# ZeroTug

## The zero-emission tugboat

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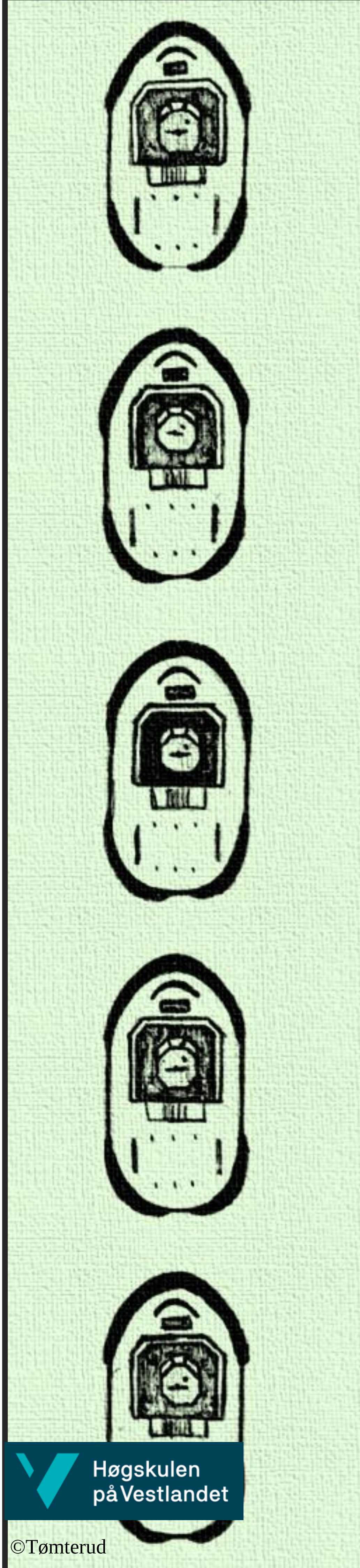

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# Preface

This report is written as a bachelor thesis in the study program Energy Technology, at the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS). The thesis is internally supervised by Dr. Velaug Myrseth Oltedal, and we are thanking her for outstanding help and guidance.

A great thanks to our supervisor Trond Strømgren at Ocean Hyway Cluster for valuable support and a superior collaboration. We would also like to thank Per Wilhelm Saltvedt at Stadt Sjøtransport for beneficial information.

For the research to be achieved, we have been in contact with several companies that have provided us with valuable information. We are grateful for the communication with IFE, Hystorsys, GKN metallurgy, Nedstack and other contacts.

The thesis follows up on an earlier written report of a zero-emission tugboat, which contributed to the interest in this report’s focus. Other factors that have had an impact of the motivation, have been the green transition the world is facing.

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# Abstract

The International Maritime Organization (IMO) has an aim of reducing greenhouse gases (GHG) by 50 % before the end of 2050. If this goal is to be achieved, extensive changes must be made, and all new vessels should be emission-free.

The aim of this thesis is to explore metal hydrides as a storing alternative for hydrogen on a tugboat, which will tow mining masses 27 nautical miles with a propulsion system of 4 MW. In a previous report, Ammonia, LOHC (liquid organic hydrogen carriers), batteries, compressed and liquid hydrogen has been looked at as possible energy carriers on the tugboat. These are briefly presented in this report, in addition to fuel cells and internal combustion engines. It is decided to continue with hydrogen as fuel, since this is the main commercial fuel available in fuel cells today. This gives the possibility of zero emissions as the only release will be water.

An exothermic chemical reaction between hydrogen and metal creates a metal hydride. The hydrogen will be stored in solid form, which decreases the energy carrier's safety issues and becomes one of the safest ways to store hydrogen today. Hydrogen is generally categorized as a dangerous substance and it is therefore important that it is produced, stored and used correctly. The hydrogen will be released from the metal using heat in a controlled manner, and only small amounts of pure hydrogen will hence be available at all times. This reduces the risk of fire and explosions as the minor amounts of hydrogen can easily be vented away in the event of a leak.

Metal hydrides are expensive and heavy due to the metals used in the compounds. The weight is one of the reasons why several companies have given up metal hydrides in the past, but high weight is not necessarily a disadvantage on a vessel. However, the volume of the total storage will be significantly large, even though some metal powders can store more hydrogen per cubic meter than liquid hydrogen and other hydrogen carriers. This external volume demand will require a larger tugboat than originally intended.

The report also addresses the possibility of producing hydrogen at Lutelandet. Electrolyser systems and access to water and electricity have been looked at, in addition to which storage method that will be best suited. Safety around production and bunkering is also looked into.

Finally, metal hydrides will be compared to ammonia, compressed and liquid hydrogen, as they are all seen as possible storing alternatives. The aim is to find the best storage option for the tugboat by, among other things, looking at weight, volume, costs, energy needs and safety.

# Sammendrag

Den internasjonale sjøfartsorganisasjonen (IMO) har et mål om å redusere utslipp av drivhusgasser med 50 % innen slutten av 2050. For at disse målene skal være oppnåelige, må det forekomme omfattende endringer, og alle nye fartøy burde ha null utslipp.

Hensikten med denne oppgaven er å studere metallhydrid som et alternativ for hydrogen-lagring i en slepebåt. Denne skal frakte gruvemasser 27 nautiske mil med et fremdriftssystem på 4 MW. I en tidligere rapport er ammoniakk, flytende organisk hydrogenbærer, batterier, komprimert og flytende hydrogen blitt sett på som mulige energibærere på slepebåten. Disse blir presentert i denne rapporten, sammen med forbrenningsmotorer og brenselceller. Det er bestemt å fortsette med hydrogen som brensel, da dette er kommersielt i brenselceller i dag. Dette gir mulighet for nullutslipp, ettersom det eneste utslippet vil være vann.

Metallhydrider blir dannet gjennom en eksoterm prosess mellom hydrogen og metall. Hydrogenet blir lagret i fast form, noe som reduserer sikkerhetsrisikoene til stoffet og gjør det til en av de sikreste lagringsalternativene per dags dato. Hydrogen er generelt kategorisert som et farlig stoff, noe som gjør at riktig bruk og lagring er svært viktig. Ettersom hydrogenet blir sluppet ut av metallhydridet på kontrollert vis, vil kun små mengder av rent hydrogen være tilgjengelig på ethvert tidspunkt. De minimale mengdene av hydrogen kan enkelt ventileres ut dersom en lekkasje oppstår, dette reduserer risikoen for brann og eksplosjoner.

Metallhydrider er tunge og dyre grunnet metallet som blir brukt i forbindelsene. Vekten er en av grunnene til at flere bedrifter tidligere har gitt opp metallhydrider, men det er nødvendigvis ikke et problem med høy vekt på et fartøy. Det totale lagringsvolumet vil uansett bli stort, selv om noe metallpulver kan lagre på mer hydrogen per kubikkmeter enn flytende hydrogen og andre hydrogenbærere. Dette ekstra volumbehovet krever en større slepebåt enn det som originalt er tiltenkt.

Rapporten adresserer også muligheten for egen hydrogenproduksjon på Lutelandet. Det blir sett på elektrolysesystemer og tilgjengeligheten for vann, og hvilke lagringsalternativer som er passende. Produksjonssikkerhet og sikkerhet ved bunkring blir også gått inn på.

Til slutt vil metallhydrid sammenlignes med ammoniakk, komprimert og flytende hydrogen, ettersom de vurderes som mulige lagringsalternativer. Målet er å finne den beste lagrings-muligheten for slepebåten, ved å studere nødvendig vekt, volum, energibehov og sikkerhet.

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# Abbreviations

AIP – Air independent propulsion

ATEX – Atmospheres explosible

BOP – Balance of plant

CAPEX – Capital expenditure

CCS – Carbon capture and storage

CCU – Carbon capture and utilization

CFD – Computational fluid dynamics

CNG – Compressed natural gas

$CO_2$ – Carbon dioxides

CWL – Construction water line

DBT – Dibenzyltoluene

DE – Diesel electric

DEP – Diesel-electric propulsion

DM – Diesel mechanical

EHC – Electrochemical hydrogen compression

ESD – Emergency shutdown system

FC – Fuel cell

GHG – Greenhouse gases

HDW – Howaldtswerke-Deutsche Werft

HT-PEMFC – High temperature PEMFC

IMO – International Maritime Organization

LCOE – Levelized cost of energy

LOHC – Liquid organic hydrogen carrier

LOX – Liquid oxygen

LPG – Liquid propane gas

LT-PEMFC – Low temperature PEMFC

MDO – Marine diesel oil

MGO – Marine gas oil

$NH_3$ – Ammonia

$NO_x$ – Nitrogen oxides

OPEX – Operating expenditures

PCI – Pressure composition isothermal

PEMFC – Proton exchange membrane fuel cells

PM – Particular matter

PMS – Power management system

SOC – State of charge

SOFC – Solid oxide fuel cells

$SO_x$ – Sulfur oxides

TCS – Tank connection space

TEG – Thermally expanded graphite

# 1 Introduction

A 50 % reduction of greenhouse gases (GHG) by 2050 is the aim of the International Maritime Organization (IMO) [1]. This applies to the maritime industry, and data from 2008 are used as reference. IMO has also determined that the allowed emission of $SO_x$ (sulfur oxides) decreases from 3.5 % to 0.5 %, and $NO_x$ (nitrogen oxides) must be under 2.0 g/kWh according to Tier III (2016), a regulation by IMO.

Globally, the shipping industry are responsible for 2.5 % of the annual total emissions of GHG, which corresponds to 940 million ton of carbon dioxide ($CO_2$) [2]. IMO desires zero GHG emissions before the next century, and they are not alone with setting goals. Norway, for instance, has determined a demand of zero emissions from shipping in the tourist-fjords by the end of 2030 [3]. To be able to reach the aim of IMO and the Norwegian government, all new vessels should be emission-free.

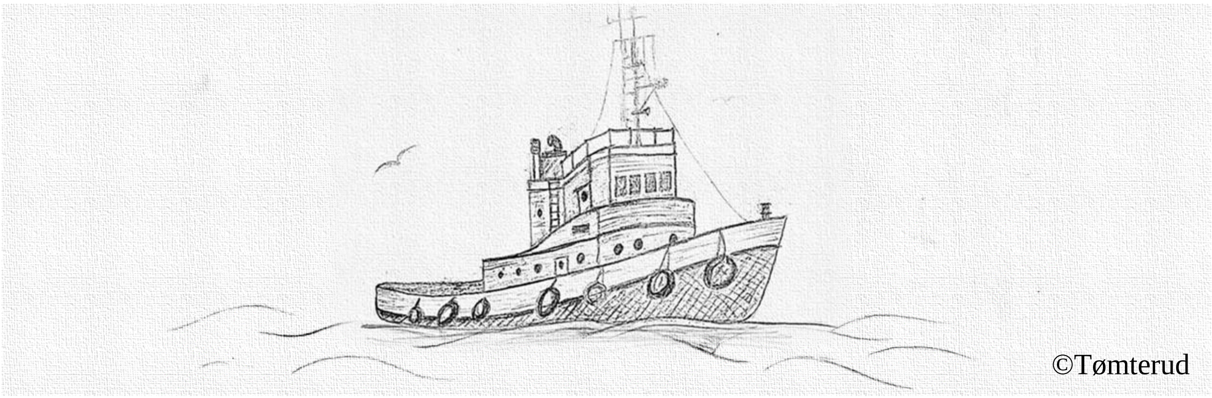
Today, there are approximately 19 000 tugboats worldwide [4]. European tugboats usually have a lifetime of 25 years. The transition to zero emissions will give a large demand for tugboats with low- or zero-emission propulsion systems. The findings in this report will therefore be relevant for vessels outside of Norway as well.

## 1.1 The task

Artic Mineral Resources is planning a mining operation located at Vevring in Førdefjorden, Norway. They want to use a zero-emission tugboat to ship the masses, provided by the mining, to Lutelandet. Tugboats normally operate near the coast which makes it essential for them to function on green fuels with zero emissions.

This thesis will look into the possibility of storing hydrogen as metal hydrides onboard the tugboat, where the aim is to have a propulsion system with zero emissions of $CO_2$. The thesis will also address the necessary land-based infrastructure and estimated costs for both the land-based infrastructure and the tugboat.

# 2. Background information



This study is a continuation of a previous project called *Zero Emission tugboat*, where hydrogen and ammonia in internal combustion engines and fuel cells (FC) were studied. The report also addresses batteries as a single and hybrid solution, liquid organic hydrogen carriers (LOHC) as a safer way to store and transport hydrogen and the possibility to crack ammonia. In this thesis, hydrogen stored in metal hydrides will be compared to the research done in the previous project. A summary of this research is presented below in addition to some general information about metal hydrides.

## 2.1 Summary of the project *Zero Emission tugboat*

To be able to compare metal hydrides with the energy carriers addressed in the previous project, a summary of the most relevant information is included.

### 2.1.1 Hydrogen

Hydrogen has a high gravimetric energy density, but a low volumetric energy density which corresponds to a need of a large storage space [5]. Therefore, hydrogen is usually stored under pressure or as a liquid. Different properties of hydrogen can be seen in *Table 2-1*. For vessels, compressed hydrogen at 250 or 350 bar will probably be normal [6]. Compressing the hydrogen requires 8-13 % of the original energy content [7]. Liquified hydrogen is achieved at -252.8 °C and requires 25-35 % of the original energy content. This might be possible to reduce to 19.2 %, according to the project *Idealhy* of the European Union [7].

| **Hydrogen state** | **Gravimetric energy density** | **Density** | **Volumetric energy density** |
|---|---|---|---|
| | kWh/kg | kg/m$^3$ | kWh/m$^3$ |
| ***1 bar*** | 33.33 | 0.09 | 3.00 |
| ***350 bars*** | 33.33 | 23.00 | 765.90 |
| ***Liquid*** | 33.33 | 70.79 | 2 357.31 |

*Table 2-1: Properties of hydrogen at different conditions* [5] [8] [9]

Hydrogens needs advanced storage conditions, due to hydrogens safety issues. A concentration of 4-75 % is inflammable and detonations can take place when the concentration of hydrogen is about 15-60 % [7] [10]. Liquid hydrogen involves a higher risk than compressed hydrogen because of its low temperatures. Normally, hydrogen gas ascent rapidly, but because of the cryogenic temperatures a leak of liquid hydrogen will make the surrounding air freeze, which will inhibit the gas from rising. This will lead to an accumulation of hydrogen gas that may become detonable. In terms of security, compressed or liquified hydrogen should be stored over deck. This is not possible on a tugboat, because it will prevent the necessary movement of the wire. If these fuels are to be stored under deck, good ventilation is important [11]. This is hard to fulfill as eventual ventilation pipes on the aft deck also will get in the way of the wire. However, the pipes can be placed along the wheelhouse.

### 2.1.2 LOHC

Another way to store hydrogen is in a liquid organic hydrogen carrier. The process consists of adding extra hydrogen to hydrocarbons in a chemical reaction, which is called hydrogenation [7]. This option is safer, and the volumetric energy density is higher than hydrogen, but the gravimetric energy densities are low. In addition, the process of dehydrogenation requires a huge amount of energy, almost 27 % of the original energy content, which needs to be included onboard. Properties of dibenzyltoluene (DBT), a common LOHC, is shown in *Table 2*.

LOHCs are mineral oils, and their properties are comparable with diesel and gasoline [12]. When it comes to transportation and storage, they are less complicated than compressed and liquefied hydrogen. LOHC do not need any compression or special temperatures, and the existing fuel tanks on the vessel can be used, but there is a need of extra tanks for the dehydrogenated oil.

The dehydrogenated oil is the by-product of the dehydrogenation process, which is a catalytic endothermic reaction. This procedure is necessary to separate the hydrogen from the hydrocarbons before use. This process must take place onboard, which means that the extra required energy must be included in the energy supply. Unfortunately, the dehydrogenation energy is high, and it leads to almost a doubling in the needed energy. Since the tugboat already requires a huge amount of energy, this is problematic. The extra energy can come from waste heat or a hydrogen-burner, which has an efficiency of 85 % [13].

| | | **DBT** |
|---|---|---|
| **Volumetric $H_2$ density** | kgH$_2$/m$^3$LOHC | 57 |
| **Heat of reaction** | kWh/kg $H_2$ | 8.9 |
| **Gravimetric $H_2$ density** | wt% | 6.2 |
| **Density** | g/cm$^3$ | 1.04 |

*Table 2-2: Properties of DBT* [14] [15]

### 2.1.3 Ammonia

Ammonia ($NH_3$) is a chemical containing 25 at% nitrogen and 75 at% hydrogen. This indicates a volumetric and gravimetric hydrogen density of 107 kgH$_2$/m$^3$ and 17.8 wt% in liquid ammonia [16]. The energy bound in the compound can either be used directly or indirectly by cracking the ammonia to pure hydrogen. The storage, transportation and production of ammonia is well known, as it is one of the most produced chemicals worldwide and has a distributed infrastructure [17]. The volumetric energy density is higher than for hydrogen, and the same amount of energy will therefore take less space if it is stored as ammonia. This is an advantage due to the poor storage opportunities at the tugboat, even though it will be heavier since the gravimetric energy density is less than for hydrogen. These properties are shown in *Table 2-3*. Ammonia is in a liquid state at atmospheric pressure and -33 °C, which makes it possible to store the fuel in an LPG (liquid propane gas) tank [18] [19].

| **Ammonia** | **Density** | **Gravimetric energy density** | **Volumetric energy density** |
|---|---|---|---|
| | kg/m$^3$ | kWh/kg | kWh/m$^3$ |
| **Liquid (-33 °C)** | 682.8 | 5.2 | 3 550.6 |

*Table 2-3: Properties of liquid ammonia* [20]

Since ammonia is toxic, it is beneficial that the risks of ammonia storage are well understood and have good procedures. The flammability limit is relatively low, 15-27 %, and do not make a huge threat for fires [21]. Ammonia is not explosive itself, but heating the tank will cause overpressure which can lead to an explosion [22].

### 2.1.4 Internal combustion engines

Hydrogen and ammonia can be used in an internal combustion engine. But as for today, ammonia needs to be cracked to hydrogen before use since the combustion engine is still under development. The world's first full-scale test with ammonia as fuel, will happen in 2021 at Stord in Norway [23]. The efficiency of the engine is estimated to be 50 % [24]. Hydrogen on the other hand, can be used in a converted diesel or gasoline engine, or in an engine intended for hydrogen. The efficiency of a standard diesel combustion engine depends on the load and engine size. Wärtsilä diesel engines have for instance efficiencies of around 40-50 % [25]. A hydrogen engine operates with 42 % efficiency [24].

An internal combustion engine produces a lot of heat which creates a chemical reaction between oxygen and nitrogen [26]. This reaction creates $NO_x$ and is one of the reasons why a propulsion system, including combustion engines, cannot be completely emission-free. At the same time, the discharge can be acceptably small. BeHydro has come up with a solution of a selective catalytic reduction system, that gives an output of only 0.2 g/kWh with pure hydrogen as the energy carrier in their engines [27]. This only corresponds to 10 % of the requirement of 2.0 g/kWh. Another known problem with combustion engines is particular matter (PM) and soot. BeHydro has solved this with a particulate filter, which reduces the emissions.

### 2.1.5 Electrical motor

To make the tugboat's propeller spin, mechanical energy is needed. Originally, this energy comes straight from the engine, but today it is also common to use a generator and an electrical motor. An electrical motor converts electrical energy into mechanical energy, and is necessary when using batteries and fuel cells. Some advantages of an electrical motor are the low cost of maintenance, the ability of easily adjusting the speed and a high efficiency [28].

As a precaution, it is advisable to have two or more engines on the vessel [29]. In that way, there will be an engine left for propulsion, even if one breaks down. It is also easier to control the boat with several engines and propellers.

### 2.1.6 Batteries

Batteries are an efficient and straightforward approach to get power for either the whole transit or only for some functions, like peak shavings or internal operations. Even though the output of the fuel cells can withstand variations, it is optimal to operate it at a constant load. To maintain the best possible efficiency of the fuel cells, batteries should be used for peak shaving.

Some calculations are generated to illustrate the volume and weight required when using batteries for the whole transit, these are shown in *Table 2-4*. The battery being used is the Corvus Orca Energy ESS. An operational limit of 30-80 % for the batteries are taken into account in the calculations [6]. The energy capacity needs to include an efficiency of 96 % for the electrical motor.

| | Stacks | Capacity | Height | Depth | Width | Weight |
|---|---|---|---|---|---|---|
| | | kWh | mm | mm | mm | ton |
| **Corvus Orca energy** | 1 | 249 | 3 000 | 738 | 1345 | 3.375 |
| **Corvus Orca energy**<br>**With operational limit** | 148 | 36 900 | 3 000 | 109 224 | 1345 | 500 |

*Table 2-4: Characteristics of Corvus Orca Energy* [30]

A full battery propulsion system will need a volume of 440 $m^3$ and have a weight of 500 ton just for the batteries. The capacity will be reduced during its lifetime, and it is therefore essential to ensure good conditions and cyclic chargings [31].

### 2.1.7 Fuel Cells

In a fuel cell, chemical energy is converted into electricity, which drives an electrical motor. The focus of reducing emissions has led to further development, and the technology is constantly adapting to the maritime sector. There are different types of fuel cells, but the most appropriate for maritime vessels are proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC) [24]. Both cells will produce heat and electricity, and water will be the only emission if the fuel is hydrogen [32].

#### 2.1.7.1 Proton exchange membrane fuel cell

There are two kinds of PEMFC, high temperature (HT-PEMFC) and low temperature (LT-PEMFC), where latter is the traditional one [32]. LT-PEMFC has operational temperatures from 50 to 100 °C, and HT-PEM can have temperatures up to 200 °C. The difference in temperatures is a result of different types of membranes in the two cells. The chemical reaction is the same, where hydrogen and oxygen are converted to electricity and water. *Figure 2-1* shows an illustration of a PEMFC system.

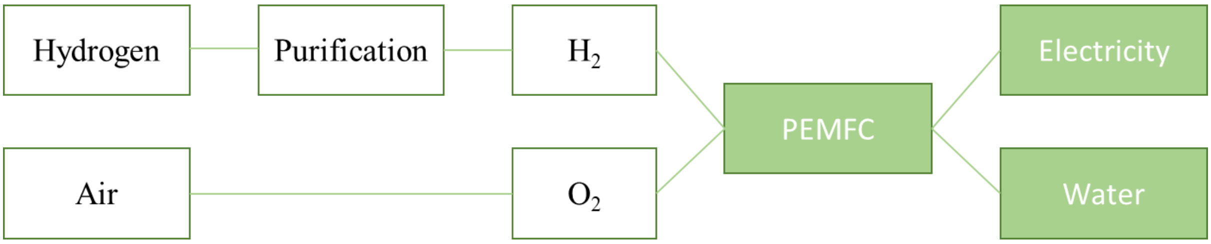


*Figure 2-1: An illustration of a PEMFC system* [32]

The electrical efficiency is around 50-60 % for both fuel cells [32]. With heat recovery, the total efficiency of HT-PEM can be increased. Since LT-PEMFC functions on low temperatures, the fuel cells require pure hydrogen [33]. However, HT-PEM has higher tolerance of fuel impurities due to the higher operating temperatures. It can therefore use hydrogen which is simply reformed from several energy carriers [32]. There are some advantages of HT-PEM compared to the traditional one. However, HT-PEM is more expensive and has lower power density, most likely as a result of less development.

#### 2.1.7.2 Solid Oxide Fuel Cell

The operating temperatures of SOFC is between 700 and 1000 °C [7], and the fuel cells are commonly used in large scale land-based power production [32]. High temperatures lead to high tolerance of fuel impurities [7]. Therefore, some carbon fuels can be reformed inside the fuel cell and be used directly. However, this results in emissions of $CO_2$ and low levels of $NO_x$ [32] [34]. By using excess heat, ammonia can be cracked inside the SOFC and be used directly in the fuel cell. At present, this technology is still under development. There is no data proving $NO_x$ emissions when using ammonia, although ammonia contains nitrogen [17].

The SOFC requires a longer start-up time than the PEMFC and operates most optimal with an even load, which makes the fuel cell less suitable for flexible operations [32]. The fuel cell is also technologically less developed than the PEMFC, but they have about the same electrical efficiencies of around 60 %. However, the total efficiency can reach 85 % or higher with heat recovery and further development [32].

### 2.1.8 Overview and comparison

*Table 2-5* demonstrates a comparison of the necessary volume and weight for fuel cells, combustion engines, batteries, and the electrical motors. While the combustion engine can operate by itself, both the fuel cells and batteries depend on an electrical motor for propulsion. Weight and volume of the electrical motors will therefore need to be added to the fuel cell and battery systems. The table includes the expected quantity of converters and batteries, and it shows the total weight, volume, and efficiencies. The size of the BeHydro engine is only an estimation. Ballard's 200 kW fuel cell module, FCWave, which is specifically designed for maritime vehicles, is used in the calculations [35].

| | | **Fuel cells (Ballard)** | **Combustion engine (BeHydro)** | **Batteries (total)** | **Electrical motors** |
|---|---|---|---|---|---|
| **Weight** | kg | 17 500 | 36 000 | 486 000 | 10 900 |
| **Volume** | $m^3$ | 39.62 | 65.88 | 429.00 | 16.94 |
| **Efficiency (Hydrogen)** | | 0.55<br>(PEM) | 0.42 | – | – |
| **Efficiency (Ammonia)** | | 0.60<br>(SOFC) | 0.50 | – | – |
| **Efficiency** | | – | – | 1.00 | 0.96 |

*Table 2-5: The necessary weight and volume of fuel cells, combustion engines, batteries, and electrical motors* [35] [36] [24] [32]

Batteries will require the highest weight and volume. The weight will be almost 500 ton when the electrical motors are included. Fuel cells have proven to be the best option, because both weight and volume are less for the fuel cells than for the combustion engines, even when the electrical motors are included. In addition, the fuel cells have better efficiency than the internal combustion engines.

The necessary weight and volume of fuel for one trip, with fuel cells as a part of the propulsion system, is calculated by formula (1), (2), (3), (4) and (5):

$$E = \frac{E_{need}}{\eta} \tag{1}$$

$$V = \frac{E}{E_d} \tag{2}$$

$$m = \frac{E}{E_s} \tag{3}$$

$$m_{LOHC} = \frac{m_{H_2}}{wt\%} \tag{4}$$

$$V_{LOHC} = \frac{m_{LOHC}}{D_{LOHC}} \tag{5}$$

*E = energy*
*V = volume*
*m = mass*
*$\eta$ = efficiency*
*$E_s$ = supply energy*
$E_d$ = energy density
D = density
wt% = weight precent $H_2$/LOHC

$E_{need}$ is the needed energy for the tugboat one way. Energy E, volume V and mass m is relative to the fuel and the system. $V_{LOHC}$, $D_{LOHC}$ and $m_{LOHC}$ is depending on the type of LOHC. Wt% is the weight percent of $H_2$ per kilo of the chosen LOCH.

The result of the calculations is shown in *Table 2-6*. PEMFC efficiencies are primarily used, but SOFC efficiencies are used in the calculations with ammonia, since it cannot be used in

PEMFC and using ammonia in SOFC are under development. The efficiencies used are 55 % for PEMFC and 60 % for SOFC. The energy needed for cracking and dehydrogenation is not included. Diesel is used for a comparison as this is the conventional fuel for tugboats. The diesel engine efficiency is in these calculations decided to be 45 % [37]. The volume and weight of the tanks are not included in the calculations.

| | | $H_2$ 350 bar | $H_2$ Liquid | LOHC (DBT) | LOHC (MCH) | $NH_3$ Liquid | $NH_3$ Cracked | Diesel (diesel engine) |
|---|---|---|---|---|---|---|---|---|
| **Energy** | MWh | 32 | 32 | 32 | 32 | 29<br>(SOFC) | 32<br>(PEMFC) | 39 |
| **Volume** | $m^3$ | 42 | 14 | 15 | 20 | 8<br>(SOFC) | 9<br>(PEMFC) | 4 |
| **Weight** | kg | 959 | 960 | 15 482 | 15 583 | 5 641<br>(SOFC) | 6 154<br>(PEMFC) | 3 267.43 |

*Table 2-6: The necessary weight and volume of different fuel for one trip, with fuel cells as a part of the propulsion system* [38]

The table shows that compressed hydrogen has the largest volume demand with 42 $m^3$, but the smallest weight. The necessary amount of ammonia will weigh around six times more than the hydrogen, but it will take up significantly less space with eight to nine cubic meters. However, diesel has a volume demand of only four cubic meters. LOHC gives the highest weight even without the extra energy for the dehydrogenation. The explanation for the high numbers is the low percentage of hydrogen, leading to a great need of LOHC to obtain the required amount of hydrogen.

As of today, there are no fuel cells that can run on ammonia. Hydrogen is the only alternative to fuel. Ammonia and LOHC therefore becomes only storage alternatives for hydrogen. The use of LOHC will not be optimal, due to the high weight and the large amount of required energy for dehydrogenation. In the future, LOHC may be a good alternative, when the needed energy can be taken from excess heat. *Table 2-7* shows a comparison of ammonia and hydrogen.

| | Gravimetric energy density | Density | Volumetric energy density |
|---|---|---|---|
| | MJ/kg | $kg/m^3$ | $MJ/m^3$ |
| **Hydrogen, liquid** | 120.00 | 70.79 | 8 494.80 |
| **Hydrogen, 350 bar** | 120.00 | 23.00 | 2 760.00 |
| **Ammonia, liquid** | 18.60 | 682.80 | 12 700.00 |
| **Ammonia, cracked** | – | 107.00<br>kg $H_2/m^3$ $NH_3$ | – |

*Table 2-7: Comparison of ammonia and hydrogen*

Liquid hydrogen is often regarded more risky than compressed hydrogen, due to the cryogenic temperatures. Moreover, compressed hydrogen has its safety issues and takes up a lot of space. It is safer to store the hydrogen as ammonia than as pure hydrogen, but this is not optimal either. Like LOHC, cracking of ammonia involves a lot of energy, in addition to its toxicity.

## 2.2 Metal hydrides

There are a lot of risks associated with hydrogen, and advanced storage methods are needed. A small leakage can lead to a deadly explosion, and the safety must therefore be a high priority. Relative to other fuels, hydrogen needs larger and more robust tanks. The tanks must withstand all possible stresses that may occur, for instance vibrations or fire. To store liquid hydrogen, tanks tolerating cryogenic temperatures are necessary. On the other hand, storage of compressed hydrogen involves high-pressure tanks.

Due to the mentioned challenges with the storing options addressed in the previous project, metal hydrides will be studied as a possibly safer storage alternative for hydrogen.

An exothermic chemical reaction between hydrogen and metal creates a metal hydride. This can be done by adding hydrogen into a tank of metal powder. The hydrogen molecule will decompose into hydrogen atoms at the metal surface, absorb into the metal, and chemically bond to the crystal structure in a random pattern [39]. This is called the α – phase and is the first step in the hydrogenation process. Throughout this α – phase, the pressure will increase. The next state is the α+β – phase. Here, the hydrogen atoms will orient themselves systematically within the crystal structure without a significant pressure growth.

The last state of the hydrogenation is the β – phase. This is the phase after the metal hydride achieves its saturation point [39]. Even though the metal hydride is saturated, it will be possible to fill the tank with hydrogen until the pressure within the storage is the same as the input pressure. Since this additional hydrogen is not bound in the metal, it will increase the pressure significantly even with small inputs, as can be seen in *Figure 2-2*. A pressure composition isothermal curve (PCI-curve) shows the relation between the pressure and the hydrogen content in the alloy at a constant temperature. A PCI – curve is illustrated in *Figure 2-2*.

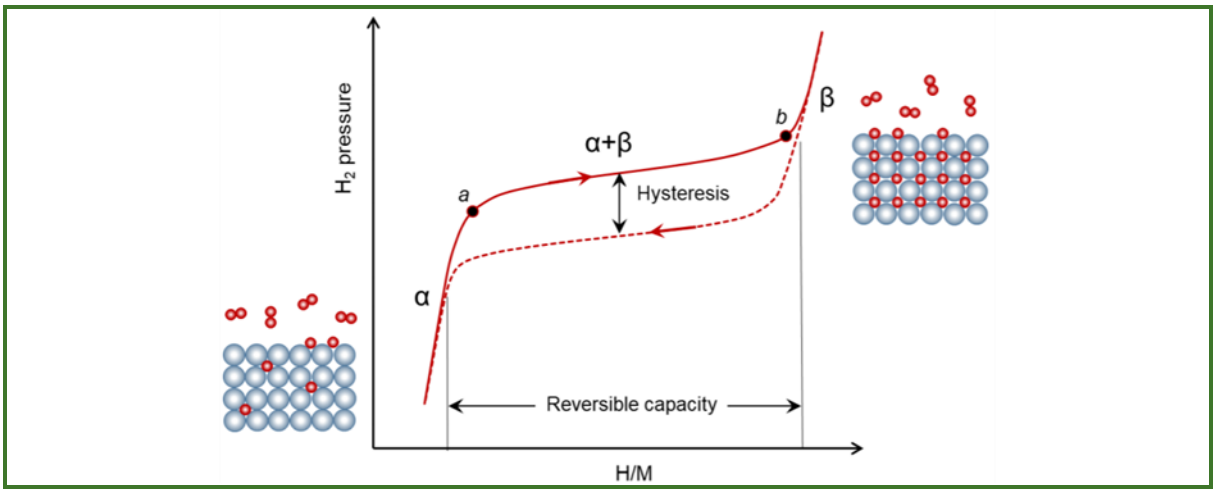


*Figure 2-2: A PCI – curve illustrated* [40]

The red loop in the figure is isothermal. The solid line represents the absorption (hydrogenation), and the dashed line symbolizes the desorption (dehydrogenation), which occurs at different pressures, but at the same temperature. The distance between the two isothermals is called hysteresis [41]. It is beneficial that this is low since it increases the efficiency of the system. The section between *a* and *b*, where most of absorption or desorption happens, is called the plateau pressure. It is beneficial if a metal hydride has this pressure and temperature, close to the environmental conditions.

Onboard the tugboat, it is necessary to get the hydrogen out of the metal hydride before it can be used in the fuel cells. As mentioned, this process is called dehydrogenation and is a desorption of hydrogen. It can take place by pyrolysis or hydrolysis.

Pyrolysis is heat application, preferably excess heat from other machines nearby, like for example fuel cells. Absorption and desorption of hydrogen can be expressed through the reversible general reaction equation (6):

Me = metal
MeH$_x$ = metal hydride
H$_2$ = hydrogen
Q = heat

$$Me + \frac{x}{2}H_2 \leftrightarrow MeH_x + Q \tag{6}$$

Pressure and temperature determine the direction of the equilibrium [39]. The process will shift to the right if the pressure is over the equilibrium pressure, and hydrogenate the metal. If the pressure is lower than the equilibrium pressure, hydrogen will be released, and the intermetallic alloy will return to its steady state. The hydrogen will also be released if heat is added, which makes the reaction shifts left.

Hydrolysis is a reaction with water and is in principle the opposite of a condensation process. [42]. Water is used to split up chemical bonds in an exothermic spontaneous reaction. In addition to hydrogen gas, a by-product is produced in the reaction. This product must be thrown away or regenerated. However, this process is not reversible and therefore not interesting in this case study. Still, it is important to remember the hydrolysis process in case of fire. The metal hydride cannot be extinguished with water or carbon dioxide, due to the risk of a violent reaction [43]. Sand has been shown to be effective in extinguishing a metal hydride fire.

Storing the hydrogen in a solid compound increases the safety and provides a higher volumetric density. The quantity of hydrogen per unit of volume depends on the metal used in the reaction. Most metals can be used, including some alloys, which leads to a large variety of different metal hydrides [42].

The volume percent and weight percent are utilized to differentiate the diverse hydrides. The temperature and pressure necessary for the absorption and desorption, are also important for characterizing the metal hydride. As mentioned, hydrogen has a low volumetric energy density, which corresponds to a need of large volumetric quantities. Therefore, high storage capacity is important. Low pressure and temperatures necessary, in addition to a rapid reaction processes for absorption and desorption, are also an advantage. Other factors that may be important are safety, toxicity, impurity tolerance, and material costs [44]. It is also beneficial if the metal powder can be reused, without getting much damaged and deformed.

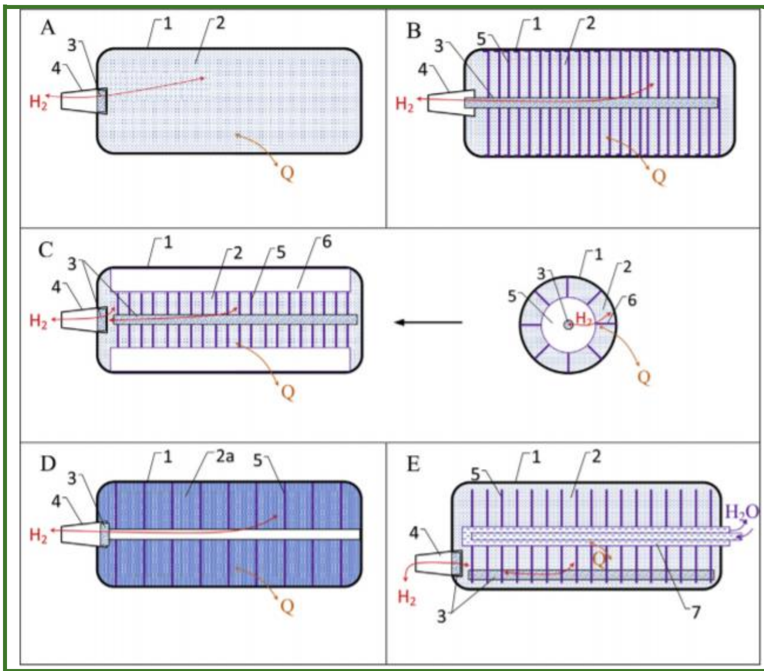
Due to the wide specter of different hydrides, it will be necessary to look at which characteristics are best suited for each application. For example, the metal hydride $LiBH_4$ has the greatest gravimetric hydrogen density of 18 wt% [45]. Furthermore, $Mg_2FeH_6$ has the highest volumetric hydrogen density of 150 kg/m$^3$. However, $BaReH_9$ has the highest ratio of hydrogen atoms per metal atom of 4.5. On a tugboat, it is essential to have a metal hydride with a high volumetric and gravimetric hydrogen density and the possibility of being reused without getting damaged. Low dehydrogenation temperatures and pressures are also important, as it can be obtained onboard through excess heat.

### 2.2.1 Storages

A metal hydride tank is a container holding metal hydride powder, a gas transportation system and heat exchanger components [46]. The tank material can be stainless steel or aluminum alloy.

It is possible to use either internal or external heat and cooling for the dehydrogenation and hydrogenation process, or a combination of both [47]. The best approach depends on the ambient temperature, the required hydrogen pressure and charge/discharge flow rate. Fast charging would for instance need water cooling through internal or external heat exchangers, due to the high heat production.

In *Figure 2-3*, some common designs of metal hydride storages are illustrated [47]. Layout A shows the simplest layout with a storage (1) containing metal powder (2), a gas connecter (4) at the end, along with an integrated gas filter (3). The purpose of the gas filter is to provide a uniform hydrogen distribution to the metal hydride bed and to avoid the metal powder contaminating the gas manifolds [48]. These components are also included in all the other designs, with an improved form of metal hydride and thermally expanded graphite (TEG) (2a) in layout D. Layout B has a tube gas filter instead of the vertical filter in A and D, layout C and E has a combination of both. B also have further improvements such as traversal fins (5), these improves the heat transfer in the metal hydride bed. This element is also included in layout C, D and E, with added horizontal fins (6) in C. The core of the inner heat exchanger (7) in E transports the water flow through the cylinder and heat/cool the material. ($H_2$) demonstrates the hydrogen flow and ($Q$) demonstrates the heat, in and out from the storage.



| | |
|---|---|
| *1* | *Container* |
| *2* | *MH powder* |
| *2a* | *MH TEG compacts* |
| *3* | *Gas filter* |
| *4* | *Gas connector* |
| *5* | *Transversal fins* |
| *6* | *Horizontal fins* |
| *7* | *Core of inner heat exchanger* |
| $H_2$ | *Hydrogen flow* |
| *Q* | *Heat supply/removal* |
| $H_2O$ | *Flow of heating/ cooling water* |

*Figure 2-3: Illustration of different metal hydride storages including components* [47]

### 2.9.1.1 Activation

Most metal hydride alloys need to be activated before it is ready for use [49]. This improves or makes it possible for the absorption of hydrogen to begin. The activation process is the first time the alloy is hydrogenated, where it is filled up with as much hydrogen as possible [44]. The kinetics of the metal hydride are also tested to the maximum.

During the activation procedure the metal is pulverized, this increases the surface-to-volume ratio [49]. The area where hydrogen can be absorbed is then greater, and the absorption and desorption can occur quicker. In addition, the nanostructure of the metal can increase the hydrogen uptake. Smaller grain sizes will increase grain boundaries significantly, these work as gateways and make it easier for the hydrogen to make its approach into the metal.

Some other essential factors are the oxidation layer and other surface barriers [49]. If the activation is done outside the storage, the material will oxidate again, so the material must be activated inside its container or in vacuum. In addition, metal hydrides might ignite in open air due to the humidity [43].

Because of other or more extreme conditions during the activation process, the metal container must withstand higher pressure and temperatures than required for dehydrogenation and hydrogenation. The activation should be done in advance of tank delivery, by the supplier. The supplier will make sure that the container can withstand the required conditions. *Figure 2-4* illustrates how the metal powder is stockpiled in the storage.

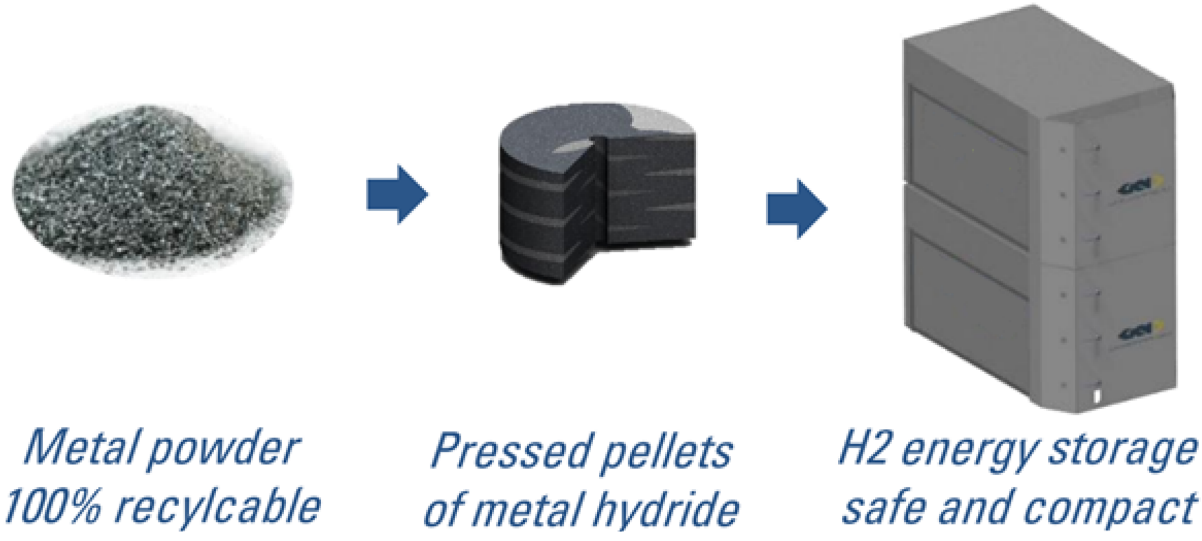


*Figure 2-4: A simple illustration of how the metal powder is stockpiled* [50]

### 2.2.2 Metal hydride in submarines

The traditional propulsion for submarines is diesel-electric, where a diesel engine charges the batteries when the submarine is almost in surface position and use the batteries when it is in submerged state [51]. A propulsion system with no need for air-based oxygen was proposed in 1930, AIP (air independent propulsion). This system allows increased submerged endurance. There are several solutions to store the energy used in the AIP, like in metal hydrides [52].

In 1996, Howaldtswerke-Deutsche Werft AG (HDW) introduced the U212 submarine [53]. This is the first submarine series using a fuel cell system, even though a PEMFC were tested on a Class 205 submarine in 1987 [54]. The fuel cells used are the Siemens proton exchange compressed hydrogen FC. The system gives a quiet and vibration-free submarine which makes it harder to be detected. It can also submerge with little exhaust heat for up to three weeks. The system is not fully hydrogen powered, it is a hybrid system containing a diesel engine. The hydrogen used is stored in 18 metal hydride storages [55]. These allow a storage of 1200 liters and weight 4.4 ton each, which provides a total of 18 MWh. For the heat required for dehydrogenation, the system uses its fuel cells cooling water system. Metal hydrides are in general an advantage due to the safety and weight since submarines require ballast to keep submerged. However, the U212's metal hydride system is so heavy that it requires extra flotation volume, which limits the opportunities of the submarines.

The German submarines U212 and U214 are in use in for instance Germany, Italy, Portugal, Greece and South Korea today. *Figure 2-5* illustrates the fuel cell system used in the two submarine types. In 2017, the Norwegian government decided to replace six already existing submarines with the German U212 [56]. These will not be received earlier than year 2030.

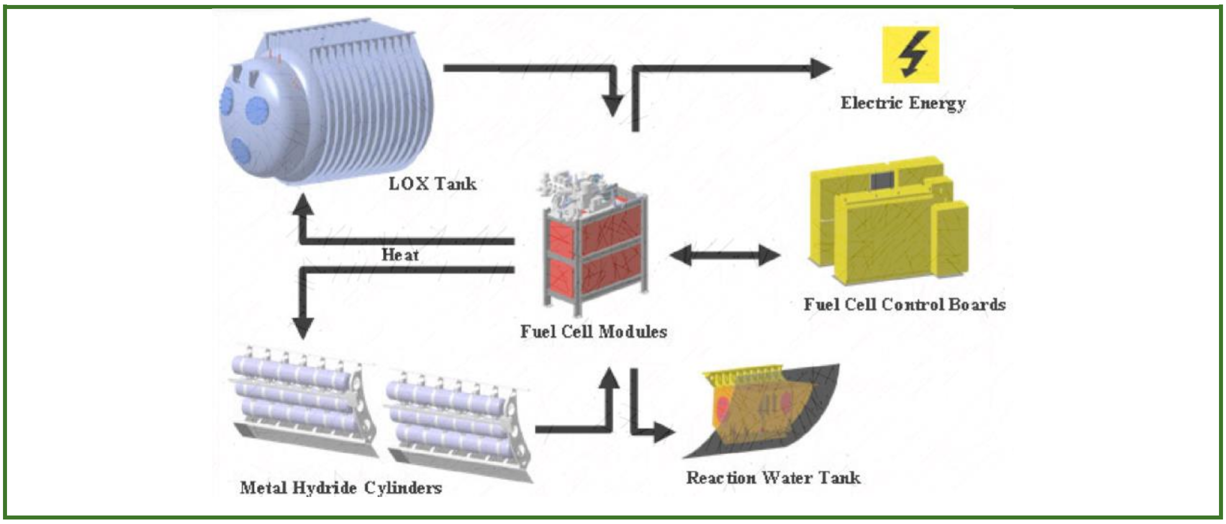
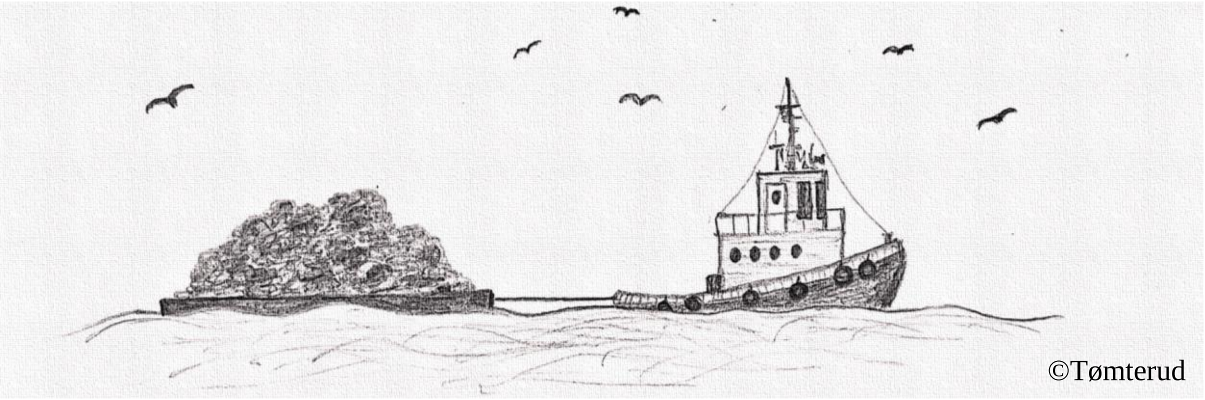


*Figure 2-5: Fuel cell system with hydrogen from metal hydrides* [57], *(LOX, liquid oxygen)*

# 3. Method



In this section, the case study will be introduced with a more technical view, together with delimitations of the case. The delimitations have been applied to simplify calculations, but also due to some lack of information. The methods used for data collection is also being described in more detail.

## 3.1 Case description

This report addresses a tugboat with a 4 MW propulsion system. It is going to move masses by using two barges with 10 000 ton capacity from Vevring, in Førdefjorden, to Lutelandet. It is desirable that the transportation of almost 27 nautical miles happens with zero emissions. This tugboat will be named the ZeroTug in this report. The design of the tugboat will be similar to the Stadt Kinn tugboat, owned by Stadt Sjøtransport.

Based on traditional tugboats, it is expected that the tugboat will have a bollard pull of 70 ton, normally this will require an engine power of 5 000 hp, which is equal to 4 MW. The estimated towing speed has an average of 5 knots, resulting in a towing time of 5.5 hours one way. It is anticipated that the tugboat should be able to tow loaded barges with 80 % engine capacity to Lutelandet, and unloaded barges with 50 % to Vevring. The theoretical energy demand for one round trip is calculated in *Table 3-1*. In accordance with the given data, the tugboat will do one round trip every week.

| **Theoretical energy demand** | | |
|---|---|---|
| **Unloaded barge, with 50% power** | 5.5 h x 4 000 kW x 50 % | 11 000 kWh |
| **Fully loaded barge, with 80% power** | 5.5 h x 4 000 kW x 80 % | 17 600 kWh |
| **One round trip** | | 28 000 kWh |

*Table 3-1: The theoretical energy demand of loaded and unloaded barges*

## 3.2 Delimitation

Since metal hydrides, hydrogen and fuel cells are technologies under development there are no prices available on the open market. This gives a limitation and makes the calculation of the total price for the zero-emission tugboat inaccurate.

The primary focus will be zero emission of $CO_2$. This report discusses the possibility of zero emissions through implementing a zero-emission propulsion system. Improvement of the tugboat’s design may lead to a reduction in emissions, but this will not be looked at in this report.

It is also assumed that there will be sufficient access to water and electricity for the electrolysis and the compressor onboard.

## 3.3 Data collection

The methodology used in this report is a feasibility and literature study, which has a qualitative method as a foundation. In the beginning, the focus was to accumulate knowledge about metal hydrides, to obtain an overview of the field. Since the use of metal hydrides for storage is unconventional, it was assumed that it would be difficult to find all the relevant information. In those areas where reports and scientific articles did not have sufficient information, direct contact with experts was made. Some information is however confidential due to the ongoing research taking place among several experts and companies. Other material is non-existing and cannot be found. Therefore, communication and interviews with specialists via emails, phone calls and meetings are a significant and important part of the primary and secondary data collection.

Otherwise, Engineering Village, Knovel and Google Scholar are used as search engines with suitable keywords to get relevant information, and to find reliable reports. Engineering magazines and company websites are used to get information about the new and relevant technologies, and their development. Several companies are contacted to find the most suitable components and products for our case.

## 3.4 Calculations

In the calculations of daily fuel consumption, one round trip is estimated by one way with loaded barges (17 600 kWh) and one with unloaded barges (11 000 kWh).

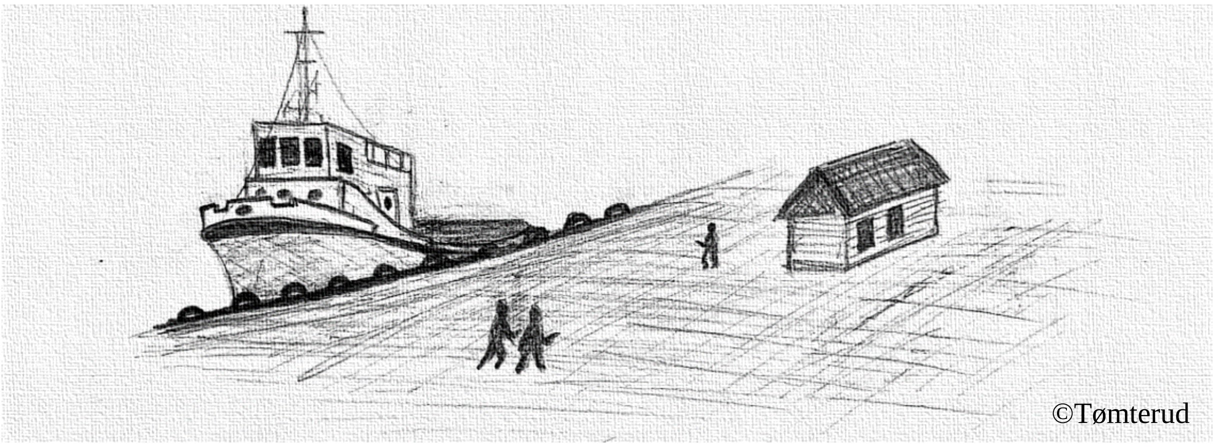
The tugboat will use the components and dimensions of Stadt Kinn as a guidance. *Table 3-2* shows some dimensions of this tugboat. Weight, volume and other adjustment will be done. For instance, Stadt Kinn currently run on MGO (marine gas oil) with a traditionally mechanical propulsion system, but this is replaced with a diesel electric propulsion system with MDO (marine diesel oil), when calculating volume and weight.

| **Stadt Kinn** | | **Length overall** | **Beam overall** | **Depth under CWL** |
|---|---|---|---|---|
| **Dimensions** | m | 34.3 | 11.65 | 4.75 |

*Table 3-2: Dimensions of Stadt Kinn, (CWL, Construction water line)*

To be able to estimate a price difference between a traditional tugboat and the ZeroTug, components that do not necessarily fit the system have been used. The estimation is only to show a simple insight in the cost. For a full and correct assessment, producers should be contacted for accurate prices of each component.

# 4. Results



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Hydrogen storage in metal hydrides have been studied for decades because of their higher safety and high volumetric energy density of hydrogen, some with higher values than liquid hydrogen [58]. Then again, metals are expensive and heavy, which is the reason many companies have rejected this technology [59]. High weight, however, is generally not a problem on a tugboat. This technology is today applied in storage, compression and purification of hydrogen [60]. Furthermore, metal hydride for hydrogen storage on the tugboat will be looked at more closely.

This chapter provides information of some appropriate metal hydrides, metal hydride storages and some examples of fuel cells. The ZeroTug is going to have a diesel-electric propulsion system, in addition to the metal hydride system. Some information about diesel-electric systems is therefore added. This information will also be relevant for the cost estimations in the last subchapter. Batteries will be a part of both systems and is addressed as well.

Later in the chapter, the possibility of self-producing the hydrogen is being studied, meaning that it will be produced by the same company who operates the tugboat. For this to be possible, a certain on-land infrastructure is needed. The safety aspects of the land-based infrastructure and the on-board system are also included in this chapter.

## 4.1 The process briefly presented

In a process of using metal hydrides, the first step is to produce hydrogen. Emission-free production of hydrogen can take place by electrolysis. In this process, where the reactant is water, electricity is used to separate hydrogen and oxygen from each other. An emission-free production requires renewable electricity.

When the hydrogen is produced, it will be stored in tanks on shore. The hydrogen has to be stored under pressure since the pressure used for filling the metal hydride storages must be higher than the equilibrium pressure at the temperature [61]. Even though the pressure will depend on the type of metal hydride, the typical pressure of 200 bar should be more than enough. This is further presented in section *4.7.1 Production.*

The hydrogen is filled from the storage tanks on land into the metal hydride storages onboard the tugboat. The hydrogenation takes place inside the metal hydride storages. This is an exothermic reaction [62], and the storages must therefore be cooled down to prevent the process from stopping [42]. Ideally, the heat can be used as heating onboard. The heat can in principle also be transferred to land, as it arises in the bunkering operation, where the tugboat is moored to quay.

The dehydrogenation process is an endothermic reaction and heat is therefore needed [62]. A heat exchanger can be implemented, as this can be used for both heating and cooling. The required heat can be obtained from the fuel cells through its excess heat, which depends on their operating temperature. How much heat can be recovered will therefore vary, as different fuel cell types operate at various temperatures. Therefore, the pyrolysis should ideally not require higher temperatures than produced by the fuel cell. The amount of required energy will vary between the metal hydrides, where the storage temperature will have a significant impact. A high storage temperature leads to a high required dehydrogenation temperature, as this always is higher than the normal state temperature. It is therefore desirable to have a low storage temperature, close to the ambient temperature, so that the heat from the fuel cell is sufficient.

Furthermore, hydrogen is used as fuel in the fuel cells. Normally, a FC require pure hydrogen and they often need a purifying system. An electrolyser produces almost pure hydrogen and due to the cleansing effect metal hydrides have on the stored gas [63] [42], there is no need for an on-board purifying system. The fuel cells convert chemical energy to electricity, which will be used in an electrical motor [64].

## 4.2 Diesel-electric propulsion system

Lately, several new ships are being constructed with diesel-electric propulsion (DEP) systems [65]. Diesel-electric with batteries appears to be an interesting option [66], and is ABB's recommendation for future tugboats [67]. DEP systems are based on electrical motors and generators driven by the diesel engine [68]. Via electrical generators, the engine power gets transmitted to electrical power for the electrical motors, which drive the shafts of the propeller. If batteries are added, it is possible to store electrical energy which can support the engine's dynamic loads, with short time boosts and peak shaving [66]. One of Wärtsilä's new tugboat designs includes a DEP system with batteries. This system consists of the components described in *Table 4-1*.

| **System** | **Diesel-electric with batteries** | | |
|---|---|---|---|
| **Components** | Diesel tanks | Electrical motor(s) | Inverters |
| | Diesel engine | Electrical generators | Converters |
| | Transformer(s) | Batteries | Process system |
| | | | DC-grind distribution |
| **Fuel** | Diesel | | |

*Table 4-1: Components and fuel in a diesel-electric tugboat with batteries* [66] [24]

An advantage of a diesel-electric system with batteries compared to the traditional diesel mechanic (DM) system, is the increase of the efficiency [66]. According to Wärtsilä, it is an increase of 38 % if the traditional system consists of high-speed engines, and 22 % if the system contains medium speed engines. When batteries are added, engines and propellers can operate closer to their design curve, resulting in a better efficiency and a reduced fuel consumption. This leads to less emissions, but a zero-emission propulsion system will be a better option for the environment. When the propulsion system includes batteries, these can also be used alone for a zero-emission transit in harbor basins.

### 4.3 Battery system

Since the tugboat does not normally run with full power, it is unnecessary to have a 4 MW fuel cell system. It is therefore decided to have a FC system of 3.2 MW. Although, the propulsion system should be able to run at 100 % for parts of the trip. It can be assumed that the time with full force is no longer than 30 minutes each round trip. This can be covered by batteries, with an energy capacity of 0.4 MWh. The power distribution when the tugboat operates at full power for 30 minutes is shown in *Table 4-2*. It is estimated that the ZeroTug primarily will use only half of the available propulsion capacity. The tugboat will operate with 50 % for nine hours. Furthermore, the ZeroTug will operate at 60 % for 30 minutes and 80 % for 30 minutes, each round trip.

| | | Full power, 100 % | Power from fuel cell | Power from batteries |
|---|---|---|---|---|
| **Effect** | MW | 4 | 3.2 | 0.8 |
| **Energy** | MWh | 2 | 1.6 | 0.4 |

*Table 4-2: Overview of the power distribution when the tugboat operates at full power*

The propulsion system will also use the batteries for peak shaving. The batteries get charged when the electrical engine consumes less energy for propulsion than produced from the fuel cells or the diesel engine. They could also be charged at shore, which will give access to cheap electricity. Bringing this energy from shore will result in a lower hydrogen requirement. It will also increase the total system efficiency as the energy does not go through hydrogen to be a part of the energy supply. However, this will not be included in this case study. The stored energy will be used when the energy demand gets higher than the stated operational frequency of the fuel cells.

The battery capacity needed can be covered by four tall packs of Corvus Orca Energy batteries [30]. Due to the limitations of the state of charge (SOC), the battery should use operational limits of 30 to 80 % which results in a 50 % use of the battery capacity. Weight and dimensions of the batteries are shown in *Table 4-3.*

| | Capacity | Height | Width | Depth | Weight |
|---|---|---|---|---|---|
| | kWh | mm | mm | mm | kg |
| **1 tall pack** | 249 | 3 000 | 1 345 | 738 | 3 375 |
| **4 tall packs** | 996 | 3 000 | 1 345 | 2 952 | 13 500 |
| **4 tall pack**<br>30-80 % limits | 498 | 3 000 | 1 345 | 2 952 | 13 500 |

*Table 4-3: Characteristics of Corvus Orca Energy battery packs* [30]

## 4.4 Metal hydrides onboard the tugboat

Due to hydrogens safety issues, it is necessary to come up with a safe way to store it. Storing hydrogen in a solid material is one of the safest ways [42]. There will be only small amounts of free gas available, and a leakage will be much easier to handle as the desorption process is endothermic and the hydrogen will leak out in a controlled manner. The leakage rate will decrease with time if the outside temperature is lower than the temperature necessary for dehydrogenation.

There are three types of metal hydride alloys that suit hydrogen powered tugboats: $AB_5$, $AB_2$ and AB alloys [69]. These are intermetallic compounds with hydrogen storage properties near ambient conditions. The $AB_5$ type, includes alloys like $LaNi_5$. Other A-elements can be Ce, Pr, Nd, Y or Ca, typically rare-earth elements. The B-element Ni can only be partially replaced by metals like Al, Sn, Mn, Co, and Fe. Hydrogen storage properties depend on the composition and the equilibrium pressure can vary from below 1 bar up to 50 bar, at room temperature. The reversible hydrogen capacity is limited to 1.3 wt%, which might be in the lower range for tugboats given their large energy demand. However, it is challenging to achieve a reversible hydrogen capacity of 2 wt% with hydrides in the vicinity of ambient temperatures [70].

The A-element in $AB_2$ alloys is Ti and/or Zr, and the B-element is Mn, Cr, V, Fe or Ni [69]. While the operating pressure for $AB_5$ alloys typically varies between 1 and 50 bar, the pressure for $AB_2$ alloys can vary in a wider range, for example from below 1 bar to more than 1000 bar. It all depends on the composition. Also, the reversible hydrogen capacity can vary between 1 and 1.6 wt%. An example of a commercial alloy which has the reversible hydrogen storage capacity of 1.6 wt%, is the Hydralloy C5. This alloy is fundamentally $TiMn_2$ modified by Zr and FeV. At room temperature, Hydralloy C5 absorbs and desorbs hydrogen at approximately 20 bar and 6 bar, respectively. Class U212 submarines operated by the German navy, has successfully used this alloy in large storage systems.

The AB type alloys are based on a TiFe intermetallic compound and have a reversible hydrogen storage capacity in the range of 1.5-1.7 wt% [50]. Further research is ongoing to figure out if and how this can be increased without losing much of the favorable temperature and pressure conditions. The volumetric energy density for these materials is high, and the gravimetric energy density is low [62], which is an advantage on the tugboat. TiFe is relatively cheap, but it has two pressure plateaus, is difficult to activate and has slow hydrogenation kinetics [69].

### 4.4.1 Metal hydride storages

Not many metal hydride storages are commercial for larger use today. Although, there are a few companies that deliver storages for maritime use. A metal hydride storage is a container holding metal hydride powder, gas transportation- and heat exchanger components [46]. The storage material can be stainless steel or aluminum alloy.

One of the storages that can be used in the ZeroTug is the HY2 Mega_7000 STO from GKN Powder Metallurgy. The system uses TiFe alloy and is expected to be approved in the last quarter of 2021 [50]. Some benefits with these metal hydride storages are no deterioration of storage capacity over time and the product is fully recyclable with only sustainable organic matter. The storages can be stacked on top of and next to each other with insulation between. The number of storages depends on the quantity of needed hydrogen. The dimensions and weight of the storage is shown in *Table 4-4* and can be seen in *Figure 4-1*. The even numbers are based on piled storages.

| **Quantity of HY2 Mega** | **$H_2$ capacity** | **Length** | **Width** | **Height** | **Weight** |
|---|---|---|---|---|---|
| | kg | mm | mm | mm | kg |
| **1** | 260 | 13 000 | 1 350 | 1 450 | 31 000 |
| **2** | 520 | 13 000 | 1 750 | 3 000 | 62 000 |
| **6** | 1 560 | 13 000 | 5 250 | 3 000 | 186 000 |
| **8** | 2 080 | 13 000 | 7 000 | 3 000 | 248 000 |

*Table 4-4: Characteristics of the HY2 Mega system* [50]

The metal hydride storage will reduce its hydrogen flow for approximately the final 30 % of the stored amount of hydrogen [50]. The required hydrogen amount will be covered by only six storages, but the last 468 kg will have a slower dehydrogenation. To gain access to the needed hydrogen at the appropriate flow rate, more storages are required. For a constant flow over the whole transit, eight storages will be needed. With fewer units, it is necessary to use some of the additional battery capacity or the tugboat might have to run at lower speeds. If wanted, the number of batteries can be increased to maintain the electrical power when the hydrogen flow is being reduced.

*Figure 4-1: HY2 Mega system component of GKN Powder Metallurgy* [50]

The metal hydride storage can provide a constant hydrogen flow from storage to a fuel cell through thermal management [50]. In case of sudden changes in power, the auxiliary battery can be utilized. The maximum loading pressure should be no more than 45 bar, if the pressure is higher than this, a safety valve opens and releases the pressure [50]. However, the pressure must be higher than the equilibrium pressure of the metal hydride, the difficulties related to this is addressed in section *4.7.3 Bunkering*.

When the metal hydride is being filled, a cooling energy of 4 kWh per kg $H_2$ is required [50]. This can be provided by supplying cold water with temperatures between 5 and 20 °C, depending on the liquid flow rate. This is to dissipate the heat generated during the hydrogenation as it is an exothermic process. The same amount of energy is needed for the dehydrogenation process, this should be provided from the same liquid that is cooling the fuel cell. The liquid temperature should be 55 to 70 °C [50].

Theoretically, high pressure will diffuse towards low pressure. The inlet pressure of the fuel cell should therefore always be lower than the dehydrogenation pressure of the metal hydride tank. The diffusion rate will increase when the pressure difference is high, and decrease when it is low. If the pressure equalizes, no hydrogen will be delivered to the fuel cell. The dehydrogenation pressure of the metal hydride storage can be as low as 1 bar, this creates a limit for the possible input pressure of the fuel cell [50].

## 4.5 Fuel cell systems

For the hydrogen demand to be as low as possible, it is essential that the fuel cell fits with the HY2 Mega storage. The inlet pressure of the fuel cell should ideally be lower than 1.5 bar to achieve a diffusion flow due to equilibrium. If this is not the case, there should be placed a compressor between the metal hydride storage and the fuel cell to be able to use all the stored hydrogen. A compressor will cause a higher energy demand, and hence more costs. The two options, with and without a compressor, will be looked at by presenting Nedstack's and Ballard's fuel cells.

### 4.5.1 Nedstack

The Nedstack FCS 13-XXL has a rated power of only 13.6 kWe, but like other fuel cells, several stacks can be merged [71]. The tugboat will need 247 Nedstacks to cover the need of 3.2 MW. The characteristics of the fuel cell is shown in *Table 4-5*.

| | Rated power | Height | Width | Depth | Weight |
|---|---|---|---|---|---|
| | kWe | mm | mm | mm | kg |
| **Nedstack** | 13.6 | 288 | 196 | 604 | 41 |
| **247 Nedstacks** | 3 211 | 288 | 196 | 149 188 | 10 127 |

*Table 4-5: Characteristics of Nedstack fuel cell stacks* [71]

Other characteristics which make the fuel cell desirable is the possibility of a low hydrogen inlet pressure of 0.3 barg and the cooling nominal temperature of 65 °C [71]. These factors match the requirements of the HY2 Mega storages.

To ensure a safe, functional and stable process, the fuel cell require a system involving sensors, controls, converters and other components. These components are included in a balance of plant (BOP), which is necessary for the fuel cell stack to function. The BOP and the FC stacks are combined in an integrated fuel cell power system. Nedstack has developed such a system, called PemGen, which includes for instance the PEM fuel cell module, a safety system, and a thermal management system [72]. In *Figure 4-2,* an illustration of an overall FC ship concept is presented [73]. The green and blue squares are the PemGen system, while the rest are components needed for the fuel cell to work properly.

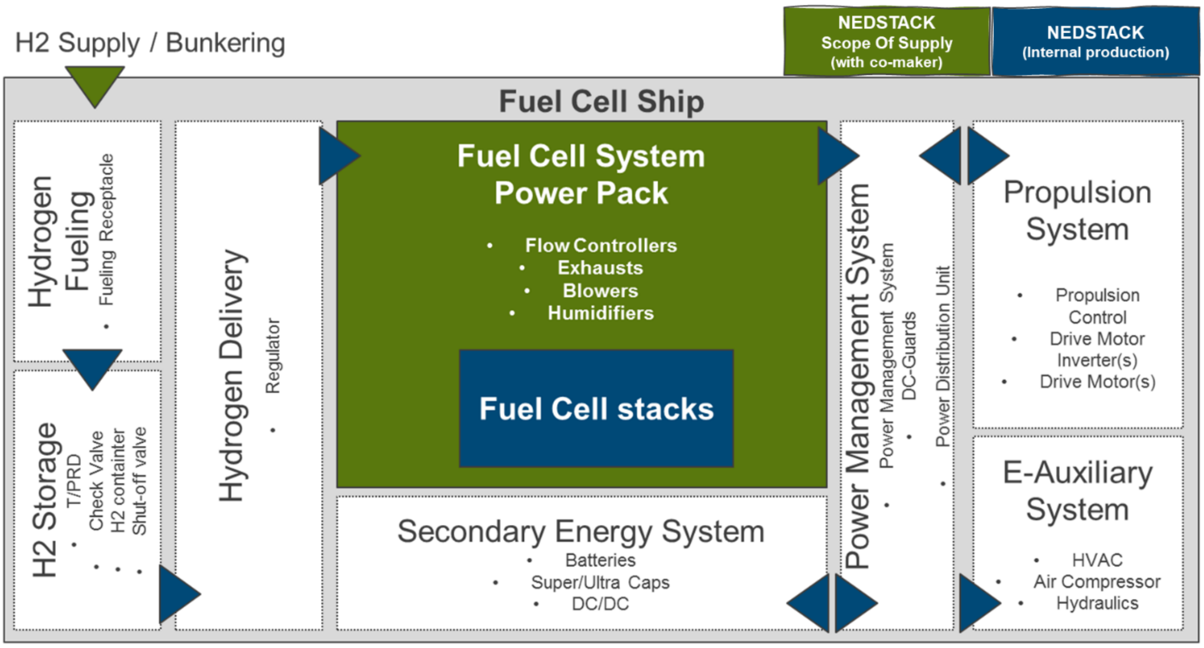


*Figure 4-2: An overall concept of a FC ship* [73]

PemGen MT-FCPI-500 and MT-FCPI-100 are maritime fuel cell power installations containing Nedstack FCS 13-XXL fuel cells and necessary BOP systems. The weight and volume will therefore be higher than the calculations in *Table 4-5*. Calculations for a suitable system onboard the ZeroTug, is presented in *Table 4-6*. This includes a total of 384 Nedstacks, which is 137 more than calculated in *Table 4-5*. The power fuel systems are oversized to make sure that the fuel cell will function as stated during its lifetime [73]. The reason for this is intern power supply, and that the fuel cell installations protect against wear and tear, and poorer production through regular use. The fuel cells have a nominal consumption of 59 kg/MWhe

[74]. To achieve the energy demand of one round trip, there is a need for at least 1690 kg hydrogen.

| | Stacks | Rated power | Height | Width | Depth | Volume | Weight |
|---|---|---|---|---|---|---|---|
| | | kWe | mm | mm | mm | $m^3$ | kg |
| **MT-FCPI-500** | 60 | 500 | 2 900 | 2 440 | 6 060 | 43 | 15 000 |
| **MT-FCPI-100** | 12 | 100 | 2 090 | 1 100 | 2 010 | 5 | 2 500 |
| 6x MT-FCPI-500<br>2x MT-FCPI-100 | 384 | 3 200 | 4 990 | 3 540 | 40 380 | 713 | 95 000 |

*Table 4-6: Characteristics of PemGen MT-FCPI-500 and MT-FCPI-100 fuel cells power systems* [74] [75]

The volume demand of the eight storages will be significant for the tugboat since 713 $m^3$ corresponds to a 9-meter sided cube.

### 4.5.2 Ballard

Ballard's 200 kW fuel cell module, FCWave, has been designed specifically for maritime operations, such as ferries [76]. According to Ballard, it is possible to scale this system from 200 kW to several MWs. The PEM fuel cell module has a system efficiency of 55 % [35], which gives a hydrogen demand of 1 560 kg to cover the energy requirement of 28.6 MWh for one round trip. To achieve 3.2 MW by using this fuel cell, 16 modules are required. *Table 4-7* provides an overview of the weight and volume of these. The BOP is included in the modules.

| | Modules | Rated power | Height | Width | Depth | Volume | Weight |
|---|---|---|---|---|---|---|---|
| | | kWe | mm | mm | mm | $m^3$ | kg |
| **FCwave** | 1 | 200 | 2 200 | 738 | 1 220 | 2 | 875 |
| **FCwave** | 16 | 3 200 | 2 200 | 11 808 | 1 220 | 32 | 14 000 |

*Table 4-7: Properties of the FCWave module* [35]

An operation lifetime of 30 000 hours is expected [77]. Using the hydrogen propulsion system for 12 hours every week, the module will have a lifetime of 48 years. The FCWave has a maximum cooling temperature of 65 °C, which indicates that the fuel cell matches one of the requirements for the HY2 Mega storages [35]. However, the required $H_2$ inlet pressure is 3.5-5 barg, which does not fit the HY2 Mega system. With this solution, more than 30 % of the stored hydrogen cannot be used due to pressure diffusion [50]. Therefore, it will be necessary with for example electrochemical hydrogen compression (EHC) between the metal hydride storage and the fuel cells. The need for a compressor gives more complexity and expense to the system.

Not all compressors can manage to compress from such a low inlet pressure as 1.5 bar. HyET H2 HCS-500 is a suitable compressor introduced by HyET Hydrogen [78]. This stack can be scaled up to a system that can compress a given amount of hydrogen. It can have inlet pressures lower than 1 bar and outlet pressures up to 875 bar. An HCS-500 compressor assembly can be built to compress for example 1 500 kg hydrogen each day. If this is the case, it will have a volume of 13.5 m$^3$. Other properties are presented in *Table 4-8*. The ZeroTug needs 60 kg more hydrogen, so the compressor might need to be slightly larger.

| | **Hydrogen capacity** | **Energy consumption** | **Inlet pressure** | **Max. outlet pressure** | **Measures (L/W/H)** |
|---|---|---|---|---|---|
| | kg/day | kWh/kgH$_2$ | bar | bar | m |
| **HyET H2 HCS-500** | 1 500 | 3.5 | <1 | 875 | 2.8/ 2.1/ 2.3 |

*Table 4-8: Properties of an HCS -500 compressor assembly which can compress 1 500 kgH$_2$/day* [78]

There is a significant difference in the volume and weight between the two fuel cells. Nedstack's system, with its 713 m$^3$ and 95 ton, is 22 times larger and almost 7 times heavier than Ballard's system. The reason for this might be that the Nedstack systems are based on industrial components and that it has a lower hydrogen inlet pressure, while the Ballard system may use automotive equipment. The Ballard system does not necessarily have its stated power at its end-of-life, like Nedstack's system does. If this is the case, there is a need for some more stacks of the FCWave, if it is desired to have the same capacity throughout the lifetime. The volume demand of the Nedstack system will require a significantly larger design than intended, which means that the tugboat may not be able to operate at the desired location. Ballard's FCWave will be used further on as the Nedstack system seems to require too much space.

## 4.6 On-board system

The propulsion system of the tugboat will consist of two systems. Hydrogen will be used as fuel for the main system, and MDO will be used for the backup system. A backup solution can be beneficial if the tugboat will be used for longer distances or other assignments than originally intended. In addition, it can be a security in the event of any faults in the main system. The backup system can be a diesel electrical system with batteries, as this is considered to be attractive in the future tugboat marked due to the increased efficiency and less emissions compared to a DM system. Consequently, a diesel tank must be included on the tugboat. Normally, Stadt Kinn has a MGO tank with 270 m$^3$ capacity [79], this is not necessary for the ZeroTug and will therefore be reduced to 100 m$^3$. *Table 4-9* shows an overview of the main components in the different systems. External batteries are added in the FC system, since there is a need for more battery capacity.

| System | Diesel-electrical with batteries | | Fuel cell with batteries |
|---|---|---|---|
| **Components** | Diesel tanks<br>Diesel engine<br>Electrical generators<br>Electrical motor(s)<br>Batteries<br>Process system | Transformer(s)<br>Inverters<br>DC-grid distribution | Metal hydride storages<br>Fuel cells<br>Power management<br>Batteries<br>Process system<br>DC- grid distribution<br>Electrical motors |
| **Fuel** | MDO | | Hydrogen |

*Table 4-9: Components and fuel of the main system and the backup system for propulsion* [66] [24]

*Figure 4-3* demonstrates a simple representation of the ZeroTug's propulsion system, where the main system holds the darkest color. To avoid wear and tear, the fuel cells and the diesel engine should ideally operate at as constant frequency as possible. Both systems will therefore have batteries for peak shaving. As shown, both systems can use the same electrical motors, and as mentioned there will be two of them in case of failure. Preferably, the same batteries should be used for both propulsion systems. In this way, some volume and weight can be cut. The power management system (PMS) is controlling the power distribution in the systems and makes sure all the components work together [80].

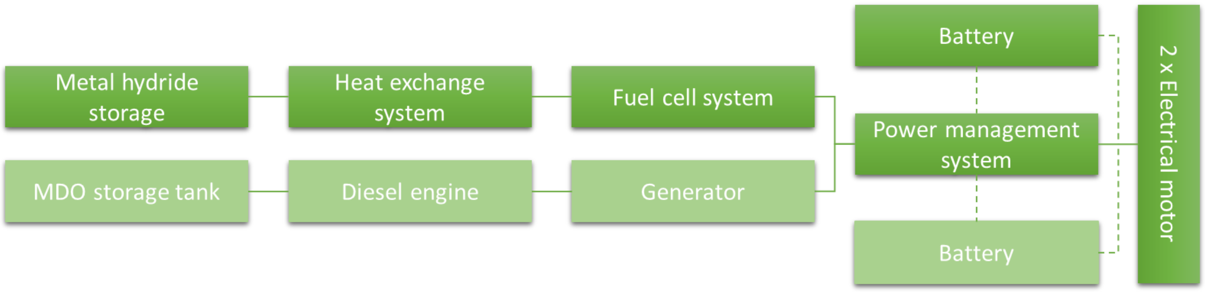


*Figure 4-3: Simplified representation of the propulsion system*

### 4.6.1 Safety onboard

As mentioned, hydrogen is very reactive and must be treated carefully. Since the metal hydride storages are going to be located below deck, they should be placed inside a secure room that can provide good ventilation and protection against fire and other external impacts. There should also be a high ventilation mast above deck, to lead the hydrogen away from the vessel. If there are many pressurized cylinders stored or many connected components, the number of connection points will increase, which means more potential leakage points. To avoid an accident, it is important to limit these points. This can be done by building components like regulators, valves and other potential leakage sources inside a tank connection space (TCS) [81]. A TCS is a gas tight room with an inert gas [82]. If there is a leak of hydrogen inside, the gases will not react with each other [83]. It should be possible to start a controlled leak from the TCS [82].

A computational fluid dynamics (CFD) analysis can simulate where the hydrogen will diffuse in the event of a leak, which can picture the consequences of different outcomes. It should also be leak detectors and hydrogen sensors onboard [11]. Since human errors often are the source of the accidents [84], it is important that the crew is aware of the hydrogen risks, its properties and are properly trained to handle a hydrogen system. For example, to ensure no use of electrical components near the hydrogen storages.

## 4.7 Land-based infrastructure

Among all the world's chemicals, ammonia is one of the most produced. Hydrogen is used in this production, and is therefore produced in large amounts every year. However, only 4 % of produced hydrogen is offered in the open marked [7]. For the substance to be used as a potential fuel, a certain infrastructure on land is needed.

The required amount of hydrogen for the ZeroTug is approximately 1 560 kg each week. This is based on one trip with the needed energy for fully loaded barges and one trip with unloaded barges. As it can be challenging to completely empty the hydrogen tank, it should contain more hydrogen than required. It is assumed that an extra amount of at least 10 % is needed in the land-based storage, which results in about 1 720 kg stored hydrogen. Due to the low volumetric energy density of hydrogen, it may be necessary to convert the hydrogen state after production. This requires energy and will therefore increase the expenses.

Calculations of volumes have been made with hydrogen in different states, these are shown in *Table 4-10*. The need of 1 720 kg stored hydrogen has been used for the volumetric estimations. However, since the extra 10 % are only to be produced once, the weekly production will be 1 560 kg, and the energy demand are estimated through this quantity.

The required storage space will be huge with hydrogen at 1 bar, due to the low volumetric density of hydrogen. As mentioned, compressing and liquifying of hydrogen require energy.

Similarly, dehydrogenation, with its huge energy demand, is necessary with LOHC and Ammonia. The energy required for each process is also shown in *Table 4-10*.

| Hydrogen state | Energy demand | Density | Volume |
|---|---|---|---|
| | kWh | kg/m$^3$ | m$^3$ |
| **1 bar** | 0 | 0.09 | 19 111 |
| **30 bar** | 2 080 | 2.37 | 726 |
| **200 bar** | 3 640 | 15.60 | 110 |
| **LOHC (DBT)** | 13 884 | 57.00<br>kg $H_2$/m$^3$ DBT | 30 |
| **Liquid** | 12 999 | 70.79 | 24 |
| **Ammonia** | 9 828 | 107.00<br>kg $H_2$/m$^3$ $NH_3$ | 16 |

*Table 4-10: Volumetric demand of on-land hydrogen storage, with hydrogen in different states* [85] [86]

Compressed hydrogen at 200 bar looks like the best alternative, due to the reasonably low volume demand and the relatively low energy requirement for conversion. At the same time, the available space on shore is around 30 000 m$^2$ [87] , which means that there is room for a sizable storage facility. Therefore, storing at 30 bar can also be an alternative. Which condition the hydrogen should be in, will depend on how much space should be used for storage and the output pressure of the electrolyser.

*Figure 4-4* gives a simple illustration of the infrastructure on land. Further on, these elements will be looked into more closely. The safety regarding the on-land infrastructure is also addressed.

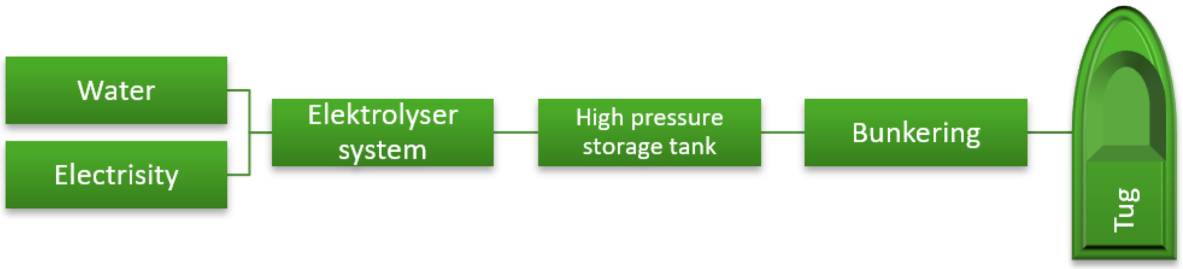


*Figure 4-4: Illustration of the on-land infrastructure*

### 4.7.1 Production

Worldwide, there is an annual demand of about 70 million ton hydrogen [11]. To produce this amount, three percent of the global energy consumption is required. 76 % of the international hydrogen production is produced by steam reforming of natural gas, and 23 % is produced by gasification of coal. These two methods are highly polluting. Today, both approaches occur with no CCS (carbon capture and storage) or CCU (carbon capture and utilization). Hydrogen produced by these methods therefore accounts for as much as 830 million ton of $CO_2$ emissions. To be able to have an emission free production of hydrogen through steam reforming and gasification, it is essential to include CCU or CCS. The hydrogen can also be produced through water electrolysis with renewable energy to achieve zero emissions. Currently, only one percent is produced through electrolysis.

The production of hydrogen can be done on or off site, but in this case, it will be on site by electrolysis from electricity to avoid unnecessary transport and emissions. The production is assumed to be run by the same company that operates the ZeroTug, as self-production of larger quantities is generally cheaper than buying the product from others.

There are two main types of electrolysers dominating the marked today, PEM and Alkaline [7]. The earliest electrolyser used was the alkaline and has been used for over 100 years, but they are both mature systems. PEM electrolysers might have a greater potential for price reduction and efficiency increase, but for now, alkaline is the cheapest alternative.

An alkaline electrolyser from NEL can be utilized. The needed storage demand of 1 720 kg will only be produced once, as the extra 10 % never will be taken out. The same principle applies to the extra 30 % in the metal hydride storage. To achieve a cost-efficient production system, the stated production capacity of the electrolyser should come close to the needed amount of hydrogen. For the needed production of 1 560 kg per week, A300 will be sufficient. More extensive electrolysers as the A3880 can be used if there is a desire for a larger production than needed, as extra hydrogen can be distributed to the market. According to NEL, this is the most energy efficient electrolyser in the world. Moreover, it is the world’s smallest electrolyser for high capacity at 200 barg [63].

The electrolysers from NEL give a hydrogen purity of 99.999 % [63], which is good as metal hydride storages and fuel cells require pure hydrogen. Further properties can be seen in *Table 4-11*.

| **Specifications** | **Dimensions** | **Electricity demand** | **Net production rate** | **Outlet pressure** | **Purity** |
|---|---|---|---|---|---|
| | $m^2$ | $kWh/Nm^3$ | $Nm^3/h$ | barg | % |
| **A300** | 200 | 3.8 – 4.4 | 150 – 300 | 1 – 200 | 99.999 |
| **A3880** | 770 | 3.8 – 4.4 | 2 400 – 3 880 | 1 – 200 | 99.999 |

*Table 4-11: Properties of two of NEL’s electrolysers, A300 and A3880* [63]

The electrolyser alone has an energy demand of around 48 kWh/kg, but the whole system will require about 55 to 60 kWh/kg [88], due to an extra energy need from the compressor and other auxiliary systems. This will result in a daily energy demand of 88 000 kWh. The outlet pressure should be higher or the same as the chosen storage pressure, so there will be no need for any additional compressors between the production system and the storage tanks.

Another scenario can be to buy hydrogen from HTWO-FUEL AS, who is already planning a hydrogen factory at Lutelandet [87]. This will result in a lower CAPEX (capital expenditure), as it will not be necessary to invest in a production facility. But as mentioned, the OPEX (operating expenditures) might be higher when buying the fuel rather than self-producing. This scenario will not be looked further into.

### 4.7.2 Water and power supply

Water and power are the only input factors for hydrogen production by electrolysis. The amount of water needed per kilo hydrogen is approximately 10 liters [89]. This corresponds to 16 $m^3$ of water each week if the daily hydrogen production is around 223 kg. The possibility of water delivery from the water network should be investigated, this might include extending the water pipes. Pumping sea water with saline purification can also be an opportunity. An indication of CAPEX and OPEX for both options should be studied before determining which one to choose. Only water from the water network is looked at in this report.

A wind farm, with an installed power of 50 MW and an estimated annual production of 150 GWh, is planned at Lutelandet [90]. The wind farm is to be tested and implemented during the year 2021. The energy needed in the hydrogen production, can be retrieved from this wind farm. Electrolysis benefits from over-production of power, and can be connected to the power grid during under-production. The development of a strong enough power grid is assumed to be completed on site since the wind farm require a strong grid to distribute the electricity produced.

### 4.7.3 Bunkering

After production, the hydrogen is stored on land before bunkering. The necessary pressure when absorbing hydrogen to the metal hydride storage will be crucial. To be able to fill hydrogen from the container on land into the HY2 Mega storage onboard, an overpressure is needed.

When filling compressed hydrogen from one tank to another, the gas will be distributed in available space, which results in reduced pressure. When the pressure becomes identical in both containers, the gas transfer will stop. It is therefore important that the hydrogen maintains a higher pressure than the equilibrium pressure of the metal hydride. Also, higher pressure gives a higher charging rate. In order to maintain the required pressure, it will be necessary to store hydrogen at around 200 bar. The electrolyser should therefore have an outlet pressure of 200 barg, to avoid additional compressors.

The bunkering system of hydrogen will be roughly the same as for compressed natural gas (CNG) [81]. For CNG, two types of bunkering stations are standardized: fast-fill and time-fill [91]. Since the tugboat has the opportunity of bunkering overnight, the time-fill option will be possible. This makes it possible to fill with a lower pressure, and even filling directly from the electrolyser can be possible. One benefit by time-bunkering is a decrease in heat, produced during the hydrogenation.

When the ZeroTug is at quay being refueled with hydrogen, a break-away coupling should be implemented. This makes the hydrogen flow stop if the boat starts to drift away and the filling hose is torn loose [92]. The bunkering system should have an emergency shutdown system (ESD) which will stop the flow of hydrogen to the dispenser immediately, so that catastrophic accidents can be avoided [93].

The bunkering time depends on the thermodynamic of the metal hydride storage and the cooling capacity (water temperature and flow rate) [50]. The water temperature should be 20 °C or lower. As mentioned, it is necessary to transport heat corresponding to 4-6 kWh/kg$H_2$ under loading time. It will take about 3-4 hours to load the entire storage. Even if there are several storages it is possible with one central feeding line since the HY2 Mega systems can be connected in a parallel manner.

### 4.7.4 Infrastructure safety

Hydrogen is categorized as a dangerous substance by the Norwegian Directorate for Civil Protection (DSB) [94]. DSB is responsible for regulations of hydrogen production and storage onshore, and for approval of bunkering facilities [95]. Since the annual production of hydrogen for the tugboat is above 50 ton, it must follow the Norwegian major accident regulations, *Storulykkeforskriften*. The regulations are guidelines and actions of how to limit the outcomes of major accidents, prepared by DSB. This includes either duty to report or preparation of a safety report, depending on the quantity of hazardous chemicals. The activity must undergo analyses of how to reduce and prevent accidental consequences for the community.

There are other regulations to be aware of, like the regulation of hazardous substances. This also includes analyzing the risk and hazard mapping. Due to the large quantities of above 50 ton, the analysis must get approved. The assessment will be the foundation for the prepared plans, and actions are to be implemented so the risks can be reduced to an acceptable level [95]. Regularly, the risk assessment must be reviewed, and in the event of changed settings in facilities or surroundings, it must be updated.

The *Planning and Building Act* requires that consideration zones of the installation are calculated, and that they are in accordance with the current zoning plan. The risk analysis provides an understanding of how extensive the consideration zones need to be to protect the surroundings and the population. The area around the industrial field is divided into three zones, these require special evaluation based on risk contours [96]. The risk contours are a calculation of possible accidents and the probability of perish. *Figure 4-5* shows how the risk contours divide the different zones.

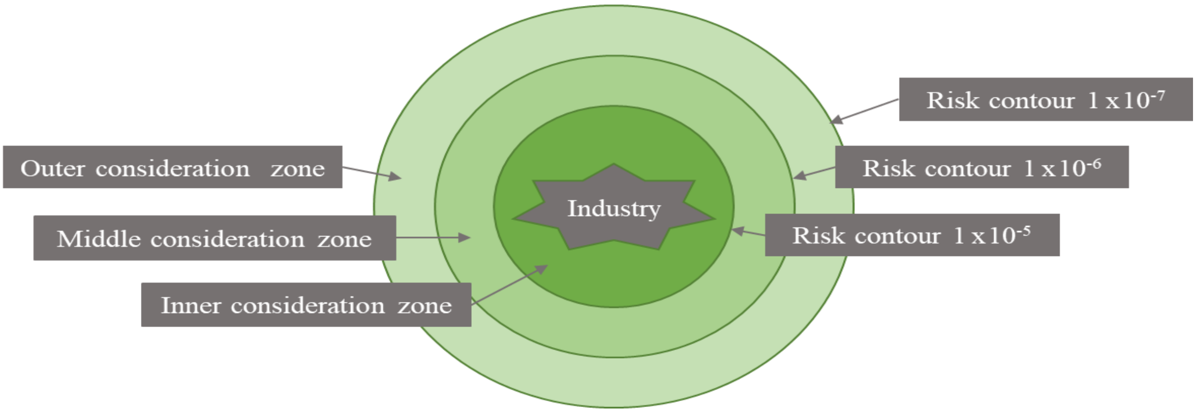


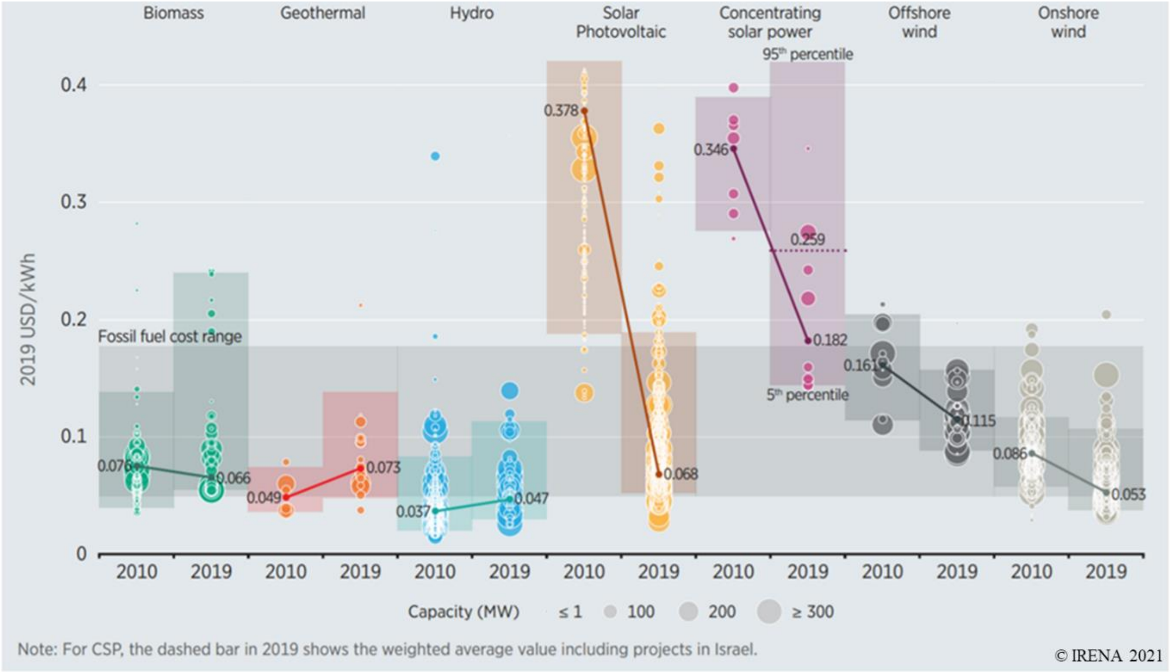
*Figure 4-5: Illustration of consideration zones and risk contour* [96]

There are rules for the different zones, which determine the type of buildings being built or standing in this area [96]. In addition to the installation, areas for agriculture and nature can be placed in the inner zone. Business activities, as well as public roads, quays, railways and other areas where the duration of the stay is limited, is allowed in the middle zone. In principle, there should not be any housing in this region. In the outer zone, housing can be located. Stores and smaller places where it is allowed to spend the night, can also be in this zone. Normally, nursing homes, hospitals, schools, kindergartens, hotels, malls and similar institutions or arenas that gather large crowds of people must take place outside the outer zone.

Atmospheres explosible (ATEX) user regulations require safety and health measures for employers exposed to explosive atmospheres [95]. The areas where the explosion may occur are divided into three new zones based on the probability occurrence of explosive atmosphere and duration. Zone 0 is defined as the area where an explosive atmosphere occurs often or for longer periods. The next area, zone 1, is where explosive atmospheres are likely to occur occasionally during normal operation. The area where it is not likely to form an explosive atmosphere during normal operation is called zone 2. The ATEX regulations affect what gear and security system that can be utilized in the zones.

## 4.8 Cost estimation

Taking renewable energy carriers in use for propulsion will be expensive. However, electricity has come a long way and is today one of the cheapest options on the Norwegian marked [97]. That gives hope for the rest of the renewable alternatives. The expenses depend on the product demand and the produced quantity. An increase in quantity will cause a decrease in the relative manufacturing cost. Competition in the marked, as well as technology improvements, will also have an impact on the product price [98]. The levelized cost of energy (LCOE) of renewable power generation have mainly decreased, as can be seen in *Figure 4-6*. This chapter includes estimated costs related to the infrastructure and the main propulsion system of the ZeroTug.



*Source: IRENA Renewable Cost Database.*

*Note: This data is for the year of commissioning. The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted-average LCOE value for plants commissioned in each year. Real weighted average cost of capital (WACC) is 7.5% for OECD countries and China and 10% for the rest of the world. The single band represents the fossil fuel-fired power generation cost range, while the bands for each technology and year represent the 5th and 95th percentile bands for renewable projects.*

*Figure 4-6: LCOE of renewable power generation* [99]

### 4.8.1 Infrastructure

The land-based infrastructure will mainly consist of the electrolyser, bunkering equipment and hydrogen storage tanks. *Table 4-12* shows an estimated CAPEX of the infrastructure. These are examples of components, better and cheaper alternatives may exist. The electrolyser system price includes the leverage of the electrolyser, but does not include any approvals, civil works, buildings, installations (pipes, cables, valves, etc.) and startup [88]. High-pressure hydrogen tanks from Reuther are being used in the estimation, where one tank can hold 33 $m^3$ $H_2$ [100]. It is assumed that the water pipe for electrolysis is installed, so there will be no CAPEX related to this. The total cost for the infrastructure on Lutelandet is estimated to be above 2.6 million euros.

| Component | Quantity | Price estimation | Total |
|---|---|---|---|
| | | € | € |
| **Electrolyser system** | 1 | 1 650 000 | 1 650 000 |
| **High-pressure tank** | 4 | 238 800 | 955 200 |
| **Bunkering equipment** | – | – | Unknown |
| **Total** | | | 2 605 200 |

*Table 4-12: Components and the CAPEX of infrastructure* [88] [100]

### 4.8.2 Tugboat

It is complex to find prices for metal hydride storages because they are currently not commercially available, and since the different metal hydrides have unlike properties. Storages is designed by companies based on several specific factors: the required hydrogen, the equilibrium pressure and the heat exchange method [50]. The numbers used are incorporated to give an implication of the cost. The price will also depend on the quantity and the year of purchase. This is because the industrial scaling for metal hydrides is at an early stage.

Metal hydrides have a high investment cost due to the raw material. Even though the TiFe material is considered to be one of the cheapest intermetallic hydrides [101], the raw material cost was approximately 49 €/kg in 2011 [102]. Now, 10 years after, the price is outdated and is probably lower. $AB_2$ alloys was about 90 €/kg in 2011, but an updated price is estimated to 60-70 €/kg in Europe [40]. If the AB material cost is reduced by the same percentage, TiFe will have a price of 36 €/kg. To use the material as hydrogen storage, it has to be melted and go through other metallurgical processes, like the activation procedure. This will cause additional expenses and can lead to a price increase by over 100 % [101].

The price of the storage container itself, including heat-exchanger sensors and piping infrastructure, will also have a significant cost contribution on the metal hydride storage system. The HY2 Mega system is stainless-steel based, keeping in mind corrosion resistance and longevity [50]. *Table 4-13* shows a price estimation for elements of the metal hydride storage. The weight of the stainless steel is calculated by subtracting the weight of hydrogen and TiFe from the total storage system. TiFe's reversible storage capacity of 1.6 wt% is being used. The price for eight metal hydride storages is estimated to 9.81 million euros. This price includes a 100 % increase of the TiFe material cost and the cost of stainless steel, 316L.

| Storages | Cost of TiFe | TiFe | Cost of 316L | Stainless steel | Total cost |
|---|---|---|---|---|---|
| | €/kg | kg | €/kg | kg | € |
| **6** (1 560 kg $H_2$) | 36 | 96 000 | 4.99 | 88 000 | 7 311 000 |
| **8** (2 080 kg $H_2$) | 36 | 128 000 | 4.99 | 118 000 | 9 805 000 |

*Table 4-13: Estimated prices of the metal hydride material* [50] [103]

As mentioned, it will be two propulsion systems onboard. One main system, which uses hydrogen as fuel, and one diesel-electric propulsion system with batteries, as a backup. *Table 4-14* shows the necessary components of the main propulsion system and the estimated CAPEX.

| Component | Quantity | Price estimation | Total cost |
|---|---|---|---|
| | | | € |
| **Metal hydride storage** | 8 | – | 9 805 000 |
| **Heat exchanger** | – | – | unknown |
| **Fuel cell** | 16 | 1 800 €/kW | 5 760 000 |
| **Batteries** | 4 | 560 €/kWh | 279 000 |
| **HyET H2 HCS-500** | – | 738 €/kg$H_2$ per day | 1 151 000 |
| **Tugboat w/DE system** | 1 | – | 5 680 000 |
| **Total** | | | 22 675 000 |

*Table 4-14: Estimated prices of the components for the ZeroTug* [104] [78]

The CAPEX of a diesel electric (DE) tugboat with battery for peak shaving, estimated to 5.68 million euros [67], is used as a bedrock for the estimation. This CAPEX includes the components listed in *Table 4-1*. The additional components of the ZeroTug are added to the price, since the components of the DE tugboat are included in its propulsion system. However, more batteries have been added since they are meant to be a part of the propulsion and not only for peak shaving.

By summing up the price of the DE tugboat and the components which only applies for the ZeroTug, the CAPEX is estimated to be € 22.68 million. The price for the ZeroTug will thus be four times higher than a diesel electric tugboat. If the ZeroTug is compared to a conventional diesel mechanical tugboat, the price will be as much as 12 times higher, as such a boat costs about 1.87 million euros [67]. It may be possible to apply for public support for financing the tugboat. Financial support is an important factor in making sustainable solutions more attractive.

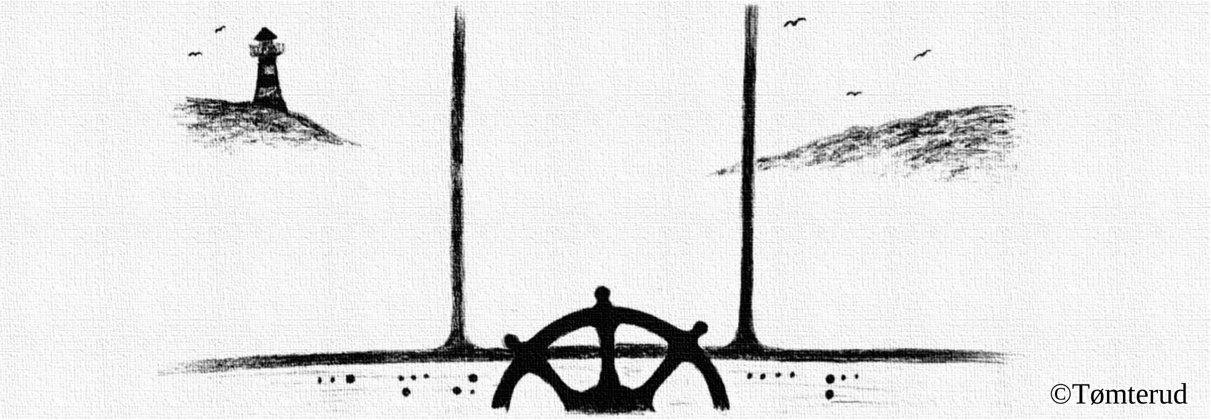
An estimated OPEX of the ZeroTug has been made based on adding operational costs for production of hydrogen to the OPEX of a DE tugboat, shown in *Table 4-15*. The OPEX also includes the costs of electricity for compressing the hydrogen between the metal hydride storage and the fuel cell. The repair and maintenance, and logistics charges, like property costs for the ZeroTug is unknown, so these are assumed to be approximately equal to the DE tugboat. The cost of a DE tugboat contains some other factors than what the ZeroTug needs, but because of the difficulty in removing specific factors, the entire OPEX is used. The OPEX of the DE tugboat is assumed to include the MDO consumption.

The calculated annual OPEX for the ZeroTug is 1.73 million euros. The calculation is based on a requirement of 1 560 kg hydrogen, which is the necessary amount of energy for one round trip. The electricity price includes power, grid rent and other charges [105]. The energy requirement of 55 kWh/kg$H_2$ for the electrolyser mentioned earlier, has been used. The electrolyser from NEL has a feed water consumption of 0.9 L/N$m^3$ [89]. This gives an OPEX of about 392 000 € more than for a DE tugboat. The OPEX of the compressor is estimated with an energy consumption based on an outlet pressure of 875 bar. This pressure is much higher than what will be necessary, and the energy consumption might be lower.

| | **One round trip consumption** | **Annual consumption** | **Price** | **Total Price** |
|---|---|---|---|---|
| **Water** | 15.6 $m^3$ | 811 $m^3$ | 1.8 €/$m^3$ | 1 460 € |
| **Electricity (electrolyser)** | 85 800 kWh | 4 461 600 kWh | 0.0824 €/kWh | 367 636 € |
| **OPEX DE tugboat** | – | – | | 1 340 000 € |
| **Electricity (Compressor)** | 5 460 kWh | 283 920 kWh | 0.0824 €/kWh | 23 395 € |
| **Total** | | | | 1 732 491 € |

*Table 4-15: The cost of water and electricity for a round trip* [106] [88] [89] [78]

# 5. Discussion



As discussed in *2.1.8 Overview and comparison*, hydrogen will be used in fuel cells for propulsion on the ZeroTug. The hydrogen can be stored in compressed or liquid form, but also in a different state. The different possibilities will be discussed in this chapter followed by a self-evaluation and reflections of further work.

In the following sections, volume and weight of the different energy carriers will be addressed. *Table 5-1* shows a comparison of metal hydrides, ammonia, compressed and liquid hydrogen. LOHC is excluded as it requires an excessive amount of energy. For metal hydrides and ammonia, extra energy will be necessary onboard for the dehydrogenations. The liquid hydrogen does not need an additional energy onboard, as the storage can maintain the cryogenic temperatures for about three weeks [107]. For volume and weight, the properties of the tanks are taken into account. Ammonia can be compared to LPG when it comes to storage, an LPG-tank is therefore used as a reference [19]. The number of metal hydride storages is estimated in *4.4.1 Metal hydride storages*. The quantity of 1 720 kg hydrogen is used for the calculations of volume and weight for the other storage alternatives, as 10 % is expected to remain in the tank. Prices include hydrogen produced by renewable energy, as this will give green hydrogen.

| | **Energy demand** dehydrogenation | **Volume** tank | **Weight** fuel + tank | **Estimated price** fuel |
|---|---|---|---|---|
| | kWh | $m^3$ | ton | €/MWh |
| **Metal hydride** | 6 240 | 273 | 248 | 148 |
| **Ammonia** | 9 828 | 36 | 15 | 90 |
| **$H_2$ 200 bar** | 0 | 137 | 26 | 148 |
| **Liquid $H_2$** | 0 | 59 | 16 | 220 |

*Table 5-1: Comparison of metal hydrides, ammonia, compressed and liquid hydrogen* [7] [108] [109] [110] [111]

The metal hydride storage will clearly take up the most space and have the highest weight. Yet, the energy needed for dehydrogenation will be excess heat from the fuel cells. The storage volume and weight for compressed hydrogen at 200 bar is high because the density is low and the tanks used for reference are small, so there will be a need for 71 tanks. If larger tanks can be procured, weight and volume will probably be reduced. Liquid hydrogen, on the other hand, gives good values of both weight and volume, but it has the highest product price.

When it comes to ammonia, the necessary energy for cracking will probably be greater than what can be retrieved from excess heat. An extra amount of energy will therefore be required onboard, which will take up more space. Despite this additional fuel, metal hydrides will require a larger volume. In this comparison, ammonia and liquid hydrogen looks like the best alternatives. However, these characteristics are not necessarily the most important.

A hydrogen leak can lead to fire and in worst case a deadly explosion. This applies to most fuels, and they must on a general basis be handled correctly in terms of safety. Since the consequences of poor safety can be fatal, this will be seen as the most important feature of the various storage methods. Safety aspects of the different storage methods will therefore be assessed. *Table 5-2* provides a projected overview of some risk factors, including an overall assessment of the safety risk.

| | Flammable | Explosive | Poisonous | Leakage consequences | Bunkering | Flame temperature | TOTAL |
|---|---|---|---|---|---|---|---|
| Metal hydride | ░ | □ | □ | ░ | ▒ | █ | ░ |
| Ammonia | ▒ | ░ | █ | ▒ | ░ | ▒ | ▒ |
| Hydrogen 200 bar | █ | █ | □ | ░ | ▒ | █ | ▒ |
| Liquid hydrogen | █ | █ | □ | █ | █ | █ | █ |

| | |
|---|---|
| Non existing | □ |
| Small risk | ░ |
| Medium risk | ▒ |
| High risk | █ |

*Table 5-2: Risk overview of the different storage alternatives*

Hydrogen has a particularly low ignition energy of 0.017 mJ [10]. For fuel, this is generally a good property, but a low ignition energy can lead to unwanted ignitions. In addition, hydrogen burns with a flame temperature of 2 254 ˚C which can cause materials, such as iron, to melt.

The same applies to ammonia which has a flame temperature of 1 800 ˚C. Ammonia is also the only toxic alternative. This is respectively if the metal powder itself is disregarded, as a leakage will only consist of hydrogen and not metal powder.

Ammonia has a well-developed infrastructure as it is one of the most produced chemicals worldwide. The main danger with ammonia is the toxicity, but the risks of storage are well understood, and good procedures are implemented. In addition, ammonia has a strong odor that will make it easy for the crew to detect a leak. Although ammonia itself is not explosive, an explosion could occur if the tank is heated. As for all other fuels, knowledge and routines around any leaks and accidents will be important.

The most serious safety risk with hydrogen is the possibility of explosion. It is therefore important that the concentration of hydrogen in air never approaches 15 %, as detonations can occur around this concentration. A leakage of liquid hydrogen can however be more fatal than a leakage of compressed hydrogen. Hydrogen gas normally ascent rapidly, but the cryogenic temperatures will make the surrounding air freeze and prevent the gas from rising. Consequently, a cloud of hydrogen gas with detonable concentrations may be formed. This also increases the dangers related to bunkering, where the risk of leaks is high. When studying *Table 5-1* and *Table 5-2*, the compressed hydrogen requires a large volume and receives a medium risk factor, this makes the alternative less attractive. The same goes for liquid hydrogen due to its dangers and high risk factor, even though it takes up less space.

Since an accident with hydrogen can cause major damage, it is important that the production, storage and use of hydrogen happens safely and with low risk. When the knowledge grows and the technology develops, guidelines specific to hydrogen will probably be established, and it may become easier to produce and buy vessels running on hydrogen. However, the missing guidelines can be helpful for innovative solutions, but analysis must be done to prove safe fuel handling, stated in *4.7.4 Infrastructure safety.*

Metal hydrides is one of the safest options for hydrogen storage today, simply because it is stored in solid form. Since heat is required for the releasing of hydrogen, there will never be much free gas available. In terms of a leakage, only small amounts of hydrogen will leak out in a controlled manner. In addition, the emission rate will decrease if the outside temperature is below the dehydrogenation temperature. Other benefits with metal hydrides are close to no deterioration of storage capacity over time and the product can be fully recyclable with only sustainable organic matter. Since keeping hydrogen in metal hydrides is a relatively new way of storing fuel in vessels, it has great potential for development. There is a desire for higher hydrogen capacity in metal powder, which will be revolutionary considering today's large footprint.

Since metal hydride and ammonia appeared to be the best options according to the risk overview, these will be compared regarding volume and weight. This will give an impression of how much extra weight and volume a zero-emission system will need. *Table 5-3* shows the additional components in the ZeroTug, compared to Stadt Kinn. Since the amount of diesel will be reduced in the tugboat, the weight and storage size related to this are deducted from the total. The electrical motors needed for the fuel cell is not taken into account as it already is a part of the Stadt Kinn system. Power management and other smaller systems like heat exchanger systems are not listed either, due to the complexities and the need for custom made systems. The ballast area will be needed for storage and will also be deducted. The table includes metal hydride storage and ammonia storage, as these are both relevant alternatives. The extra amount of energy for cracking is included as ammonia in the ammonia storage, which results in the need of a larger tank.

<table>
<tr><th></th><th colspan="2">Weight</th><th colspan="2">Size</th></tr>
<tr><td></td><td colspan="2">ton</td><td colspan="2">$m^3$</td></tr>
<tr><td>**Metal hydride storage (8)**</td><td colspan="2">248</td><td colspan="2">273</td></tr>
<tr><td>**Ammonia storage**</td><td colspan="2">19</td><td colspan="2">55</td></tr>
<tr><td>**Fuel cells**</td><td colspan="2">14</td><td colspan="2">32</td></tr>
<tr><td>**Batteries (4)**</td><td colspan="2">13.5</td><td colspan="2">12</td></tr>
<tr><td>**Diesel tank**</td><td colspan="2">– 153</td><td colspan="2">– 170</td></tr>
<tr><td>**Ballast (water)**</td><td colspan="2">– 8.6</td><td colspan="2">– 8.6</td></tr>
<tr><td>**Available deck area**</td><td colspan="2">0</td><td colspan="2">0</td></tr>
<tr><td>**Total**</td><td>MH<br>114</td><td>$NH_3$<br>-115</td><td>MH<br>138</td><td>$NH_3$<br>80</td></tr>
</table>

*Table 5-3: Additional components in the ZeroTug and calculations of weight and volume with both ammonia and metal hydrides as storing alternative* [112]

The table shows an additional weight and storage space of 114 ton and 138 $m^3$ when using metal hydrides, compared to the Stadt Kinn tugboat. With ammonia as storage alternative, there will be an additional need of 80 $m^3$ and the system will result in less weight than the original system. Consequently, more ballast is needed due to Archimedes' physical law of buoyancy, which will lead to a greater volume necessity.

Since the towing winch is placed right behind the wheelhouse and the cable will need sweep area behind, there is no extra space for storing machines or fuel on deck. To store the added components, the ZeroTug must have a larger design than Stadt Kinn. The additional volume of the tugboat must be compensated with weight, so that the boat maintains its balance and position in the water. An extra cubic meter below the water surface corresponds to a need of an extra ton [113]. For metal hydrides this corresponds to 2.2 more meters for the length of the boat, compared to Stadt Kinn. The drawing of Stadt Kinn, in *Appendix 1*, is used as reference and the calculations can be seen in *Table 5-4*. An illustration of the ZeroTug with the additional space for the metal hydride system is shown in *Figure 5-1*.

| | **Weight** | **Volume** | **Width** | **Height** | **Length** |
|---|---|---|---|---|---|
| | ton | $m^3$ | m | m | m |
| **Above the water surface** | 20 | 24 | 11 | 1.25 | 1.75 |
| **Below the water surface** | 94 | **114** | 11 | 4.75 | **2.18** |
| **Total external dimensions** | **114** | 138 | 11 | 6 | 2.18 |

*Table 5-4: Calculations for the external length of the ZeroTug relative to Stadt Kinn*

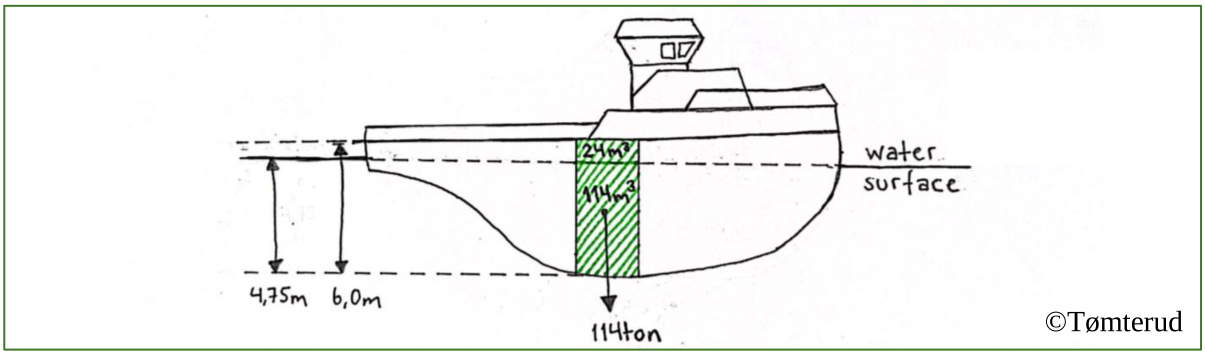


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*Figure 5-1: Simple illustration of the ZeroTug with the additional space for the metal hydride system*

With the ammonia storage, extra ballast must be included due to the "negative" total weight. This will result in an additional volume demand of 195 $m^3$ if the usual ballast substance, water, is used. The ammonia system will therefore require more space than the metal hydride system. The volume demand will require even more ballast weight due to Archimedes' physical law of buoyancy. With ammonia as fuel, 115 extra ton must be included on the tugboat to maintain the balance of the boat. In order to get the smallest possible increase in the boat's area, it is ideal to get as much weight as possible in the smallest possible volume. Every extra cubic meter below the water surface will, as mentioned, require one additional ton. A substance with higher density than water should therefore be used, so that the requirement for the ratio between weight and volume can be met. Still, to meet this ratio can be problematic. To put this in perspective, the world's heaviest metal Osmium can be seen as an example of ballast. This metal will require as much as 5 $m^3$ to gain enough weight [114]. Consequently, it will be difficult with a large system with a light weight, but it may be feasible with smart solutions. The actual boat frame could for example be constructed with heavier materials, which would probably increase the CAPEX of the boat. The additional length for the ZeroTug with an ammonia system is not calculated, due to the high number of potential solutions.

As expected, it will be expensive to invest in a zero-emission propulsion system. The estimated price for the ZeroTug is 279 % higher than for a diesel electric tugboat with batteries. Therefore, financial support in form of intensives should be applied for. The price will probably be seen as a disadvantage, but it is important to keep in mind the positive aspects of zero emissions.

New innovative technology is generally more expensive. The reasons, among others, are no competitors, the need for development, and lack of an economy of scale. Historically, the cost is reduced when these factors come in place. An example of such is the solar photovoltaic technology which has had a markedly price reduction in a short period of time [99]. This can be seen in *Figure 4-6* in *4.8 Cost estimation.* It is reasonable to believe that this will apply to other green technologies, like metal hydride storages.

As of today, Norway requires carbon taxes from several industry sectors. This should, and will possibly, be implemented in the maritime sector to reach a 50 % reduction of GHGs which is the aim of IMO. The current tax price is 60 euros per ton emitted $CO_2$, but this will increase to 200 euros by 2030 [115]. This price will correspond to an additional cost of 3600 €/round trip, with MDO as fuel. Resulting in approximately 187 200 euros yearly if the boat operates one day each week, just like with the hydrogen. If the tugboat is to operate five times a week, a tax of almost 1 million euros must be paid annually. If the same missions are done with hydrogen as fuel on the ZeroTug, would the investment in the zero-emission tugboat pay off after 15 years.

## 5.1 Self-evaluation

Contact with companies was made in the first stage of the research to get a swift progress from the start. This has been important for the work and the results. In future projects, it would be an advantage to have a more comprehensive plan for how to move forward and what to include in the report. Due to a lack of information from the startup, this was not achievable in this process.

The finding in this study has been made by studying reports, news articles, and interviews. There have been dialogs with several experts which have been critical and valuable for the project since the literature available is limited. Their subjective opinions may have had an unwanted impact on the final result. Other possible sources of error are misunderstandings of given information or misinformation itself. Since the report is written in a second language, the dissemination can come out wrongly. Calculations and estimations that have been done is also potential sources of error.

## 5.2 Further work

Further work of the report should be deeper analysis with more details in mind. Next step should be to map a complete component overview and system outline. Details and datasheets of all the components should be presented and studied to be sure they work properly together. Following this, a price assessment should be possible to attain. More companies could be contacted to get better offers and further assistance. To achieve the most efficient and cheapest solution, several components can be compared.

More accurate calculations of the CAPEX and OPEX should be done to get a more correct result. Precise analysis of these calculations could be helpful to look into how pricy the project would be. The availability of incentives and the likelihood to obtain it should be investigated, especially if the profit is low or negative.

A more comprehensive project plan and budget should be completed if the ZeroTug is a desired solution for the project in Førdefjorden.

# 6. Conclusion

Most people know that current fuels need to be replaced. The price is high, but with today's development concerning environmental requirements, there is reason to believe that investments in green technology will pay off.

To make a conclusion of what storage alternative is the best suited for the tugboat, several possibilities have been addressed and compared. Which factors to emphasize will vary on the type of use. For the ZeroTug, the safety will matter more than weight and volume. However, the size should not come in the way for maneuvering and the weight must be representative.

Ammonia seems to take up the smallest space, but the low weight in relation to the volume, might lead to difficulties in manufacturing the tugboat. Metal hydrides on the other hand, will have a demanding volume and weight requirement, but this does not create any special challenges in expanding the boat. Ammonia also comes out well in the safety assessment, but metal hydride seems to be the safest option. Safety should always be the most important feature, especially when using non-commercial methods.

Metal hydride storage seems to have a bright future, but needs development and price reducing to compete on volume and weight. However, it appears to be a good option for the ZeroTug.

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# 8. List of figures

# 9. List of tables