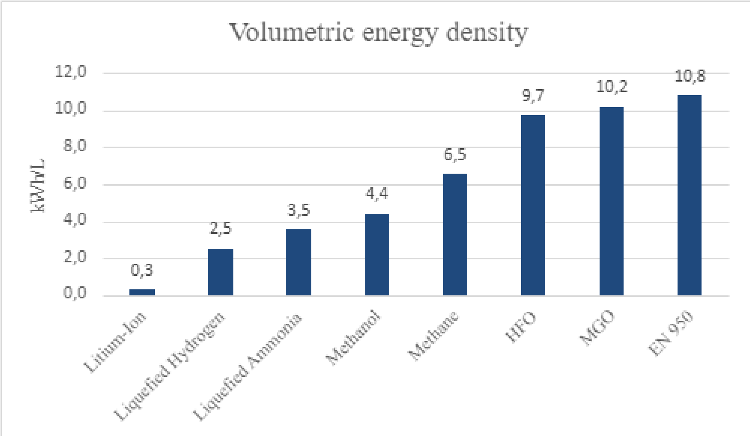

Figure 5: Volumetric energy density [1] [24]

In the case of seagoing vessels, safety is important. It is more difficult to handle a dangerous situation at sea compared to on land. Most fuels are flammable, and fire is one of the biggest concerns. This includes methanol, which is a highly flammable liquid, has a non-luminous blue flame, and its vapour mixed with air can be explosive. In addition, the alcohol is toxic to humans by ingestion, inhalation, and skin exposure [1].

2.3.3 Choice of methanol as a range extender

Green methanol as a range extender has several advantages compared to other alternatives. Like green hydrogen, green methanol will reduce greenhouse gas emissions compared to fossil fuels. The use of green methanol has net-zero CO_2 emissions but can give small emissions of NO_x and PM depending on whether a fuel cell or internal combustion engine is used. Green ammonia is also carbon-free, but there are uncertainties about nitrous oxide emissions during combustion. N_2O has a higher heating potential than CO_2, and therefore ammonia will have somewhat higher greenhouse gas emissions than hydrogen and methanol [1].

The properties of methanol compared to alternative fuels make it more relevant to use it in a range extender. Methanol is compatible with the existing infrastructure, which makes it easier to transport and distribute it, unlike gas-based fuels. In addition, methanol has a higher volumetric energy density than other alternative fuels. These factors of methanol are crucial in determining the range extender in this thesis.

2.4 Fuel cells for methanol

Methanol is a versatile fuel that can be used in fuel cells, combustion engines, and different hybrid systems. The methanol's high-octane rating and cooling effect from the heat of vaporization reduce the risk of engine knock or pre-ignition. Therefore, methanol is well suited for an Otto engine with spark ignition (SI) [25]. However, fuel cells offer several advantages compared with combustion engines. It has higher efficiency, a simpler system, lower emissions, and is quiet. This thesis investigates methanol used in fuel cells [26]. This chapter gives a general introduction of the chosen fuel cells. Further, in the results, the properties of the fuel cells will be more deeply explained and compared.

Fuel cells are electrochemical cells that convert chemical energy into electrical energy. Fuel cells have the same function as batteries but need a continuous supply of fuel and air. The cell consists of two electrodes immersed in an electrolyte. Hydrogen will first be oxidized at the anode, which is the negative electrode. Afterwards, there will be a reduction at the cathode, which is the positive electrode. Electrons will pass through an outer circuit and generate electricity that can be utilized [27].

There are several fuel cell technologies, each with its characteristics. Usually, fuel cells are separated based on their membrane, operating temperature, and the type of fuel. This report will focus on alkaline fuel cell (AFC), proton-exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), and direct methanol fuel cell (DMFC). Alkaline fuel cell and proton-exchange membrane fuel cell require hydrogen as fuel. Solid oxide fuel cell and direct methanol fuel cell can use methanol as fuel without reforming [27]. Table 5 gives a general overview of the fuel cells.

2.4.1 Alkaline fuel cell

Alkaline fuel cell is the earliest developed fuel cell and has the most mature technology. The electrolyte is a concentrated liquid of potassium hydroxide. The reaction in an AFC is slightly different from a standard acid fuel cell reaction. In an AFC, the electrolyte conducts hydroxide ions rather than protons. At the anode, hydrogen splits into hydrogen ions and electrons. The electrons will pass through an outer circuit and transfer to the cathode. Meanwhile, oxygen molecules at the cathode split into atoms. The oxygen atoms will take up two electrons, react with water, and form hydroxide ions. Further, the hydroxide ions will pass through the membrane to the anode. At the anode, the hydroxide ions will react with hydrogen ions and regenerate water [28].

$$\text{Anode: } 2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$$

$$\text{Cathode: } O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

$$\text{Total reaction: } 2H_2 + O_2 \rightarrow 2H_2O$$

Alkaline fuel cells operate at relatively low temperatures and have a compact design. The operation temperature varies from 60-100 °C [29]. The efficiency of alkaline fuel cells is around 60%, which is the highest efficiency for all fuel cells [28]. Both the electrolyte and the catalysts are inexpensive. The relatively low costs of the components reduce the total capital cost. The main challenge with the fuel cell is the low CO_2 tolerance, which restricts its applications. In the case of too high CO_2 concentration, the electrolyte will react with carbon dioxide and form CO_3^{2-} and water. Further, CO_3^{2-} will be precipitated as K_2CO_3. If the precipitation takes place on the electrodes, the gas transportation will be blocked and reduce the cell performance. This reaction is called carbonisation and will be a problem for the fuel cell over time. Today, the AFC is used in space programs and submarines [29].

2.4.2 Proton exchange membrane fuel cell

Proton exchange membrane fuel cell has an acidic polymer membrane as its electrolyte, called poly-perfluorocarbon sulfonate. The acidic sulfonate group attached to the polymer provide conductivity. The membrane is saturated with water allowing it to conduct hydrogen ions. The membrane has a thickness of 50–175 microns. The electrodes are made of porous carbon-containing platinum printed directly on the membrane [28].

The fuel cell requires both hydrogen and oxygen during combustion. Hydrogen splits at the anode into hydrogen ions and electrons. Hydrogen ions will pass through the membrane, simultaneous the electrons pass through an outer circuit to the cathode. At the cathode, oxygen is supplied and reacts with the hydrogen ions and electrons to form water [28].

$$\text{Anode: } 2H_2 \rightarrow 4H^+ + 4e^-$$

$$\text{Cathode: } O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

$$\text{Total reaction: } 2H_2 + O_2 \rightarrow 2H_2O$$

PEMFC has an operating temperature of around 80 °C. The low temperature allows for fast start-up time, and response time and makes it withstand power variations. However, the disadvantage related to the low temperature is that PEMFC is more prone to catalyst poisoning than other high-temperature fuel cells. If PEMFC is supplied with pure hydrogen, the fuel cell is capable of theoretical efficiency of 60 %, but in practice, the efficiency is closer to 50 %. Additionally, PEMFC has a low weight compared to the other fuel cells and is more compact.

The lifetime is around 10,000 hours. The components have high costs and increase the capital cost [28].

Both PEMFC and AFC can use methanol as fuel, but the methanol needs to be reformed to hydrogen first. If the hydrogen is a product of reformed methanol, the efficiency of PEM reduces. In practice, the fuel cell will achieve an efficiency of 42 %. The reformer needs a higher operating temperature which results in a longer start-up time of around 20 min [28].

2.4.3 Direct methanol fuel cell

Direct methanol fuel cell is a variant of PEMFC, where methanol is used directly as a fuel. The concept of PEM and DMFC is similar, but the biggest difference is that DMFC uses liquid methanol as fuel, not hydrogen gas. The fuel cell can use methanol mixed with water without the need for reforming [28].

The reactions in the fuel cell combine the reforming of methanol and a conventional hydrogen fuel cell reaction. First, methanol mixed with water reforms to hydrogen and carbon dioxide at the anode. Hydrogen atoms will release electrons and form hydrogen ions. The hydrogen ions will pass through the electrolyte to the cathode. At the cathode, oxygen supplied by the air will react with hydrogen ions and form water [28].

$$\text{Anode: } 2\mathrm{CH_3OH} + 2\mathrm{H_2O} \rightarrow 2\mathrm{CO_2} + 12\mathrm{H^+} + 12\mathrm{e^-}$$
$$\text{Cathode: } 3\mathrm{O_2} + 12\mathrm{H^+} + 12\mathrm{e^-} \rightarrow 6\mathrm{H_2O}$$
$$\text{Total reaction: } 2\mathrm{CH_3OH} + 3\mathrm{O_2} \rightarrow 4\mathrm{H_2O}$$

Since methanol can be used directly without reforming, this will simplify the cell and make fuel processing much easier. However, there are several challenges related to DMFC. The efficiency is low compared to other fuel cells and is around 25 %. DMFC has a short lifetime of around 1000 hours. The operation temperature is 60-130 °C. Today, DMFC is used in portable electronic devices such as laptop computers and mobile phones [28].

2.4.4 High-temperature proton exchange membrane fuel cell

Another version of PEM fuel cell is high-temperature PEM fuel cell (HTPEM). This fuel cell has polybenzimidazole (PBI) doped with phosphoric acid as a membrane, which gives PEM a higher proton conductivity. PBI is a high temperature- resistant polymer, while phosphoric acid is thermally stable and has a low vapour pressure. The operation temperature is between 120 and 200 °C. Below 120 °C, the conductivity is too low. While above 200 °C, the acid polymerises too easily which also leads to reduced conductivity [29].

Higher operation temperature results in higher tolerance for CO, and the fuel cell does not require purification after the reform system. Additionally, cell cooling is easier and only a small radiator is needed. On the other hand, the high-temperature PEM have a longer start-up time than low-temperature PEM [29].

2.4.5 Solid oxide fuel cell

SOFC is different from the other fuel cells because it has a solid electrolyte, making it the most robust fuel cell. The electrolyte is made of zirconia (ZrO_2) stabilized with yttria (Y_2O_3) to make it capable of conducting oxygen ions. The electrolyte is thin with a thickness of 100 microns. However, this conductivity requires high temperatures up to 1000 °C [28].

The electrolyte is an electrical insulator so the electrons and hydrogen ions cannot pass through it. However, the high operating temperature allows oxygen ions to pass. At the cathode, oxygen ions split, take up electrons and form oxygen ions. These oxygen ions migrate through the electrolyte to the anode. At the anode, hydrogen splits and releases electrons that pass through the outer circuit. The hydrogen ions react with oxygen ions and produce water vapour [28].

$$\text{Cathode: } O_2 + 4e^- \rightarrow 2O^{2-}$$
$$\text{Anode: } 2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$$
$$\text{Total reaction: } 2H_2 + O_2 \rightarrow 2H_2O$$

SOFC has an operating temperature between 800–1000 °C, and because of the high temperature, there is no need for an electrode catalyst [26]. Another advantage related to the high temperature is that the fuel cell can withstand higher CO concentrations and can use several fuels. However, the high temperature also results in a long start-up time and should run for long periods. The theoretical efficiency at the operation temperature of 1000 °C is 60 %. Practical cells have achieved an efficiency of 43 %, and the limit efficiency is expected to be around 50 %. SOFC has a long lifetime around 60,000 hours [28].

Table 5: General overview of the fuel cells

Fuel cell	**AFC**	**PEMFC**	**DMFC**	**HTPEM**	**SOFC**
Operation temperature [°C]	60-100	80	60-130	120-200	800-1000
Efficiency [%]	60	42-50	25	Not found	43-50
Lifetime [h]	5000 [28]	10,000	1000	Not found	60,000
Fuel [29]	Hydrogen Ammonia	Hydrogen	Methanol	Hydrogen	Hydrogen Methanol Ammonia
Electrolyte	Potassium hydroxide	Poly-perfluorocarbon sulfonate	Poly-perfluorocarbon sulfonate	Poly-perfluorocarbon sulfonate	Zirconia
Area of use [26]	Space program	Vehicles and mobile applications	Portable electronic devices	Vehicles and mobile applications	Larger vessels, power plants and heat recovery

2.4.6 Reforming methods

If methanol is to be used as a fuel in PEM or AFC, reformation is necessary. There are two main reforming methods for methanol which are steam reforming (SR) and partial oxidation (POX). Of these, steam reforming is the most fundamental reforming method.

Steam reforming takes place in two reaction steps, where the first is a steam reforming reaction and then a water-steam-shifting reaction. Steam reforming of methanol can follow two reaction paths. In one of the reaction patterns, methanol will decompose to carbon monoxide and hydrogen. Furthermore, carbon monoxide will react with water to form carbon dioxide and hydrogen [30].

$$\text{I } CH_3OH \rightarrow CO + 2H_2$$

$$\text{II } CO + H_2O \rightarrow CO_2 + H_2$$

In the second reaction pattern, methanol and water will react to form carbon dioxide and hydrogen. Carbon dioxide and hydrogen will further react with each other and form a thermodynamic equilibrium [30].

$$\mathrm{I}\ CH_3OH + H_2O \rightarrow CO_2 + 3H_2$$
$$\mathrm{II}\ CO_2 + H_2 \leftrightarrow CO + H_2O$$

Steam reforming is an endothermic reaction, which requires a supply can of external heat for the reaction to take place. Methanol mixed with water will be heated to 300 °C and a catalyst of copper/zinc oxide is used [30].

In the case of partial oxidation, methanol is evaporated and further mixed with oxygen. This produces carbon monoxide, carbon dioxide and water. Furthermore, the fuel is converted together with water and oxygen into a hydrogen-rich gas mixture. The reaction is exothermic and releases heat. A palladium- zinc oxide catalyst is used [30].

Total reaction: $2CH_3OH + O_2 \rightarrow 2CO_2 + 4H_2$

3. Method

This chapter gives an overview of the methods used to achieve the solutions in this thesis. The various alternatives, scenarios and cases will also be presented.

3.1 Feasibility study

The thesis is investigating two different alternatives. First, alternative A is considered, which is using methanol directly into a fuel cell. If this turns out not to be beneficial, alternative B is considered further. In alternative B, methanol is used as a hydrogen carrier and is reformed into hydrogen on board before using a hydrogen fuel cell. The fuel cells under each alternative will be assessed if they are suitable for a range extender system. Weight, volume, efficiency, and operating conditions will be the decisive factors. Figure 6 illustrates the differences between alternative A and alternative B.

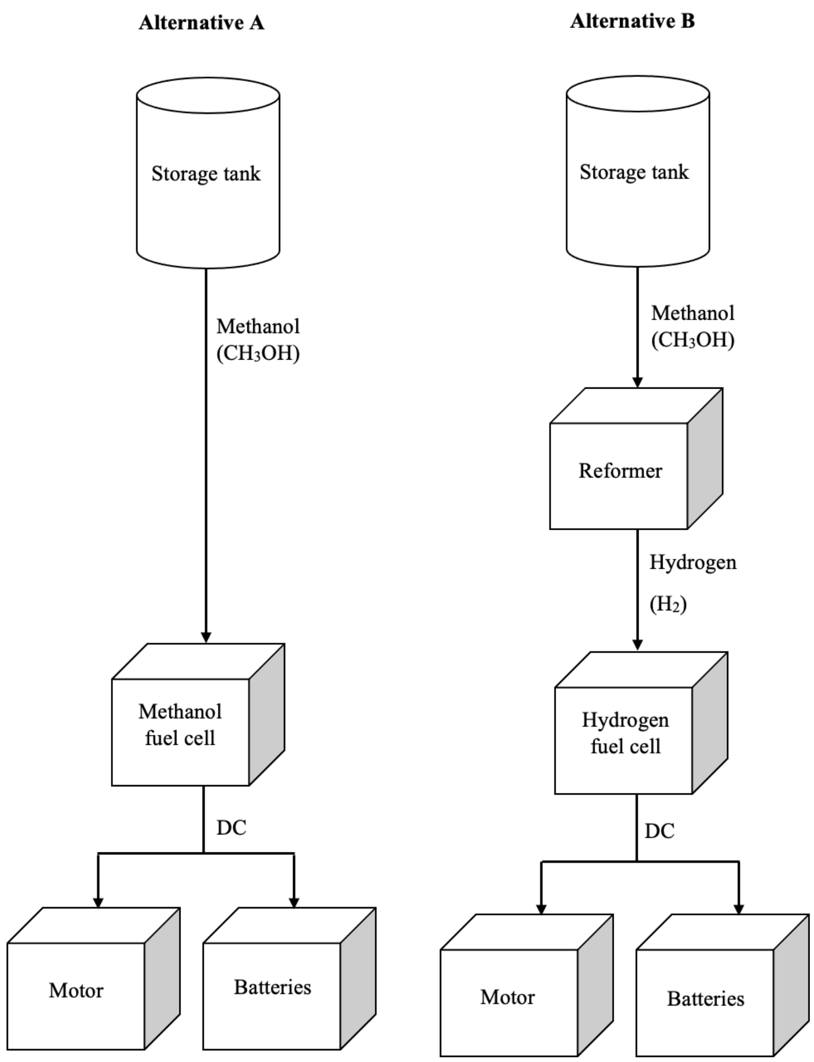

Figure 6: Illustrate the range extender system for alternative A and B

3.2 Scenarios

The bachelor thesis is provided by Evoy and concerns methanol based range extenders in electric boats between 20 and 50 feet. The purpose is to investigate whether methanol can be used as a range extender in boats where the batteries do not cover the desired driving distances. As the battery has both low gravimetric and volumetric energy density, upscaling of the battery will rapidly increase the weight of the boat and the energy consumption [1].

The thesis is using three boats with sizes between 20 and 50 feet as examples in four scenarios. Boat 1, which is a codename because of anonymity, represents the largest boat. Goldfish X9 represents the medium-sized boat, and Skarsvåg 799 represents the smallest boat. The scenarios are four different driving distances, two based on fish farming and two based on tourism. Tourism and fish farming represent a large proportion of Evoy's customers, as such, it is natural to use these industries for the scenarios. Boat 1 and Skarsvåg 799 have a speed of 25 knots at all driving distances, which corresponds to cruising speed. Goldfish X9, on the other hand, has a hull and weight that makes it more energy efficient to drive at 35 knots [6].

3.3 Literature study

A literature study is important for obtaining information. A systematic collection process was initiated by gathering information on the chosen boats, methanol as a fuel, and fuel cell technology. In addition, information has been gathered about methanol-powered boats, to investigate whether similar systems exist on the market today and what solutions they utilize.

3.4 Data collection

Datasheets are important to organise information about the various components and boat types, as well as their operating conditions. The data have been necessary to assess which type of fuel cell system will best suit the solutions. In addition, the chemical data sheet for methanol has been an important factor in the energy calculations. Data collection has also been used in economic analysis. Nord Pool's statistics on electricity prices in Norway have been used to estimate electricity prices for north and south of Norway.

Through the process, meetings have been held with several companies and professionals to gather necessary information that has not been available in the public domain. There has been a close dialogue and guidance with the supervisor from Evoy. It has also been an excursion to Evoy in Florø, to gain insight and a greater understanding of the electric motor system in the boats.

Contact persons for the selected boat types have been an important resource for obtaining sketches and data on the boats. There have been several meetings with contact persons for boat 1, where important issues are highlighted. These issues address energy consumption and the structure of the overall system.

Meetings have also been held with professionals in the technical fields concerning methanol as fuel, and fuel cell technologies. A professional from the company Glocal Green has been helpful with the choice of the fuel cell and the status of methanol today. A professional from Clara Venture Labs has given us information about SOFCs and highlighted many challenges in using such a fuel cell. This has been helpful to justify the choice of fuel cells.

3.5 Technical analysis

Several energy calculations have been made. Firstly, to determine how much energy the electric motor system of the various boats can deliver. Secondly, to determine the amount of methanol needed in the range extender system. Economic analyses have also been made for the various solutions to assess whether it is profitable to implement in practice.

3.5.1 Energy calculations

Table 6 represents the different values used in the energy calculations. The volumetric energy density of methanol is calculated by multiplying the density by the gravimetric energy density of methanol.

Table 6: Values for energy calculations

	Value	**Unit**	**Symbol**
Depth of discharge [7]	70	%	DoD
Density of methanol [31]	791	kg /m³	ρ_M
Gravimetric energy density of methanol [32]	5.56	kWh/kg	$\rho_{G, M}$
Volumetric energy density of methanol	4 397.96	kWh/m³	$\rho_{V, M}$
Volumetric energy density of diesel EN950 [24]	38.8	MJ/L	$\rho_{V, EN950}$
Density of stainless steel [33]	8 000	kg /m³	ρ_{steel}
Density of plastic (PE) [33]	900	kg /m³	ρ_{PE}
Density of Evoy`s battery	1 225.7	kg /m³	ρ_B
Efficiency of fuel cell [34]	45	%	η_{FC}
Energy consumption of Boat 1 [4]	17	kWh/nm	E_C
Energy consumption of Goldfish X9 [6]	4	kWh/nm	E_C
Energy consumption of Skarsvåg 799 [6]	6	kWh/nm	E_C
Wall thickness storage tank [35]	15	mm	t_W

The weight of the methanol storage tank ($m_{Tank,steel}$) is calculated using Equation 1. The weight is calculated by multiplying the weight of the original plastic tank ($m_{Tank,PE}$) by the density ratio of steel and plastic ($\frac{\rho_{Steel}}{\rho_{PE}}$).

$$m_{Tank,steel} = m_{Tank,PE} * \frac{\rho_{Steel}}{\rho_{PE}} \text{ [kg]} \tag{1}$$

Equation 2 is used to calculate the energy of the batteries, taking the depth of discharge (DoD) into account ($E_{ink\ DoD}$). The energy including DoD is calculated by multiplying DoD by the nominal energy capacity of the battery (E_B).

$$E_{inc\ DoD} = DoD * E_B \text{ [kWh]} \quad (2)$$

The range (R) of the boats is calculated using Equation 3. It is calculated by dividing the energy in the battery including DoD by the energy consumption (E_c).

$$R = \frac{E_{inc\ DoD}}{E_c} \text{ [nm]} \quad (3)$$

The lack of energy (E_L) needed to drive the distances is calculated using Equation 4, which multiplies the lack of range (R_L) with the energy consumption.

$$E_L = R_L * E_c \text{ [kWh]} \quad (4)$$

Equation 5 is used to calculate the amount of energy needed from methanol (E_M). It is calculated by multiplying the ratio of the lack of energy and the fuel cell efficiency (η_{FC}) by the volumetric density of methanol ($\rho_{V,M}$).

$$E_M = \frac{E_L}{\eta_{FC}} * \rho_{V,M} \text{ [kWh]} \quad (5)$$

Equation 6 is used to calculate the required volume of methanol (V_M). It is calculated by dividing the energy in methanol by the volumetric density of methanol.

$$V_M = \frac{E_M}{\rho_{V,M}} \text{ [m}^3\text{]} \quad (6)$$

The weight (m) of the batteries in Blue World Technologies' fuel cell system is calculated using Equation 7. The weight is calculated using the volume and weight ratio of the Evoy's batteries. It is assumed that the batteries of the Blue World Technologies' fuel cell system cover 1/3 of the system and that the weight and volume ratio is the same as Evoy's batteries.

$$m = V * \rho \text{ [kg]} \quad (7)$$

Equation 8 is used to calculate the necessary power (P_N) by multiplying the speed (v) and the energy consumption.

$$P_N = v * E_c \text{ [kW]} \quad (8)$$

Equation 9 is used to calculate the number of fuel cells needed (n_{FC}). It is calculated by dividing the necessary power by the power of the fuel cells (P_{FC}).

$$n_{FC} = \frac{P_N}{P_{FC}} \tag{9}$$

Equation 10 is used to calculate the inner dimensions of the cubic storage tank (l_i) in case 3. It is calculated by taking the cube root of the volume of the amount of methanol needed.

$$l_i = \sqrt[3]{V_M}\ [\mathrm{m}] \tag{10}$$

Equation 11 is used to calculate the outer dimensions of the cubic storage tank (l_o) in case 3. It is calculated by adding the twice the thickness of the storage tank (t_w) to the inner dimensions.

$$l_o = l_i + 2 * t_w\ [\mathrm{m}] \tag{11}$$

Equation 12 is used to calculate the tare mass of the storage tank (m_T) in case 3. It is calculated by using the difference between the volume of the storage tank and the volume of methanol, then multiplying it by the density of steel.

$$m_T = ((l_o)^3 - V_M) * \rho_{steel}\ [\mathrm{kg}] \tag{12}$$

3.5.2 Cost calculation

In the thesis, there are several economic analyses, where investment and operating costs are calculated for the range extender systems. The costs of the various components are collected. Low-cost components such as storage tanks, have little effect on the total investment cost and are therefore neglected. The fuel cell system is under development and thus has an unknown cost. Therefore, the cost of the fuel cell system is set to NOK 365,000 which is based on an estimate by Ocean Hyway Cluster [36].

Operating costs have been calculated for each driving distance. The electricity cost difference in the north and south of Norway has been taken into account. The reason for this is the large price difference. Electricity spot prices are based on the average spot price from May 2021 to May 2022, taken from Nord Pool's statistics. The price for green methanol is set to 15 NOK/l which is estimated by THEMA Consulting Group AS [37]. Table 7 represents the methanol, diesel, and electricity prices.

Table 7: Values for operating calculations

	Value	**Unit**	**Symbol**
Price of methanol [37]	15.00	NOK/l	$Price_M$
Price of diesel for fish farm	15.00	NOK/l	$Price_D$
Price of diesel for tourism [38]	17.50	NOK/l	$Price_D$
Spot price in the south of Norway [39]	1.07	NOK/kWh	Spot price
Spot price in the north of Norway [39]	0.37	NOK/kWh	Spot price
Consumption of diesel [40]	38	L/h	

Equation 13 is used to calculate the actual electricity price without VAT ($Price_{EL}$). To take the average total electricity bill into account, the spot price is divided by 0.35. In addition, the spot price is divided by 1.25 to get the price without VAT [41].

$$Price_{EL} = \frac{Spot\ price}{0.35} * \frac{1}{1.25}\ \text{[NOK/kWh]} \tag{13}$$

Equation 14 is used to calculate the OPEX which is the fuel and electricity costs. OPEX is calculated by adding energy in methanol multiplied with the price of methanol ($Price_M$) and energy in batteries (E_{EL}) multiplied with the electricity price ($Price_{EL}$).

$$OPEX = (E_M * Price_M) + (E_{EL} * Price_{EL})\ \text{[NOK]} \tag{14}$$

The operation price including price of electricity and price of green methanol ($Price_F$) used in Evoy's investment analysis is calculated by using Equation 15.

$$Price_F = \frac{OPEX}{E_M + E_{EL}}\ \text{[NOK/kWh]} \tag{15}$$

The operating time per driving distance ($t_{distance}$) is calculated by using Equation 16, which divides the range by the speed.

$$t_{distance} = \frac{R}{v}\ \text{[h]} \tag{16}$$

The operating time during a year (t_{year}) is calculated by using Equation 17. It is calculated by multiplying the operating time per distance, number of trips per day (n_{day}), number of operating days (n_{week}) and number of operating weeks in a year (n_{year}).

$$t_{year} = t_{distance} * n_{day} * n_{week} * n_{year}\ \text{[h]} \tag{17}$$

4. Result of alternative A and alternative B

As mentioned in Chapter 3, this thesis considers two different alternatives. The first alternative is alternative A, which involves using methanol directly in a fuel cell. If this turns out not to be beneficial, alternative B will be considered further. Alternative B involves reforming methanol into hydrogen and then using the hydrogen as fuel in a hydrogen fuel cell.

4.1 Alternative A

The advantage of using methanol directly in a fuel cell is that the system is simplified. It will include fewer components than alternative B, as it will not need a reformer. Fewer components also result in less maintenance and maintenance costs. Only DMFC and SOFC can use methanol directly without reforming. In this chapter, it is considered if it is beneficial to use SOFC and DMFC as range extenders in an electric motor system.

SOFC has received more attention in recent years in the transport sector, as the fuel cell has high efficiency and more fuel options. The high operating temperature offers potential for higher conversion efficiency and using the waste heat for other applications. On the other hand, the high operating temperature also results in a long start-up and shutdown time [29]. This makes the fuel cell impractical for smaller mobile applications. The company Bloom Energy supplies SOFCs with a power output of 300 kW, which corresponds to the same capacity as Evoy's motor. However, the fuel cell weighs 15,800 kg and will exceed the maximum weight capacity of the boat [42]. Kyocera Global supplies SOFCs with a power output of 0.70 kW and a weight of 5 kg. As the power output of a single fuel cell is very low, it is necessary to use 429 fuel cells to reach adequate power output [43]. The high weight and operating temperature, limit the applications of SOFCs. This type of fuel cells will therefore not be considered further in this thesis. The fuel cell may be relevant in the future if weight and operating temperature are reduced [29].

There are few suppliers of DMFCs, and the power output of these fuel cells are too low for boat applications. Currently, DMFCs are used for small-scale applications such as portable electronic devices like laptop computers and mobile phones [29]. EFOY supplies several different sizes of DMFCs. The two with the highest power output are considered. EFOY Pro 2800 has a power output of 125 W and a weight of 7.8 kg, while EFOY Pro 12,000 DUO has a power output of 500 W and a weight of 32 kg. Like SOFC, the weight of DMFCs will exceed the maximum weight capacity of the boat at a required capacity [44]. In addition, DMFCs has the lowest efficiency among the fuel cells. In general, DMFCs has an efficiency of 25 %. The weight and the low efficiency make DMFCs unsuitable for use as a range extender [28].

Table 8 gives an overview of the properties of SOFCs and DMFCs. High operating temperature, low efficiencies, and weight, limit the application of these fuel cells and makes them unsuitable as range extenders. Further in this thesis, the focus will therefore be on alternative B.

Table 8: Properties of SOFCs and DMFCs

	SOFC		**DMFC**	
Supplier	Bloom Energy [42]	Kyrocera Global [43]	EFOY [44]	EFOY [45]
Model	-	Gen 3	PRO 2800	PRO 12,000 DUO
Power output [kW]	300	0.70	0.125	0.50
Weight [kg]	15,800	5.00	7.80	32
Power to weight ratio [W/kg]	19.0	140	16.0	15.6
Volume [dm^3]	17	6.00	24	87
Power to volume ratio [W/dm^3]	17,647	116.7	5.20	5.70
The efficiency of the fuel cell [%]	52	55	-	-

4.2 Alternative B

As alternative A is unsuitable for the use as a range extender, alternative B is further considered. In alternative B, methanol is used as a hydrogen carrier, and is reformed into hydrogen before being used in a fuel cell. Utilizing methanol in this way requires an evaporator and a reformer in the fuel cell system.

4.2.1 Fuel cell technology

This section considers which hydrogen fuel cell is best suited for the range extender system. Alkaline and PEM fuel cells are considered. Further in this section, the chosen fuel cell system is described.

4.2.1.1 Choice of fuel cell

To this date, research and development have mainly been focused on PEM for small and medium-sized applications, and SOFC for larger applications [29]. In the development of transport fuel cells, the focus is mainly on PEM [46].

AFC has the highest efficiency of current fuel cells and has a low capital cost. The disadvantage of the fuel cell is related to the sensitivity to carbon dioxide, which gives deposits of carbonate. AFC will in any case be exposed to some carbon dioxide, and thus reduce the lifetime of the fuel cell. The lifetime is approximately 5000 hours, which is low compared to the other fuel cells. The company AFC Energy is one of the few suppliers of AFC. There is limited data available on their fuel cells. In general, AFC tends to have a power output of 0.5 kW to 10 kW. This power output is too low to cover the energy demands of any of the boats [26]. The sensitivity to carbon dioxide and the short lifetime, limit the applications of the fuel cell [28]. In addition, there is limited data available on the fuel cell and therefore this option will not be considered further in this thesis.

Currently, the focus is mainly on PEM for the development of the use of fuel cells in transportation. PEM is common and there are several suppliers. The advantages of PEM are a fast start-up, dynamic operation, and frequent shutdown. Also, it has a lower weight and can be shaped into very compact units, which is an advantage where weight and space are a limitation. On the other hand, one of the major disadvantages of PEM is the high cost associated with components such as catalysts [29]. Despite the cost, PEM is considered the best alternative among the fuel cells for usage in range extenders of electric boats.

Of high-temperature PEM (HTPEM) and PEM, HTPEM is selected further in this thesis. The low operating temperature of PEM results in stricter requirements on hydrogen from reforming to keep the CO content down to 20 ppm. HTPEM has a higher tolerance for CO as a result of a higher operating temperature. By using HTPEM, the hydrogen from a reformer does not need more CO-purification than a shift reactor. Another advantage of HTPEM is that cell cooling is simpler. As a result of the temperature difference between the fuel cell and the ambient temperature, only a small radiator is needed. Like SOFC, the waste heat from HTPEM can be used for other purposes, such as heating the evaporator and reformer [29].

4.2.1.2 HTPEM system with combined heat and power

HTPEM will often be combined with a steam reformer [47]. Partial oxidation requires high operating temperatures, and the process is exothermic. Without a catalyst, a temperature of 1400 °C is required, and 870 °C when using a catalyst [46]. A steam reformer operates at a temperature of around 300 °C and the process is endothermic [30]. As steam reforming is an endothermic process and requires heat, this will be well combined with an HTPEM. If an HTPEM fuel cell has an efficiency of 45 %, 55 % of the energy is wasted in form of heat [28]. Large parts of this waste heat can be recycled and utilized. The waste heat from the fuel cell is transferred to the evaporator that operates at a lower temperature than the fuel cell. Residues of hydrogen and carbon dioxide from the fuel cell will burn in a flameless combustor and produce heat. This heat is transferred to the reformer. The thermal cycle is maintained and external heat is not required [47]. Combined heat and power systems are not a new technology, but fuel cells with such a system have received increasing attention in recent years [48].

Several companies are developing HTPEM fuel cells with combined heat and power. Blue World Technologies and Palcan are among the companies developing such a fuel cell system for methanol-based transport. Table 9 gives an overview of the properties of the HTPEM systems. Palcan delivers a smaller system with a power output of 5 kW and a weight of 60 kg, while Blue World Technologies delivers a larger system with a power output of 15-25 kW and a weight of 200 kg [49] [50]. To get the necessary power, several HTPEM fuel cells can be stacked together. As Palcan has a smaller system with lower power output, more fuel cells will be needed compared with Blue World Technologies' system. In addition, Palcan is a Chinese company headquartered in Canada, while Blue World Technologies is a Danish company [49][50]. Importing the fuel cell system from Denmark is a more local solution and will probably reduce supply time. In this thesis, the methanol range extender system will use the HTPEM system from Blue World Technologies.

Table 9: Properties overview of the HTPEM systems

	Blue World Technologies [34]	**Palcan [49]**
Country of origin	Denmark	China
Power output [kW]	15-25	5
Weight [kg]	200	60
Power to weight ratio [W/kg]	75-125	300
Length [m]	1.30	0.69
Width [m]	1.00	0.45
Height [m]	0.19	0.27
Volume [dm^3]	247	83.8
Power to volume [W/dm^3]	60.7-101	716
Fuel consumption [L/kWh]	0.50	1.00
The efficiency of the system [%]	45	47

Blue World Technologies' fuel cell system can be designed according to boat type and available space. The fuel cell system can be cubic or in a flat pack configuration. The system can be delivered with and without batteries [51]. This thesis will use the system without batteries.

The fuel cell system includes an evaporator, steam reformer, fuel cell, and a flameless combustor. Figure 7 illustrates the fuel cell system. The figure is made based on a sketch of Blue World Technologies' fuel cell system. From the storage tank, methanol will be fed to the evaporator. Here, a mixture of 60 % methanol and 40 % water will evaporate to meet the prerequisites of the reformer. The water supplied to the evaporator is recycled from the fuel cell. The evaporator operates at a temperature of around 100 °C and the heat supplied is recycled heat from HTPEM. After exiting the evaporator, the mixture is reformed into hydrogen and carbon dioxide at a temperature of 300 °C. The hydrogen will pass to the fuel cell which operates at a temperature of 160 °C and react with oxygen from ambient air. This reaction will generate a current that is supplied directly to the electric motor or stored in the batteries. Hydrogen and carbon dioxide residues from the fuel cell will be fed to a flameless burner which produces heat that is transferred to the reformer. Only water and carbon dioxide will exit the exhaust. The flameless combustor and the waste heat from the fuel cell will ensure a recycled heat transfer in the system, and it is assumed that no external heat supply will be required [50] [47].

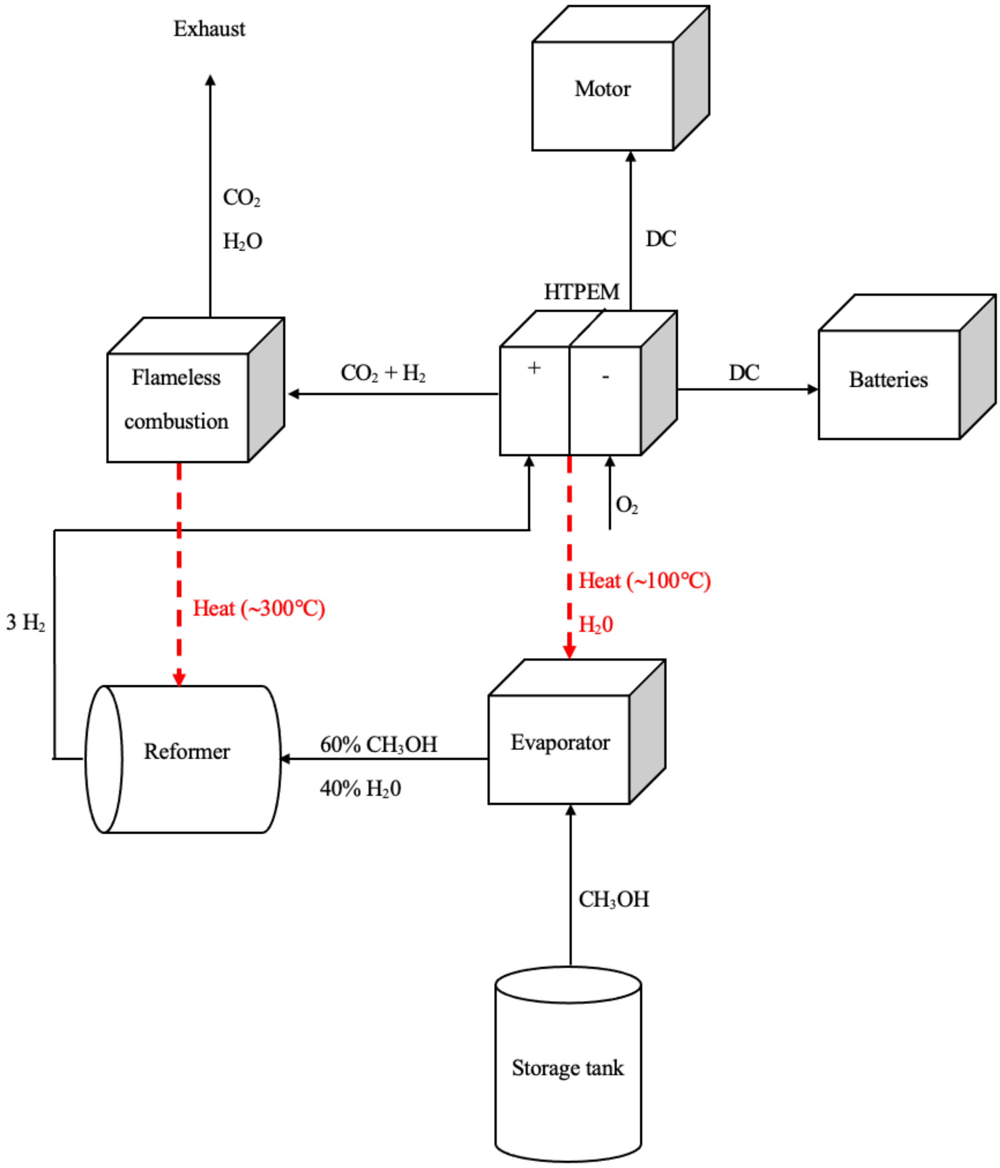

Figure 7: The range extender system including the fuel cell system and the electric motor system [34] [50]

4.2.2 Methanol storage

The design of the storage tank for methanol is essentially the same as for gasoline and other flammable liquid feedstocks. However, there are physical and chemical properties of methanol that are different from other flammable liquids stored in bulk. These properties need to be considered when storing [52].

An important factor to consider is the flammability range of methanol. The flammability range describes the minimum and maximum concentrations of a given vaporous substance that will ignite or combust when mixed with air. When the concentration of the vapour is below the lower flammable limit, the amount of hydrocarbon gas in the air is insufficient to support combustion. The concentration of the vapour over the upper limit is also insufficient to support combustion. Concentrations of vapour in the air within the lower and upper limits are able to ignite and burn. The lower and upper flammability limits are therefore important for safety considerations. The lower flammability limit for methanol is 6.7 % and the upper is 36 % by volume. This is a large interval for flammability compared to gasoline which has a lower limit of 1.4 % and an upper limit of 7.6 % by volume [53]. Methanol vapour, therefore, has a higher risk of ignition inside the tank compared to gasoline [52].

Corrosion is also important to be taken into account. Methanol is a conductive polar solvent, which means that galvanic corrosion is more prevalent in methanol than in other fuels. If two different metals are in contact and are surrounded by methanol which becomes an electrolyte, redox reactions will take place. To avoid corrosion, it is, therefore, necessary that incompatible materials are not placed in electrical contact with each other. It is also possible to prevent the risk by using cathodic protection and regular inspection of the storage tanks [52].

Methanol absorbs moisture from the air. When the fuel level in the storage tank decreases, it will be possible for moisture-laden ambient air to be drawn into the tank. In a coastal environment, such moisture-laden air will carry dissolved chloride salts that will contaminate the methanol. Where purity of methanol is required, dry inert gas padding and stainless-steel tanks will be a risk-reducing measure [52].

The methanol tanks can either be made of carbon steel or 300 series austenitic stainless steel. Carbon steel has a low capital cost, but higher costs related to maintenance and corrosion protection. The relatively high conductivity of liquid methanol has resulted in corrosion-induced defects in carbon steel tanks. Carbon steel is more likely to corrode and cause methanol pre-purification than stainless steel. This risk can be limited by filling the tank's free space with a dry inert gas such as nitrogen. Stainless steel has higher capital costs, but lower life cycle maintenance costs and less likelihood of methanol pre-purification [52].

The methanol storage tank is made of 300 series austenitic stainless steel and the dimensions of the tank are set to be the same as CIPAX’s plastic storage tanks. The methanol storage tank has a volume of 60 dm^3 with a rectangular floor area. The weight of the tank is calculated by using Equation 1 and equals 50 kg. Table 10 shows the different dimensions of the tanks and the total weights [35].

Table 10: Weight and volume of the tanks [35]

	Tank
Volume [dm^3]	60.00
Length [m]	0.60
Width [m]	0.36
Height [m]	0.33
The volume of the steel material [dm^3]	11.28
Weight of PE tank [kg]	5.65
Weight of stainless-steel tank [kg]	50

4.2.3 The driving distances for the boats

This section describes the driving distances the range extender systems are based on. Figure 8 shows an overview of the four scenarios. As mentioned in Chapter 3, the boats are mainly used for tourism and fish farming. Two driving distances for each application are considered. For tourism, the boats drive four trips every day, and are in operation five days a week, 40 weeks a year. For fish farming, the boats drive two trips every day, and are in operation six days a week, 52 weeks a year. Boat 1 and Skarsvåg 799 have a speed of 25 knots at all driving distances, which corresponds to cruising speed. Goldfish X9, on the other hand, has a hull and weight that makes it more energy efficient to drive at 35 knots [6].

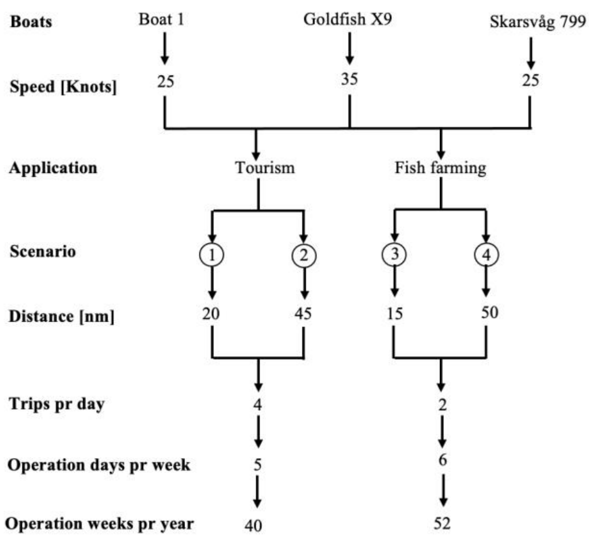

Figure 8: The scenarios and driving distances for the boats

In the scenario of tourism, there are mainly shorter routes of 20 nm, but often routes with a length of 40–50 nm are needed [6]. 20 nm and 45 nm are therefore considered for driving scenarios 1 and 2 respectively. For fish farming, 15 nm and 50 nm are considered for scenarios 3 and 4 respectively.

Without a range extender, it is not possible to use Evoy's current electric motor system for scenario 4, as the batteries do not store enough energy. In this scenario, the boat drives out to a location 50 nm from the land base and will not have a charging option at the fish farming locations. However, using methanol as a range extender, opens for the possibility of charging the batteries with the range extender system. Slow charging speed does however limit the practicality [4].

The amount of energy Evoy’s electric motor system is able to supply, depends on the energy capacity of batteries in the system. Both Goldfish X9 and Skarsvåg 799 have an energy capacity of 126 kWh. They get this by utilizing two batteries of 63 kWh. Boat 1 utilizes eight of these batteries, for a total energy capacity of 504 kWh. Taking depth of discharge into account, the actual energy capacities are reduced. This is calculated by using Equation 2. The actual energy capacity gives the range of the boats according to Equation 3. In Table 11, the energy data and driving range of the boats are shown.

Table 11: Energy data and the driving ranges of the boats

Boat model	**Boat 1**	**Goldfish X9**	**Skarsvåg 799**
Energy consumption [kWh/nm]	17	4	6
Speed [knots]	25	35	25
Total battery energy capacity [kWh]	504	126	126
Actual battey energy capacity considering DoD [kWh]	353	88	88
Driving range considering DoD [nm]	21	22	15

By comparing the different driving distances in Figure 8 and the ranges of the boats in Table 11, it is possible to determine in which scenarios the boats need a range extender. Boat 1 and Goldfish X9 will only need a range extender for scenarios 2 and 4. Skarsvåg 799 will need a range extender for scenarios 1, 2, and 4. However, in scenario 1, the required range extension is very low, only 5 nm. Increasing the range by 5 nm is possible by lowering the driving speed. The drawbacks of installing a range extender system, cost and lost weight and volume capacity, are probably more drastic than the drawbacks of lowering the driving speed.

4.2.4 Weight and volume

This section assesses the weight and volume of the components in the range extender systems. The weight and volume vary according to the number of storage tanks and fuel cells required. The energy needed from the range extender to cover the full distances, is calculated by using Equation 4. The required amount of energy from methanol is calculated using Equation 5 and the corresponding required volume of methanol is calculated by using Equation 6. Table 12 shows the required range extensions and volume of methanol in the different scenarios.

Table 12: Required energy and volume of methanol for the various scenarios

Boat model	**Boat 1**		**Goldfish X9**		**Skarsvåg 799**	
Scenario	2	4	2	4	2	4
Required range extension [nm]	24	29	23	28	30	35
Required additional energy [kWh]	421	507	92	112	182	212
Required energy from methanol [kWh]	936	1 127	204	248	404	471
Required volume of methanol [dm^3]	213	256	46	57	92	107

The methanol tank has a storage capacity of 60 dm^3 and weighs 50 kg. Skarsvåg 799 needs two storage tanks for scenarios 2 and 4. Boat 1 needs four storage tanks in scenario 2, and five in scenario 4. Goldfish X9 only needs one storage tank for both scenarios 2 and 4. In practice, the weight of the tanks will decrease as the methanol fuel is spent. With less weight, the energy consumption will be reduced, but the weight reduction is so small, that it is neglected. As such, the energy consumption is kept constant.

The entire Blue World Technologies' 20 kW fuel cell system, including batteries and reformer, weighs 200 kg. It is assumed that the batteries cover 1/3 of the volume of the fuel cell system, and thus have an estimated volume of 81 dm^3. Furthermore, it is estimated by using Equation 7, that the batteries will weigh 100 kg in total, assuming that the weight and volume ratio is the same as for Evoy's battery. Thus, the fuel cell system will weigh 100 kg and have a volume of 165 dm^3 without the batteries.

The number of fuel cells required in each boat depends on the speed. Table 13 shows how many fuel cells the boats need. The necessary power of the boats is calculated by using Equation 8, and the corresponding number of fuel cells is calculated using Equation 9. Boat 1, Goldfish X9, and Skarsvåg 799 need a power output of 430 kW, 140 kW, and 160 kW respectively, which corresponds to 22, 7, and 8 fuel cells respectively.

Table 13: Number of fuel cells needed

Boat model	**Boat 1**	**Goldfish X9**	**Skarsvåg 799**
Speed [knots]	25	35	25
Necessary power [kW]	430	140	160
Required number of fuel cells	22	7	8

Table 14 shows the total weight of the range extender systems for scenarios 2 and 4. As mentioned earlier in Chapter 2, the electric motor system weights 3 886 kg for Boat 1, and 1 143 kg for Goldfish X9 and Skarsvåg 799.

Table 14: Total weight of the range extender system

Boat model	**Boat 1**		**Goldfish X9**		**Skarsvåg 799**	
Scenario	2	4	2	4	2	4
Weight of EL-system [kg]	3 886	3 886	1 143	1 143	1 143	1 143
Number of storage tank	4	5	1	1	2	2
Weight of storage tank [kg]	200	250	50	50	100	100
Weight of methanol [kg]	168	203	37	45	73	85
Weight of fuel cell system [kg]	2 200	2 200	700	700	800	800
Total weight [kg]	6 454	6 539	1 930	1 938	2 116	2 128

Boat 1 is a larger and heavier vessel than the other two models. The electric motor system and design of the boat result in high energy consumption and a need for more fuel cells [6]. As shown in Table 13, the boat needs 22 fuel cells at a speed of 25 knots. This solution is not considered beneficial, as the weight of the range extender system is too high. Furthermore, this section considers two other options. The first option keeps the current electric motor system but reduces the speed. In this way, the energy consumption and the required range extension are reduced, which in turn reduced the required number of fuel cells. The second option reduces the components of the electric motor system such that the weight and energy consumption decreases. This also decreases the required number of fuel cells.

This section considers the two options with two cases each. Within option 1, case 1 and 2 are considered with the speeds of 25 and 19 knots respectively. Within option 2, case 3 and 4 are considered with the speeds of 25 and 10 knots respectively. The speeds in the four cases are based on the number of fuel cells and are calculated by using Equation 8. Table 15 shows the four cases. The actual battery energy capacities in both options are calculated by using Equation 2, and the corresponding ranges of the electric motor system are calculated by using Equation 3. The required number of fuel cells are calculated by using Equation 9.

Table 15: Overview of the four cases for boat 1

	Option 1: Current EL-system		**Option 2: Reduced El-system**	
	Case 1: 25 knots	Case 2: 19 knots	Case 3: 25 knots	Case 4: 10 knots
Number of batteries	8		4	
Number of motors	2		1	
Total battery energy capacity [kWh]	504		252	
Actual battey energy capacity considering DoD [kWh]	352		176	
Speed achieved by the EL-system [knots]	25		25	
Required energy to drive at the selected speed [kWh] [4]	430		300	
Energy consumption [kWh/nm] [4]	17		12	
Range by EL-system [nm]	21		15	
Number of fuel cells	22	16	15	6

Table 16 shows the required range extensions for scenarios 2 and 4 in option 1 and 2, as well as the required volume of methanol. By keeping the current electric motor system, a larger amount of methanol is required.

Table 16: The required range extensions in option 1 and 2 for Boat 1

	Option 1: Current EL-system		**Option 2: Reduced EL-system**	
	Scenario 2: 45 nm	Scenario 4: 50 nm	Scenario 2: 45 nm	Scenario 4: 50 nm
Required range extension [nm]	24	29	30	35
Required additional energy [kWh]	421	517	364	424
Required energy from methanol [kWh]	936	1 127	808	941

Required volume of methanol [dm^3]	213	256	184	214

Table 17 shows the weight of the various components, as well as the total weight of the range extender system for the four cases. The volume of the storage tank is calculated by using Equations 10 and 11. The weight of the storage tank is calculated by using Equation 12. By reducing the number of batteries and motors, the total weight will be significantly lower.

Table 17: The total weight of the range extender systems for the four cases

	Case 1		**Case 2**		**Case 3**		**Case 4**	
Scenario	2	4	2	4	2	4	2	4
Weight of methanol [kg]	168	203	168	203	145	169	145	169
Weight of storage tank [kg]	270	304	270	304	245	271	245	271
Weight of fuel cell [kg]	2 200	2 200	1 600	1 600	1 500	1 500	600	600
Weight of batteries [kg]	3 200	3 200	3 200	3 200	1 600	1 600	1600	1 600
Weight of motor [kg]	686	686	686	686	343	343	343	343
Total weight [kg]	6 524	6 593	5 924	5 993	3 833	3 883	2 933	2 983

The total weight in cases 3 and 4 are significantly lower than for cases 1 and 2. By reducing the batteries and motors, the energy consumption is lowered, and the range extender system requires fewer fuel cells. Fewer components will also result in lower investment costs and maintenance. Case 4 requires 6 fuel cells, which is significantly fewer than case 3 which requires 15. However, the speed in case 4 is 10 knots which is very low and results in high time consumption. Case 3 proves to be the most beneficial solution. The total weight of this range extender system is almost twice as high as for Goldfish X9 and Skarsvåg 799, but significantly less than cases 1 and 2. In case 3, boat 1 requires 15 fuel cells and can drive at a speed of 25 knots. Further, in the results, case 3 for boat 1 will be considered.

4.2.5 Placement of the system in the boats

The principle of the system placements is the same in all of the boats, which is to place the heaviest components low, and at the back of the boat. This is necessary to allow the boat to achieve optimal driving performance, and thus decrease energy consumption. The weight at the starboard and port is also evenly distributed. This is necessary for the boat to be stable at the water level and able to adjust to different conditions at sea [4].

Table 18 shows the dimensions of the various components in each boat, as well as the weight. The table shows the combined dimensions for each type of component. The weight of the tank and the methanol content is set to scenario 4, as this has the greatest weight. However, the weight difference is small and will not have a meaningful impact on the placement. The placement of the methanol tank will thus be the same for both scenarios.

Table 18: Dimensions and weight of the battery [3], motor [3], tank [35] and fuel cell system [34]

Boat	Component	Length [mm]	Width [mm]	Height [mm]	Volume [m^3]	Weight [kg]
Boat 1	Batteries	1 111	1 590	702	0.31	1 600
	Motor	1 089	1 047	795	0.29	343
	Storage tanks	628	628	628	0.25	440
	Fuel cell systems	3 480	1 000	760	2.65	1 500
Goldfish X9	Batteries	1 111	795	702	0.62	800
	Motor	1 089	1 047	795	0.31	343
	Storage tanks	600	360	330	0.14	94
	Fuel cell systems	1 740	1 000	760	1.32	700
Skarsvåg 799	Batteries	1 111	795	702	0.62	800
	Motor	1 089	1 047	795	0.31	343
	Storage tanks	600	360	660	0.14	184
	Fuel cell systems	1 740	1 000	760	1.32	800

Figure 9 illustrates the placement of the components in Skarsvåg 799, but the placements are approximately the same for all of the boats. The colour blocks in the figure represent the placements of the various components. Grey shows the battery package, yellow fuel cell system, blue motor, and pink methanol tanks.

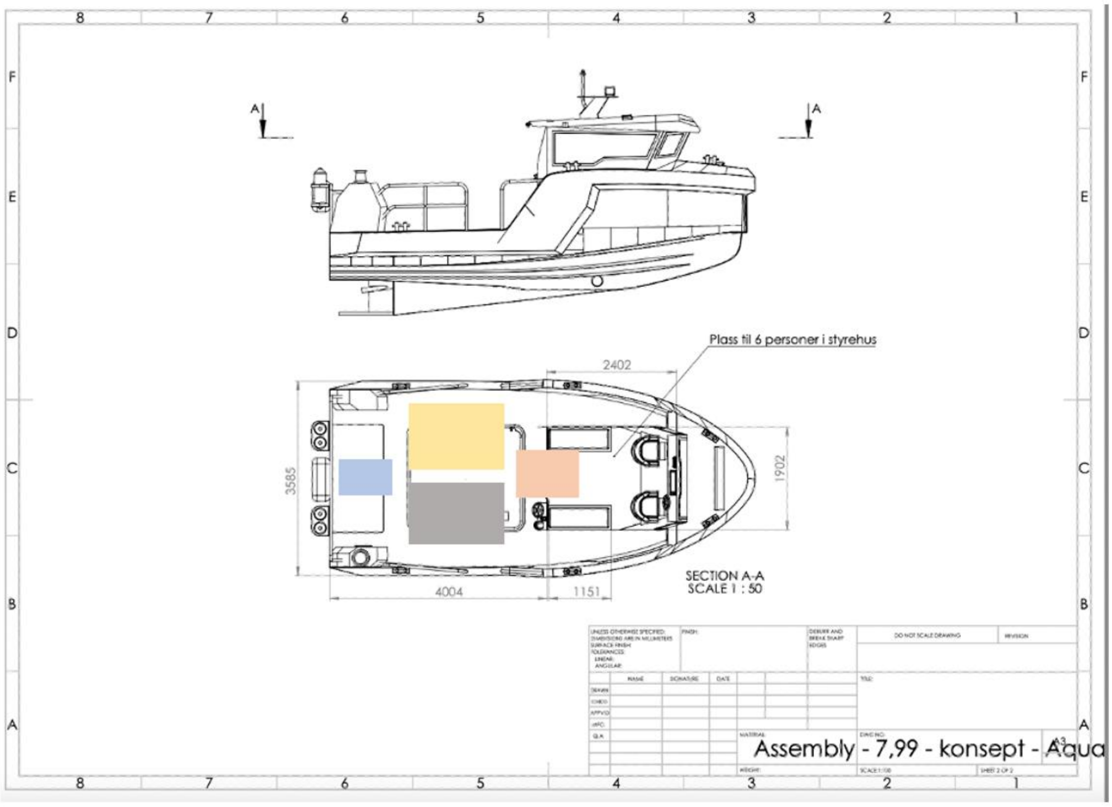

Figure 9: Placement of the components [54]

The battery pack and the fuel cell system are placed parallel in the middle of the stern. The battery pack in Goldfish X9 and Skarsvåg 799 consists of two batteries that are stacked on top of each other. Boat 1 has four batteries and will thus have two rows. For Goldfish X9 the battery pack is heavier than the fuel cell system and is placed closer to the centre of the boat to achieve equilibrium.

Boat 1, Goldfish X9, and Skarsvåg 799 have fuel cell systems containing 15, 7, and 8 fuel cells respectively. The fuel cells are stacked on top of each other, with four fuel cells in height. Skarsvåg 799 and Goldfish X9 have two rows, while Boat 1 has four. One of the rows in Boat 1 and Goldfish X9 have three fuel cells in height, as a result of odd numbers. This row is placed at the far end where the hull slopes the most up. The motor is placed at the rear of the boat close to the propeller, while the storage tanks are placed further inside the boat. Considering that the weight of the tanks decreases as the boat drives, it is natural for the tanks to be placed in front of the other components with constant weights.

4.2.6 Maintenance

Maintenance is necessary to maintain the quality of the system and ensure that everything works as intended.

The methanol tanks are made of stainless steel which is corrosion resistant. To maintain this property, cleaning will be a necessary measure. Cleaning and inspection are important to prevent the accumulation of particles that over time can lead to corrosion [55].

The fuel cell system has no moving parts and thus requires less maintenance than an engine. Maintenance is limited to inspections and air filter replacement. In the event of any deviations, parts or whole components will be replaced. In addition, Blue Word Technologies system involves monitoring that ensures reliable operation [56]. The lifetime of the system is typically 10,000 operating hours but will vary depending on the system design and operating point [57].

Evoy's battery system requires checking the cooling oil level and cooling water level regularly. In addition, periodic inspections and replacements are necessary. Temperature and humidity are important factors to preserve battery performance [7].

4.2.7 Safety

Several guidelines must be followed when using fuel in vessels. The global approach to addressing greenhouse gas emissions from vessels is led by the International Maritime Organization (IMO). IMO is a specialized agency of the United Nations (UN) that ensures the safety and pollution prevention of ships. In Norway, the Norwegian Maritime Directorate sets requirements and rules related to the regulation of boats. The requirements and regulations are based on international rules and standards established by the IMO, European Maritime Safety Agency (EMSA), standardisation agency and class companies. The guidelines for methanol as a fuel in maritime use are still under development [58].

Rules and requirements for methanol as fuel are subject to regulations on ships that use fuel with a flashpoint below 60 °C. This regulation further refers to the IGF code, which is an international security code for the implementation of alternative fuels with a low flash point for maritime use. The purpose of this code is to reduce risks to the ship, crew, and environment. The code contains mandatory requirements for fuel systems, tanks, and operational requirements for maritime use. This includes arranging, installing, controlling, and monitoring machinery, equipment, and systems. Chapter 2 refers to the scope that applies to LNG and has detailed rules. Methanol and other alternative fuels are covered by chapter 2.3 which deals with alternative design. This is because such fuels must show equivalent safety as a standard fuel [59].

The classification societies have a purpose to safeguard the interests of marine insurers, and have inferred rules for the construction and inspection of ships. In Norway, the Norwegian Veritas (DNV GL) is the largest classification society. Under section 6 of DNV's rules for the classification of ships, low flashpoint liquid applies to methanol and ethanol. The rules in this section have requirements for the arrangement and location of fuel tanks and all fuel installations. There are also requirements for control, monitoring, and safety systems [60].

The Norwegian Maritime Directorate leads the entire approval process and must approve each case. An organized risk mapping is carried out and compared to IFG code and other requirements [58].

5. Result of economical analysis

This chapter analyses the economics of the different range extender systems in the boats. The total investment cost and operating cost will be calculated. Blue World Technologies' HTPEM system is under development and the price is thus an estimate.

5.1 Financial Support

In Norway, there are several financial support opportunities for new technology and technology development. In this section, it is investigated whether there are financial support opportunities from Enova and Innovation Norway.

Enova provides financial support for hydrogen technology, hydrogen carriers and fuel cell technology. Although methanol is a hydrogen carrier, Enova will most likely not support methanol technology at this time. There are two main reasons for this. First and foremost, methanol technology is a more mature and widespread technology than other alternative fuels such as hydrogen and ammonia. In addition, there are carbon dioxide emissions from methanol when combustion. Although methanol can be carbon neutral when using biogenic carbon dioxide, such a solution does not exist in Norway today. Biogenic carbon dioxide is also a limited resource, and it is thus uncertain whether there is enough biogenic carbon dioxide available for such a solution to be competitive. The fact that methanol is a mature technology and produces emissions during combustion, results in such a project not receiving financial support from Enova [61].

Innovation Norway can provide financial support to Norwegian companies that develop green technology. The EU taxonomy is a classification system that defines what is green enough for the environmental technology scheme. In this way, it will establish a common standard for what is defined as green and sustainable to counteract greenwashing. For a project to be defined as green and sustainable, it must meet three criteria. Under the first criterion, the project must contribute to one of six environmental goals: [62]

1. Limiting climate change
2. Climate adaptation
3. Sustainable use and protection of water and marine resources
4. Transformation to a circular economy
5. Prevention and control of pollution
6. Protection and restoration of biological diversity and ecosystems

The second criterion is that it does not harm the other environmental goals. The third criterion is that it must adhere to the guiding principles for responsible business in accordance with the OECD's guidelines for multinational companies and the UN guiding principles for business and human rights [62].

Green methanol is considered to meet all these criteria, but it is not possible to regulate the end user's choice of green or grey methanol. In addition, green methanol does not seem to exist in the Norwegian market today and an end-user will therefore most likely use grey methanol in their boats. As it is not possible to regulate the type of methanol used, the development of methanol technology will not be supported by Innovation Norway.

Although the methanol system will probably not receive economic support today based on the availability of green methanol, it is assumed that support will be granted in the future. It is assumed that in the long term more facilities for green methanol will be established in Norway and by that time Enova and Innovation Norway will grant support. The cost calculations further in this thesis are based on support for the methanol system from Enova or Innovation Norway.

5.2 Investment costs

Table 19 shows the cost of the various components needed in the methanol system. The price of the fuel cell system is estimated, and the price is based on an estimate from Ocean Hyway Cluster [36]. Low-cost components such as storage tanks, have little effect on the total investment cost and are therefore neglected.

Table 19: Cost of the components

Components	CAPEX [NOK]
HTPEM system (20 kW) [36]	365,000
Battery (63kWh) [7]	349,000
Motor (300kW) [7]	749,000

Table 20 shows an overview of the number of components needed in the various boats and the total investment cost based on the numbers in Table 19. The table shows that an investment of the methanol system in Boat 1 will have an investment cost almost twice as high as for Goldfish X9 and Skarsvåg 799.

Table 20: CAPEX for boat model

Boat model	Boat 1	Goldfish X9	Skarsvåg 799
Number of HTPEM system	15	7	8
Number of batteries	4	2	2
Number of motors	1	1	1
CAPEX [NOK]	7,620,000	3,993,000	4,358,000

5.3 OPEX and investment analyses

This section calculates OPEX for the four scenarios. For the boats in this thesis, OPEX is limited to fuel and electricity costs. This cost is calculated by using Equation 14. Repayment periods and cost savings for scenarios 2 and 4, are also calculated. This is done by using Evoy's investments analysis program. The operation costs used in the analysis are based on the price of electricity and green methanol. The price of green methanol is set to 15 NOK/l which is estimated by THEMA Consulting Group AS, and is converted to NOK/kWh [37]. The electricity prices take the spot price in the north and south of Norway into account. The spot price for electricity is estimated based on Nord pool's statistics from May 2021 to May 2022. The estimated electricity prices are calculated by using Equation 13, and are set to 1.07 NOK/kWh in the south and 0.37 NOK/kWh in the north of Norway [39]. Electricity prices will most likely increase in the future, but this has not been considered in the analyses. The combined operation costs are calculated by using Equation 15.

The operating time during a year depends on how long it takes for the boats to drive scenarios 2 and 4. Some assumptions have been made for the various scenarios. In tourism, it is assumed that the boat will drive four trips every day, five days a week, 40 weeks a year. When farming, the boat will drive two trips per day, six days a week for the whole year. The operating time per trip is calculated by using Equation 16, and the operating time during a year is calculated by using Equation 17.

Evoy's investment analysis program is also used to analyse the financial savings from investing in electric boats with a methanol system, compared to diesel-powered vessels. The diesel price will vary, but in the analyses, the price is set to 15 NOK/l for fish farming and estimeded to 17.5 NOK/l for tourism [38]. Fish farming often has agreements with cheaper diesel prices, while in tourism the diesel price will be approximately the pump price. The consumption of diesel is estimated to be 38 l/h [24].

5.3.1 Boat 1

The investment analyses for Boat 1 are based on the values in Table 21 which shows the operating time during a year and the operating costs for Boat 1.

Table 21: Operating time and operation costs for Boat 1

	Scenario 2: 45 nm		**Scenario 4: 50 nm**	
Operation time per distance [h]	1.8		2.0	
Operation time during a year [h]	1 440		1 248	
Region of Norway	North	South	North	South
Operation costs [NOK/kWh]	2.95	3.25	3.01	3.27

Figure 10 shows accumulated cost savings in scenario 2, with operating costs from the south of Norway. The graph shows two lines, where the top-line represents cost savings with support from Enova and the bottom-line cost savings without support. The top-line includes support for both Evoy's electric motor system and the methanol range extender system. On the lines, there are some bumps. The components in the boats have different operating lifetimes, and the bump at year 13 illustrates necessary reinvestment during the lifetime of the boat itself. The electric motor has a lifetime of 15 years, while the fuel cell system has a lifetime of 10 years. Because of limitations in the investment analysis program, the reinvestment of the electric motor and the fuel cell system is set to a lifetime of 13 years [10].

The graph shows that Boat 1 will have a repayment period of 6 years with support and 11 without support. Without support, the range extender system has apparently reached the repayment period at year 9. When reinvesting in a new electric motor and the fuel cell system, the cost savings decrease before it rises again. By year 13, the system will reach a new repayment period. The investment analysis calculates the average repayment period, which in this analysis is at 11 years.

In the south of Norway, the cost savings at the end of the boat's lifetime are NOK 21,418,963 with support and NOK 17,833,963 without support. The analysis for the north of Norway will have approximately the same graph as Figure 10. In the north of Norway, the cost saving with support is NOK 23,676,950, and has a repayment period of 5 years. Without the support, the cost saving is NOK 17,833,963 and has a payback period of 9 years. OPEX are calculated to be 2,792,443 NOK/year in the north of Norway, and 3,079,273 NOK/year in the south of Norway.

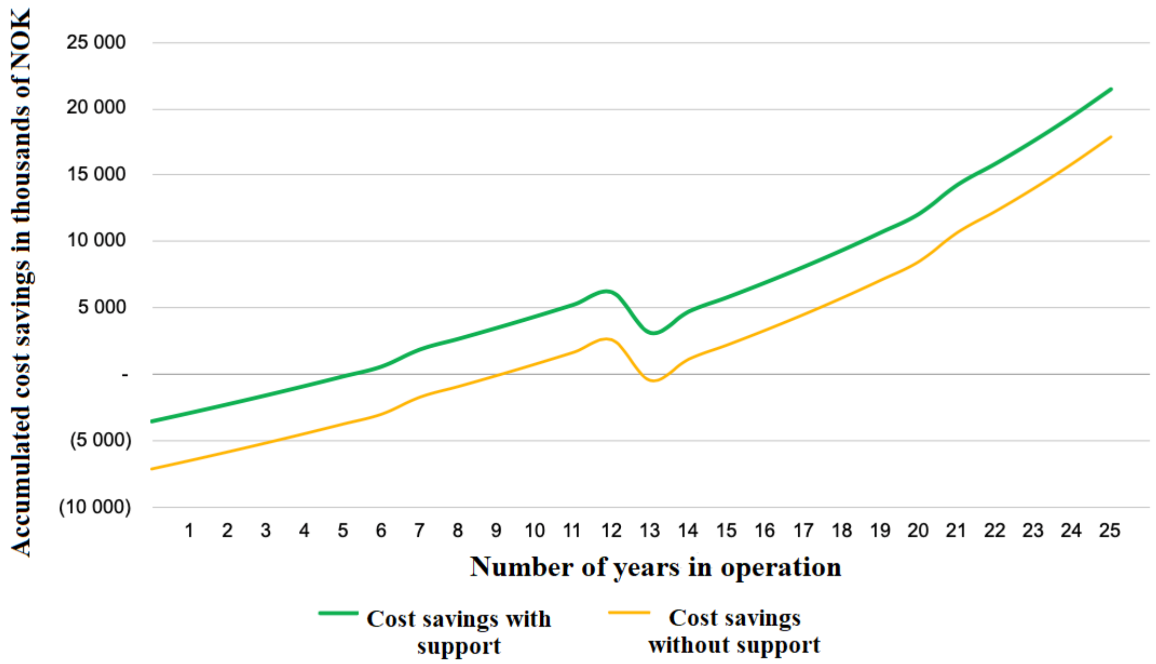

Figure 10: Cost savings with and without support for Boat 1, scenario 2 in the south of Norway

Figure 11 shows accumulated cost savings in scenario 4 with operation costs from the south of Norway. With financial support, the repayment period is an average of 10 years, and the cost savings is NOK 10,374,968. Without the support, the repayment period is 20 years, which is twice as long as with support. The cost savings is NOK 6,789,968 without support. In the north of Norway, the repayment period is 9 years with support, and 19 years without. The cost savings with and without support, are NOK 11,788,301 and NOK 8,203,301 respectively. OPEX are calculated to be NOK 2,279,445 in the south and NOK 2,098,856 in the north.

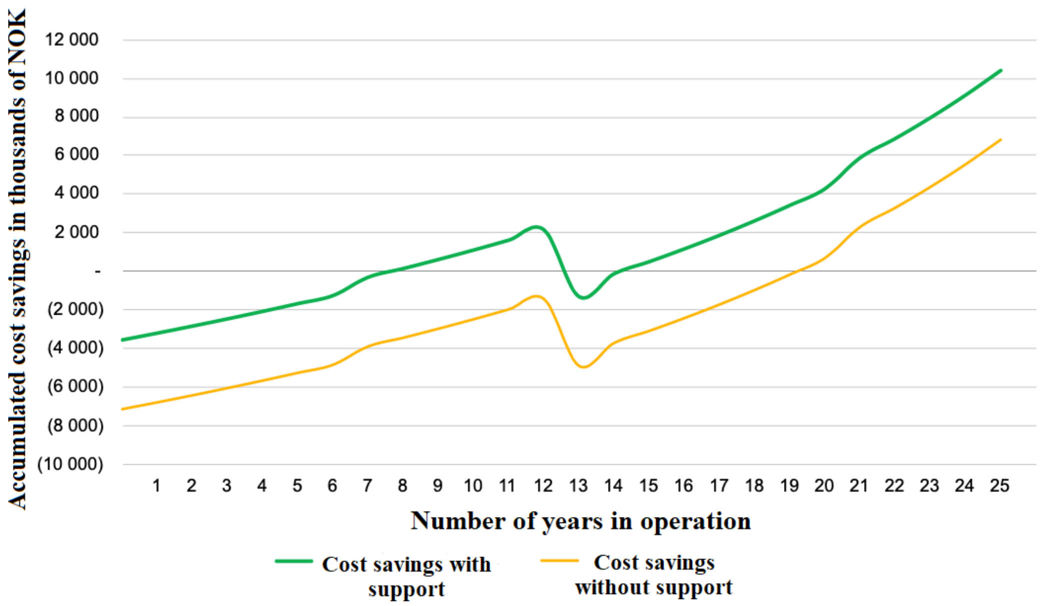

Figure 11: Cost savings with and without support for Boat 1, scenario 4 in the south of Norway

Table 22 shows an overview of OPEX, repayment periods, and cost savings with and without support. The table shows that the OPEX is more expensive for the south of Norway, which results in a longer repayment period and lower cost savings.

Table 22: OPEX, repayment period and cost savings for Boat 1

	Scenario 2: 45 nm		**Scenario 4: 50 nm**	
Region of Norway	North	South	North	South
OPEX [NOK/year]	2,792,443	3,070,273	2,098,856	2,279,446
Repayment period with support [year]	5	6	9	10
Repayment period without support [year]	9	11	19	20
Cost saving with support [NOK]	23,676,950	21,418,963	11,788,301	10,374,968
Cost saving without support [NOK]	20,091,950	17,833,963	8,203,301	6,789,968

5.3.2 Goldfish X9

Table 23 shows the operating time during a year and the operation costs for Goldfish X9.

Table 23: Operating time and operation costs for Goldfish X9

	Scenario 2: 45 nm		**Scenario 4: 50 nm**	
Operation time per distance [h]	1.3		1.4	
Operation time during a year [h]	1 029		891	
Region of Norway	North	South	North	South
Operation price [NOK/kWh]	2.64	3.14	2.74	3.17

Figure 12 shows the accumulated cost savings in scenario 2 with operation costs from the south of Norway. The graph shows a repayment period of 4 years with support, and 7 years without. The cost savings with and without support are NOK 18,649,898 and NOK 16,873,898 respectively. In the north of Norway, the repayment period is 3 years with support, and twice as long without support. The cost savings with and without support are NOK 21,283,607 and NOK 19,507,607 respectively. OPEX are calculated to be NOK 880,288 in the south and NOK 736,601 in the north.

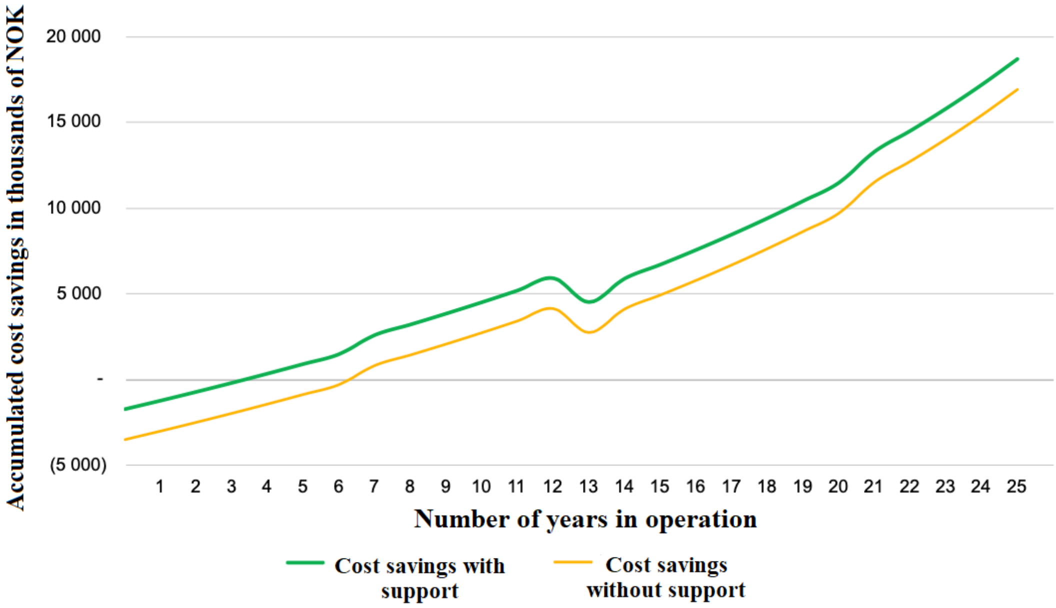

Figure 12: Cost savings with and without support for Goldfish X9, scenario 2 in the south of Norway

Figure 13 shows the accumulated cost savings in scenario 4 with operation costs from the south of Norway. The graph shows a repayment period of 6 years with support, and an average of 11 years without. The cost savings with and without support are NOK 10,518,769 and NOK 8,742,769 respectively. In the north of Norway, the repayment period is 5 years with support, and 9 years without. The cost savings with and without support are NOK 12,187,562 and NOK 10,411,562 respectively. OPEX are calculated to be NOK 666,776 in the south and NOK 576,481 in the north.

Figure 13: Cost savings with and without support for Goldfish X9, scenario 4 in the south of Norway

Table 24 shows OPEX, repayment period, and cost savings with and without support for Goldfish X9. Like Boat 1, the OPEX costs for Goldfish X9 are more expensive in the south than in the north of Norway. However, the OPEX costs for Goldfish X9 are approximately half the OPEX costs of Boat 1.

Table 24: OPEX, repayment period and cost savings for Goldfish X9

	Scenario 2: 45 nm		**Scenario 4: 50 nm**	
Region of Norway	North	South	North	South
OPEX [NOK/year]	741,373	880,288	576,481	666,776
Repayment period with support [year]	3	4	5	6
Repayment period without support [year]	6	7	9	11
Cost saving with support [NOK]	21,283,607	18,649,898	12,187,562	10,518,769
Cost saving without support [NOK]	19,507,607	16,873,898	10,411,562	8,742,769

5.3.3 Skarsvåg 799

Table 25 shows the operating time during a year and the operation costs for Skarsvåg 799.

Table 25: Operating time and operation costs for Skarsvåg 799

	Scenario 2: 45 nm		**Scenario 4: 50 nm**	
Operation time per distance [h]	1.8		2.0	
Operation time during a year [h]	1 440		1 248	
Region of Norway	North	South	North	South
Operation price [NOK/kWh]	2.95	3.25	3.01	3.27

Figure 14 shows the accumulated cost savings in scenario 2 with operation costs from the south of Norway. The cost savings with and without support are NOK 20,583,277 and NOK 18,624,777 respectively. In the north, the cost savings with and without support are NOK 22,527,655 and NOK 20,569,155 respectively. The repayment period is the same for the south and north, which are 4 years with support and 7 years without. OPEX are calculated to be NOK 1,163,518 in the south and NOK 1,279,281 in the north.

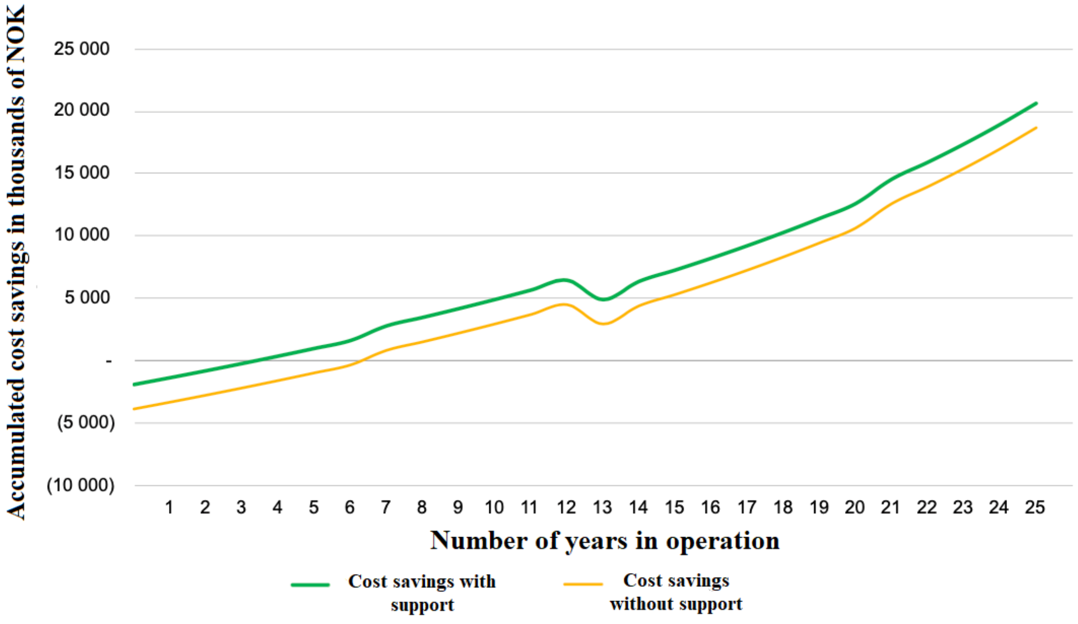

Figure 14: Cost savings with and without support for Skarsvåg 799, scenario 2 in the south of Norway

Figure 15 shows the accumulated cost savings in scenario 4 with operation costs from the south of Norway. The repayment period is 5 years with support, and 8 years without. The cost savings with and without support are NOK 13,654,051 and NOK 11,695,551 respectively. In the north, the repayment period is 6 years with support, and 10 years without. The cost savings with and without support are NOK 15,067,384 and NOK 13,108,884 respectively. OPEX are calculated to be NOK 1,139,723 in the south and NOK 1,049,428 in the north.

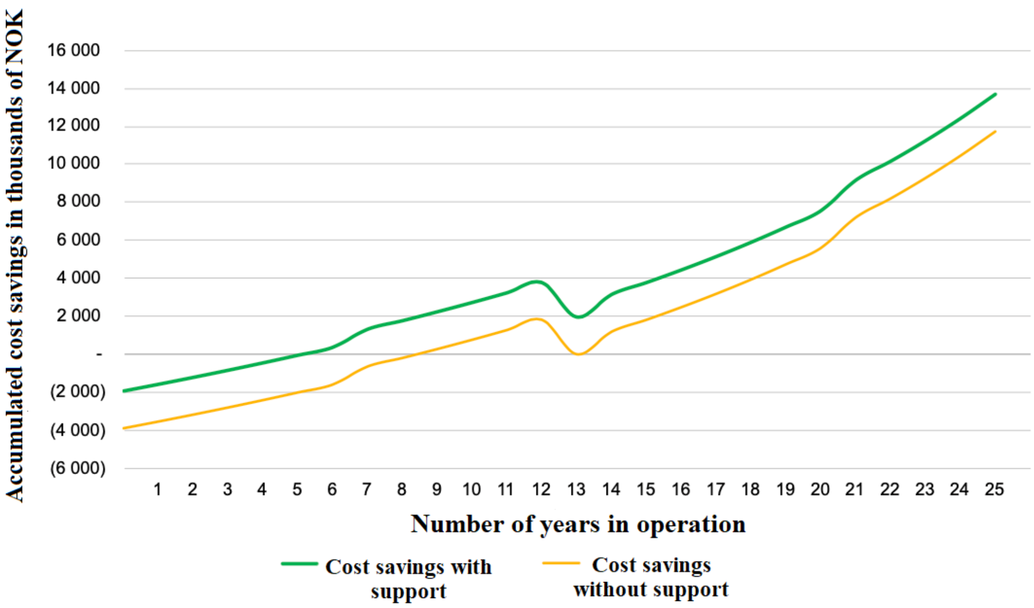

Figure 15: Cost savings with and without support for Skarsvåg 799, scenario 4 in the south of Norway

Table 26 shows OPEX, repayment period, and cost savings with and without support for Skarsvåg 799. Like the two other boats, the OPEX costs are slightly higher in the south than in the north of Norway. Skarsvåg 799 has slightly higher OPEX costs than Goldfish, but significantly lower than Boat 1.

Table 26: OPEX, repayment period and cost savings for Skarsvåg 799

	Scenario 2: 45 nm		**Scenario 4: 50 nm**	
Region of Norway	North	South	North	South
OPEX [NOK/year]	1,163,518	1,279,281	1,049,428	1,139,723
Repayment period with support [year]	4	4	5	6
Repayment period without support [year]	7	7	8	10
Cost saving with support [NOK]	22,527,655	20,583,277	15,067,384	13,654,051
Cost saving without support [NOK]	20,569,155	18,624,777	13,108,884	11,695,551

6. Discussion

The results are simplified as there is limited time on a bachelor project. It would be possible to further optimize the range extender solutions with a longer time period. The total weight limits for the boats are unknown, and it is uncertain whether the weight and volume of the range extender systems are too high. However, if the range extender systems are too heavy, the boat builders will be able to optimize the solution and design of the boat accordingly.

The thesis contains several calculations that are based on assumptions and estimates. Blue World Technology's fuel cell system is under development, and the weight and volume of the system are estimates. Based on a sketch of the fuel cell system including batteries, it is assumed that the batteries cover 1/3 of the volume. The weight of the battery is also calculated by assuming that the ratio of weight to volume is the same as Evoy's batteries. The weight and volume of the Blue World Technologies fuel cell system are thus inaccurate and may affect the results of this thesis.

It is assumed that energy consumption is constant at the given speed. In reality, the boat will drive at different speeds and conditions, thus the energy consumption will vary. Required energy and energy consumption will increase according to wind speeds and wave height. Therefore, the boats may need more fuel cells and lager storage tanks in real-life conditions.

The thesis only takes two different areas of use into account. Other areas of use may have different driving distances and patterns. This will require different solutions for the number of components and possibly their placement. However, using the data and method from this thesis, it should be easy to adapt the range extender system designs for other areas of use.

For investment costs, saving costs and OPEX calculations, assumptions and estimates have been made. The price of Blue World Technologies' fuel cell system is unknown, but it is assumed it has a price of NOK 365,000 based on an estimated by Ocean Hyway Cluster. The total investment cost is a pointer to what the actual price will be. In addition, there are uncertainties about the price of green methanol and electricity. The price of green methanol is estimated by THEMA Consulting Group AS, and the electricity prices are based on Nord pool's statistics over the past year. The assumptions will affect the calculations and as such, the costs will be inaccurate.

Evoy's investment analysis only considers cost savings with and without the financial support for the range extender system. As of today, the methanol range extender system will most likely not receive financial support from Enova or Innovation Norway. However, Evoy's electric motor system is currently receiving support from Enova, and will continue to do so regardless of the methanol range extender. The analysis considers the case where both the electric motor system and methanol range extender receives support. It is assumed that the actual cost savings and repayment period will be with partial support of the range extender system.

The thesis is based on green methanol, but in reality, it will not be possible to regulate the type of methanol used by the end-user. There are currently no existing green methanol facilities, but there are two facilities planned in northern Norway. As there is no market for green methanol today, the end-user will probably use grey methanol. The use of grey methanol will not provide a climate benefit and has the same emission profile as petrol and diesel. However, the industry is being pushed to use green production methods. Although green methanol is not available today, it will probably be available in the Norwegian market in the near future. The technology for the use of methanol in boats will thus be fully developed before green methanol is available.

Goldfish X9 and Skarsvåg 799 have approximately the same investment cost. Boat 1, on the other hand, has a higher investment cost, almost twice as high as the other two. However, Evoy's investment analysis shows that it is more profitable to invest in a methanol range extender system for all the boats, compared to traditional diesel power. The range extender systems in all boats will provide a cost saving. The cost savings vary in the different scenarios, but lie between 6 and 24 MNOK.

7. Conclusion

All three boat models will need a range extender for driving 45 nm and up. Skarsvåg 799 will also need a range extender for driving 20 nm. However, in this scenario, the required range extension is so small, that it will be more beneficial to drive at a slower speed.

Goldfish X9 and Skarsvåg 799 represent the middle and smallest boat sizes respectively. Their range extender system includes a motor, two batteries and high-temperature PEM fuel cell system. The boats have a relatively low energy consumption, and the required number of fuel cells is deemed reasonable. Goldfish X9 and Skarsvåg 799 require seven and eight fuel cells respectively. The total weight of the systems is approximately two metric tonnes. The estimated investment costs for the systems in Goldfish X9 and Skarsvåg 799 are NOK 3,993,000 and NOK 4,358,000 respectively.

Boat 1 represents the largest boat and has a higher energy consumption than the two others. Four different cases have therefore been investigated. The most beneficial solution is to reduce the number of batteries and motors, such that the energy consumption and weight are reduced. In this case, the boat requires 15 fuel cells and the total system weight is approximately four metric tonnes. The solution has an estimated investment cost of NOK 7,620,000.

Investment analyses show that all of the three boats will provide cost savings, compared to a traditional diesel-powered boat. The savings will vary in the different scenarios, but they all lie between 6-24 MNOK. When receiving full financial support, Boat 1, Goldfish X9, and Skarsvåg 799 will have cost savings between 10-24 MNOK, 11-21 MNOK, and 12-23 MNOK respectively. With no financial support, the cost savings are lower, but still provide savings compared to traditional diesel power.

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