Mapping the potential future hydrogen demand in Florø and Måløy

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PREFACE

This thesis was written as part of a bachelor's degree in Energy Technology at the Western Norway University of Applied Sciences, department of Mechanical and Marine Engineering in partnership with Ocean Hyway Cluster. The thesis aims to assess the demand of hydrogen-based fuels to satisfy the energy demand and the CO2-emission reduction of the Norwegian government by 2030.

It has been both challenging and exciting to work on this project and use our engineering skills for a real-world scenario. The thesis statement was not a quick fix problem. It was very challenging to get relevant data for the project because of its scope and due to our unfamiliarity with the subject of the maritime industry.

The COVID-19 restrictions made our daily life as students more challenging, and we mostly communicated via Teams and other social platforms. Fortunately, we managed to adapt to working on these platforms well and there were no problems.

We want to sincerely thank to our supervisors, Shokri Amzin from HVL and Steinar Kostøl from Ocean Hyway Cluster for their advice and academical feedbacks. They were both patient when listening and very helpful when answering the challenges we were faced with and giving us suitable advice.

We would also like to express our deep and profound gratitude to our families, wife/girlfriend and children for being patient, helpful and by giving us continuous encouragement throughout our years of study.

ABSTRACT

This thesis is aimed at evaluating different types of hydrogen-fuel solutions in the maritime industry, and finally estimating the total hydrogen-based fuel demand of the ports Florø, Florø Base and Måløy. It includes a literature review describing different fuel types relevant for use, along with the technologies of those fuel types including production methods, storage and energy conversion. The fuel types relevant for this thesis are compressed hydrogen, liquid hydrogen, Liquid organic hydrogen carriers and ammonia. These fuel types are compared highlighting their advantages and disadvantages.

Furthermore, the ship traffic in Florø, Florø Base and Måløy is analyzed and the data of vessels that have arrived in the area has been recorded and mapped for further analysis regarding fuel consumption and energy demand. By tracking the energy consumption on voyages arriving in the area it is possible to provide an estimate of the fuel consumption by using generalized values for engine efficiencies along with the specific energy of the fuel used. This same method applies to hydrogen-based fuels used in fuel cells, which allows for calculations in hydrogen-based fuel demand.

For analysis of hydrogen fuel demand, different scenarios were made to represent a percentage of ship energy satisfied by hydrogen-based fuels, and the corresponding CO_2 emission reductions were calculated by using the reduction in diesel fuel demand and multiplying that with a CO_2 factor. Scenarios for which type of fuel that would be most relevant for each ship category were also created, and the resulting fuel-demand for each fuel type was calculated using these.

After an energy demand analysis of a total of 197 different ships, the resulting diesel equivalent showed a daily fuel demand average of 152,7 tons in Florø, Florø Base and Måløy, where most of this fuel demand was from platform supply vessels and anchor handling tug supply ships.

CO_2 emissions were calculated through the diesel consumption in the previous section, and the subsequent emission reductions were calculated by using hydrogen-fuel ship scenarios. The result of this showed that one of the scenarios seemed likely with a 56% reduction in emissions with a corresponding energy demand of 140 500 MWh to be satisfied by hydrogen-based fuels.

The next step was to calculate how much of each fuel type would satisfy this energy demand, which was done through two fuel type scenarios, one representing a hydrogen-weighted demand, and the other representing an ammonia-weighted demand. By using the scenario that satisfied the emission reduction the results and the conclusion of the analysis was that the future demand for compressed hydrogen would be between 263-415 tons, the demand for liquid hydrogen would be between 2091-5151 tons, and the demand for ammonia would be between 8208-24624 tons. Each of these values depend on which of the fuel type scenarios are representative of the real-world scenario in 2030.

SAMMENDRAG

Den norske regjeringen har fastsatt et mål om å halvere alle CO_2 utslipp i skipsnæringen innen 2030, dette fører til at sjøfartsnæringen må se på nye løsninger for å oppnå disse målene, som er bakgrunnen for denne bacheloroppgaven.

Denne bacheloroppgaven har som mål å evaluere og beskrive ulike løsninger for hydrogenbaserte drivstoff for skipsnæringen, og til slutt estimere et totalt mulig drivstoffbehov for disse hydrogenbaserte drivstoffene i Florø havn, Florø base og i Måløy. Oppgaven inneholder en teoridel som beskriver de ulike relevante hydrogenbaserte drivstoffene, i tillegg til den tilhørende teknologien for de samme drivstofftypene. Dette innebærer ulike produksjonsmetoder, lagringsmetoder, og brenselsceller. Drivstofftypene som er relevante for denne oppgaven er komprimert hydrogen, flytende hydrogen og ammoniakk. Teoridelen inneholder også et kapittel om LOHC, som er en mulig lagringsmetode for hydrogen. Disse drivstofftypene vil bli sammenlignet etter ulike fordeler og ulemper som setter et grunnlag for videre analyse.

Metodedelen i oppgaven handler om å analysere og kartlegge skipstrafikk for skip som ankommer Florø, Florø base og Måløy for å finne drivstoffbehovet i de havnene i dag, i tillegg til å muliggjøre estimater for fremtidig behov for hydrogenbaserte drivstoff. Ankomster til de nevnte havnene vil kartlegges, og skipene som står for disse ankomstene blir analysert gjennom en excel-datamodell ved bruken av AIS-data i kombinasjon med skipsdata for hvert enkelt skip. Ved å analysere seilasene til skipene sammen med skipsdataene er det mulig å estimere energibehovet for de ulike turene. Videre brukes generaliserte verdier for virkningsgraden for hovedmotorene til skipene i tillegg til det spesifikke energiinnholdet for drivstoffet de bruker for å finne drivstoffbehovet, og det er også mulig å bruke den samme metoden for å estimere behovet for hydrogenbaserte drivstoff ved å bruke den spesifikke energien til drivstoffet sammen med virkningsgraden til brenselscellen.

Drivstoffbehovet i området er også regnet ut gjennom datamodellen, og ved analyse av 197 forskjellige skip, er det kommet frem til at behovet er på 152,7 tonn diesel ekvivalenter hver dag, hvor mesteparten av dette er fra forsyningsskip og ankerhåndteringsskip.

Det er opprettet ulike framtidsscenarioer rettet mot 2030, som beskriver andelen skip som har gått over til hydrogenbaserte drivstoff. Fra disse scenarioene er den korresponderende reduksjonen i CO_2 utslipp kartlagt, og det ble valgt ett scenario som virket mest sannsynlig, og som oppfylte regjeringens mål med en reduksjon i utslipp på 56% som tilsvarer et energibehov på 140 500 MWh som må bli oppfylt av hydrogenbasert drivstoff.

Videre er det gjort beregninger for å estimere fremtidig behov for hydrogenbaserte drivstoff, som ble gjort ved å lage to ulike scenarioer der hvor ett var vektet mot hydrogen, og det andre var vektet mot ammoniakk. Ved å bruke det samme scenarioet som oppnådde reduksjonen på 56%, ble resultatet av dette at det fremtidige årlige behovet for komprimert hydrogen blir mellom 263-415 tonn, behovet for flytende hydrogen blir mellom 2091-5151 tonn, og behovet for ammoniakk blir mellom 8208-24624 tonn. Disse verdiene er avhengige av hvilket av drivstoffscenarioene som blir reelle innen 2030.

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1. Introduction

Thesis Statement

The Norwegian government has an ambition of halving the carbon emissions by inland shipping and fishing within the year 2030[1]. This requires companies to adopt new technologies to improve their carbon emissions. Hydrogen and hydrogen-based fuels can be very helpful in the process of reaching this goal. This is an analytical thesis aimed at different ways to deliver hydrogen and mapping the potential fuel requirement of hydrogen-based ships from the port and the Base in Florø. The year 2030 is used as a benchmark for our analysis in fuel requirement for the ships, which includes different scenarios based on fuel conversion to zero-carbon energy carriers. Current-day technology is used as a baseline for the comparisons in fuel types regarding consumption, storage, production, and efficiency.

The thesis will include a description of relevant hydrogen-based fuels, comparing the different existing technologies and feasibility of said technologies.

It is divided into 4 main parts:

1. A literature review containing descriptions of the different hydrogen fuels, comparing basic hydrogen to LOHC. Advantages and disadvantages will be looked at, focusing mainly on safety, storage, CO2 footprint, and means of production.
2. Mapping the different types of ships that operate in Måløy, Florø port and Base. Generating operational profiles, and presenting movement data.
3. Mapping the amount of fuel that is stored in Florø, along with current CO_2 emissions of ships arriving in the area and estimating the effect hydrogen fuel conversion has on CO_2 emissions in the area with different scenarios.
4. Calculating the necessary capacity of hydrogen production. Making different scenarios for different hydrogen-based fuels such as compressed hydrogen, liquid hydrogen, and ammonia. And evaluating this against the emission-reduction goals.

These points can be summarized into the following points of assessment. What is the future energy demand, which types of hydrogen fuels will be most relevant, and how much of these hydrogen-fuel-types have to be delivered to Florø to satisfy this demand?

Different fuel types as mentioned in point four for different categories of ships will be evaluated. To make this possible and fruitful we must limit the number of ships and their types and specific traffic routes.

The thesis statement is based on the former assessments made by Ocean Hyway Cluster such as the mapping 2030 hydrogen demand in the domestic car ferry sector, 2030 hydrogen demand for the coastal route Bergen-Kirknes and 2030 hydrogen demand in the Norwegian maritime sector.

2. Literature review

This literature review is focused on providing an overview of technologies and current commercially available solutions for hydrogen, and hydrogen-based fuels.

2.1 Hydrogen

The use of hydrogen as an energy carrier as has been a widely researched and discussed topic recently as governments around the world are looking to reduce their carbon footprint to prevent climate change from getting out of hand. This report highlights the possibilities of using hydrogen, along with hydrogen-based fuels such as Ammonia (NH3) and hydrogen carriers such as Liquid Organic Hydrogen Carriers (LOHC) as a solution to reduce carbon emissions in the maritime sector, as industries around the world move towards greener technologies.

2.1.1 General information

Hydrogen is the first element in our periodic system and consists of a single proton in its nucleus and an electron in the outer shell. Because of this it is also the lightest chemical element that exists with a molecular weight of 2,016 g/mol. It is the most abundant element in the universe with an estimated 90% of all existing atoms [2, 3]. Under natural atmospheric conditions hydrogen exists as a gas molecule containing two hydrogen atoms covalently bound to each other. However, hydrogen is not found naturally in the world in large amounts such as fossil fuels do, hydrogen atoms are instead bound to several different molecules that occur in abundance on earth, the most prevalent being water and hydrocarbons [3]. In order to acquire pure hydrogen, it has to be extracted from a substance containing hydrogen which requires energy. This classifies hydrogen as an energy carrier instead of an energy source, which is an important distinction as it means that if hydrogen is to be used as a true zero-emission fuel the entire hydrogen value-chain has to be emission free.

There are several industrial processes that produce hydrogen today, the resulting hydrogen from these processes can be categorized in three ways as a generalization of how the hydrogen was produced. The three main categories of hydrogen are green, blue, and grey hydrogen. The main difference between these three classifications is the amount of CO_2 released as a biproduct of the production process. Green hydrogen is produced without the release of $CO_{2,}$ and is achieved through the electrolysis of water. Blue hydrogen is classified as hydrogen produced with CO_2 as a biproduct, where most of the CO_2 is recaptured using Carbon Capture Systems (CCS), making the net CO_2 emissions either low or zero depending on the effectiveness of the CCS-system. Grey hydrogen is produced in the same way as blue hydrogen, but without the use of CCS-systems, meaning that the CO_2 from the process is released into the atmosphere. (ref) As this report is based on reducing carbon emissions, the use of green hydrogen will be the primary focus.

2.1.2 Synthesis and production of green hydrogen

Production of green hydrogen is done through electrolysis of water by using renewable energies as the source of energy for the reaction. There are two major methods of electrolysis that are technologically mature today, namely Alkaline electrolysis (AEC), and Proton Exchange Membrane-electrolysis (PEMEC), the main differences between different types of electrolysis is the type of electrolyte being used. Another type of electrolysis which is currently being tested and researched for viability in the future is known as Solid Oxide Electrolysis Cell (SOEC), current results have shown that SOEC is more efficient than the previously mentioned AEC and PEMEC [4, 5], but a lot of continued research and development is required for the technology to become a viable option. Higher efficiencies for electrolysis is an important part of reducing the costs of hydrogen, and newer and more efficient technologies are

AEC uses a solution comprised of alkaline metals and oxygen hydride as its electrolyte, where NaOH or KOH are most common. It is comprised of two electrodes immersed in the electrolyte, that allow for transfer of electrons into the solution for the electrolytic reaction [5, 6]. Microporous diaphragms are used to let hydroxide ions (OH^-) and water to pass through from one chamber to the other, and to separate the product gases from each other. The separation of the product gases is important as it prevents the O_2 from reacting with the hydrogen and catalyzing into water which reduces the efficiency, and prevents hydrogen buildup on the oxygen side for safe operation [4]. However, the diaphragm does not completely stop cross diffusion of the product gases.

Electrolysis for hydrogen production is described in the following chemical reactions:

Cathode reaction:

Equation 1: Cathode reaction of an Alkaline electrolysis cell

$$2H_2O + 2e^- \rightarrow 2H_2 + 2OH^-$$

The hydrogen is released from the process, and the charged hydroxide ion moves to the anode which presents the next step in the reactionary process.

Anode reaction:

Equation 2: Anode reaction of an Alkaline electrolysis cell

$$2OH^- \rightarrow H_2O\ ½O2\ +\ 2e^-$$

Total reaction:

Equation 3: Total reaction of an Alkaline electrolysis cell

$$H_2O \rightarrow H_2 + {}^1/_2\, O_2$$

The main advantages of alkaline electrolysis are that it is a well-researched and mature technology, and it is scalable for large industrial processes with high efficiency [4-6]. However, there are some major downsides to the technology. They have a low maximum current density due to high resistance in the electrolyte and diaphragm, and a low maximum operating pressure due to the porosity of the diaphragm [4]. The diaphragm stops most of the product gases from cross-diffusing into the opposite chambers, yet it does not completely prevent it from happening, which can cause lower efficiencies and possible safety concerns[3, 6].

PEMEC uses polymer exchange membranes or polymer electrolyte membranes as its electrolyte, which is a membrane designed to only allow protons (H^+ ions) to pass through [4, 6]. The membrane is extremely thin (ins val), providing additional structural support, allowing for a more stable and safe method of hydrogen production compared to AEC, as the issue with gas buildup and cross diffusion of product gases is negated [6]. It is a fairly new concept compared to AEC, where the first prototype was developed in the 1960’s by General Electric [6]. PEM electrolysis is currently a technology mature enough for industrial use. Being a newer technology means that there are also possibilities for further improvement in regards to the efficiency and cost-reduction [5]. It has the advantage of a high operating pressure, which reduces the energy requirement to compress the hydrogen after synthesis [6], while being able to operate at much higher energy current densities than alkaline electrolysis [ref].

The electrolytic reaction of water into hydrogen and oxygen in a PEM electrolyzer is:

Cathode reaction:

Equation 4: Cathode reaction of a PEM electrolysis cell

$$H_2O \rightarrow 2H^+ + {}^1/_2\, O_2 + 2e^-$$

Anode reaction:

Equation 5: Anode reaction of a PEM electrolysis cell

$$2H^+ + 2e^- \rightarrow H_2$$

Combined reaction:

Equation 6: Total reaction of a PEM electrolysis cell

$$H_2O \rightarrow H_2 + {}^1/_2\, O_2$$

SOEC uses a ceramic-based electrolyte, and high operating temperatures between 700-900˚C. It is more efficient than the other two electrolyzer, yet it is not currently commercially viable as it is a newer technology in the research stage [4, 6]. The first prototype of a SOEC was made in the 1980s, and the technology has gained traction ever since as an alternative for more efficient electrolysis ever since [6]. It uses a ceramic based electrolyte where a common material for use is yttria-stabilized zirconia, which serves as a conductor of O^{2-} ions [4]. The main benefit of SOEC electrolyzers is the possibility of reversible usage, meaning that it can also be used to generate electricity from hydrogen as well [4].

2.2 Hydrogen storage

Hydrogen currently has two main competitive solutions for storage: By compressing the hydrogen gas, or by liquefying it. This is crucial for hydrogen to be a viable fuel solution due to its low volumetric density of 0,089kg/m^3 [2].By compressing or liquefying the hydrogen a higher volumetric density is achieved, which in turn increases the amount of energy stored in the tanks. Both these storage methods have an inherent energy cost for their respective thermodynamic conversions, lowering the total energy efficiency [5] [2, 5, 7].

2.2.1 Compressed hydrogen storage

Compressed Hydrogen is currently the most common and commercially available way of hydrogen storage today [2]. For the end user, the hydrogen is compressed and stored in pressurized tanks at pressures ranging from 30-70 MPa, the process consuming around 8-13% of the energy contained in the hydrogen [5]. After this process the hydrogen has a volumetric density between 20-40 kg/m^3 depending on the magnitude of compression[5]. Hydrogen embrittlement is a phenomenon that occurs when hydrogen diffuses into the material, which weakens the molecular structure of the metal, and reduces its strength and durability [hydrogen embrittlement,]. In order to prevent this, the pressurized tanks have to be made out of materials that are resistant to this effect,

2.2.2 Liquid hydrogen storage

Liquid hydrogen is hydrogen that has been cryogenically cooled lower than its boiling point of -252,9 ˚C. During liquefication, the density of hydrogen is increased almost 800 times, allowing for a much greater amount to be stored. [3, 7] The liquefication process is very energy intensive, consuming a theoretical amount of stored hydrogen energy of 25-35% [2, 5, 7]. It is then stored in cryogenic tanks with high insulative properties, a common design for these tanks is a dual hull-system with a vacuum between the outer and inner tank. However, boil-off inside the tank still occurs due to temperature increases and must be corrected by a release of hydrogen to regulate the pressure increase in the inner tank [2, 3].

For maritime use liquid hydrogen is relevant for ships that require greater amounts of stored hydrogen, with a lower limit of 1000kg [8], it is less relevant for ships requiring large amounts of stored energy on board, yet have a low rate of bunkering as the effect of boil-off and the total energy costs would be too great to make it a viable solution.

2.3 Liquid organic hydrogen carrier (LOHC)

As mentioned, hydrogen is a promising energy carrier because of its excellent gravimetric energy storage density. There is about 33.33 kWh/kg hydrogen. Although hydrogen is considered a key energy carrier, again it has major challenges when it comes to its volumetric storage density[9]. Hydrogen is the smallest chemical element with the lowest density. Therefore, there is only about 3 Wh per 1 l gaseous hydrogen [9, 10].

To solve this problem scientists and engineers developed existing technical applications such as: compressed gaseous hydrogen (CGH2) and liquid hydrogen (LH2) as mentioned **2.2**. But there are other alternative concepts aiming to solve the volumetric problem of hydrogen by using liquid organic hydrogen carrier (LOHC).

LOHC is a new concept which is based on hydrocarbons that can take up extra hydrogen atoms by catalytic hydrogenation reaction at high pressures. The loaded LOHC can be stored long term at ambient conditions without hydrogen loss. It can later be transported to the end-use consumers and hydrogen can be released by catalytic dehydrogenation [9, 10]. Hydrogenation means hydrogen binds covalent with the LOHC substance and dehydrogenation means releasing of hydrogen from the LOHC substance. The hydrogenation process is an exothermic process at high temperature and pressure. The dehydrogenation process is catalytic endothermic reaction with less pressure and high temperatures[9]. LOHC is not consumable itself, but a carrier that can be loaded and unloaded with hydrogen. Generally, it is estimated that only 1% of the energy is used in the hydrogenation while 20% of energy is needed in the dehydrogenation process [10]. At ambient conditions LOHC is liquid and has the characteristics of crude oil. Therefore, it can be easily handled, transported, and stored by using the traditional crude oil infrastructure [9, 10]. That makes LOHC effective, safe, and may be economically cheaper than other means of storing and transporting of hydrogen. Figure 1 shows the reactionary processes in a LOHC system.

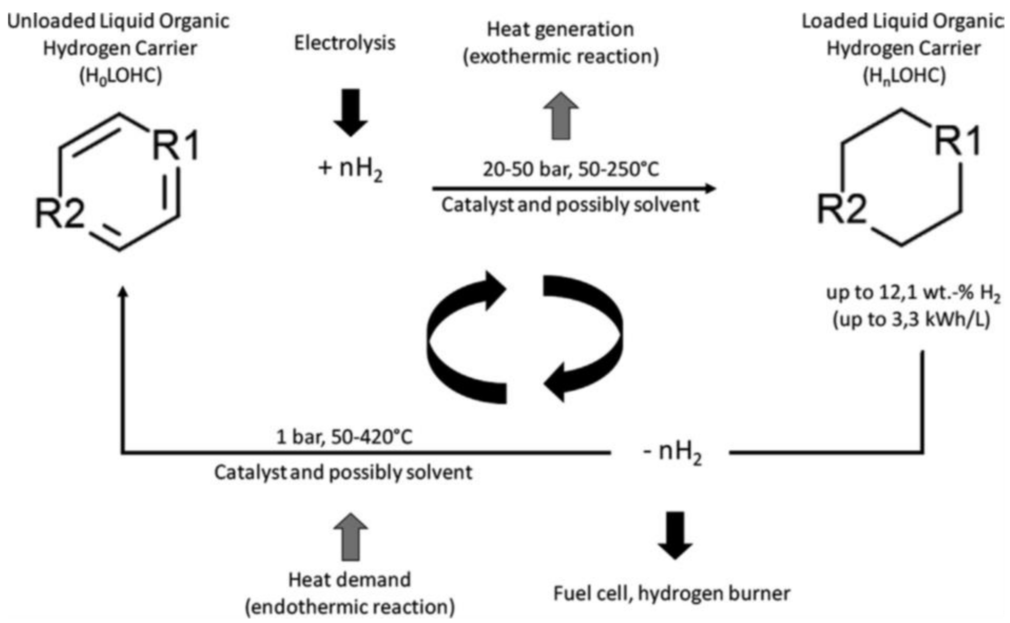


Figure 1: LOHC storage concept [9]

There are many other hydrogen carbonates that can be used as LOHC. Many of them had been researched and evaluated in the past years such as toluene, dibenzyl toluene, monobenzyl toluene, N-ethyl carbazole, methanol and many other possible LOHCs[9]. In this thesis, dibenzyl toluene which are commercially available[11], N-ethyl carbazole and methanol that have future potential for farther consideration, will be discussed.

2.3.1 Dibenzyl toluene (DBT)

Dibenzyl toluene ($C_{21}H_{20}$) is cycloalkane, which is mainly used in industry as Heat Transfer Oil (HTF). It is used to carry thermal energy. DBT is an existing fluid which is suitable as carrier material because of its properties. For example, its thermal stability and low volatility. DBT's physical properties are very similar to diesel, meaning that it can be handled easily[9].

Production of DBT

DBT ($C_{21}H_{20}$) is a compound that is made of multiple structural isomers. It is commercially available in the market under the brand-name, "Marlotherm SH"[12]. One of the leading companies in LOHC systems (Hydrogenious), uses DBT in its energy systems[11, 13]. The molecular structure of DBT is as shown in Figure 2.

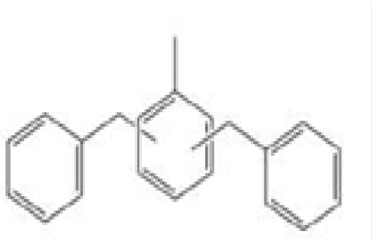


Figure 2: molecular structure of DBT

The main raw materials used in production of DBT are toluene and chloride. The most significant factor of the price in production of DBT is the price of toluene, as shown in **Figure 3**. The price of DBT is estimated to be 4-5 euro/kg according to two different assessments[9, 12].

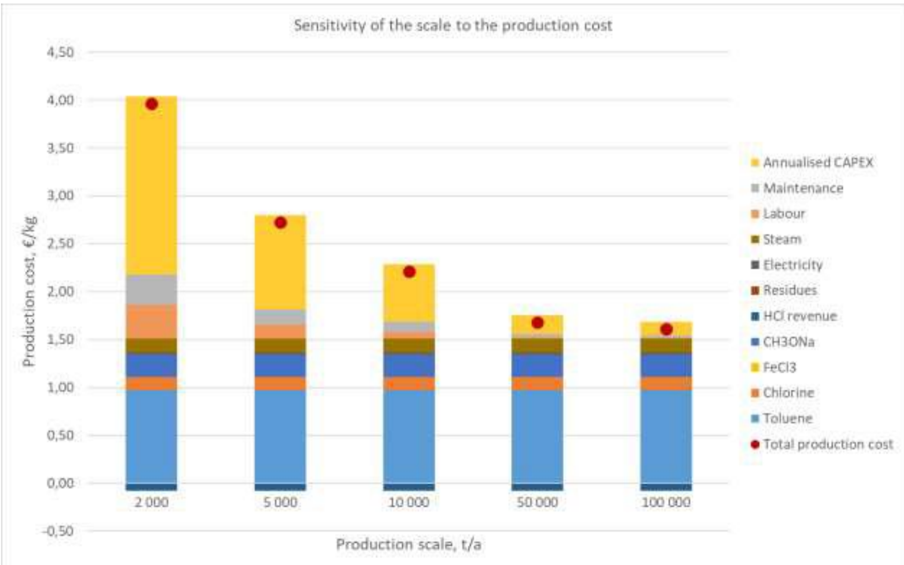


Figure 3: sensitivity of the scale of the plant including the annuity of CAPEX[12]

Sensitivity analysis, whereby both mono benzyl toluene and dibenzyl toluene are assumed as main products, shows that when the production scale increases the price of MBT and DBT decreases.

In the future, it is estimated that if the use of DBT in LOHC systems increase, it will increase the market demand of DBT. Which will probably increase the production scale and decrease the production cost of DBT, according to the sensitivity analysis as shown in **Figure 3**. This will give a high advantage for the use of BDT in LOHC systems and boost the hydrogen-storage technology, in the long run. It is important to highlight that the study has some assumptions, which may not to be realistic in large-scale production plant[12]. For example, it is assumed that two-person-per-shift for both small- and high-capacity production is adequate. The production method is based on the patent of Commandeur et al (1993) and produces both MBT and DBT; However, MBT can be enhanced to DBT through processing in reactors [12].

Properties of DBT

DBT has unique properties that makes it more suitable for LOHC, such as thermal stability and low volatility. Here are some of the key points that make DBT attractive as a hydrogen storage system:

- DBT storage capacity is 6.2 wt.% that has an energy density of 1.9 kWh/L.
- Practically the storage capacity is 6.0 wt.% due to the limitation of the de-hydrogenation.
- DBT's density is 1016 kg/m3 and 1 m^3 of DBT can carry 630 m^3 of hydrogen, corresponding 57 kg hydrogen [13].
- Hydrogenation of DBT requires precious metals as catalysts, such as Platinum (Pt) and ruthenium (Ru) with the support of aluminium oxide (Al_2O_3).
- Palladium and ruthenium are used as catalysts supported by carbon (C) for dehydrogenation of DB [9].

There is a research done by the North-West University in South Africa, that shows that Ni can be used as catalyst in hydrogenating DBT[14]. Dehydrogenation of DBT, requires high temperature to increase the hydrogen yield. That means the degree of hydrogenation of DBT is dependent on the temperature. For example, at 290 degree Celsius the degree of H2 release is 89%. At 310 degree Celsius it is 97%[15]. This makes the energy demand of dehydrogenation of DBT is about 65.4 kJ/mol_{H2} [15]. DBT has low vapor pressure which is beneficial for storage and handling. The dynamic viscosity of DBT at 20 °C is 44,1 mPas and 258 mPas at 10℃ dehydrogenated DBT, which is causes pumping resistance[9].

LOHC technology

LOHC technology is new to the market. Hydrogenious is one of the leading companies in LOHC systems. Here are some of their systems that are currently available in the market. Hydrogenious classifies their systems into categories of series; C-series (containerized) and P-series (plant), which have both storage and release unit. C-series storage boxes er systems for medium-scale, while p-series are large scale systems[13]. **Figure 4** shows a C-series release unit.

Figure 4 C-series release unit [13]

In additional to that on-site storage tanks are available in different sizes both in swap body container and stationary tanks[13]. **Figure 5** shows different types of on-site storage tanks.

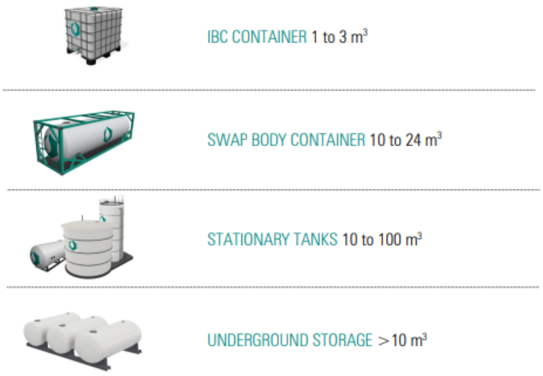


Figure 5 On-site storage tanks [13]

2.3.2 9-Ethylcarbazole (NEC)

9-ethylcarbazole (NEC) is a nitrogen heterocycle and is one of the well-studied nitrogenous LOHC[9]. Normally NEC is hydrogenated and dehydrogenated by using catalysts like palladium (pd) ruthenium (Ru) supported by aluminum oxide (Al_2O_3)[9]. It can be fully hydrogenated in 180 minutes at 150 °C with 50 bar[15]. NEC has a storage capacity of 5.8 wt.% and the energy density is 2.5 kWh. The research on NEC was mostly focused on the development of LOHC systems for automotive applications [15].

Dehydrogenation of NEC is only about 90% during the process because of its liquid temperature is between 68-270℃. Which means it becomes solid under 68 °C. In terms of availability NEC is a expensive material. It costs around 40€/kg [9]. Which makes it less competitive compared to other LOHC systems. NEC is taken in this thesis to show the LOHC technology has been studied a lot in the past two decades. **Figure 6** shows the hydrogenation and dehydrogenation process of NEC.

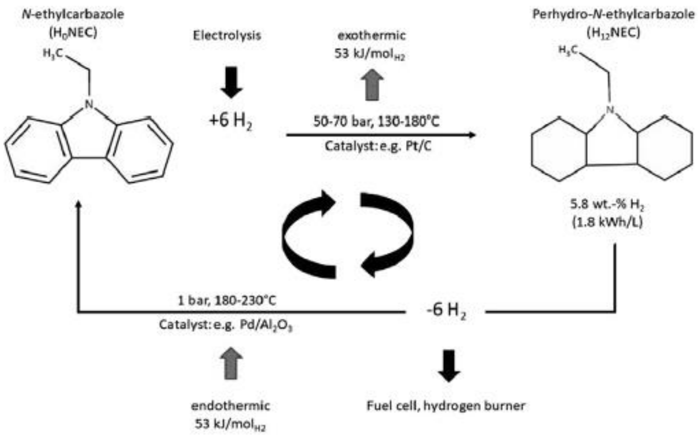


Figure 6 Hydrogenation and dehydrogenation process of NEC [9]

2.3.3 Methanol (MET)

Methanol is an alcohol, flammable liquid at ambient temperatures and it is miscible in water[9]. It is chemical formula is CH_3OH. The boiling point is around 65 °C and the density is 0.79 kg/L Methanol is synthesized mainly in two ways [16]:

1. Hydrogenation of carbon monoxide under high pressure with the help of catalyst
2. Partial oxidation of hydrocarbons from natural gas

In Norway it is produced by partial oxidation of hydrocarbon from natural gas. There are other renewable ways of generating methanol as shown in **Figure 7**.

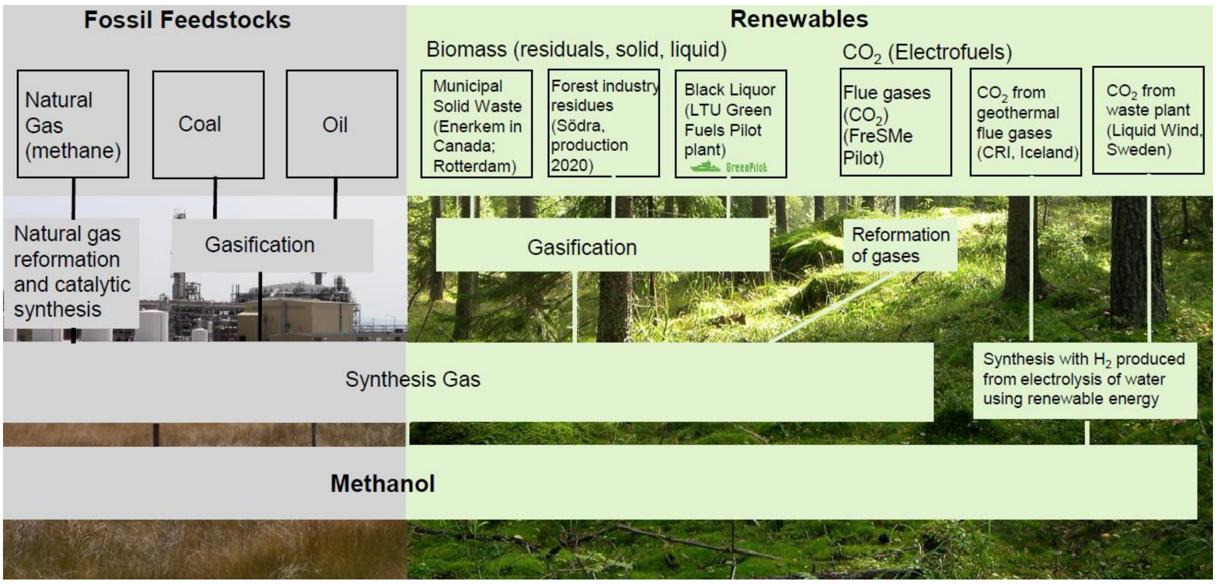


Figure 7: Different feedstocks of methanol[17]

Particularly in LOHC systems carbon dioxide (CO2) is used as raw material [9] to generate methanol in a renewable way.

By hydrogenating CO2, the outcome of the reaction can be two results: 1) methanol and water or 2) carbon dioxide and water. To get methanol and water the hydrogenation process uses copper (Cu) based catalysts at temperatures between 220 and 270 °C and pressure between 20-80 bar. Dehydrogenation process of methanol produces CO2, CO and H2. It is important to avoid producing CO since its toxic gas. According to the LOCH studies dehydrogenation can be done by high temperature Steam Reforming of Methanol (SRM) at 420 °C with the help of catalysts (iridium and platinum) and low temperature dehydrogenation (<100 °C). By high temperature 6mol-% of carbon monoxide is detected. By low temperature, the reaction takes between 600 and 1,440 minutes. The hydrogen yield is estimated to be 15-84%, depending on the type of catalyst used in the reaction [9]. **Figure 8** shows the reactionary process of a LOHC system based on methanol.

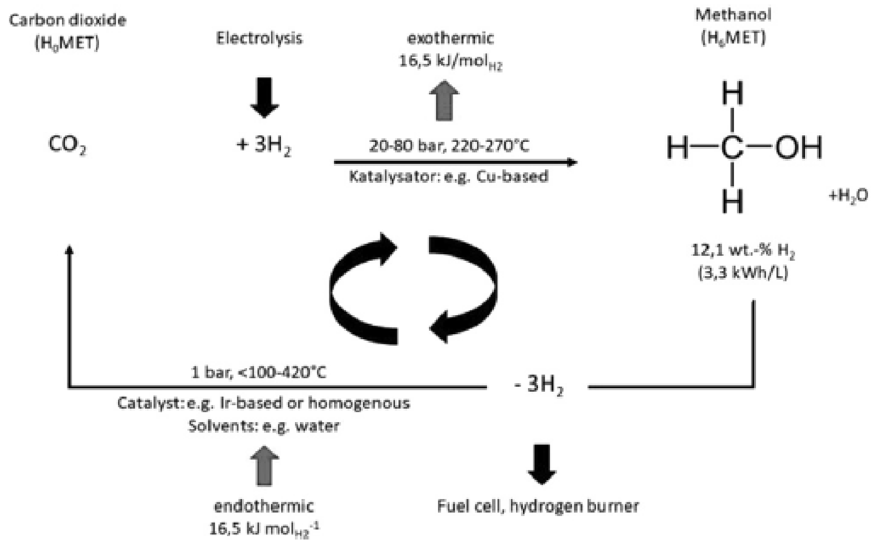


Figure 8: Storage process of CO2/methanol system [9]

As shown in **Figure 8** – methanol has high storage capacity of 12.1 wt.% and the energy density is 3.3 kWh/L. The capacity is reduced due to the solvents used in the dehydrogenation process. Therefore, high temperature dehydrogenation has a capacity of 10 wt.% and an energy density of 2.7 kWh/L, while low temperature has 4 wt.% and 1.1 kWh/L. The raw material of this system is CO2, and a potential source can be gases from combustion of fossil fuel which can be captured. The dehydrogenation process demands heat energy of 16.5 kJ/mol H2. Methanol is flammable and toxic and needs to be handled properly, which can be challenging.

There are other interesting ways of using methanol as fuel. For example, methanol is used in combustion engines of Stena Germanica. Stena Germanica has four dual fuel methanol engines, and it is the world's first methanol powered commercial vessel. **Figure 9** shows the vessel Stena Germanica.

Figure 9: World's first methanol powered vessel [18]

Additionally, methanol can be used direct in fuel cells, such as direct methanol fuel cell (DMFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC) and more. **Figure 10** shows some of the mentioned fuel cells which can operate methanol. In this thesis methanol is LOHC system.

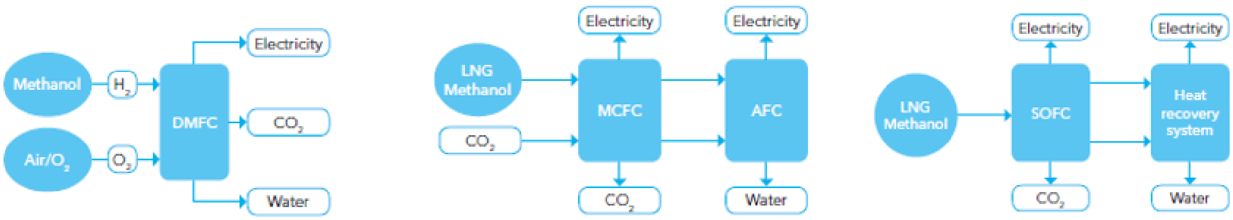


Figure 10: Different fuel cells which can operate methanol [19]

2.3.1 Safety

In terms of safety LOHC systems have similar properties as oil fuel-based liquids, such as gasoline and diesel. They can be stored, transported, and handled as oil. The different LOHC systems har different properties. LOHC systems differ in toxicity levels. For example, the TPI of NEC, DBT are 5.1 TPI/mg, 13.8 TPI/mg, respectively. Whereby MET is flammable and toxic[9]. Which means MET is more hazardous and should be handled with more caution.

2.4 Ammonia

Ammonia molecule consists of a single nitrogen atom, covalently bonded to three hydrogen atoms. Ammonia is a described as a colorless poisonous gas with a sharp odor and can easily be inhaled, absorbed, or contacted. Its boiling and freezing points are 240 K and 195.5 K, respectively. The density of ammonia is 0.73 kg/m^3 and its autoignition temperature is 924 K under ambient condition[20, 21].

The amount of ammonia used in agriculture represents approximately 80% of the global ammonia production. The remaining 20% is used in various industrial products such as explosives, hair dye, plastics, pesticides, animal nutrition, household goods etc. [22]. In other words, ammonia is a chemical product that humans have used generations and there is solid competency in handling it. Historically Norway is one of the leading countries in ammonia production. There are two ammonia production facilities in Norway, namely Yar Porsgrunn ang Yara Glomfjord [23]. **Figure 11** shows a simplified pie-chart of ammonia usage.

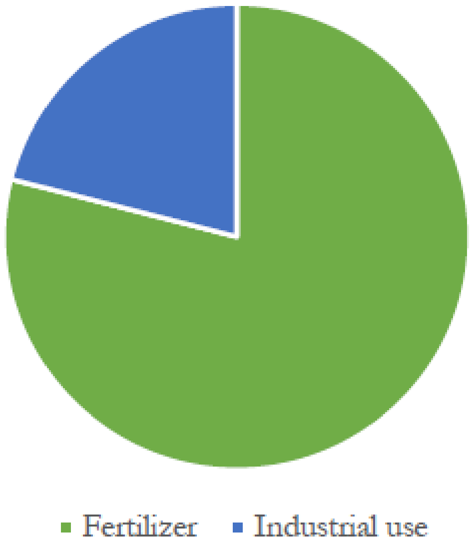


Figure 11: Main fields ammonia is used globally [22]

2.4.1 Production

Ammonia is produced from nitrogen in the atmosphere and hydrogen. There are different pathways of producing ammonia, but mainly the Haber-Bosch process dominates the industrial production of ammonia. Here is the thermocatalytic reaction of Haber-Borsch.

Equation 7: Haber-Borsch thermocatalytic reaction[21]

$$N_2 + 3H_2 \rightarrow 2NH_3$$

This is an exothermic process that combines nitrogen and hydrogen, as shown in **Equation 7** to produce ammonia with the help of iron-based catalyst and the process requires both high temperature and pressure range of 450-600 °C and 100-250 bar respectively [21, 22]. Due to the law efficiency per single run the unreacted gases are recycled again until the overall conversion is 97% [21, 22]. Nitrogen in the process is from an air separation unit while hydrogen comes from steam reforming of methane. The greenhouse emission from this process depends on the source of methane [21].

Beside Haber-Borsch process there are other possible pathways of ammonia production such as electrochemical synthesis and renewable ammonia. The electrochemical synthesis is based on a synthesized ammonia in a single electrochemical reactor using water, steam, nitrogen, and electricity. This process can reduce the production energy usage, but it is not commercially available[22]. Renewable ammonia can be achieved by using a solid oxide electrolysis cell to combine green hydrogen and nitrogen from water, and air then sent into the Haber-Borsch process. It is a combination of Haber-Bosch and electrolyzer. This technology is developed by Haldor Topsoe and its commercialization is expected by 2030 [22]. **Figure 12** shows the different production pathways of ammonia.

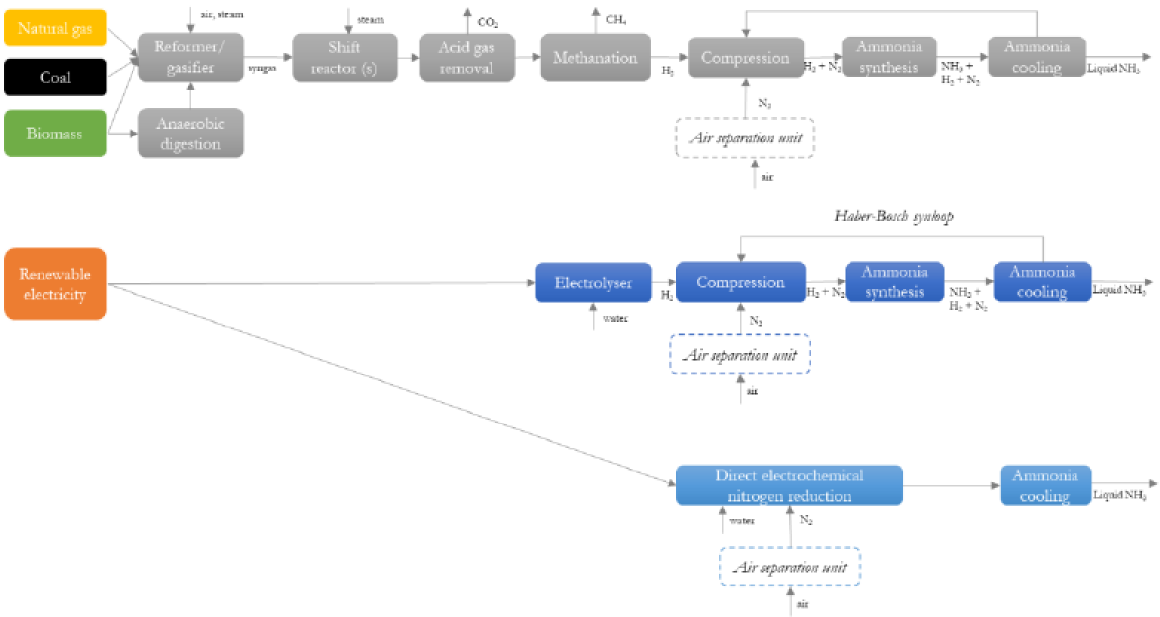


Figure 12: Different production pathways of ammonia [22]

Ammonia is a very essential chemical product in food production and other industrial usage; It is expected that the ammonia production will increase due to the market demand. In addition to that ammonia is about to be used as fuel or hydrogen energy carrier. According to Ocean Hyway Cluster report the production development and the marked demand is highly expected to increase [23]. **Figure 13** shows a timeline of ammonia production and development from 2020-2030.

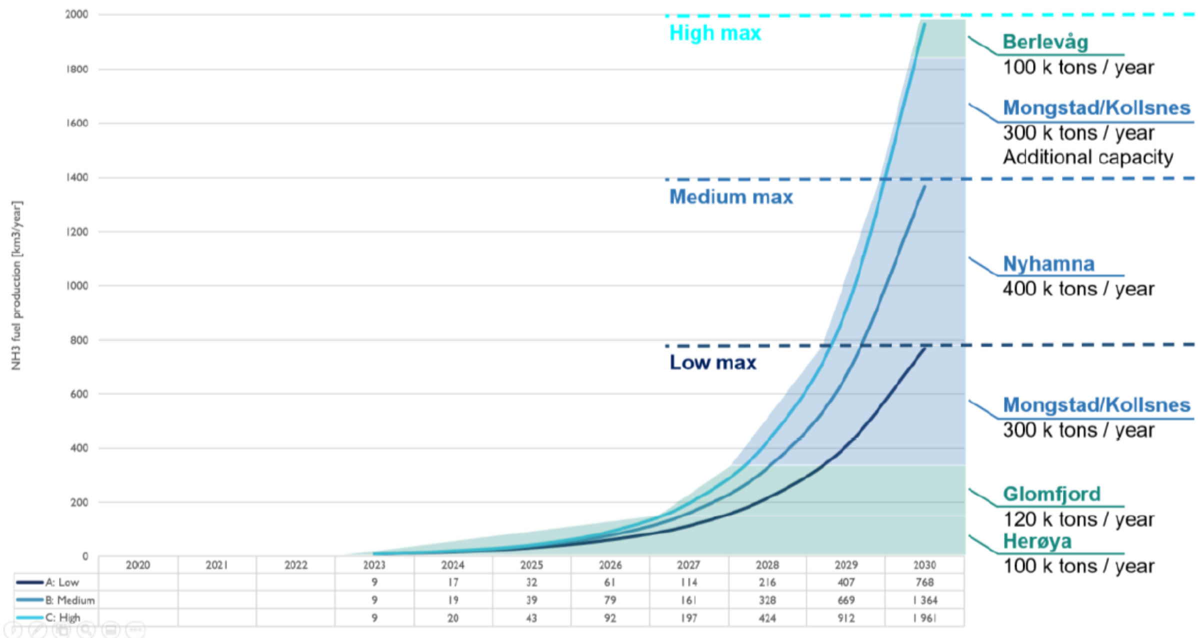


Figure 13: Ammonia production and demand development 2020-2030 [23]

2.4.2 Storage and safety

In terms of storage and safety of ammonia there is an existing infrastructure and solid competence globally because of the experience of handling ammonia. The distribution, storage, and transportation of LNH_3 is quite safer than H_2. It is easy to liquify ammonia and store it at low pressure (1 bar) at ambient temperature. Ammonia can be handled safely because handling of large quantities of ammonia is well established and documented whether it may be transportation by rail, road or pipeline and the infrastructure is available in many countries [21].

Concerning safety, ammonia is toxic and corrosive element. Its possibly hazardous to inhale and meet the environment, especially living organisms in water. Ammonia can be detected easily because of its pungent odor in small concentration. Furthermore, ammonia is lighter than air and can quickly disappear in the atmosphere in the case of leakage [21, 22]. According to the ammonia safety data sheet the limits of ammonia at workplace in EU is 20 ppm for 8 hours [24]. The flammability of ammonia is not high, but at high temperature and concentration range between 16-25 % ammonia can catch fire in case of leakage [25].

There is experience and regulation related to handling of ammonia transport, storage, and usage, but specific safety measurements related to the use of ammonia as marine fuel are essential [22]. These measurements should be taken into consideration when designing the fuel system and the storage system, for example separate spaces for fuel storage, double-walled pipelines in case of leakage, gas detection system and etc. [22, 26] **Table 1** shows a simplified risk analysis of the different fuels.

Substance	Health	Flammability	reactivity
Ammonia	3	1	0
Hydrogen	0	4	0
Natural gas	1	4	4
Methanol	1	3	0

Table 1: Risk analysis of different fuels, where 0 indicates “no hazard” and 4 indicates “severe hazard” [27]

2.4.3 Ammonia as a marine fuel

The safety and the volumetric challenges of handling hydrogen poses on maritime industry, creates the demand of alternative fuel. Ammonia is pointed to be a potential marine fuel. Ammonia is a carbon-free green fuel (when produced renewably) and it can be liquified by increasing the pressure to 1 bar at ambient temperature, which is much higher than that hydrogen can be liquified (-253 °C) [21-23, 28]. in addition to that the volumetric energy density of ammonia is more compared to liquid hydrogen and compressed hydrogen [21, 28]. Meaning that it can store more energy per unit volume.

In terms of energy, ammonia can easily be cracked and used in fuel cells or used directly in combustion engines [21]. Using ammonia directly in combustion engines produces only water and nitrogen. It can be used in SOFC and alkaline high temperature fuel cells because of their resistance against anhydrous ammonia. In the contrary ammonia is not suitable in low temperature fuel cells (PEM fuel cells) because of degradation or install purifier to avoid degradation [22]. SOFC can be a good candidate as a direct ammonia fuel cell, but it is not commercially available and there is a risk for NOx emissions that can be handled with proton-conducting electrolytes. This requires more space on board a ship than marine fuels [22].

Figure 14 shows different possible propulsion systems based on ammonia as its source of energy.

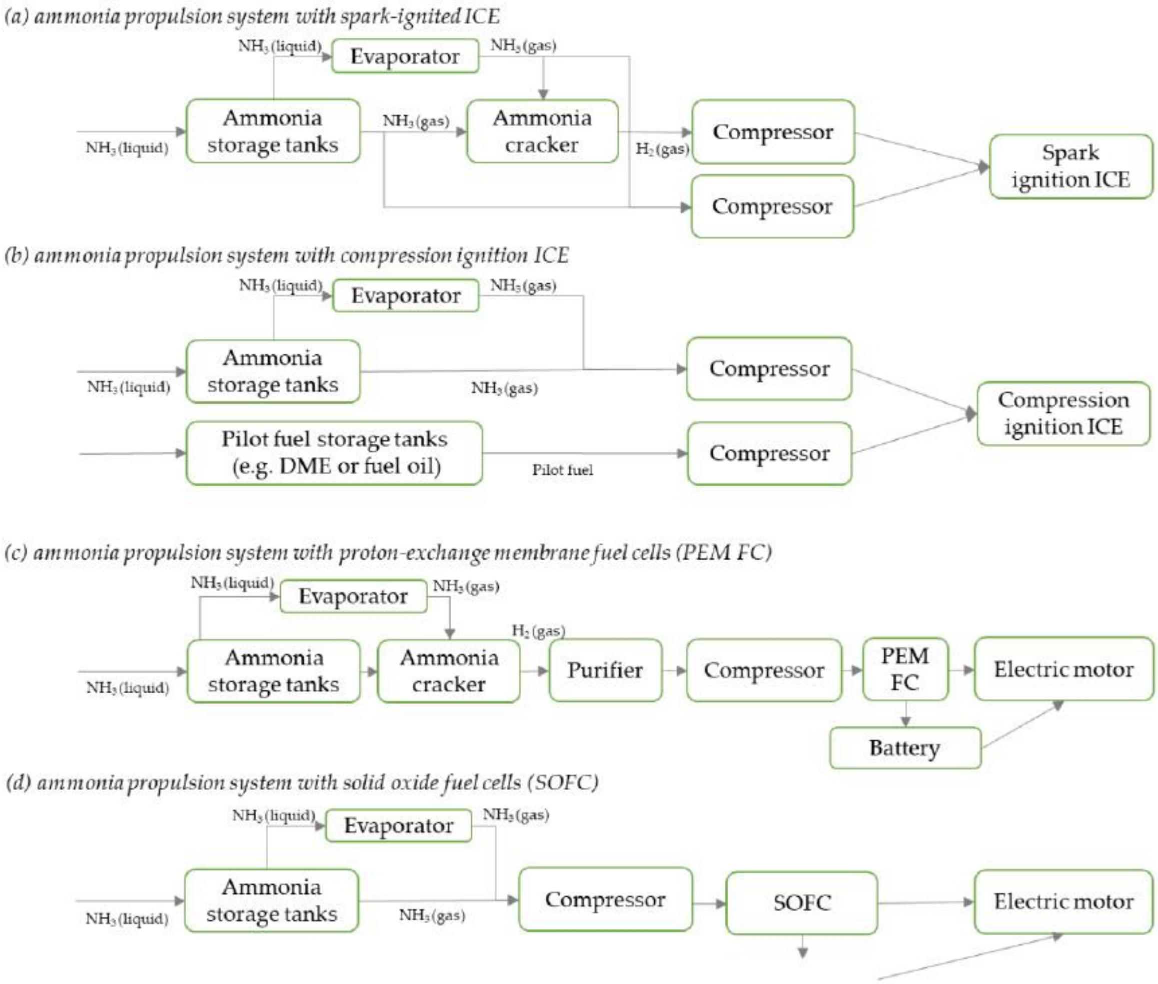


Figure 14: simplified propulsion system using ammonia as marine fuel [22]

Historically ammonia has been used in combustion engines because of lack of oil in 1940s. It was used as fuel in buses without any propulsion related difficulties [21, 28]. Some of the disadvantages of ammonia when used as fuel in combustion engines are that ammonia has a high auto-ignition temperature, low flammability, low flame speed, toxicity and requires bigger tank space/weight compared to conventional fuel like marine diesel oil. Furthermore, ammonia is corrosive for example to copper, copper alloys, nickel, and plastics [22, 28]. **Table 2** shows a comparison between the properties of ammonia and other fuels.

Fuel	Ammonia	Hydrogen-L	Hydrogen-G	LNG	MGO/diesel oil	Methanol
Storage phase	L	L	G	L	L	L
Storage Temperature (C)	25	-253	25	-162	25	25
Storage Pressure (kPa)	1000-1700	101-3600	25000	101-125	101	101
Density (kgm-3)	603*	71	17.5	430-470	840	786
LHV (MJ/kg)	18.6 -18.8	120	120	49	43	19.7
Flame velocity (m/s)	0.015	3.5	3.5	0.34		0.43

Table 2: Properties of ammonia versus hydrogen, LNG, Methanol and MGO/diesel oil [22]

*Liquid ammonia at 25 °C

Therefore, it is necessary that these issues to be addressed while designing energy system that uses ammonia as fuel in the maritime industry. In addition to that, there is no existing bunkering infrastructure for ammonia as marine fuel. The existing infrastructure and technology of handling ammonia needs to be upgraded in order to build a bunkering network as the demand of ammonia increases [23].

It is challenging task to develop commercially combustion engines using ammonia as fuel. MAN Energy solutions claims that their dual-fuel engine for LPG can use ammonia as fuel. Moreover, MAN indicates that LNG engines can easily be converted to ammonia with smaller adjustment [26]. There is an ongoing pilot research project, whereby Eidesvik's vessel, the Viking Energy, will be equipped with ammonia powered fuel cells. It is a joint industry research aiming to develop the world's first ammonia powered fuel cell between different companies such as Wartsila, YARA, IMM and Fraunhofer to mention some of them[29, 30]. **Figure 15** shows the new energy system of the vessel Viking Energy.

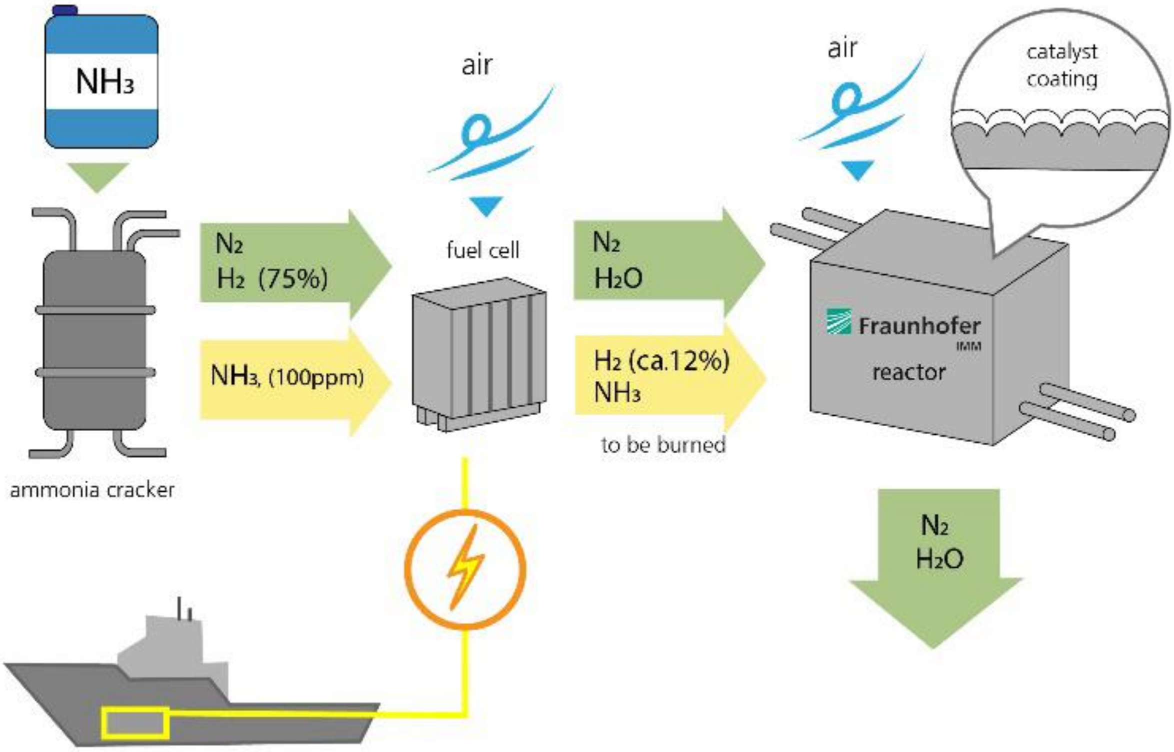


Figure 15: Viking Energy ammonia based energy system [30]

2.5 Batteries

Battery technology has been in the market for the past 150 years. Despite its lower energy density, low power density and self-discharge [29], it plays an important role in fighting the climate change. There have been performance improvements in recent years, but the maritime sector requires significant power except short costal voyages with frequency charging, such as ferries and short-sea shipping [29, 31].
Batteries use electrochemical processes to store energy [32]. There are different types of batteries both rechargeable and non-rechargeable. In this report only the rechargeable ones are relevant. The rechargeable ones are galvanic cells by discharge and electrolytic cell by charging. The electrochemical reactions are reversible by using electricity[33].There are lid-acid, nickel-metal-based and lithium-ion batteries to mention few of them. There is an ongoing active research to develop new battery technology such as lithium-air battery and magnesium-ion battery [29].
The leading and most dominating battery technology is lithium-ion battery which many companies believe can be further improved [29, 31]. **Figure 16** shows the battery capacities of different rechargeable battery types.

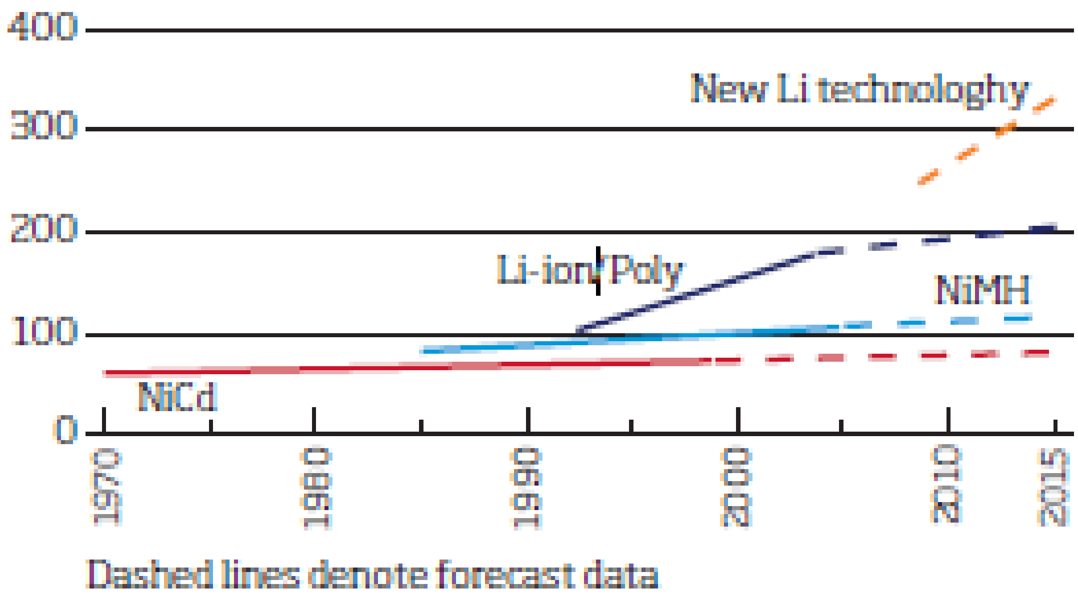


Figure 16: Rechargeable battery capacity Wh/kg [29]

In addition to improved performance the battery prices are significantly decreasing because of the demand in the automotive and consumer electronics industries. By 2016 the price of lithium dropped by 50 per cent. For large installation such as in shipping the cost is higher because of additional cost of system integration. In terms of safety and fuel efficiency batteries are more controllable [31]. **Figure 17** shows the developments in battery price from the period 2005-2030.

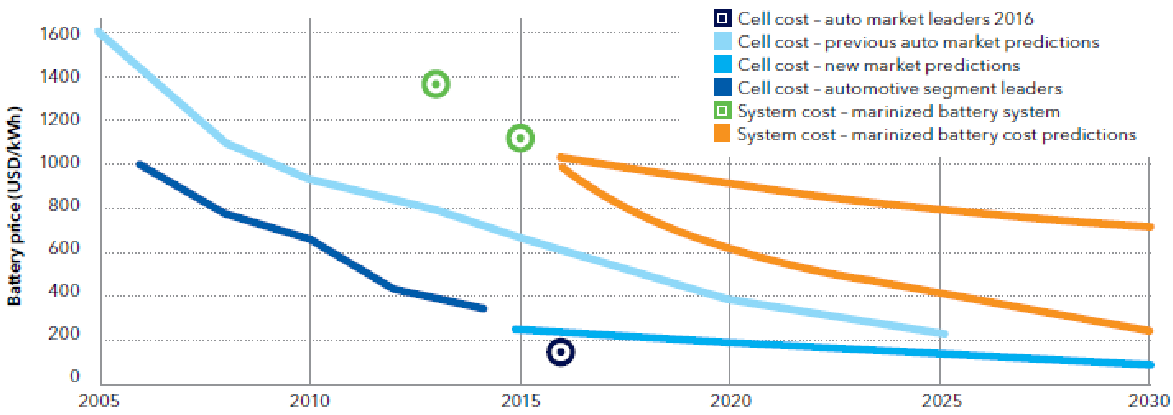


Figure 17: the development of battery price [31]

During operation batteries emit zero emissions. However battery production consumes a lot of energy and the battery life cycle can provide environmental problems if not handled probably [31]. It is estimated that large battery packs suitable for maritime sector may cost less per kWh. Despite that estimation there is a challenge in the accessibility of for example the row materials of lithium-ion battery. The reason is that the rate of lithium consumption is increasing, and the world lithium reserve is 10-11 million tons [29].

In shipping the energy demand is high, and batteries have low energy density. In addition to that they take more space and reduce the DWT of the vessel. That does not mean that they are not good alternatives. Batteries are suitable to car-ferries operating in short distances. Ampere is the world's first electrified car-ferry. It has 10 ton battery onboard that is equivalent to 5 percent of its capacity [34]. After realizing Ampere in 2015, it is expected that around 80 ferries would use battery as an energy source [1]. That brings Norway closer to its climate goals. Additionally, battery is suitable for hybrid solutions whereby the battery covers the temporary overload energy demand [5] and can be recharged by either fuel cell or the grid. **Figure 18** shows an example of a hybrid propulsion system, using Viking lady as an example.

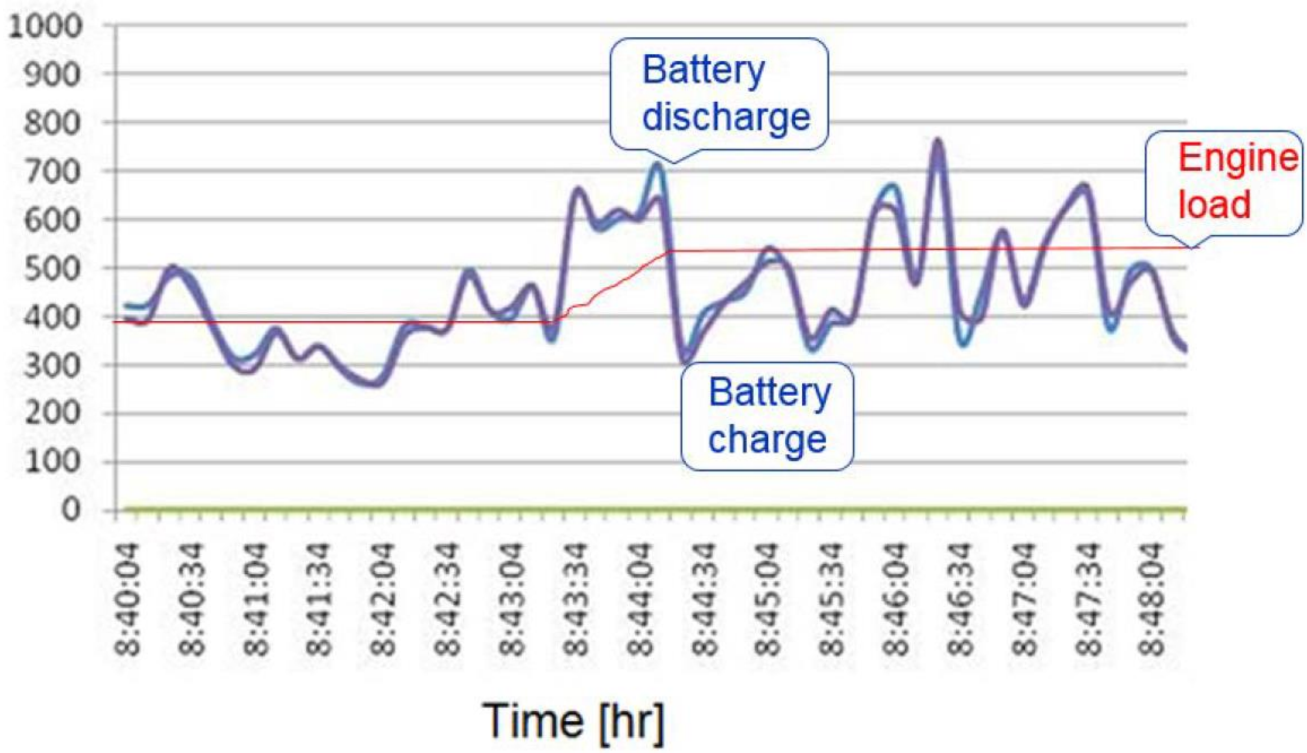


Figure 18: Hybrid solution of "Viking Lady" operation profile [35]

2.6 Fuel cells

Fuel cell is like a battery generating electricity and heat from a combustion-free electrochemical process. There are no moving parts in fuel cells, but they need assisting equipment such as pumps, fans and etc. [29, 31]. Unlike battery in which the chemical reactants are stored in the battery, the fuel cell reactants are stored externally and supplied into the fuel cell. The electrical efficiencies can reach up to 60% or more, depending on the type of fuel cell and the fuel [31].

2.6.1 How do fuel cells work?

As mentioned before fuel cells convert the chemical energy stored in the reactants directly into electrical and thermal energy by oxidation. Fuel cells are environmentally friendly means of producing electricity when green hydrogen is used, given that their production is free from greenhouse gases. **Figure 19** shows a simplified fuel cell illustration highlighting the process. The result after the overall reaction is only water. For example, fuel cell using hydrogen as fuel generates electricity by undergoing the following reactions [36]:

Equation 8: Fuel cell energy conversion stage 1

$$2H_2 \rightarrow 4H^+ + 4e^-$$

Equation 9: Fuel cell energy conversion stage 2

$$O_2 + 4e^- + 4H^+ \rightarrow \ 2H_2O$$

Equation 10: Fuel cell energy conversion stage 3

$$2H_2 + O_2 \rightarrow \ 2H_2O + heat$$

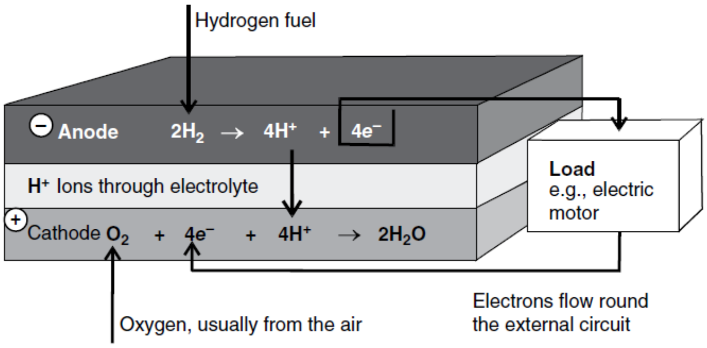


Figure 19: Electrode reactions and charge flow of fuel cell [36]

There are different types of fuel cell technologies, such as alkaline fuel cells (AFC), proton exchange membrane fuel cells (PEMFC), high-temperature PEMFCs (HT-PEMFC), solid oxide fuel cells (SOFC), Molten carbonate fuel cells (MCFC) direct methanol fuel cells (DMFC), and phosphoric acid fuel cells (PAFC). Three of them are promising fuel cell technologies for use of maritime sector; SOFC, MCFC and HT-PEMFC, but PEMFC is suitable for lower powers [29, 31]. **Figure 20** shows a comparison between different types of fuel cells.

Fuel cell type	Mobile ion	Operating temperature (°C)	Fuel	Applications and notes
Alkaline (AFC)	OH^-	50–200	Pure H_2	Space vehicles, e.g., Apollo, Shuttle
Proton-exchange membrane (PEMFC)	H^+	30–100 +[a]	Pure H_2	Vehicles and mobile applications, and for lower power CHP systems
Direct methanol (DMFC)	H^+	20–90	Methanol	Portable electronic systems of low power, running for long times
Phosphoric acid (PAFC)	H^+	~220	H_2, (low S, low CO, tolerant to CO_2)	Large numbers of 200-kW CHP systems in use
Molten carbonate (MCFC)	CO_3^{2-}	~650	H_2, various hydrocarbon fuels (no S)	Medium- to large-scale CHP systems, up to MW capacity
Solid oxide (SOFC)	O^{2-}	500–1000	Impure H_2, variety of hydrocarbon fuels	All sizes of CHP systems, 2 kW to multi MW

CHP, combined heat and power.
a) New electrolyte materials as described in Chapter 4 are enabling higher operating temperatures for the PEMFC.

Figure 20: Principle types of fuel cell [36]

In terms of use of fuel cells in designing energy system for maritime sector, the three high temperature types mentioned are possible candidates for maritime use. According to the report “Future Ship Powering Options” [29] high temperature fuel cells combined with heat engine to recover the waste heat, have the possibility to accomplish higher efficiencies than diesel engines. But that will increase the CAPEX of the energy system. In this approach an overall potential efficiency approximately 80% is achievable. So high temperature fuel cells such as SOFC are suitable for maritime operations with waste heat recovery system. **Figure 21** shows the effect of combining a fuel cell with a heat engine.

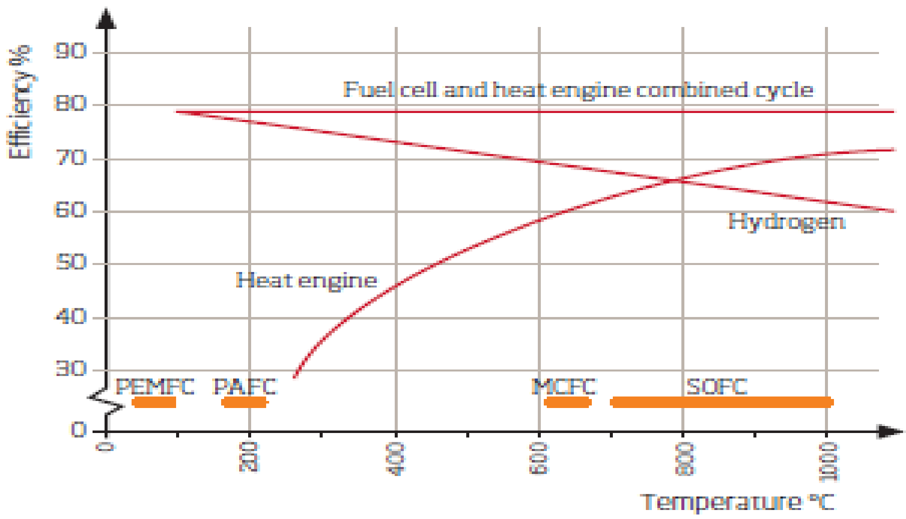


Figure 21: Combination of fuel cell and heat engine [29]

Hybrid systems are crucial for the management of peak loads in order fuel cells to be alternative for maritime industry. For example, fuel cells combined with batteries is another good option to handle peak effects and improve lifetime of the fuel cells [31]. In addition to the overall efficiency fuel cells have no moving parts which makes them quieter than conventional machinery. They produce DC electrical power and therefor are suitable for ships with electrical transmissions. Fuel cells do not emit GHG when used green hydrogen[29].

The main challenge of fuel cells is their fuel itself. The easiest is hydrogen, but the worldwide marine infrastructure is to be developed to meet the demand of hydrogen supply. Fuel cells can use other conventional fuels such as LNG or methanol but will lead to GHG emissions. Additionally, the fuel cell technology is a “diminutive business” that makes it less cost competitive [19]. Mass production is needed, in order to reduce the production costs. There is an expectation of mass production after 2022 which can allow production costs to be at a competitive level [31]. **Figure 22** below shows the potential scale effects of mass production of fuel cells

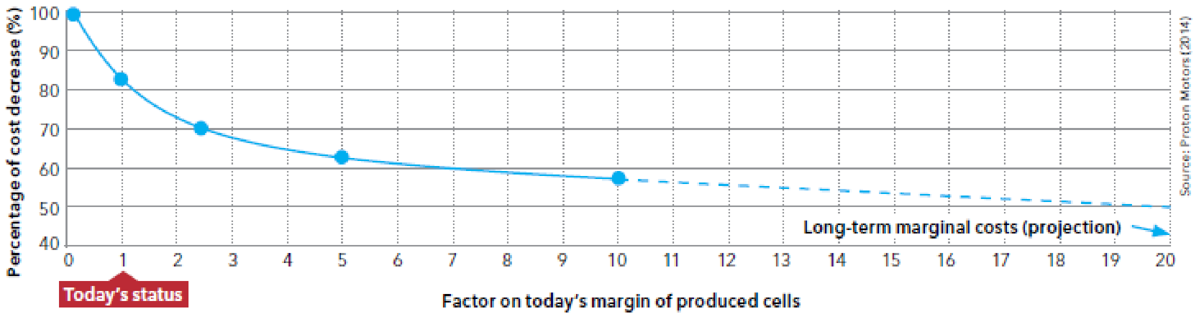


Figure 22: The potential effect of mass production [31]

The use of fuel cell technology in maritime sector is on the rise [19]. In Norway there is a pilot project aiming to use ammonia as fuel in a fuel cell. There will be used a 2MW fuel cell to meet the energy demand of the vessel. This energy system will enable the vessel to travel over 3000 hours yearly with renewable fuel. "Viking Energy" will be the first ship to be installed with fuel cell using ammonia as fuel [37]. **Figure 23** shows a summary of the current relevant fuel cell technologies.

Technology	Relative cost	Module Power levels (kW)	Lifetime	Tolerance for cycling	Fuel	Maturity	Size	Sensitivity to fuel impurities	Emissions	Safety Aspects	Efficiency
Alkaline fuel cell (AFC)	Low	Up to 500 kW	Moderate	Good	High purity hydrogen	High, experience from several applications including one ship	Small	High	No	Hydrogen	50-60 % (electrical)
Phosphoric acid fuel cell (PAFC)	Moderate	100-400 kW	Excellent	Moderate	LNG, Methanol, Diesel, Hydrogen	High, extensive experience from several applications	Large	Medium	CO_2 and low levels of NO_X if carbon fuel is used.	High temperature (up to 200 C). Hydrogen and CO in reforming unit	40 %(electrical) 80 % (with heat recovery)
Molten carbonate fuel cell (MCFC)	High	Up to 500 kW	Good	Low	LNG, Methanol, Diesel, Hydrogen	High, extensive experience from several applications including ships	Large	Low	CO_2 and low levels of NO_X if carbon fuel is used.	High temperature (600-700 C), Hydrogen and CO in cell from internal reforming	50 %(electrical) 85 % (with heat recovery)
Solid oxide fuel cell (SOFC)	High	20-60 kW	Moderate	Low	LNG, Methanol, Diesel, Hydrogen	Moderate, experience from several applications including ships	Medium	Low	CO_2 and low levels of NO_X if carbon fuel is used.	High temperature (600-700 C),Hydrogen and CO in cell from internal reforming	60 %(electrical) 85 % (with heat recovery)
Proton Exchange Membrane fuel cell (PEMFC)	Low	Up to 120 kW	Moderate	Good	Hydrogen	High, extensive experience from several applications including ships	Small	Medium	No	Hydrogen	50-60 % (electrical)
High Temperature PEM fuel cell (HT-PEMFC)	Moderate	Up to 30 kW	Unknown	Good	LNG, Methanol, Diesel, Hydrogen	Low, experience some applications including ships	Small	Low	CO_2 and low levels of NO_X if carbon fuel is used.	High temperature (up to 200 C). Hydrogen and CO in reforming unit	50-60 % (electrical)
Direct methanol fuel cell (DMFC)	Moderate	Up to 5 kW	Moderate	Good	Methanol	Under development	Small	Low	CO_2	Methanol	20 % (electrical)

Figure 23: Summary of fuel cell technology [19]

2.7 Climate goals

Both nationally in Norway and globally, there are efforts to tackle climate changes and reduce the greenhouse gasses (GHG). For that reason, some of the world leaders signed Paris agreement in 2015. The goal is to hold the increase of the global average temperature below 2 °C above pre-industrial levels according to article 2 [38]. The agreement is very essential for the world because of the climate challenges the world is facing. The climate change is negatively affecting both the seas and land. It is causing global warming that leads to poor food security [39]. According to article 27 of the agreement, it says "no reservations may be made to this agreement" [38] to highlight how significant and urgent the climate change issue is.

As a part of Paris agreement Norway plans to reduce its GHG emissions to 40% by 2030 compared to 1990 [1, 39]. To exceed the matter the government has updated the reduction to be 50-55% by 2030 [40]. The Norwegian government is committed to reach these goals in cooperation with EU (European union) [1]. In addition to that Norway is working on to reduce its emissions that are not subjected to quotas to 45% within 2030 compared to 2005 [1, 41, 42]. **Figure 24** shows the emission reductions not subjected to quotas.

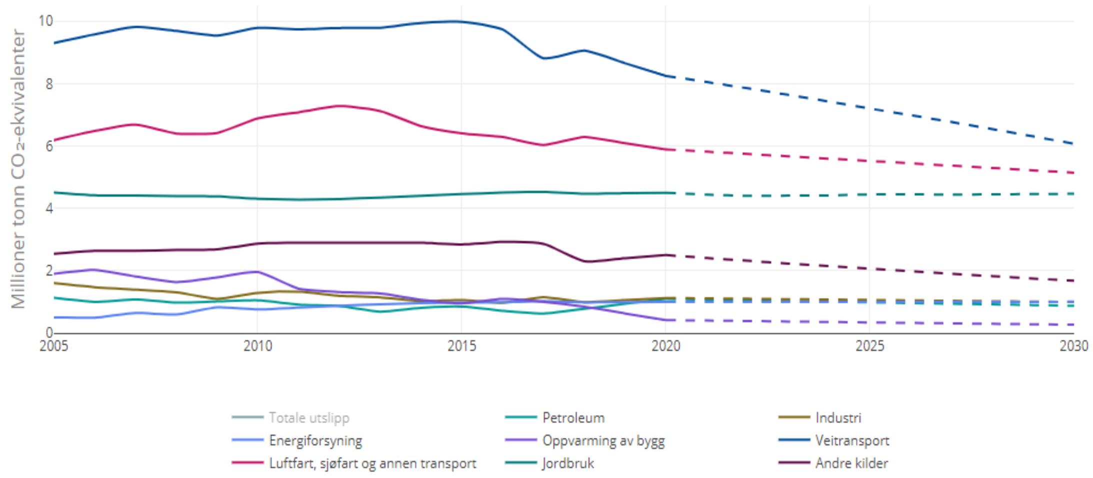


Figure 24: Reducing emissions that are not subjected to quotas [42]

Within 2050 Norway is planning to be low-emission society according to the low of climate 2050 [43].To realize the goals these measures are introduced.

- Plan of green shipping and a hydrogen strategy
- Strategy for research, new technology and use of hydrogen as energy carrier
- Stimulate zero-emission solutions in the shipping sector
- Stimulate furthermore the growth of green technology and a competitive maritime sector, facilitating export of low and zero-emission technology in maritime sector
- Set requirements for renewable solutions in the public ferry and speedboat tenders where possible [1]

Almost 60% of the emissions are not subjected to quotas. Therefore, the government sat a price for 450 NOK/ CO2 tons to reduce these emissions in the sectors such as fishing ships and coastal shipping sector and etc. [39].

Feil! Fant ikke referansekilden. shows the price of EU carbon allowance is approximately 44 Euro which is equivalent to 440 with an exchange rate of 0.0995 (1 euro equals ca. 10 NOK) [44]. The price is unrepresentative because it is little bit higher than normal price. The average price of the last two years is 26.57 euro/CO2 ton which is equivalent to 267 NOK/ CO2 ton. Besides that comes the CO2 fee for the emissions that are not subjected to quotas (450 NOK/CO2 ton) [39]. The total price is approximately 700 NOK/CO2 ton. The government is planning to increase the CO2 fees up to 2000 NOK/CO2 ton by 2030 to reach its climate goals but will make sure that total sum does not exceed 2000 NOK/CO2 ton CO2 equivalent [41].

Figure 25:Daily EU emission trading system (ETS) carbon market price [45]

Globally the International maritime organization (IMO) has as goal to reduce 50% of the total GHG emission for international shipping by 2050 [45]. Furthermore, Maersk, the container shipping company set an ambitious target in 2018 to have net-zero CO2 emissions from their operations by 2050 [46] to contribute to achieve Paris agreement goals.

2.8 Economic feasibility

The price of hydrogen depends on the production pathway. There are different methods of producing hydrogen as mentioned **Synthesis and production of green hydrogen**. For both green hydrogen and blue hydrogen. Grey hydrogen is not considered as relevant in this thesis because of its CO2 footprints. Approximately, 98 per cent of electricity production in Norway is renewable energy and comes from hydropower and wind power [47]. The price of electricity is estimated to be 0.34-0.67 NOK/kWh exclusive VAT in 2020 and 0.38-0.77 NOK/kWh exclusive VAT in 2030 [5].

As shown in **Figure 26**, the estimated price of hydrogen produced by using electrolysis is around 20-50 NOK/kgH2 and production by using damp reformation with carbon capture is around 10-15 NOK/kgH2 as shown in **Figure 27**. On top of that comes the cost of compressing and liquefying hydrogen, plus transport, storage, and bunkering. So far the analyses that are done show that hydrogen may not be economically competitive with marine diesel by 2030 [5]. But there are efforts to uplift hydrogen awareness, such as giving subsidies to the companies investing in hydrogen [1]. This will be described in (**Climate goals)**. A study done by BloombergNEF claims that the price of hydrogen can be 2$/kg (15$/MMbtu) by 2030 in many parts of the world under the requirement of $150 billion of subsidies. This price is equivalent to around 17 NOK/kg[44]. But according to the study green hydrogen is referred to both green and blue hydrogen.

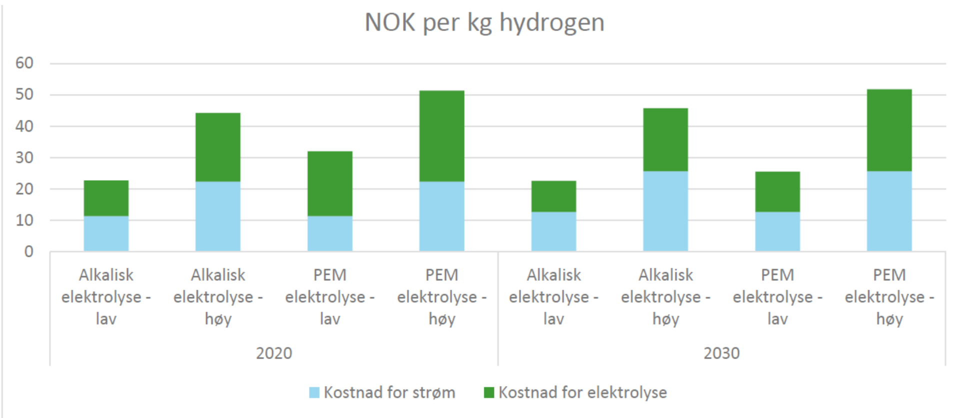


Figure 26: Estimated cost of hydrogen by using electrolysis in Norway 2020 & 2030 [5]

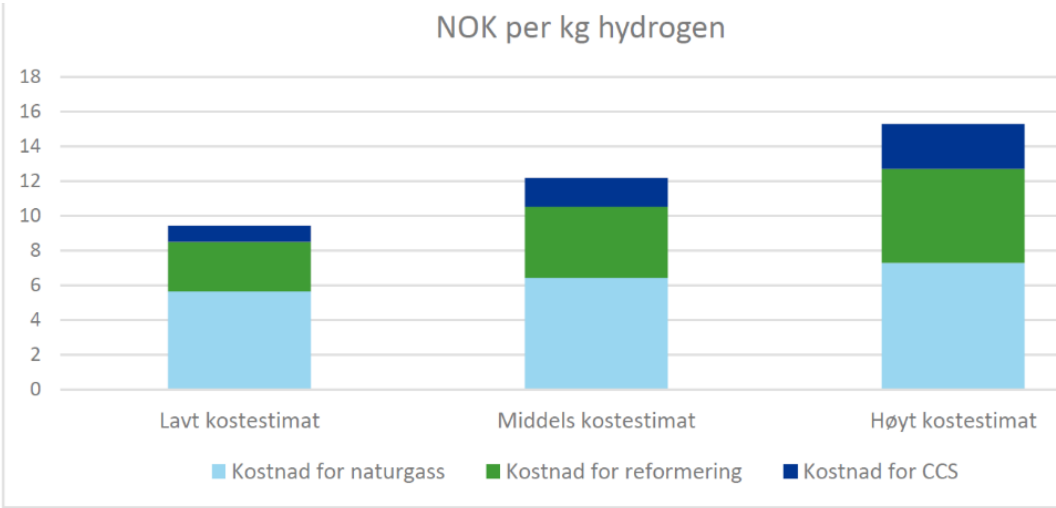


Figure 27: Estimated cost of grey hydrogen [5]

A company called Hyfuel is planning hydrogen plant in Florø [48]. That will probably cut the transport cost. Furthermore, Florø is an industrial area and there are other ways to reduce the hydrogen cost. For example, by increasing the production scale; there is a possibility to receive government incentives to reduce the CAPEX, but that depends on the market demand. In addition to that biproducts of the plant such as oxygen and waste heat can be sold to nearby fish farms **Figure 28** illustrates.

Figure 28: The planned hydrogen plant in Florø [48]

By doing this approach a future hydrogen price of 30 NOK/kgH2 can be realistic as shown in **Figure 29** case B. The difference between Case A and Case B is based on the different assumptions, such as electricity cost, transport, subsidies, sale of heat and oxygen etc. The price of hydrogen in Case A is around 50 NOK/kgH2 as shown in **Figure 29** . In this thesis it is estimated that hydrogen price is 50 NOK/kgH2 in 2021 and 30 NOK/kgH2 by 2030.

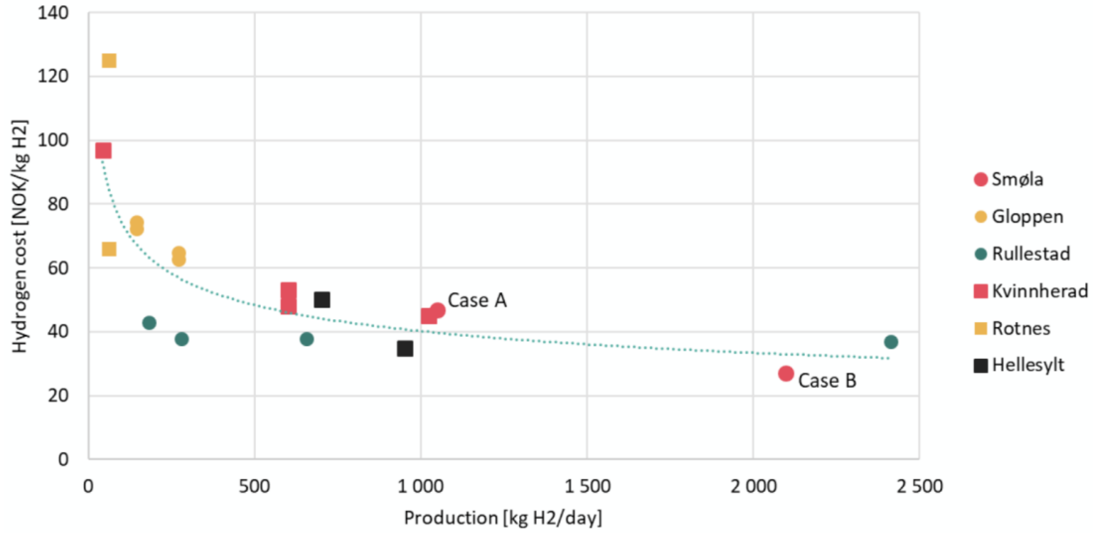


Figure 29: Hydrogen production and hydrogen cost relationship [49]

The price of oil (brent) per litre is 0,43 USD in the international market [50]. That is equivalent to 3.59 NOK when the exchange rate is 0.1199 [44] . The price of maritime diesel including 1.58 NOK/L for CO2 fee and 1.74 NOK/L [51] for the basic tax of maritime oil, is around 7 NOK/L.

3. Method and analysis

There have been a lot of discussions about different methods that would suit the thesis statement. One of the ideal methods was the method of using power-to-speed characteristics, which is unique to each ship, to calculate and find the fuel consumptions of each ship that arrives and bunkers at Florø. In addition to the auxiliary equipment onboard, heating and hotel loads if applicable. This type of approach is more precise and suitable, but it is very time consuming, and most of this data is not available in public because of its sensitivity on the market. Due to the time planned for this project and the limited accessible data related to the project the following method is a semi-qualitative method based on the assumptions and simplifications below **3.2.1**.

3.1 Comparison between the fuel types

Figure 30 shows the volumetric energy density compared to the (specific energy) gravimetric energy density of different fuel types.

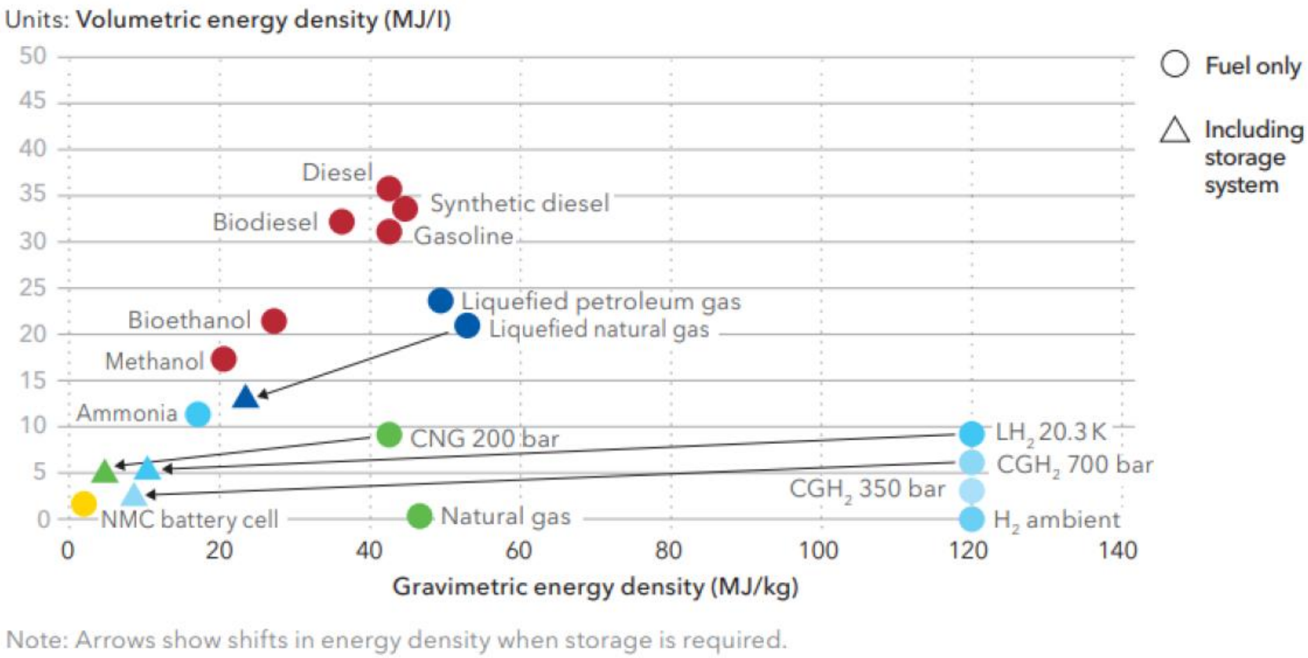


Figure 30: comparison of volumetric energy density and volumetric density

As mentioned in **2.1.1** hydrogen is lightest of all gasses and a non-poisonous gas. Its lightness makes it very reactive and reacts quickly with other elements. It has high specific energy density, but low volumetric energy density which makes it very challenging as a climate friendly alternative fuel.

To overcome volumetric challenges of hydrogen, there are different pathways of storing hydrogen. The two most common ones discussed in **2.2** er CGH2 and LH2.

It is easier to produce CGH2 than LH2 because liquification demands 20-35% more energy **2.2.2**. Holding the temperature at -253 °C is energy demanding. More energy means more OPEX. That makes CGH2 technically easier to transport and store. Compressed hydrogen gas is sensitive for leakage. In terms of price CGH2 is cheaper and cost effective compared to LH2. On the other hand, CGH2 can be produced in Norway, while there is no LH2 production plant in Norway. BKK, Equinor and Air Liquide are planning a LH2 production plant in Norway, Mongstad. Both CGH2 and LH2 can be produced using natural gas with and without CCS. Production of each one kilo LH2 produced by using natural gas emits approximately ten kilo CO2 which is not climate friendly without CCS [52]. **Figure 31** shows an overview of the different fuel data.

	Boiling point (°C 1 bar)	*Density (kg/m³)*	*Specific energy LHV (MJ/kg)*	*Specific energy LHV (kWh/kg)*	*Energy density (MJ/m³)*	*Storage temp/pressure*	*Chemical comp.*
Hydrogen	-253	0,089	120	33,3	10,8		H_2
Hydrogen compressed		23 (350 bar)	120	33,3	5 040	Ambient 200-1000 bar	
Hydrogen liquid		71	120	33,3	8 500	Cryogenic Atm./Low pressure	
MGO	175-650	890	42,7	11,97	38 000	Ambient atmospheric	Hydro-carbon
LNG	-162	440	50	12,50	22 000	Cryogenic Atm./Low pressure	Mainly CH_4
LPG	-42	490	46,4	12,90	22 740	Amb. or Cryogenic/ Atm.	C_3H_8
Liquid ammonia	-33,3	653,1	18,6	5,17	14 100	Ambient High/Atm. pressure	NH_3
Methanol	65	780	20	5,56	36 700	Ambient Atm.	CH_3OH

Figure 31: Properties of hydrogen compared to other fuels[55]

LH2 has high energy density and can be used for long distances and bigger ships that need more energy storage. LH2 needs a boil off system because when the temperature increases some of the LH2 become gas and cause a pressure increase in the cryogenic tanks. Therefore, a boil of system is needed to release the gas and maintain the pressure. LH2 takes less space than CGH2 which practically saves more space for the ship. Since hydrogen is fluid, it takes less time to bunker than CGH2 [53]. It needs less pressure than CGH2 and it can be produced in a large scale. Additionally, LH2 has three times higher density compered to CGH2 as shown in Feil! Fant ikke referansekilden.. In terms of bunkering land-based hydrogen refuelling infrastructure is commercially available, for maritime purpose the technology has not been yet adopted. Considering the challenges of LH2 such as low temperature, safety, boil off handling, makes bunkering procedure more complex and challenging. On the contrary bunkering of CGH2 is less complex, nevertheless challenging in terms of safety.

In terms of security, hydrogen is easily flammable, and it cannot be seen directly. CGH2 is very light and rises in the air easily through the ventilation system in case of leakage. On the other hand, LH2 freezes the other gasses in the atmosphere and can be on the ground for a while. Therefore, it is important to clean the surroundings of LH2 storage system for combustible materials, in case of leakage.

As mentioned in **2.4** ammonia is a well-known chemical material that people have handled for å long time. Ammonia is a colourless gas with bad smell, and it is poisonous compared to hydrogen. Ammonia as an alternative fuel in the maritime sector is not very well developed and it is in a research stage. Ammonia has higher volumetric energy density than both CGH2 and LH2, but less specific energy density as shown in Feil! Fant ikke referansekilden.. Additionally, ammonia can be used directly in combustion engines producing only water and nitrogen. That makes it the only carbon free fuel and applicable for the most ship types. Ammonia can catch fire in case of leakage, but at high temperature and concentration as mentioned in **2.4** (chapter storage and safety). In terms of bunkering ammonia is less complex than LH2 and CGH2, but safety challenges are to be expected due to the toxicity and corrosiveness.

Both hydrogen and ammonia have low energy density per mas or volume compared to conventional fuels. Thus, using them as alternative fuel is space demanding on board, such as tanks, fuel cells, heat recovery system, and battery system. That will lead to decrease of DWT of the ship. It is import to high-light that ammonia is promising because it is the only emission free fuel which is more likely to be competitive with the conventional fuels without dramatic change of existing infrastructure.

LOHC is a new concept to overcome the volumetric challenge of hydrogen as reviewed in **2.3.** It is easy to handle, like conventional fuels such as diesel and gasoline. The existing infrastructure can be used for both storage and transport at ambient temperature, which is the contrary of both hydrogen and ammonia. In terms of safety LOHC is not explosive and hardly flammable, but it can be poisonous when swallowed. The price of LOCH is low. For example, DBT price is around 4-5€ and it is reusable 300 times according to Hydrogenious. DBT cannot be used directly as fuel. It is used as energy carrier whereby, it is hydrogenated to load the hydrogen and dehydrogenated to unload the hydrogen. Dehydrogenation demands more energy than hydrogenation. The energy demand depends on the type of LOHC used. Methanol and ammonia can be directly used in combustion engines and they can be used as LOHC system. Hydrogen can be extracted from ammonia by cracking. Methanol is a cheap LOHC, but it is poisonous, and it is system is based on carbon capture as mentioned in. LOHC system is suitable for large scale storage, and there is no leakage sensitivity. The stored hydrogen in LOHC system does not need energy to keep it stored as per CGH2 and LH2. DBT as LOHC system has weight problems. For example, one cubic meter DBT can carry only 57 kg hydrogen which is small amount compared to the weight of the DBT. That can cause problems for the DWT of the ships. Therefore, LOHC system is more suitable for stationary storage. In the future it may be used for the large ships that have enough space. Hydrogenious claims that they are planning to deliver an onboard LOHC energy system based on DBT.

Battery is another form for energy storage and usage as reviewed in **2.5**. This form of energy system is more suitable for ships that travel short distance and have frequency port calls for the possibility of battery recharge. It is not suitable for ships that sail long distances to use such energy system because of the weight and space demand compared to LNH3, CGH2 and LH2. Nevertheless, batteries can effectively contribute to the use of green technology, without highly effecting the DWT. The battery can be dimensioned to cover the peak load of the vessels that use fuel cells. This is an important factor for the lifetime of a fuel cell. By this approach battery technology is a crucial element for the green technology.

3.1.1 Comparison of LOHC systems

The three LOHC systems analyzed in this thesis are as mentioned in **2.3**; NEC, DBT and MET. First and foremost, the most important aspects are the energy aspects, such as energy storage, transport, and mobility. These aspects have of course different criteria that is essential for the use of the LOHC system. Some these criteria are:

For energy storage availability, cost, stability, safety, and low energy demand for dehydrogenation are important parameters to be considered. For transport availability, safety, toxicity, material handling are crucial parameters for an easy and safe transport. For mobility it is essential to have high storage capacity and energy density since they are factors that highly effect volume and weight. **Table 3** shows a comparison between the three different LOHC systems relevant for this thesis.

Properties of the three LOHC (NEC, DBT and MET)			
	NEC	DBT	MET
	H0/H12	H0/H18	H0/H6
Hydrogenation [wt. %]	5,8	6,2	12,1
Enthalpy [kJ/molH12]	-53,2	-65,4	-16,5
Dehydrogenation temperature [°C]	180-270	270-310	90-420
Gas strømning [gH2/L/h]	68,0-163,1	11,0-27,5	0,8-44,8
Energy density [kWh/h]	2,5	1,9	3,3
Viscosity at 20 °C [mPa s]	O,5/5,9	49/425	-/0,6
Vapor pressure 40 °C [Pa]	0,1/4,4	0,07/0,04	-/35,400
Toxicity [TPI/mg]	5,1/ n.d (no data)	13,8/n.d	-/29,7
Price [€/kg]	40	4-5 [12]	0,03

Table 3: Comparison between the three different LOHC systems

Methanol (MET) and DBT are good candidates of energy storage system because of their availability, cost, and high storage capacity, 12.1 and 6.2 wt.%, respectively. MET has some other challenges that can make it unsuitable as a good energy storage system, such as high dehydrogenating temperature, toxicity and low hydrogen yield when using low temperature **2.3.3 Methanol (MET**). The challenge of DBT is that it demands high energy and access of thermal energy can be a source that can cover the energy demand. This also applies to MET system.

NEC can be favourable for transport because it can be easily handled, and it is not toxic. NEC is expensive compared to the other LOHC systems. Therefore, availability is challenging factor as it is an essential parameter for transport. Furthermore, NEC is fast form at 68 °C and it can only be hydrogenated 90% which decrease the capacity to 5.2 wt. % as mentioned **2.3.2 9-Ethylcarbazole (NEC)**. On the contrary DBT is easily available on the market and can be produced in a large scale to reduce the cost. It can easily be handled, and its toxicity is not so high, but It can be harmful when swallowed **0**.

It is challenging to use LOHC systems as energy carrier for maritime sector as they are energy demanding in the dehydrogenation process, by means of high temperature. There is a possibility that thermal energy can be harvested from the heat waste of high temperature fuel cells, such as SOFC, MOLT and HTPEM.

In the mobility sector Hydrogenious is planning to implement a LOHC integrated with fuel cell-system within 2024 based on DBT [53]. **Figure 31** shows a simplified illustration of a possible LOHC on-board system.

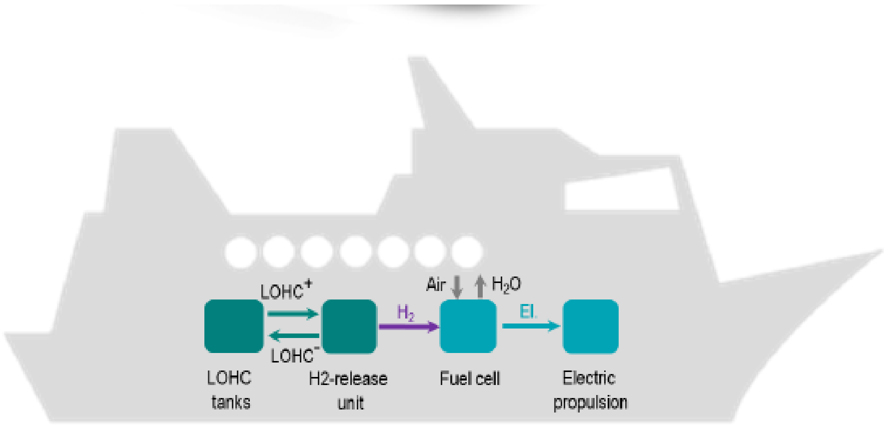


Figure 32 Hydrogenious on-board system[53]

This system allows vessels to integrate an energy system based on LOHC system on board the vessel. That means the vessel has its own dehydrogenating system on board, LOHC tanks and release unit. But this will be more likely suitable for bigger ships because of the weight of the system that will decrease the DWT of the ship. On the other hand, DBT viscosity can be challenging because the viscosity increases in low temperatures H18-DBT increases from 425 cP at 20 °C to 1520 cP at 10 °C [54]. This can be very challenging to bump, but it is interesting to see the technology development. another disadvantage which is the viscosity of DBT

DBT has promising future as energy storage system, transport, and mobility system as it satisfies the main parameters needed. It is noteworthy that DBT has disadvantages that need to be considered, such as viscosity and weight challenge.

3.2 Calculation method and results

There have been a lot of discussions about different methods that would suit the thesis statement. One of the ideal methods was the method of using power-to-speed characteristics, which is unique to each ship, to calculate and find the fuel consumptions of each ship that arrives and bunkers at Florø. In addition to the auxiliary equipment onboard, heating and hotel loads if applicable. This type of approach is more precise and suitable, but it is very time consuming, and most of this data is not available in public because of its sensitivity on the market. Due to the time planned for this project and the limited accessible data related to the project the following method is a semi-qualitative method based on the assumptions and simplifications below.

3.2.1 Assumptions

The following assumptions are made to simplify the method in order to use the available data and to be able to use a consistent method for all fuel calculations in this thesis.

It is a challenging task to calculate the fuel consumption of a vessel in a specific area. There are many factors to be considered when calculating fuel consumption such as the design and size of the vessel, the service speed, the total power needed, the type of main motor(s), the auxiliary engines and machinery, heating systems, and the weather. To provide an estimated fuel demand, simplifications and generalizations have to be made. The list below contains all assumptions made for the method in this report, along with a description of why that assumption has been made.

International arrivals are not included for the calculation of hydrogen-based fuel demand.

The problem of the thesis is centered around reducing CO_2 emissions from inland vessels, which means that calculating the hydrogen needed to supply international ships running on hydrogen is not as relevant. They will however be included in calculations of current fuel stored in the ports in question, due to them possibly bunkering there.

The efficiency of fuel cells and combustion energy are generalized based on current commercial technology. Reusing heat to increase fuel cell efficiency is neglected.

This is assumed to simplify the calculations for fuel consumption. It is likely that the efficiencies will be higher in the future. However, during the period of 2021-2030 these increases will likely be minor unless a major breakthrough in new technology happens. The result of these calculations can also be adjusted according to the newer efficiencies in the future. For some fuel cell applications, the heat can be reused in a cyclical system to increase the total system efficiency. Due to volume constraints on ships, and high costs these systems are not included in the calculations.

It is assumed that the electrical losses from the fuel cell system to the electrical motor down to the propeller is assumed to be 6% for vessels using fuel cell-based propulsion systems.

This assumption is made to account for the electrical losses that occur from the electrical engines to the propulsion system of the ships.

It is assumed that hydrogen as a marine fuel is technologically mature and safe by 2030.

In order for this report to be relevant, the fuel-types that are considered have to be safe for use, and the technology has to be mature enough for the users.

Ship propulsion is assumed to be an engine to propulsion system, instead of an engine to electric to propulsion-based system.

It is assumed that all ships have diesel-direct system in this report. But it is worth noting that many newly built ships use a diesel-electric based propulsion system. This system is more energy efficient when it comes to specific energy consumption. Both systems have the highest efficiencies around 70%-80% of the engine load, but the overall efficiency of diesel-electric is higher because the diesel engines act as generators, providing the possibility of shutting down some of the engines to better match the power requirements at lower speeds [55]. Figure 37 shows a comparison between the efficiencies of the two propulsion systems.

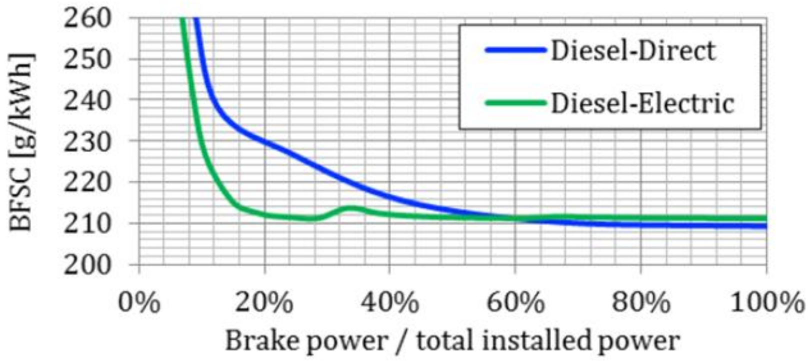


Figure 33: Diesel-direct versus diesel-electric

Assume that all recorded ship arrivals require to bunker fuel equal to the fuel consumption spent on the same voyage as the arrival.

Due to a lack of data for ships bunkered in the ports relevant for this report this assumption has been made to make it possible to provide a result of bunkered fuel in Florø. This assumption does not affect the calculated consumption, and it only affects where the fuel is bunkered. The ships that convert to a hydrogen-based fuel type for their energy systems have to bunker at a port supplying the fuel they use, and if that is Florø this assumption does not influence the result of bunkered fuel in such a way that it becomes inconclusive.

Ships smaller than 1000 GT, and with fewer than 6 arrivals in port are filtered out of the data model. Ships that only have one reported arrival to the ports are also not included.

This filters out any ships unlikely to operate in the area as well as ships with lower fuel consumption.

This assumption is made in order to filter out ships that do not influence the fuel requirements in a large degree and lowers the workload for a similar result.

CO_2 emissions are calculated on a "tank to wake" basis.

This assumption is done in order to determine the effect of fuel types on CO_2 emissions for the end-user, removing the value-chain from the equation to limit workload and provide a more useful result.

Auxiliary power consumption and power consumed during is based on an estimated percentage of the total engine power for each ship category.

As the method is built around calculating power consumption during transit, auxiliary power also has to be accounted for. The ships within each category mainly have the same functionalities and operational profiles, and by adding a power margin for these categories is useful to simplify the calculation in the data model.

For simplification of the calculation model, fuel consumption today as well as CO_2-emissions is calculated by its diesel equivalent

Some of the ships analysed in this report use LNG as their primary fuel, however this is done to simplify the calculations, and also provide a singular fuel consumption value for each ship category.

Due to uncertainties in which ports in the future will supply hydrogen-based fuels, the hydrogen-fuel demand in Florø is assumed to cover current energy demands for ships arriving in port.

There is a possibility that in the future, not all ports that the ships in this report arrive at supply the hydrogen-based fuels that these ships require. In this case, more of the energy demand has to be satisfied from ports that actually supply this fuel, which in this case would be Florø. The result of this would be a massively increased fuel demand, which is not likely to be representative of the real-world scenario. It is therefore important to assume that most or all the other ports that the ships arrive at today, will be able to satisfy this fuel demand. The total amount of arrivals or voyages those ships have made are shown in Feil! Fant ikke referansekilden. for comparison of the total voyages the ships analysed have made over an yearly duration to the arrivals in Florø, Måløy and Florø Base.

3.2.2 Mapping different types of ships in the area

The different types of vessels that are in this report are based on all ship arrivals in year 2020 in Florø harbour, Kinn (Måløy) harbour and Florø base (Botnaneset) filtered according to the assumptions. The AIS-data is collected from The Norwegian Coastal Administration's database, by filtering for the year 2020 and selecting the county name (Kinn). The marked area shown in **Figure 34** below is the boundary ranges of Kinn county, where the AIS-data is collected. The area contains all three ports that are relevant for the analysis in the thesis and allows us to map the historical arrivals to these ports. The AIS-data provides a complete overview of ship movements, which includes the identification of the ship, velocities, positions, and course. By tracking reported arrivals in port, we can produce a solid foundation for the traffic. Coupling this with specific ship data, allows for analysis of energy and fuel consumption as described in chapter **3.2.2.**

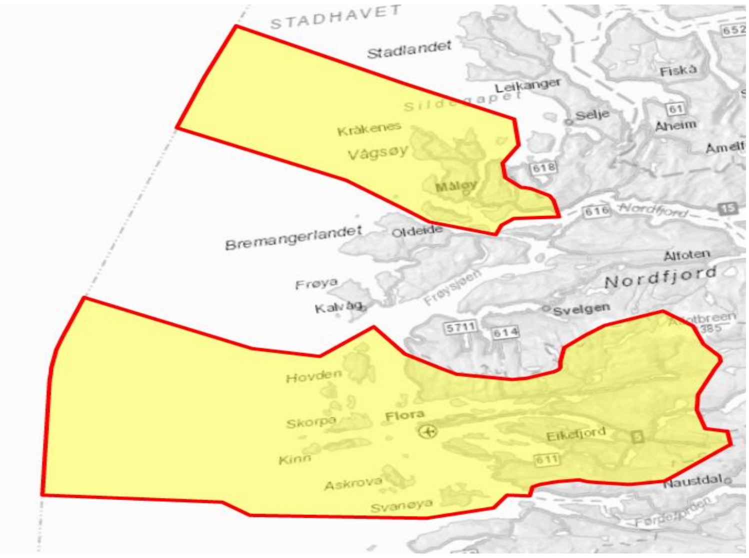


Figure 34: Boundary lines for mapping arrivals

The selection of the reference year 2020 is based on the number of the arrivals registered, as well as it being the most recent traffic in the area provides a solid basis for analysis on future demand. As shown in **Figure 35**, year 2020 has the highest number of arrivals compared to the other years. It is important to note that the diagram below shows data which is unfiltered according to the assumptions. Therefore, the number of arrivals analysed in this report is less than the number shown in the diagram. It is only meant to show the reason the reference year 2020 is selected.

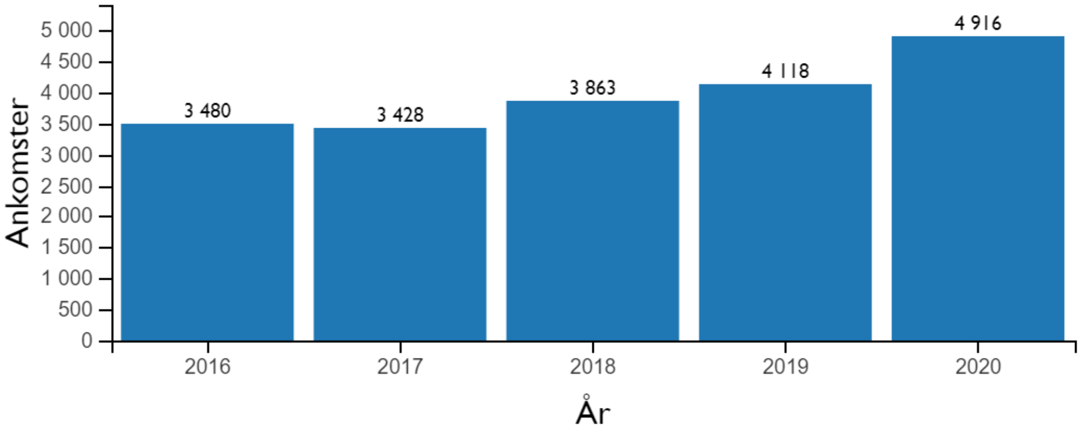


Figure 35: The amount of arrivals in relevant ports from 2016-2020 [56]

3.2.3 Ship categories and ship data

The ships have been categorized based on their function and operational profiles. The categories relevant for this report are briefly described below. **Table 4** represents the number of ships shown in the AIS-data for registered arrivals to the designated area in 2020 as well as the total amount of voyages those vessels have made over the same year.

Ship Category	Registered Ships in area	Arrivals in Florø and Måløy	Total amount of voyages registered
Cargo Vessel	77	811	18768
Fishing Vessel	30	260	1247
Harbor Vessel	7	1371	2188
Live Fish Carrier	12	223	1933
PSV/AHTS	43	1403	4711
Tanker Vessel	15	144	3298
Bulk Carrier	13	13	413
Total	**197**	**4225**	**32558**

Table 4: Ship arrivals [56-58]

- PSV/AHTS

Platform Supply Vessels and Anchor Handling Tug Supply ships are mid-sized vessels that primarily serve the function of supporting oil platforms. The main function of Platform Supply Vessels is to provide logistic support to the platforms in the form of transporting goods, equipment, personnel to offshore installations. Anchor Handling Tug Supply ships are designed to be able to supply offshore installations, but their main function is to tow oil rigs or other larger offshore installations. Both these ship types mainly travel in between the mainland and offshore installations and are designed to be able to stay offshore for sustained periods of time. Because of to their similar operational profiles and functions, these ships have been grouped into the same category.

- Cargo Vessel

The following ship types have been grouped into this category: General Cargo ships, Container ships, Ro-Ro Cargo ships and Refrigerated Cargo Ships. They all serve the primary function of transporting a certain type of cargo from one point to another, and as such have been grouped together to simplify the analysis.

- Harbor Vessels

Harbor vessels are necessary to support optimal harbor functions. Within this category we have: Tugs, Pollution Control Vessels, and Pilot Vessels. They travel short distances in between a small number of ports to provide support wherever needed. Tugs are mainly used to tow larger vessels that arrive, or to tow vessels that experience mechanical failure into shore. Pilot Vessels support larger vessels to ensure safe arrival and departure. Pollution control vessels assist in recovering and cleaning up eventual oil spills or other forms of pollution.

- Live fish carriers

Live fish carriers are used to assist fish farming operations. They handle any transfers of fish between one site to another, as well as treat and medicate the fish should the need arrive. These ships generally serve a small area of operation and thus travel short distances.

- Tanker vessels

Tankers have a similar operational profile as cargo ships and serve the same function of transporting liquids from one area to another.

- Passenger vessels

Passenger vessels included into this category are mainly high-speed light crafts. They sail over specific routes at high speeds, and transport either only passengers, or passengers and cars. The fuel demand for these vehicles have already been calculated by OHC, and their fuel demand is not calculated using this data model, but rather taken from that report.

- Bulk Carriers

Bulk carriers are large vessels that travel long distances between countries and continents to transport goods. In the year 2020, each ship that data was gathered from only had 1 arrival in Florø, and due to the low frequency has been deemed unlikely to bunker hydrogen fuels and therefore has not been included in the further calculation process for hydrogen demand.

The AIS-data for the voyages of these ships is gathered into the data model to map the operational profiles for further calculation of fuel consumption. The result of the average operational profiles for each ship category relevant for calculation is shown in the two tables below:

Table 5 represents the average voyage data for the ships relevant for the thesis and is based on data gathered from their global voyages over a yearly period. While **Table 6** represents the averages of the data gathered from the voyages where the ships arrived in either Florø or Måløy. The transit time is calculated by using the distance travelled and average speed from each ship in both these tables.

Ship Category	Average voyage distance [nm]	Average speed [knots]	Global Transit time [h]
Cargo Vessel	478	10,25	77
Fishing Vessel	545	7,80	30
Harbor Vessel	60	8,00	7
Live Fish Carrier	163	8,85	12
PSV/AHTS	164	8,10	43
Tanker Vessel	249	9,80	15

Table 5: Average ship movement data based on global averages [58]

Ship Category	Florø average distance [nm]	Average speed [knots]	Florø Transit time [h]
Cargo Vessel	243	10,25	22
Fishing Vessel	439	7,80	46
Harbor Vessel	56	8,00	8
Live Fish Carrier	194	8,85	16
PSV/AHTS	169	8,10	22
Tanker Vessel	170	9,80	18

Table 6: Average ship movement data on Florø Arrival [58]

The arrivals of the ships selected for analysis in the year 2020 are represented in the pie chart below in **Figure 36**. This chart shows that there is a clear dominance in traffic towards platform supply vessels, harbor vessels and cargo vessels in the area. **Figure 37** represents the arrivals in the designated ports, relative to other ports, highlighting which ship categories have their energy demand covered by the ports in question. This is done by a simple comparison of total arrivals to arrivals in the highlighted area during the year 2020. From this graph it is easy to see that from the ships analysed PSV/AHTS, Harbor vessels and Fishing vessels most consistently operate and bunker in either Florø or Måløy. Based on the assumption that all ships bunker fuel on arrival, it is possible to deduce that the ports in this analysis are responsible for satisfying the fuel demand relative to the percentages in **Figure 37**.

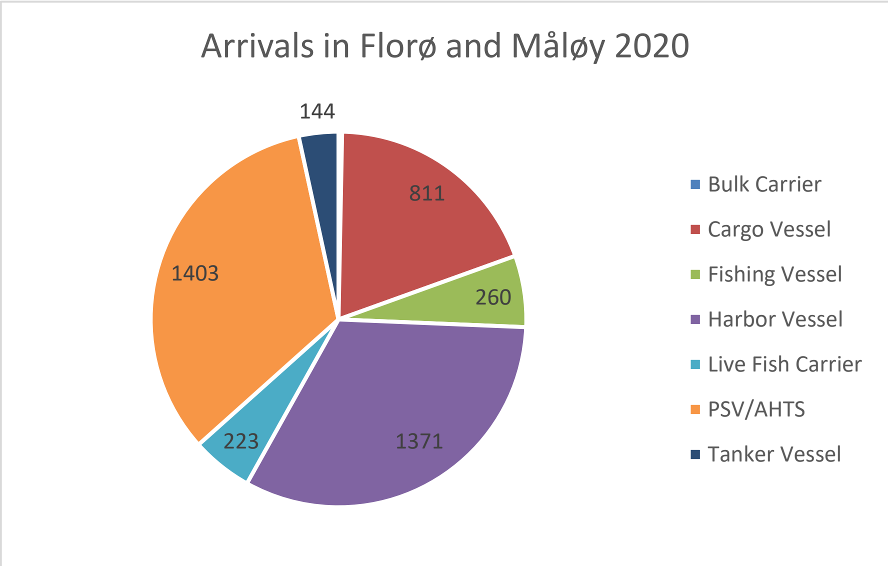


Figure 36: Arrivals in the specified ports by ship class after filtering by assumptions

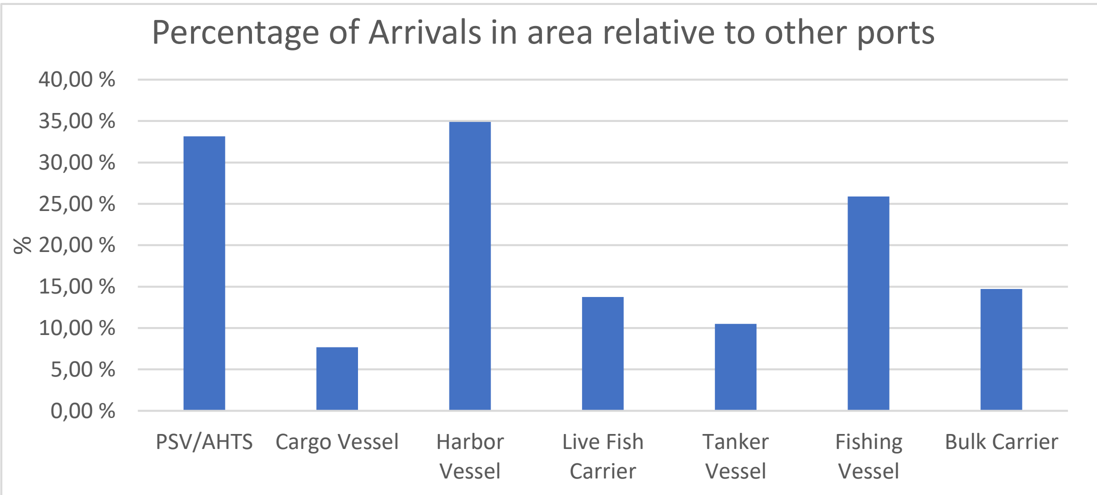


Figure 37: Arrival percentage relative to other ports for each ship category

Figure 38 shows the arrival distribution between the three different ports. From this it is possible to see that Harbor vessels, Live Fish Carriers, and fishing vessels mainly arrive or bunker at either Florø or Måløy harbor, while Cargo Vessels and tankers arrive at all three ports about the same number of times. PSV/AHTS almost exclusively arrive/bunker at Botnaneset – Florø (Florø base), and sometimes in Florø port.

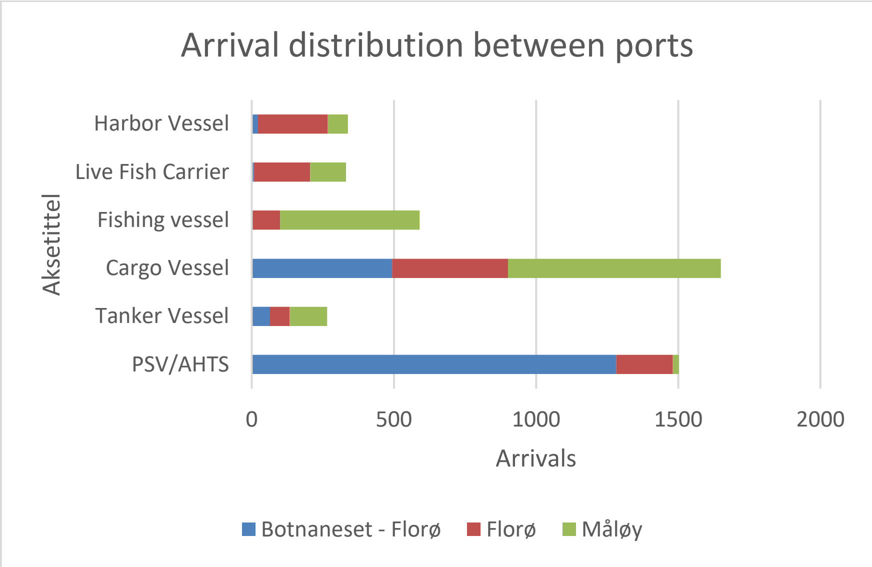


Figure 38: Arrival distribution between relevant ports

3.2.4 Hydrogen conversion scenarios

Traffic routes and bunkering scenarios presented here are based off the recorded arrivals of the ships. The data is based on the recorded AIS – data of The Norwegian Coastal Administration [56, 57].

The table below represents the scenarios of vessels bunkering hydrogen-based fuels in 2030. Ships arriving in the area relevant for the thesis are more likely to be able to continuously bunker hydrogen-based fuels from that same port **3.2.1**. The table is only to provide an estimate of future ships running on hydrogen, and the percentages are assumed based on the movements of each ship category.

Because of infrastructural requirements for transport and production of hydrogen-based fuels, the ships with the highest frequency in a specific area is deemed more likely for conversion and bunkering of these fuel types.

Cargo vessels and tankers provide critical logistical support, and travel over longer distances in their shipping routes compared to the other vessel types except seagoing fishing vessels. However, their traffic distribution and port arrivals range over a much wider area compared to the fishing vessels, and therefore require hydrogen-fuel infrastructure over more ports to be able to satisfy their fuel demand and allow for flexibility. Due to this, they have been set as the least likely ship categories to convert to hydrogen-fuels.

Passenger vessels, PSV and AHTS, and Harbor vessels are set as the highest prioritized ships for conversion in this report. Passenger vessels travel over set distances, and as a ship category are mainly active in areas with higher population density, and thus more ship activity. PSV and AHTS represent a large part of the energy demand, and therefore also CO_2 emissions. They operate within specific areas near offshore operations with high traffic and are therefore a highly prioritized vessel type for possible hydrogen-fuel conversion. Harbor vessels are smaller vessels operate within small ranges, and bunker mainly at a set number of ports within their operating area. Due to this they are also a vessel type that is considered high priority. **Table 7** shows the three assumed bunkering scenarios within year 2030. The scenarios illustrate possible conversion rates for potential use of hydrogen-based fuels for the different vessel types.

Ship Type	Number of ships	Hydrogen-based fuel scenarios		
		Low	Medium	High
PSV/AHTS [59]	43	30 %	60 %	100 %
Cargo Vessels	77	10 %	20 %	40 %
Harbor Vessels	7	35 %	70 %	100 %
Live Fish Carriers	12	15 %	30 %	60 %
Tanker Vessels	15	10 %	20 %	40 %
Fishing Vessels	4	25 %	50 %	100 %
Passenger vessels	8*	50 %	75 %	100 %

Table 7: Hydrogen-based fuel scenarios

*the number of passenger vessels is referred to the number of vessels used in the different segments

3.2.5 Fuel consumption

The method for calculation is divided into the following parts:

a) Calculation of the energy consumption per voyage of each ship relevant for analysis, followed by a conversion from energy to diesel giving us the diesel consumption for each voyage of the ships.
b) The calculation of the daily/monthly fuel demand(diesel) at bunkering stations at Florø
c) The calculation of yearly CO_2 emissions in the area based on ship arrivals and the carbon emissions that may be reduced by the year 2030 depending on the three different scenarios.
d) The calculation of the daily/yearly future hydrogen-based fuel demand in year 2030 categorized into different scenarios based on the potential vessel that may convert their energy system to use hydrogen-based fuels.

The fuel consumption of the ships is calculated using the data model in excel [58]. The formulas below illustrate the calculation process for a single ship in the data model. The data used in these calculations is based on average yearly ship movements, providing an average of the fuel consumption for each voyage [57, 60].

Equation 11: Time in transit

$$Time\ in\ transit\ [hr] = \frac{Distance\ traveled\ [nm]}{Average\ voyage\ speed\ [\frac{nm}{hr}]}$$

Equation 12: In transit energy per voyage

$$EPV\ in\ transit\ [kWh] = (Time\ in\ \ transit\ [hr] * Rated\ power\ [kW] * LF\ [\%]$$

Where time in transit is the average time, the ship takes to travel its average distance for each voyage. LF represents the load factor, which is an estimated percentage of the engine load required to maintain cruising speed.

Equation 13: Time spent in DP/idle

$$Time\ DP/Idle\ [hr] = Average\ Voyage\ duration\ [hr] - Time\ in\ transit\ [h]$$

Equation 14: Auxiliary and idle/DP energy per voyage

$$EPV\ Aux\ and\ DP\ [kWh] = Time\ DP/idle\ [hr] * Rated\ power\ [kW] * LF\ [\%] * Power\ margin\ [\%]$$

Equation 15: Summed Energy per voyage

$$Total\ EPV\ [kWh] = EPV\ in\ transit\ [kWh] + EPV\ Aux\ and\ DP\ [kWh]$$

It is important to note that this formula for energy consumption per voyage is calculated using the average values of a ship in transit, rated power, load factor and an additional margin representing the energy requirements during idle or DP. This margin is based on the operational profile for each ship type, and includes energy consumption for auxiliary engines, acceleration, dynamic positioning, and auxiliary loads such as heating/cooling etc. This margin is derived from the operational profiles and machinery of each ship category. The fuel consumption of a ship is then possible to calculate using this formula:

Equation 16: Fuel consumption per voyage for combustion engines

$$Fuel\ consumed\ per\ voyage\ [kg] = \frac{Total\ EPV\ [kWh]}{Specific\ fuel\ energy\ \left[\frac{kWh}{kg}\right] * \eta c\ [\%]}$$

Where ηc is the engine efficiency for the fuel during combustion.

The yearly fuel consumption is calculated by using the amount of fuel consumed per voyage and multiplying it with the total amount of voyages the ship made during that year, the amount of voyages during a year is based on the total amount of port arrivals of that same ship. This formula is used to both calculate the yearly fuel consumption, along with the fuel stored in the ports. For fuel consumption the total amount of arrivals have been used, and for fuel stored the arrivals to that specific port has been used.

Equation 17: Yearly fuel consumption in tons

$$Yearly\ fuel\ consumption\ [tons] = \frac{Fuel\ consumed\ per\ voyage\ [kg] * Number\ of\ voyages}{1000}$$

Hydrogen fuel demand is calculated by using the current fuel consumption of each ship. Depending on how much fuel is bunkered today we can estimate the total hydrogen demand based off the energy needed for each voyage for each ship.

To convert the energy into hydrogen it is assumed that the energy requirements of the vessel is fulfilled by batteries and fuel cells. As mentioned, (ref-fuel cells) the peak load of vessels is necessary to be handled by battery to avoid reducing the lifetime of the fuel cells. That means the battery can offset the load on the fuel cell. The energy conversion to hydrogen is then calculated:

Equation 18: Hydrogen-based fuel demand conversion

$$Hydrogen\ based\ fuel\ demand[kg] = \frac{Total\ EPV[kWh]}{\eta_{el}\ [\%] * \eta_{fc}\ [\%] * Specific\ fuel\ energy \left[\frac{kWh}{kg}\right]}$$

Where η_{el} [%] represents the electric losses, η_{fc} [%] represents the efficiency of the fuel cell for the hydrogen-based fuel and the specific fuel energy is the energy of the hydrogen-based fuel in question per mass unit [kg].

3.2.6 CO2 emissions

CO_2 emissions are calculated using the emission factor of (3,17 kg CO_2/kg diesel) [61]. By multiplying this factor with the amount of marine diesel it is possible to calculate the emissions.Thus, from the data model we get this table for the CO_2 emissions, containing the global emissions of the ships and the emissions from the voyages where the ship arrived in the area. **Figure 39** is a visual representation of the emissions by each ship category, and is based on the data in **Table 8**.

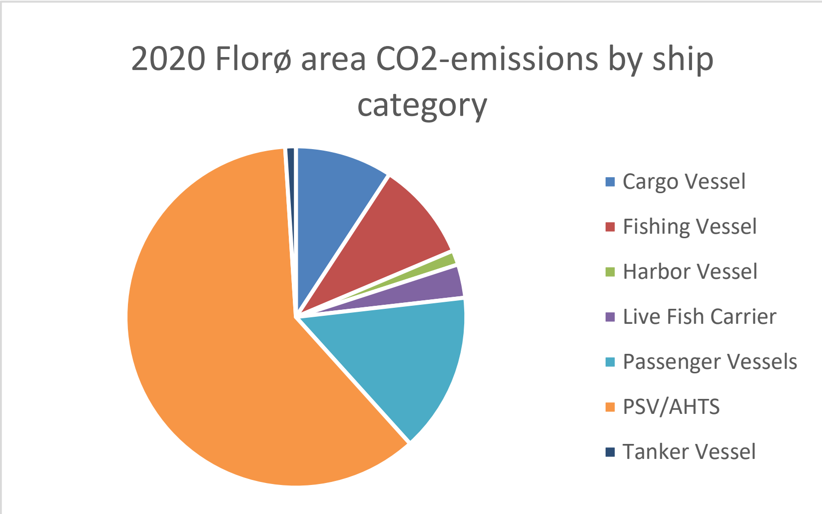


Figure 39: CO2 emissions by ship category [58]

Ship category	Yearly CO2-emissions on Florø, Måløy arrival [tons]	Yearly global CO2 Emissions
Cargo Vessel	15041	395546
Fishing Vessel	15317	70300
Harbor Vessel	2229	9098
Live Fish Carrier	5165	39697
Passenger Vessels	24621	24621
PSV/AHTS	98758	337098
Tanker Vessel	1649	54350
Total	**162779**	**930709**

Table 8: CO2 emission data

The hydrogen used as fuel is assumed to be green hydrogen, or zero emission-ammonia. From these results it is clear to see that platform supply vessels and AHTS represent a much greater part in CO_2-emissions and should be the primary target for reducing those emissions. This is likely due to them representing a large part of the amount of traffic in the area, as well as being larger vessels with higher power requirements.

To be able to reach the goal of reducing CO_2 emissions by 50%, the resulting total CO_2 emissions would have to be reduced by 81389 tons a year. The graph below shows the relationship between CO_2 emission reduction along the respective energy demand to be met by hydrogen fuels in order to satisfy that reduction. From this data, the logical conclusion regarding goal satisfaction of emission reductions is that the “low” scenario does not satisfy the conditions of the climate goals, whereas the “medium” and “high” scenarios do. **Table 9** shows the percentage of CO_2 reduction based on each scenario, showing the total effect the scenarios have on reductions. The “medium” scenario seems the most likely, due to the “high” scenario having a near 90% reduction in emissions, which would require almost all ships to bunker hydrogen. **Figure 40** is a visual representation of this data, showing the respective CO2-reduction dependent on each conversion scenario.

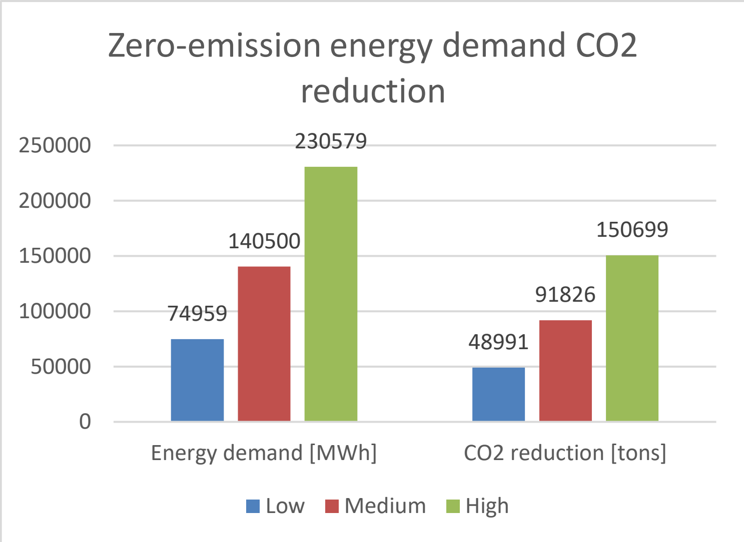


Figure 40: CO2 reduction based on the hydrogen-conversion scenarios

Bunkering Scenarios	Percentage of CO2 reduction
Low	30,10 %
Medium	56,41 %
High	92,58 %

Table 9: Percentage of CO2 emission reductions for the hydrogen conversion scenarios

3.2.7 Economic analysis

The economic analysis is a simplified analysis. The analysis does not include the investment costs, such as energy system and installation price. It does not give picture about the total ownership of a vessel converted to hydrogen fuel, which is a main factor when selecting an energy system. The analysis is meant only to compare the costs hydrogen and MDO fuels for the end-user and analyse how hydrogen can be competitive with the conventional fuels to reach the climate goals of Norway in Florø. The analysis is based on the scenarios presented in **0** to compare the cost of fossil fuels in 2021/2030 and the cost of hydrogen 2021/2030 and discuss the pros and cons of this development. The price of hydrogen is estimated to be 30NOK/kg by 2030 and 50 NOK/kg by 2021 based on Case A and Case B respectively as shown in **Figure 29**. **Figure 41** shows a comparison in fuel demand with reductions in emissions, zero-carbon fuels used in this illustration is calculated by its hydrogen-equivalent, and fossil fuels by its diesel equivalent.

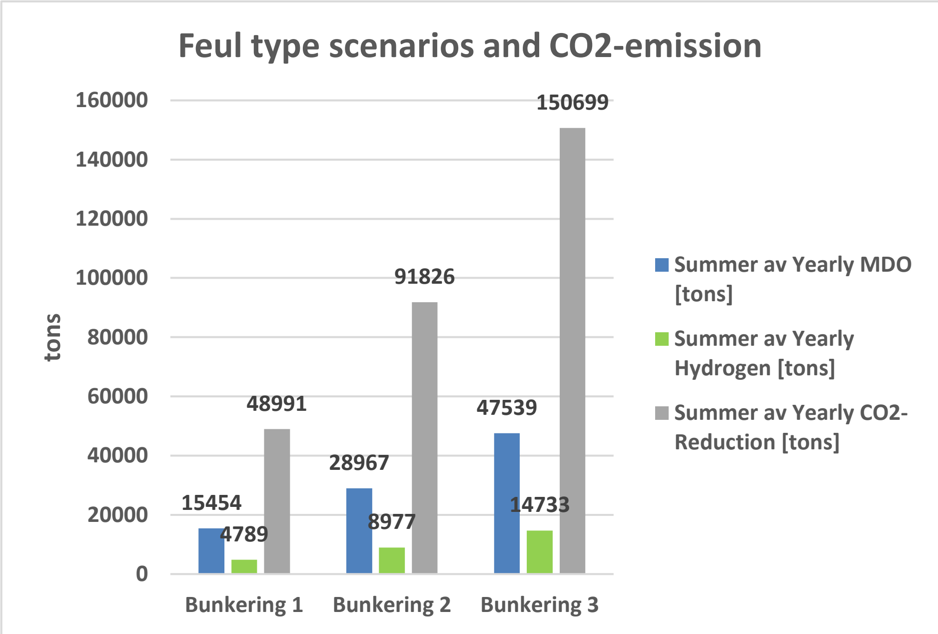


Figure 41 Fuel type scenarios and CO2 emission

The prices are calculated as shown in **Table 10**, given that the price of oil (brent) and the basic CO2-fee will remain stable, while the CO2-fee is doubled.

Name	MDO Price 2021 [NOK/L]	MDO Price 2030 [NOK/L]
Oil (brent)	3.59	3.59
Basic CO2-fee	1.74	1.74
CO2-fee	1.58	3.16
Total	7	8.5

Table 10 Calculation of MDO price 2021 and 2030

There is a gap between the price of hydrogen and MDO as shown in **Figure 42.** The reason is todays (2021) hydrogen infrastructure and production scale are not on a stage to compete with fossil fuels. Although there are growing efforts nationally and globally as reviewed in **2.7**, hydrogen-based fuel production scale and infrastructure need to be invested to reach a competitive stage.

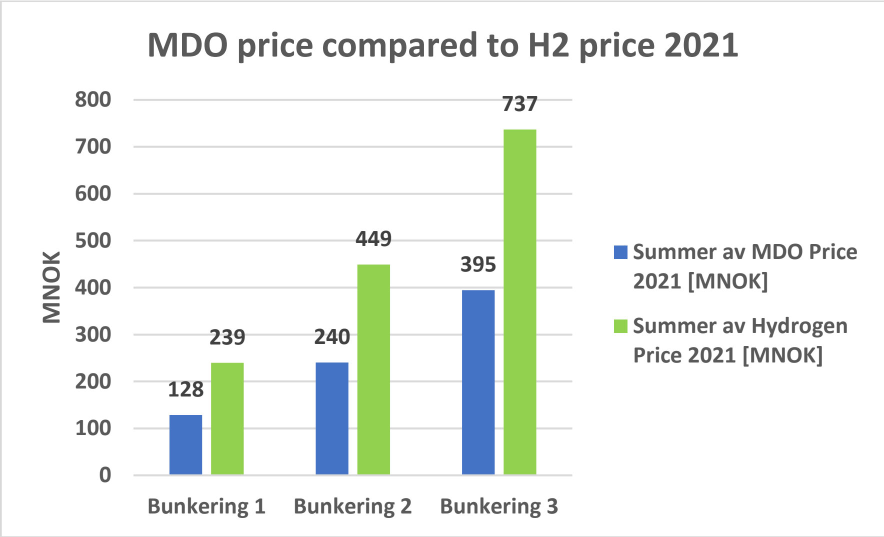


Figure 42 MDO price compared to H2 price 2021

Figure 43 below shows the differences in price in each scenario based on the hydrogen price in 2030. From this, it is shown that the 30NOK/kg hydrogen price would be very competitive with the price of MDO in 2030. Bunkering 2 is the target goal to be achieved as it represents the climate goals set by the Norwegian government. The goal is to reduce 50-55% of the GHG emissions by 2030 as mentioned in 2.7. With this price the goal seems to be achievable but there are a lot of things to be considered and measurements to be set.

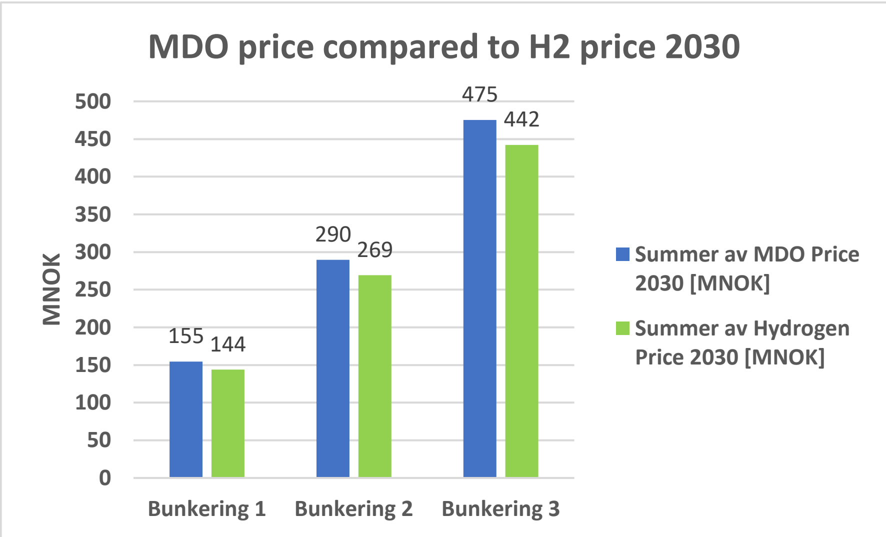


Figure 43 MDO price compared to H2 price 2030

Considering this result the price of hydrogen is much lower than MDO. which can be non-representative price by 2030. The reason is the estimated price is based on Smøla project as reviewed in **2.8**. It is important to highlight that estimated price the 2030 hydrogen price is related to number of conditions, such as selling the waste heat and oxygen to fish farmers. The waste heat can be seasonal product, whereby the demand is high in the wintertime and low in the summertime. In addition to that there will be some uncertainty related to the price of these products and the income they can probably generate such that hydrogen price reaches 30 NOK/kg.

On the other hand, the price of MDO 2030 is based on the doubling of CO-2 of today's (2021) CO-free. The reason is that the climate plan of Norway is aiming to double the Co-fee by 2030 as reviewed in **2.7**. Increasing CO-fee is one of the essential measurements to boost hydrogen-based fuels so that they be more attractive and competitive. The main goal is to reduce 50% of GHG as reviewed in **2.7**.

Other ways to reduce expenses can be using heat recovery system with fuel cells to increase the overall efficiency **2.6**, which can make hydrogen competitive. But that will also increase the investment. Storage systems like LOHC **2.3 s**ystems that can reduce energy in hydrogen value chain, can reduce hydrogen price and make it more competitive. **Figure 44** shows price comparisons for end-users for the different hydrogen prices in 2030.

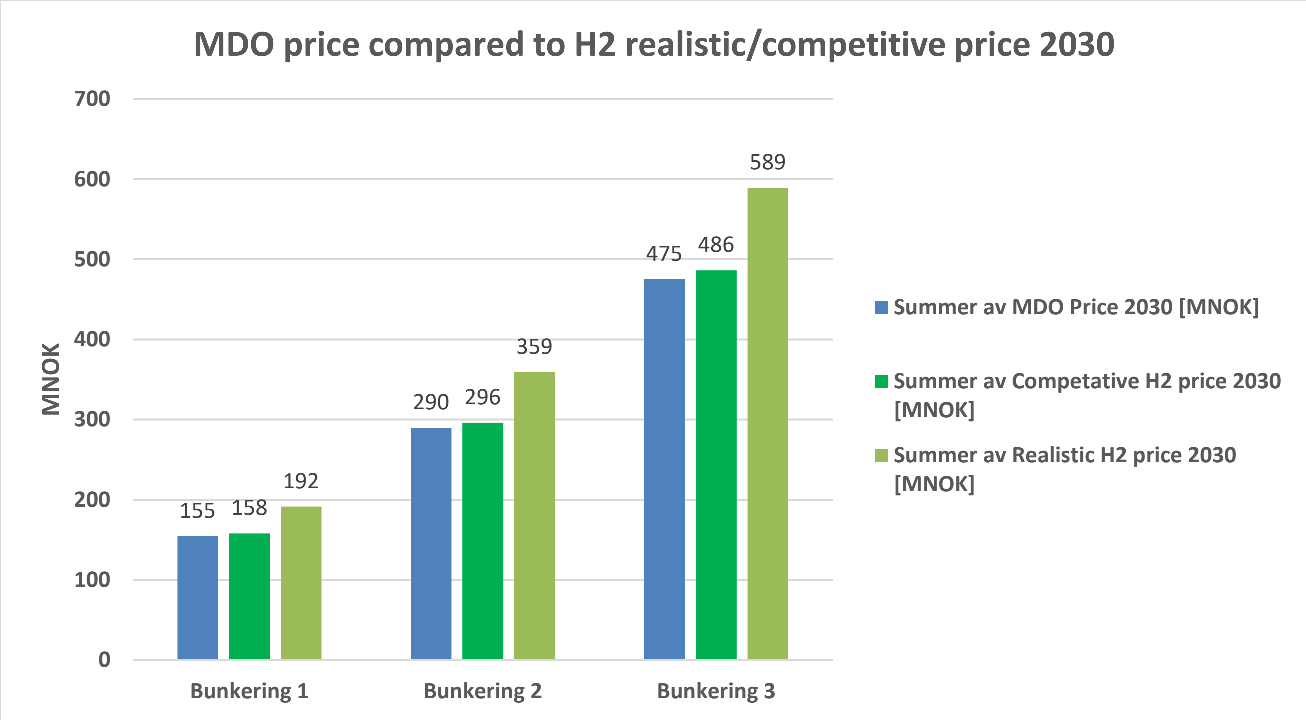


Figure 44 MDO price compared to H2 realistic/competitive

The price of H2 is between 20-50 NOK/kg as reviewed in **2.8**. To get a representative price the average is 35NOK/kg, but to be more realistic the H2-realistic price in 2030 is estimated to be 40 NOK/kg.

It is important to be realistic about the situation of the gas and oil industry. The industry has already invested millions in fossil driven vessels in many years. All though the industry is willing to contribute the country to reach its climate goals and reduce the GHG gasses, but the price of converting to a climate friendly energy system can be high and non-profitable. Considering that issue there must be another approach that can make the green technology more attractive and adoptive, in form of incentives and government investments.

3.2.8 Bunkered fuel and diesel consumption in Florø area

The fuel amount stored in Florø area is estimated using the calculation method in chapter **3.2.5**, using the operational profiles and voyage data from voyages on arrival in Florø or Måløy, along with the number arrivals to those ports. **Figure 45** below shows monthly diesel consumption in and is an estimate based on the traffic movements each month in 2020 [56].

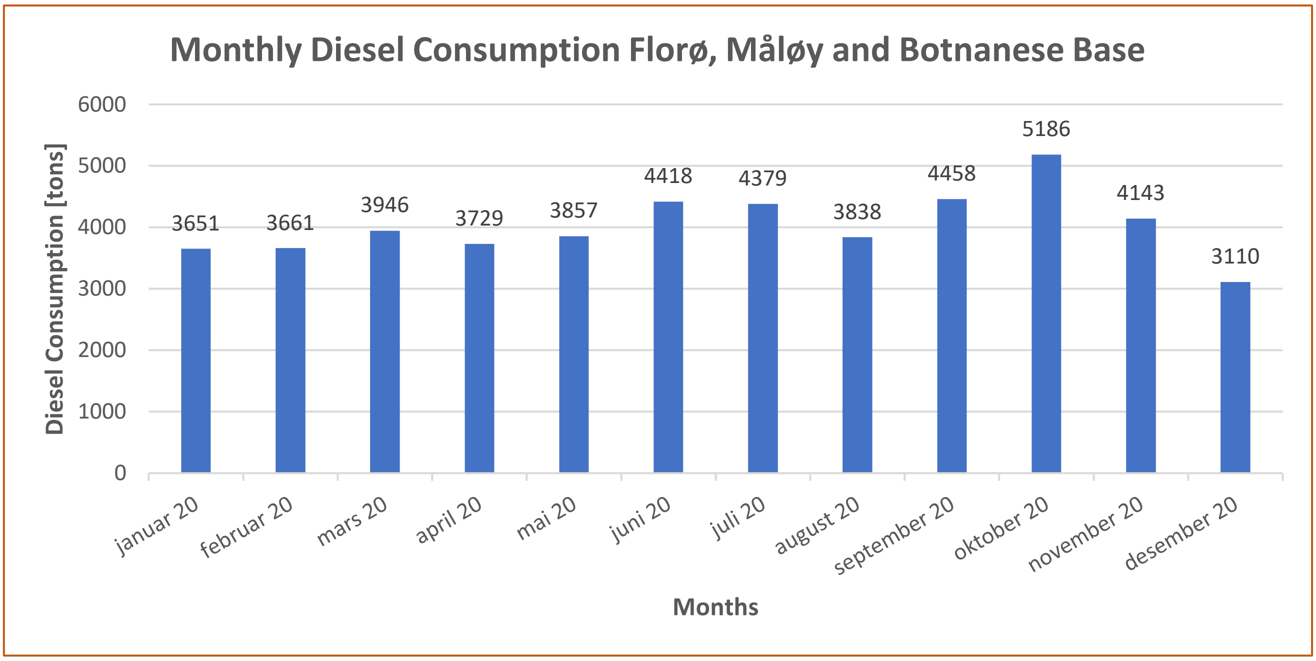


Figure 45 Monthly diesel consumption of the specified ports

Figure 46 shows the average of the daily diesel consumption for each ship category. It is calculated using the described method, by using the global voyage data with total voyages over the year 2020. This does not reflect the daily fuel demand in Florø, but rather highlights the consumption requirements of each vessel type.

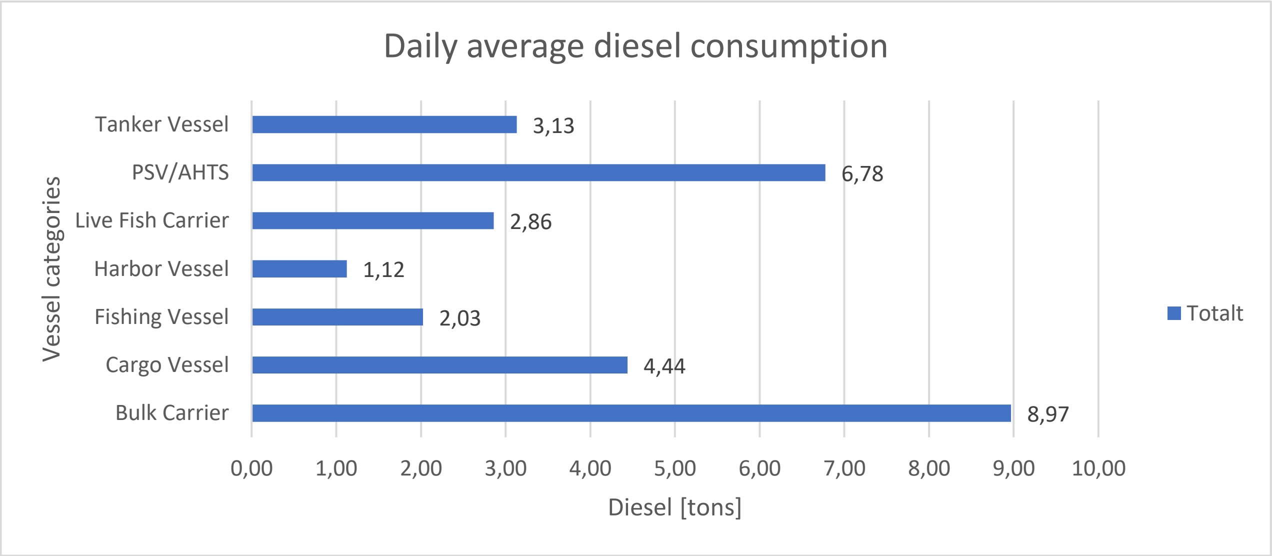


Figure 46 Daily average diesel consumption per ship in each category [58]

From **Figure 47** below, PSV/AHTS are dominant when it comes to the average daily fuel requirements, this is due to the amount of arrivals in the area, as well as the higher energy requirements of those vessel types. The total result of daily bunkered in all three ports is **152,7** tons. This data is shown to give an indication of the fuel demands of each vessel type category in the ports relevant for this thesis.

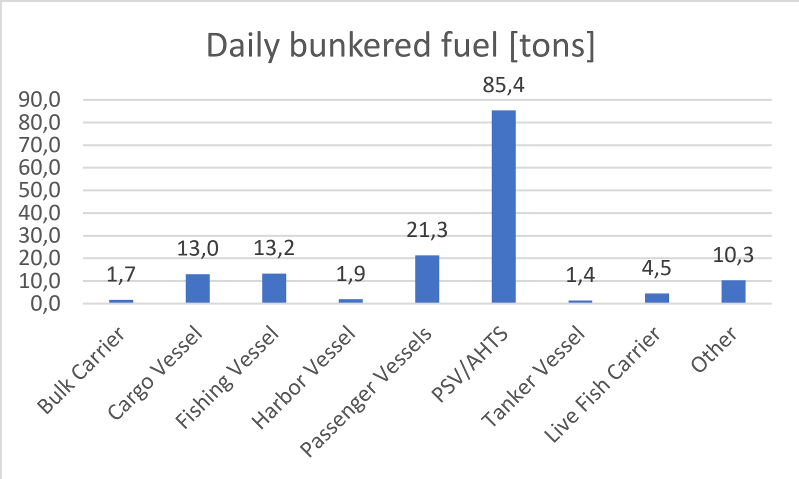


Figure 47: Averages of the daily diesel bunkered by each ship category [58]

3.2.9 Estimating hydrogen-based fuel demand

The estimations of hydrogen-based fuel demand is derived from the fuel calculation model described in chapter **3.2.5**, by using both the bunkering scenarios in Feil! Fant ikke referansekilden. and the fuel type scenarios described below. Combining all of the scenarios and adding them to the data model makes it possible to calculate the fuel demand of each fuel type dependent on each scenario. **Table 11** below summarizes the different fuels relevant for each ship.

Vessel type	Primary zero carbon energy carrier	Secondary zero carbon energy carrier
Passenger vessels	Compressed hydrogen	Liquid hydrogen
Harbour operating vessels	Battery	Compressed hydrogen
Live Fish Carrier	Ammonia	Compressed hydrogen
Coastal fishing vessels	Compressed hydrogen	Battery hybrid
Seagoing fishing vessels	Ammonia	Liquid hydrogen
General cargo vessels	Ammonia	Liquid hydrogen
Tanker vessels	Ammonia	Liqud hydrogen
PSV and AHTS	Ammonia	Liquid hydrogen

Table 11: Table highlighting the relevant hydrogen-based fuel types for each ship category [8]

3.2.10 Fuel Type Scenarios and data used in fuel calculations

The hydrogen fuel scenarios are based on the primary and secondary hydrogen-based fuel types. Each ship category has two specific types of hydrogen-based fuels, and the following scenarios are created to estimate the demand of each fuel type depending on which technology becomes dominant. There are two different scenarios, each with their own percentage of vessels in each category using either primary or secondary fuels. From the table highlighting primary and secondary zero carbon energy carriers[8], most of the primary zero carbon energy carriers are Ammonia, while most of the secondary energy carriers are hydrogen. Therefore, the scenario with primary energy carriers is described as Ammonia weighted, while the other scenario is described as hydrogen weighted. To account for variations in operational patterns and differing requirements [8] both of the two scenarios assume that a quarter of the ships converted to hydrogen-based fuels use the other fuel-option. The resulting scenarios are presented in **Table 12** below.

Fuel type scenarios	Primary Fuel type	Secondary Fuel Type
Ammonia weighted (Primary)	75 %	25 %
Hydrogen weighted (Secondary)	25 %	75 %

Table 12: Fuel type scenarios

3.2.11 Hydrogen-based Fuel demand

The graphs and tables below show the total estimated hydrogen demand in Florø port, Florø base and Måløy based on the bunkering scenarios, and the fuel type scenarios. **Figure 48** is a visual representation of the results from the fuel calculations according to ammonia weighted scenario.

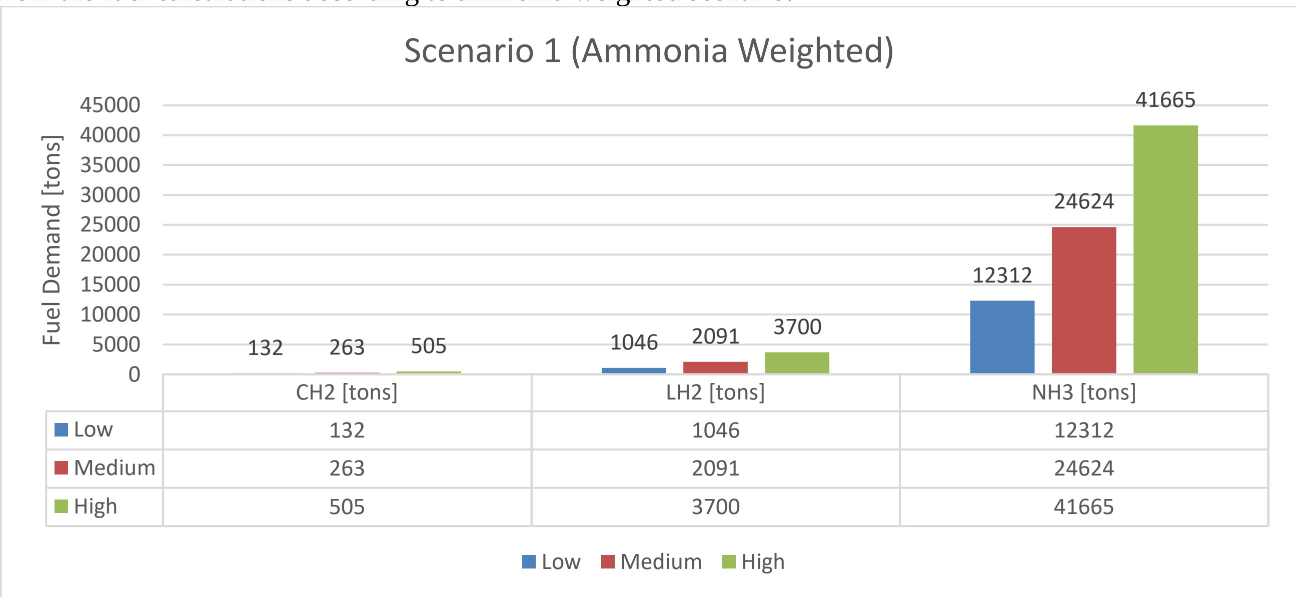
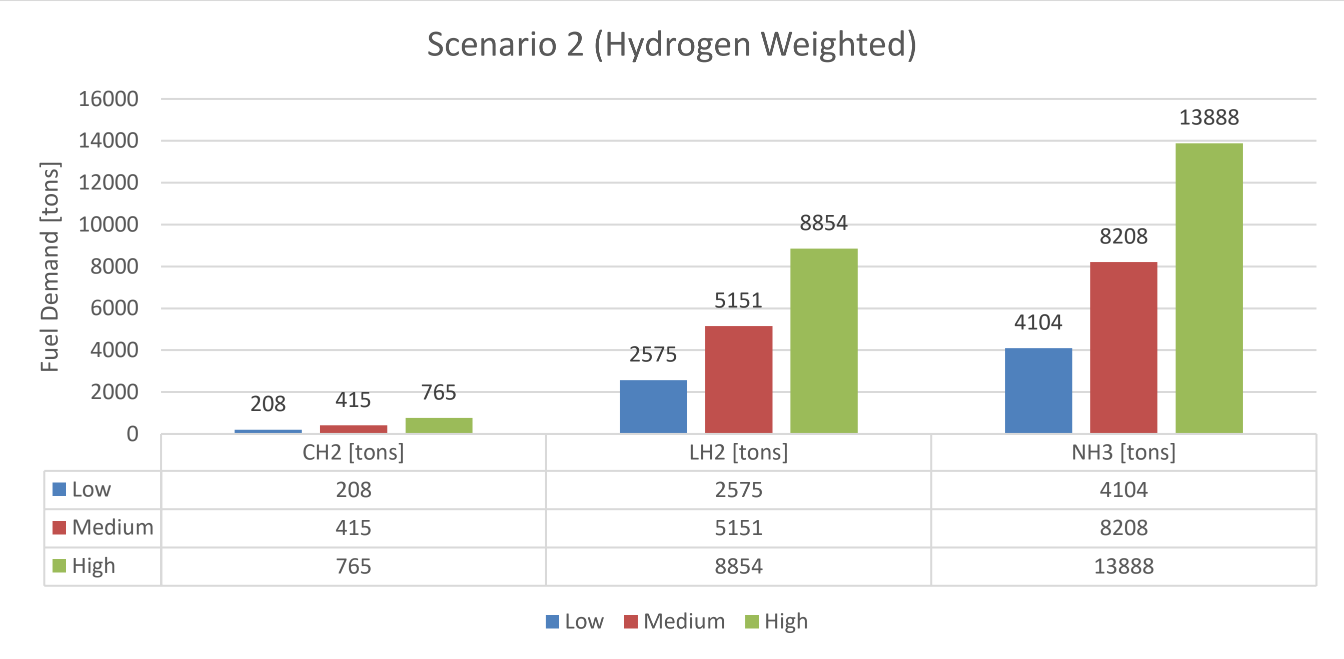


Figure 48: Fuel demand results from fuel type scenario 1

The results of scenario 1 (Ammonia weighted) show a future ammonia demand where 75% of ships run on their primary zero-carbon emission energy carrier. Due to this scenario being directed towards the primary zero-carbon energy carriers of the different vessel types it is considered the most likely of the two fuel type scenarios.

Figure 49 below shows the results from the second fuel type scenario. Scenario 2 is included in the event that hydrogen becomes the industry choice, which is considered less likely because of the constraints previously mentioned with boil-off of LH2, lower volumetric density, and more complex storage systems.



	CH2 [tons]	LH2 [tons]	NH3 [tons]
Low	208	2575	4104
Medium	415	5151	8208
High	765	8854	13888

Figure 49: Fuel demand results from fuel type scenario 1

4. CONCLUSION

From the thesis statement the main goals of this thesis were to evaluate how much hydrogen-based fuel would be required in Florø in order to satisfy the CO_2 emission reduction goals set by the Norwegian government, as well as providing an overview of different hydrogen-based technologies relevant for the ships. After an energy demand analysis of 197 different ships, analyzing the diesel fuel demand made it possible to calculate CO_2 emissions.

The result from the diesel fuel analysis based on 4225 arrivals in Florø, Florø Base and Måløy for the year of 2020 showed a fuel demand average of 152,7 tons every day, where most of this fuel demand was from platform supply vessels and anchor handling tug supply ships.

The CO_2 emissions was calculated from these results, and the "medium" bunkering scenario satisfies the conditions set by the Norwegian government at a 56,41% reduction in emissions equivalent to 81389 tons of CO_2, resulting in a respective energy demand of 140 500 MWh to be satisfied by hydrogen-based fuels. The "medium" scenario considered the most relevant scenario presented in this report and became the primary focus for fuel demand. The results from the fuel type analysis in chapter **3.2.11** based on the "medium" scenario, yielded two different results according to each of the fuel type scenarios. From these it is possible to conclude that the hydrogen-based fuel demand in Florø by 2030 is, according to the assumptions and the scenarios highlighted in each chapter represented by **Figure 50** showing the yearly demand and **Figure 51** showing the daily demand.

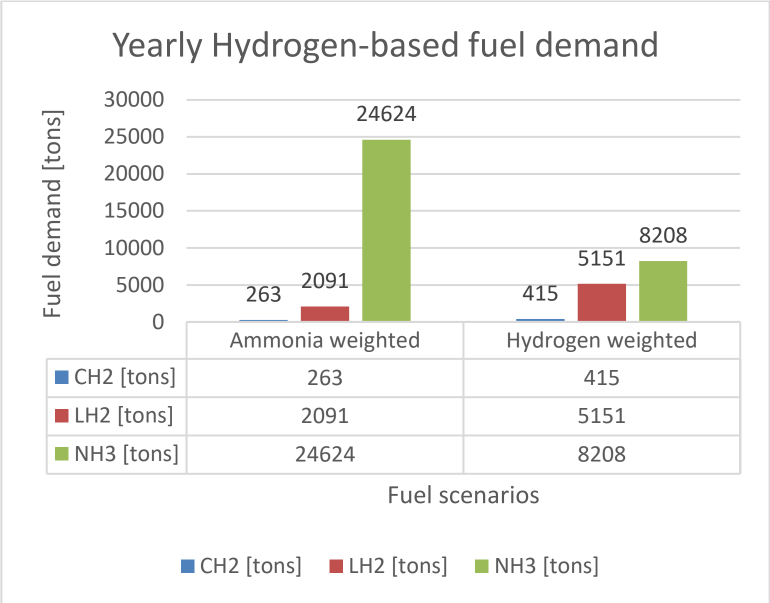


Figure 50: Yearly hydrogen-based fuel demand based on the "medium" scenario

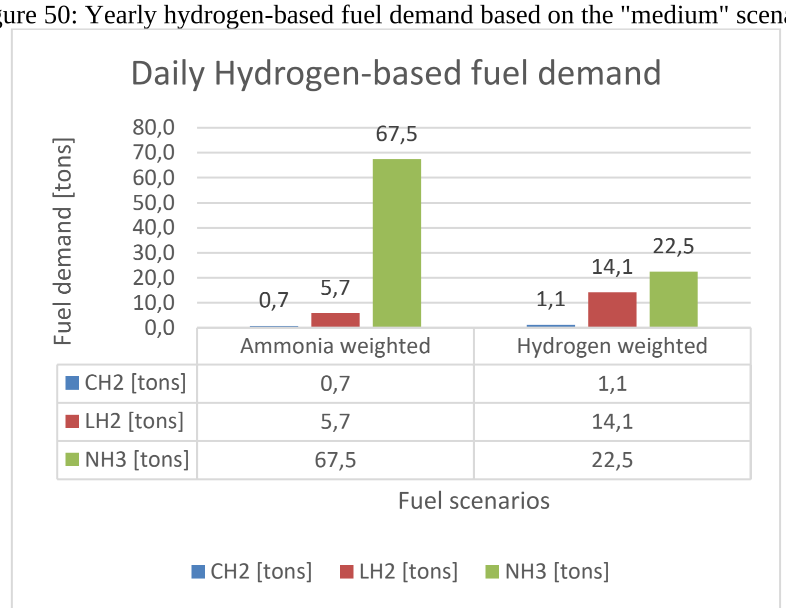


Figure 51: Daily hydrogen-based fuel demand based on the "medium" scenario

The reason for the graphs looking very skewed towards ammonia is due to its much lower gravimetric specific energy as described in **3.1**, resulting in much more mass required for equal energy potential.

As a continuation of this work it would be relevant to assess the LOHC equivalents for hydrogen delivery as time constraints for the scope of this thesis and difficulties in obtaining data made this difficult to assess in a precise enough way to include in this report.

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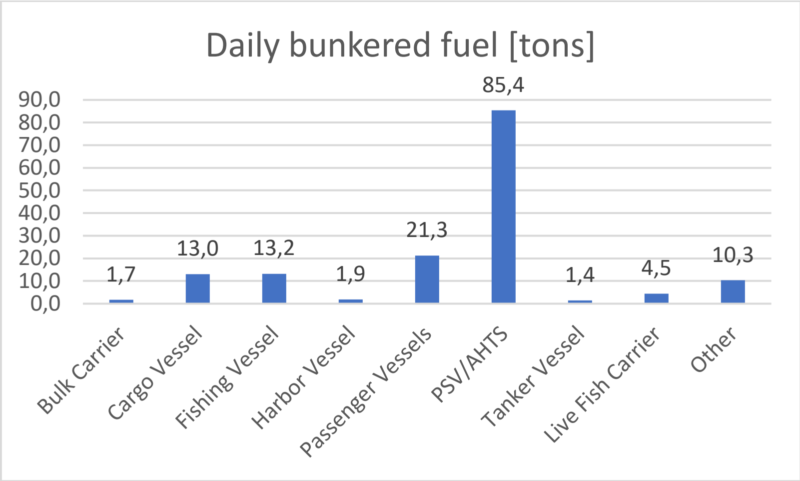
6. Figures, equations and tables



7. Appendix

7.1 Attachments

7.1.1 Data model used for all energy calculations

Excel file: Energy calculation data model

7.2 Additional Ship data

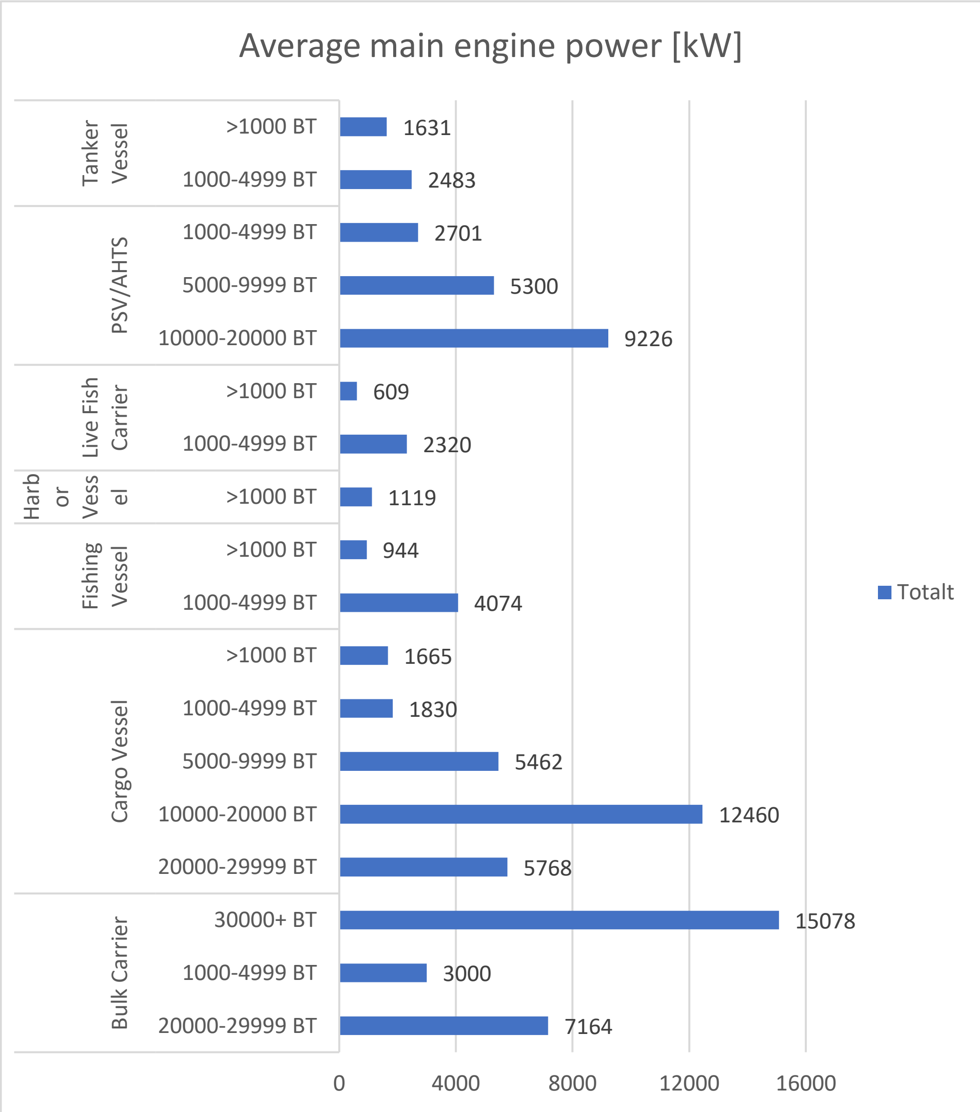


Figure 52: Main engine power distribution of each ship type

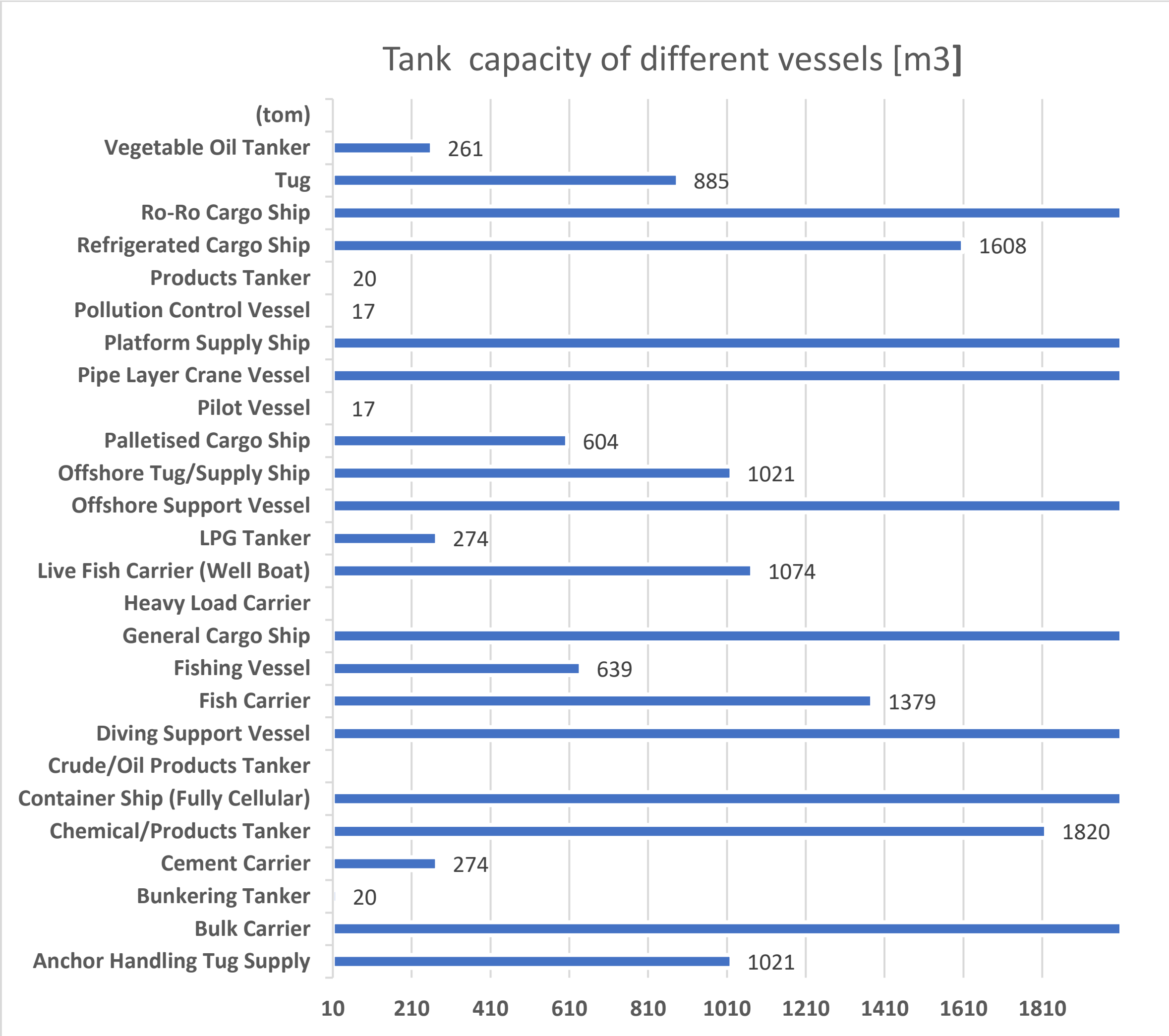


Figure 53: Mapped tank capacities of each ship type