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A Proton Exchange Membrane & Solid Oxide Fuel Cell comparison

Possible fuel cells and fuel costs

Bachelor thesis in Marine engineering

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

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Abstract

With increasing pollution to air from the shipping industry and future stricter regulation concerning marine fuels, new ways are required to power ships. Fuel cells could be a solution to decrease emissions that ships contribute with. They have higher efficiency and can be run on cleaner fuels. In this study, two fuel cell techniques are compared: PEMFC (proton exchange membrane fuel cell) and SOFC (solid oxide fuel cell). The technical performance and cost of the fuel cells were assessed based on a literature review combined with data from consultations with industry representatives. Within the field there is plenty of literature, articles and reports. Fuel cost calculations are also included in the study where present and possible future fuels are included. In the study one can see that both PEMFC and SOFC have higher efficiency than combustion engines. If hydrogen is used as fuel the only emission is water. Both techniques have comparable electrical efficiency. PEMFC is compact and handles generally load variations better. SOFC is not as compact and works at higher temperatures than PEMFC. The SOFC can be combined with a gas turbine increasing its efficiency. If waste heat recovery is used its efficiency is further increased. PEMFC has a lower capex compared to SOFC but SOFC can utilize natural gas which is cheaper than hydrogen. PEMFC has the highest power to volume ratio, however it runs on hydrogen which has low volumetric density compared to tradition marine fuels. With this, new challenges will arise at same time as fuel cells will offer a sustainable choice.

Keywords

hydrogen, fuel cell, PEM, PEMFC, SOFC, LNG, shipping, fuel cell fuel cost

Sammanfattning

Med ökande utsläpp till luft från sjöfarten och framtida strängare regelverk gällande fartygsbränslen, krävs nya sätt att driva fartyg. Bränsleceller skulle kunna vara en lösning för att minska utsläpp som fartyg bidrar med. De har högre verkningsgrad och kan drivas med renare bränslen. I denna studie jämförs två bränslecellstekniker PEMFC (proton exchange membrane fuel cell) och SOFC (solid oxide fuel cell). Studien är framförallt en litteraturöversikt kombinerad med konsultationer med representanter från branschen. Inom ämnet finns gott om litteratur, artiklar och rapporter. Bränslekostnadsberäkningar ingår även i studien för befintliga och potentiella bränslen inom sjöfarten. I studien kan man se att både PEMFC och SOFC har högre verkningsgrad gentemot dagens förbränningsmotorer. Om vätgas används är det enda utsläppet vatten. Båda teknikerna har snarlik elektrisk verkningsgrad. PEMFC är kompakt och hanterar generellt lastförändingar bättre. SOFC arbetar vid högre temperaturer än PEMFC. SOFC kan kombineras med gasturbin för att ytterliggare öka sin verkningsgrad. Använder man värmåtervinning kan verkningsgraden förbättras ytterligare. PEMFC har ett lägre inköpspris jämfört med SOFC, dock kan SOFC drivas med naturgas vilket är billigare än vätgas. PEMFC har högst energidensitet sett till storlek, dock drivs den av vätgas som har låg volumetrisk densitet gentemot traditionella sjöfartsbränslen. Med detta kommer nya utmaningar samtidigt som bränsleceller kommer att erbjuda ett hållbart allternativ.

Nyckelord

vätgas, bränsleceller, PEM, PEMFC, SOFC, LNG, sjöfart, bränslecellsbränsle kostnad

Foreword

The authors want to thank their families for their endurance and support. We would also like to thank Selma Brynolf who has been our mentor throughout the process. A special thanks is also given to Jan Froitzheim at Chalmers and Johan Burgren at Powercell for taking time to answer our questions.

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Nomenclature

\$/kW	Price in dollars per kW of the system
AFC	Alkaline Fuel Cell
APU	Auxiliary Power Unit
CGH_2	Compressed Hydrogen Gas
CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon dioxide
DMFC	Direct Methanol Fuel Cell
DNV-GL	Det Norske Veritas and Germanischer Lloyd
DOE	US Department Of Energy
FC	Fuel Cell
GHG	Greenhouse Gases
H_2	Hydrogen
HFO	Heavy Fuel Oil
HT- PEMFC	High Temperature Proton Membrane Exchange Fuel Cell
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGF-Code	International Code of safety for gas fuelled ships
IMO	International Maritime Organization
kWh	Kilo watt hour
kWh_e	Electric kilo watt hour
LH_2	Liquid hydrogen (-253^{O}C)
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LT-PEMFC	Low Temperature Proton Membrane Exchange Fuel Cell
MCFC	Molten carbonate fuel cell
MEPC	Marine Environment Protection Committee
MFO	Marine Fuel Oil
MGO	Marine gas oil
MOU	Memorandum of Understanding
mt	Metric tonne
NECA	Nitrogen Emission Control Areas
NG	Natural Gas

NO_x	Nitrogen Oxides
ODS	Ozone depleting substances
O_2	Oxygen
PAFC	Phosphoric acid fuel cell
PEMFC	Proton Exchange Membrane Fuel cell
PM	Particulate matter
SECA	Sulphur Emission Control Areas
SOFC	Solid Oxide Fuel Cell
SOFC GT	Solid Oxide Fuel Cell with Gas Turbine
SOFC HR	Solid Oxide Fuel Cell with heat recovery
SO_x	Sulphur Oxides
VOC	Volatile organic compounds

1 Introduction

During the past decades air pollution has been a widely discussed subject, not at least in the shipping industry. As stricter air emission regulation comes into force the demand for cleaner fuels will increase. This puts shipowners and operators in a position where they need to start considering the use of abatement technologies or other fuels than those of today. Fuel cells is a technology that can provide an efficient and clean energy conversion compared to traditional marine engines.

In 2012 the shipping industry contributed with about 3% of global carbon dioxide (CO_2) emissions (Andersson, Brynolf, Lindgren, & Wilewska-Bien, 2016). According to IMO (International Maritime organization), CO_2 emissions are expected to increase between 50-250% by 2050 depending on how the world market develops (IMO, 2014). On the 13th of April 2018 during the 72nd Marine Environment Protection Committee (MEPC 72) it was decided that greenhouse gases (GHG) must be decreased by at least 50% by 2050 compared to 2008 (IMO, 2019).

Out of a historical perspective one can say that interest in fuel cells is increasing. In the maritime sector during the 80 and 90's, fuel cells powered only a handful smaller submarines and naval vessels (Barbir, 2005) (Van Biert, Godjevac, Visser, & Aravind, 2016). This has come to change where testing of fuel cells onboard ship has been on the increase during the past 20 years (EMSA, 2017). In the search of more sustainable shipping new developments can for example be seen in the Swedish maritime sector. By 2020 at least 13 new buildings are expected to be able to utilize liquified natural gas as fuel (Energigas, 2019). Between Helsingborg and Helsingör battery propelled ferries already provide fossil free transportation (Forsea, 2019). In 2019 the Norwegian parliament adopted a resolution that will make the Norwegian world heritage fjords emission free by 2026 (Sjofartsdirektoratet, 2019). Furthermore, several cruise ship operators have acknowledged their interest in fuel cell technology (Langfeldt, 2018). In 2018 the electronic maker ABB and Ballard Power Systems announced that they are collaborating in the development of the next generation of fuel cells to be used onboard a ship. The fuel cell system onboard will have the capacity of 3MW (Margaronis, 2018). These are only a few examples of present and future developments in the shipping industry.

In the latest report from European Maritime Safety Agency on fuel cell technology in the shipping industry, it can be seen that the shipping industry has been evaluating alternatives to today's burning of fossil fuels (EMSA, 2017). Fuel cells have on several occasions been tested during the past 20 years in the maritime sector and could provide the shipping industry with an alternative means of power production. They are efficient in their energy conversion and quiet. If pure hydrogen is used as fuel the only emission would be water.

1.1 Purpose and research questions

This report aims to review Proton Exchange Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC) technology and evaluate their maritime feasibility.

The following research questions are asked:

- What is the difference in power density, system size, lifetime, efficiency and capex for PEMFC and SOFC in marine applications?
- What types of fuels can be used and what are their difference in cost?

1.2 Delimitations

The study will be limited to two fuel cell technologies that could be used in shipping, proton exchange membrane fuel cells and solid oxide fuel cells. Both technologies have been tested in the maritime environment.

Although regulatory requirements are an important aspect of the subject, they will not be handled in this thesis.

2 Background

The first fuel cell was invented in 1839 by William Groove. Further developments of fuel cells were not made until 1939. By the end of the 1950s a 6 kW fuel cell had been developed. Fuel cells didn't find any practical use until the U.S Space Program. The first fuel cell that was used was of the type PEMFC, this was used throughout the Gemini space program (Barbir, 2005). During the Apollo program an Alkaline fuel cell (AFC) of 1.5 kW was used, it provided space shuttles with electricity and drinking water (Fuel Cell Today, 2019). Between the 60's and 90's fuel cells had been successfully used in U.S space program. In 1989 a fuel cell powered submarine was demonstrated by the company Perry Energy Systems. In 1993 many new fuel cell powered vehicles were developed. Ballard power systems developed a fuel cell power bus. The company Energy Partners developed the first fuel cell powered passenger car (Barbir, 2005). During the 2000's fuel cells have been used in buses in both Europe, China and Australia. In 2007 fuel cells began to be available on the commercial market as auxiliary power units (APU) both in civilian and military application. The types seen in these applications were mainly PEMFC and DMFC (direct methanol fuel cell). In 2009 PEMFC started to become more readily available on the Japanese market for residential use (Fuel Cell Today, 2019). In 2018 it was announced that the installation of Daesan Green Energy Fuel cell powerplant has commenced, a hydrogen fuelled fuel cell power plant of 50MW (Bulletin, 2018). The power plant is aimed to be finished in 2020. A summary of fuel cell projects in the shipping industry can be read in chapter 2.1.

2.1 Maritime Fuel cell projects

In the past 20 years there has been an increase in the number of maritime fuel cell projects. Between the year 2000 and until early 2017 there were 27 studies of fuel cells onboard ships (EMSA, 2017). Among these projects various fuel cell types have been studied and some of the projects are still ongoing. The projects range from 12 kW to 2.5 MW and incorporate MCFC (molten carbonate fuel cell), SOFC, PEMFC, HT-PEM (high temperature PEM) (EMSA, 2017). Another project called Maranda started in late 2017 which is evaluating PEMFC, with a capacity of 165 kW onboard a research vessel called Aranda (Ihonen, 2017). In figure 1 it can be seen that PEMFC is the most tested fuel cell. It can also be seen in figure 2 that hydrogen is the most used fuel during these projects. This can be explained by PEMFC being sensitive to fuel impurities and therefore has to use hydrogen as its primary fuel (Van Biert et al., 2016). Although HT-PEMFC can use hydrogen it is not limited to this fuel. Some of the projects according to EMSA's report did not share what fuels were used and were labelled with unknown (EMSA, 2017). See table A1 for the full table.

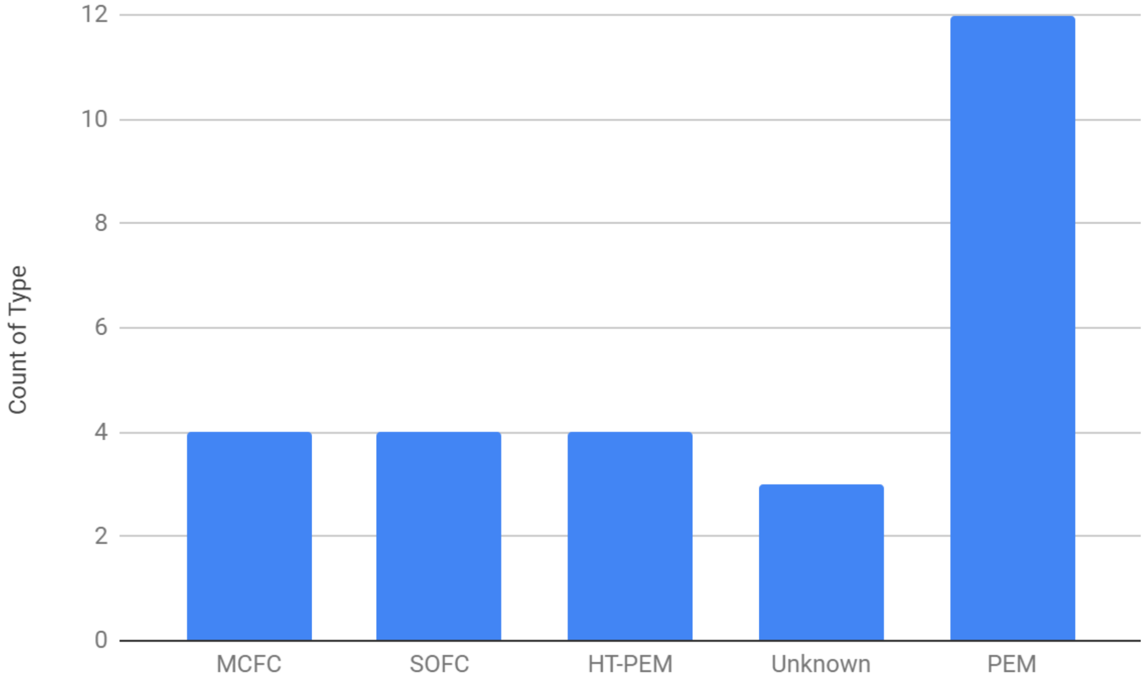

Figure 1 Types of fuel cells investigated in different projects from 2000 until 2017 ((EMSA, 2017; Ihonen, 2017)).

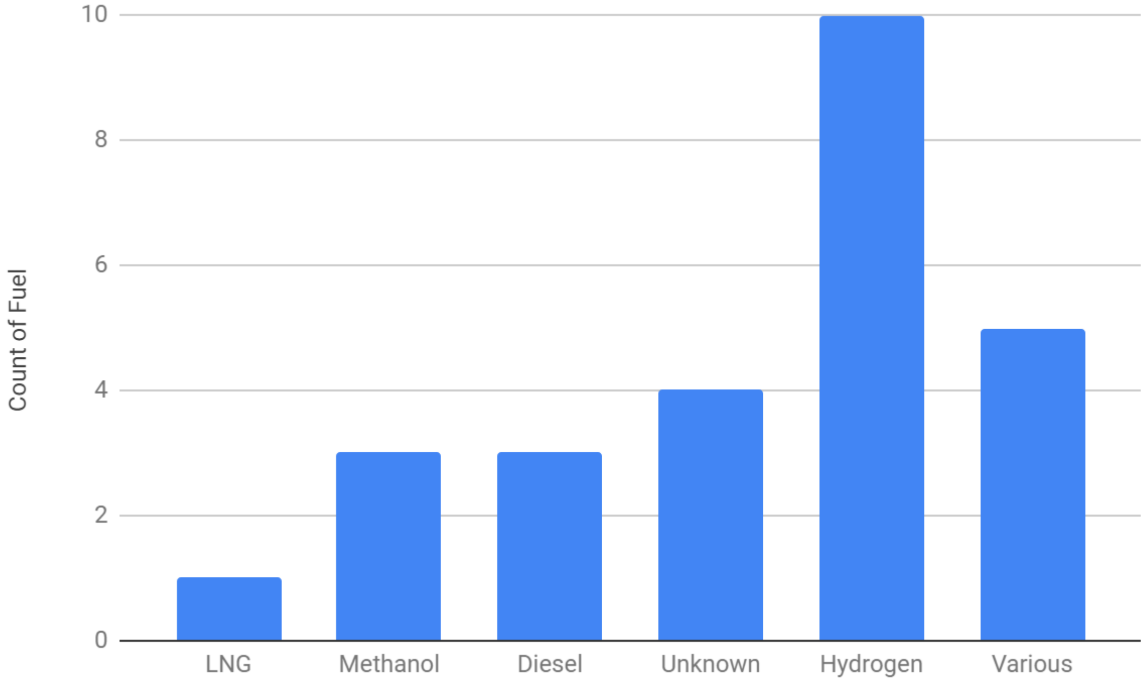

Figure 2 Types of fuel used in different projects from 2000 until 2017 (EMSA, 2017; Ihonen, 2017). 4 projects did not specify the type of fuel and is thereby labelled unknown.

2.2 What are fuel cells?

Fuel cells convert chemical energy in a fuel directly to direct current electricity (Barbir, 2005). Fuel Cells in general are composed of three parts: An anode, a cathode and an electrolyte (Kreuer, 2013). The Anode and the cathode are physically separated by a membrane. The anode and cathode are electrically connected. Depending on the type of the fuel cell the chemical reaction happens differently.

In PEMFC hydrogen is used as fuel. When hydrogen enters the fuel cell, hydrogen ions travel through the membrane and react with oxygen on the cathode side. SOFC are different in this aspect. Here the oxygen ions pass the membrane and reacts with the fuel on the anode side (EMSA, 2017). Comparing this to a traditional combustion engine, a combustion engine involves several more steps before the energy converted can be used. The traditional way to produce electricity onboard is by the use of an auxiliary engine or genset, were a diesel engine drives a generator. In this way the energy is converted 3 times. From chemical energy to heat, heat to mechanical, mechanical energy to electricity. Whereas in a fuel cell, the energy conversion is only one step, from chemical energy directly to electric energy (Barbir, 2005).

2.3 Fuel cell types

There are many types of fuel cells. In this report PEMFC and SOFC have a central part. AFC, PAFC (phosphoric acid fuel cell) and MCFC are mentioned for the understanding of the result and the history of fuel cells.

2.3.1 Proton exchange membrane fuel cell (PEMFC)

PEMFC can also be called Low Temperature Proton Exchange Membrane (LT-PEMFC). Throughout this thesis PEMFC is used as LT-PEMFC. The PEMFC has a high power to weight/volume ratio compared to other fuel cell types. The PEMFC uses pure hydrogen as fuel and it is sensitive to impurities like carbon monoxide (EMSA, 2017). If a reformer is used the PEMFC can use other fuels such as methanol, methane (Powercell, 2017). Start-up times are considered as fast and the electrochemical process produces low amounts of heat compared to SOFC, MCFC. The material used as a catalyst in the PEMFC is mainly platinum which is a quite rare and an expensive metal. As an electrolyte it uses a humid polymer membrane that allows protons to move through the membrane. PEMFC operates at temperatures between 50-100°C and the efficiency is between 50-60% (EMSA, 2017). PEMFC has its highest efficiency at lower loads which peaks at around 30% load (Burgren, 2019). When load is increased efficiency drops.

2.3.2 High temperature PEMFC (HT-PEMFC)

HT-PEMFC differs from the PEMFC mainly from the operating temperature. HT-PEMFC operates at 200°C and this is possible due to the electrolyte not being water based, instead the electrolyte is a mineral based acid. HT-PEMFC is considered to be slightly less sensitive against impurities in the fuel compared to the PEMFC. Another trait of the HT-PEMFC is that it can use several other fuels including hydrogen. The others are LNG, Diesel and Methanol. The efficiency of both PEM and HT-PEMFC is similar but due to the higher operating temperature of HT-PEMFC there is a greater potential of utilizing excess heat. By utilizing excess heat, a higher total efficiency of the system can be reached (EMSA, 2017).

2.3.3 Solid oxide fuel cell (SOFC)

The solid oxide fuel cell has an electrical efficiency of 60% and operates at a temperature of between 500-1000°C. If the SOFC system is equipped with waste heat recovery the overall efficiency can be increased to 85% (EMSA, 2017). Equipping the SOFC system with a gas turbine could increase the electrical efficiency up to 70% (J Markowski, 2019). SOFC can use several different fuels as it is not sensitive to impurities. It can use hydrogen, methane, methanol and diesel as fuel. A drawback of SOFC is long start up times (US Department of Energy, 2019). The electrolyte is composed of a solid ceramic material. It is not uncommon that yttrium stabilized zirconia is used (EMSA, 2017). The solid oxide fuel cell has longer expected lifetime than the PEM fuel cell.

2.3.4 Molten carbonate fuel cell (MCFC)

The working temperature of this fuel cell is between 600 and 700°C. The efficiency is about 50% but with heat recovery up to 85%. It can utilize many different fuels, such as hydrogen, methane, diesel and methanol. The electrolyte is a molten carbonate salt. A distinguishable difference to other fuel cells is that it needs both CO_2 and Oxygen (O_2) on the cathode side (EMSA, 2017). In comparison to other fuel cell types the most common element on the cathode side is O_2.

2.3.5 Phosphoric acid fuel cell (PAFC)

Phosphoric acid fuel cells use acid as electrolyte. They have an efficiency of 40% and if heat recovery is utilized overall efficiency can be increased. It has a high operating temperature, about 200°C, and can use different fuels such as methane or methanol (EMSA, 2017). According to EMSA, it is a well-tested fuel cell (EMSA, 2017). (Vogler & Sattler, 2016) states that it "is the most mature fuel cell technology".

2.3.6 Alkaline fuel cell (AFC)

It uses pure oxygen and hydrogen as fuel. It is sensitive to impurities on both the anode and the cathode side. The most common electrolyte is potassium hydroxide solution. The efficiency is around 50-60% (EMSA, 2017).

2.4 Fuels for fuel cells

In this chapter, fuels will be described that are important for fuel cells. The different fuels that are used in the calculations can be found in table A2 and A4, figure 6 and figure 7.

2.4.1 Hydrogen

Hydrogen can be stored as a pressurized gas or liquid. Other possible ways of storing hydrogen is chemically and physically. This means that hydrogen is stored with other materials. These materials are known as: Liquid Organic Hydrogen Carrier (LOHC) (Schneider, 2015), metal hydrides, glass microspheres, chemical hydrides and cryo absorbers (Barbir, 2005). Hydrogen is highly flammable and will ignite between 4-75 vol% of hydrogen in air (Deniz & Zincir, 2016).

Pressurized containers for hydrogen gas hold pressures between 350 and 700 bar. To compress hydrogen it requires between 5-20% of Lower Heating Value (LHV) (Department of Energy Hydrogen and Fuel Cells Program Record, 2009). Density for hydrogen at these pressure ranges between 25-40 kg/m^3 depending on the pressure, see figure 3.

Liquefaction of hydrogen happens below its boiling point at minus 253°C. The density for hydrogen at this temperature is 70.8 kg/m^3 (OECD & IEA, 2005). The process of compressing and cooling hydrogen is equivalent of 9-30% of the available energy in the hydrogen that is being cooled. Another source states that liquefaction alone requires 30-40% of LHV (Department of Energy Hydrogen and Fuel Cells Program Record, 2009). In this report it is assumed that liquefaction of hydrogen requires 3 times more energy compared to compressing. A price for liquid hydrogen has not been found. According to US Department of Energy liquefaction of hydrogen requires 10-13 kWh/kg H_2 and compressing to between 350 and 700 bar requires between 1.7-6.4 kWh/kg H_2 (Department of Energy Hydrogen and Fuel Cells Program Record, 2009).

LOHC is a method of storing hydrogen by using an oil that can absorb hydrogen by reforming. By letting for example dibenzyltoluene and hydrogen react in a catalyst, hydrogen can be bound to the oil. When the hydrogen is bound to the oil, hydrogen can be stored at an ambient temperature without the need of high pressures or low temperatures (Schneider, 2015). By doing this one can ease handling of hydrogen since the flashpoint of dibenzyltoluene is much higher, even in its charged state compared to pure hydrogen gas. The handling of hydrogen becomes much safer. The cost for 1kg dibenzyltoluene has a price range between 4-5 €/kg (Schneider, 2015). When calculating the cost for 1 mt dibenzyltoluene the price 4€/kg was used. To be noted, LOHC is not a fuel itself.

Currently there are 5 hydrogen fuelling stations in Sweden (Vätgas Sverige, 2019b). According to Shell the price of 1 kg hydrogen is 9.5 € in Germany (SHELL, 2019). The hydrogen price of 9 €/kg received from (Burgren, 2019) is used in the calculations in the report. The price of 9.5 €/kW was found after the calculations with 9 euro had been made. Using an average of both prices would have been more representative but a difference of 50 cent is marginal. According to Vätgas Sverige, 1 kg of hydrogen costs between 3.77 and 6.60 € to produce when produced from electrolysis (Vätgas Sverige, 2019a). In another article hydrogen production costs are estimated to 3 €/kg by electrolysis and by reforming of methane to 1.5 €/kg (Preuster, Papp, & Wasserscheid, 2017).

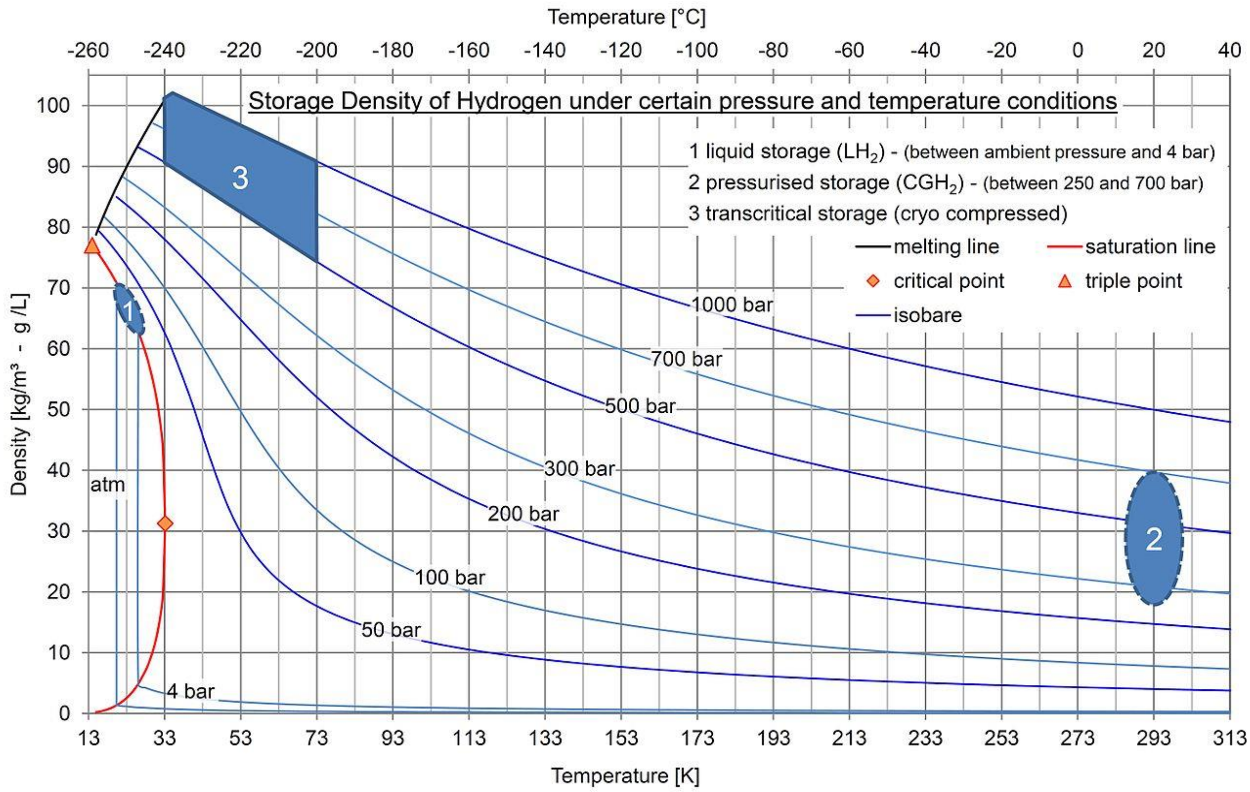

Figure 3 Storage density of hydrogen under certain pressure and temperature conditions (ILK Dresden, 2015). CC BY-SA 4.0

2.4.2 LNG

Liquid natural gas is stored cold at -162°C at its atmospheric boiling point. Typical tank construction materials are nickel alloyed steels, stainless steels or aluminium. Cryogenic tanks require insulation to reduce boil-off. This is important in order to protect both the tank and the structure surrounding it. Typical insulation materials onboard gas carriers are: Balsa Wood, Mineral Wool, Perlite, Polystyrene and Polyurethane (White, 2000). Natural gas consists of about 90% methane (Nationalencyklopedin, 2019). The chemical formula for methane is CH_4 (Svein Erik Pedersen, 2015).

The price for LNG on 15.02.2018 was 6.55 $/mmBtu (DNVGL, 2019).

2.4.3 Methanol

Methanol is an alcohol and a low flashpoint fuel. These require advanced system concerning ventilation, alarms and fire protection (EMSA, 2017). The Chemical formula is CH_3OH. Methanol boils at 64.6°C and has a density 793 kg/m3 at 20°C (Svein Erik Pedersen, 2015). The price for methanol is ~400 $/mt (Methanex, 2019).

2.5 Fuel energy density

Figure 4 shows gravimetric density of hydrogen, marine fuel oil, marine gas oil, natural gas, a liquid organic hydrogen carrier and methanol. Of all the fuels in figure 4 hydrogen has the highest volumetric density. This is followed by natural gas, marine gas oil and marine fuel oil. LOHC should be seen as a fuel carrier and not a fuel itself. All figures are taken from table A2

Figure 5 compares Volumetric energy density of liquid hydrogen (LH_2), compressed hydrogen (CGH_2), marine gas oil, marine fuel oil, natural gas, LOHC and methanol. Marine fuel oil 380 has the highest amount energy per cubic meter of all the fuels in figure 5. Marine gas oil has slightly less energy than MFO 380 and is followed LNG which has almost half the energy of MFO 380. Liquid hydrogen at -253 C has the highest amount of energy per cubic meter compared to LOHC and compressed hydrogen.

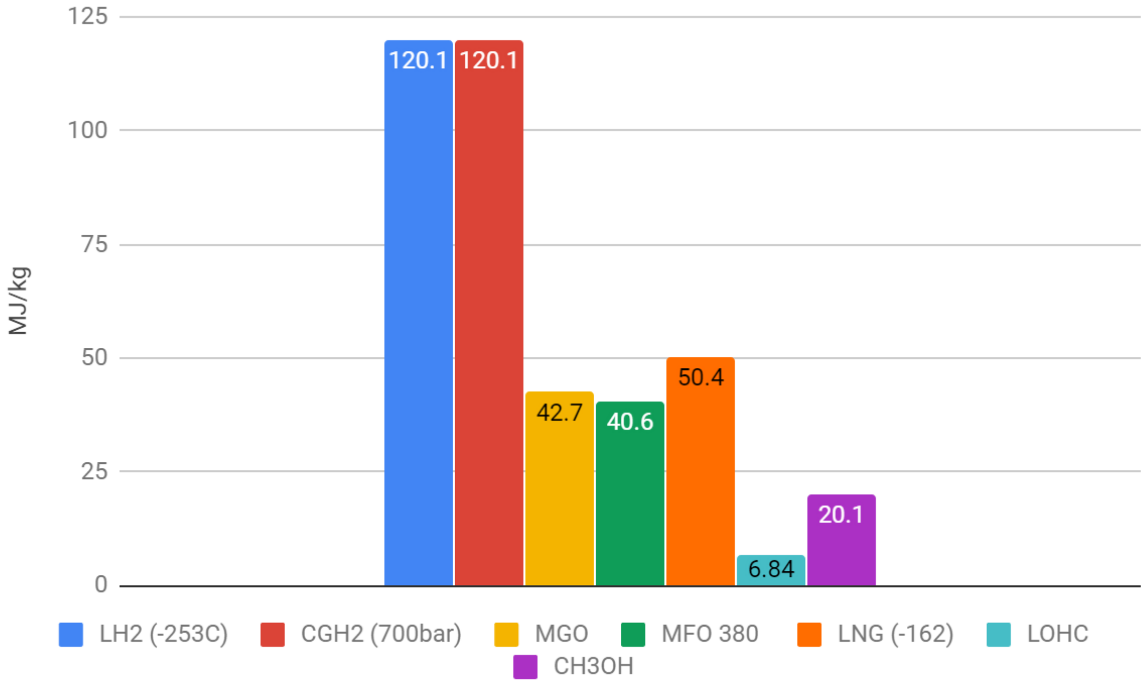

Figure 4 Gravimetric energy density of LH_2, CGH_2, MGO, MFO 380, LNG, LOHC & CH_3OH.

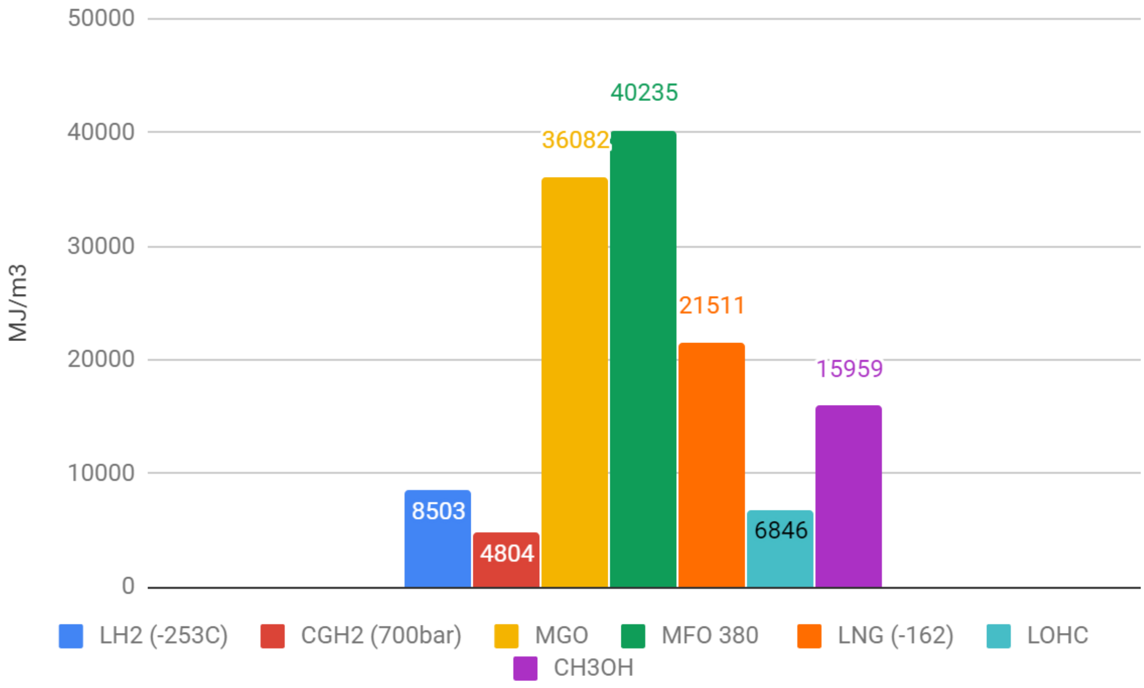

Figure 5 Volumetric energy density of LH_2, CGH_2, MGO, MFO 380, LNG, LOHC & CH_3OH.

3 Method

3.1 Choice of method

To assess and compare PEMFC and SOFC for marine applications we conducted a literature review which was complemented with interviews from industry representatives. From the literature review we identified the following important performance areas: cost, dimensions, energy density, lifetime, fuels that can be used, efficiency load variations and emissions. Mixing methods seemed to be the most viable approach for this study. Both proton exchange membrane and solid oxide fuel cells are still quite young technologies.

This thesis is divided into two parts, a literature review and a calculation. The literature review comprises of several parts: fuel cell cost; fuel cell dimensions; fuel prices; lifetime; electric efficiency. Some data included in the literature review origins from two consultations that were made during the study. The calculations use data from the literature review.

The purpose of a literature review is to give an overview of the current knowledge within a subject. This is done through systematic and objective review of current research within a field. Gathering of literature is done through specific methods and search words. The findings are then presented in an overview and a subjective conclusion is drawn from the data gathered (Denscombe, 2016).

In order to gather information and to build a better understanding for the subject we consulted two representatives working with fuel cells. A set of questions were prepared for both consultations and field notes were taken during the meetings. The first representative was Jan Froitzheim, Associate Professor in Chemistry and Chemical Engineering, Environmental Inorganic Chemistry, at Chalmers. The second representative was Johan Burgren, Business Manager at Powercell, a Gothenburg based fuel cell company. Information gathered during these consultations are personal communication.

3.2 Data collection

Data was gathered both through scientific articles, published reports and manufacturer’s data sheets. Scientific articles included in the review were acquired through Chalmers library search function. Manufacturer’s data sheets were acquired through the manufacturer’s website where they were openly available. Performance data on the Nuvera fuel cell was found through a news article. Reports were gathered through the web while scientific articles were found using databases. The databases used were the following: Science direct, Complementary Index, Gale Academic OneFile, Chalmers Library Catalogue, Chalmers Library E-book Collection, Scopus®, Science Citation Index, Directory of Open Access Journals & Academic Search Index.

Some data was also gathered through consulting a fuel cell company and an Associate Professor in Chemistry and Chemical Engineering, Environmental Inorganic Chemistry, at Chalmers. In the literature review fuel cell costs, dimensions, energy density, lifetime, efficiency are compared for proton exchange membrane and solid oxide fuel cells. Furthermore, produced kilowatt hours electric is calculated for fuel cells and combustion engines using performance data from the literature review.

The consultations were made through two meetings in total. Both meetings were prepared with similar generic questions about fuel cells. Some questions had to be adapted depending on the technology as they work differently. During the consultations both researchers were present. One was made in person and the second was a telephone conference. Answers to the questions were directly written down by the person holding the secretary role.

3.3 Inclusion and exclusion criteria

The criteria for scientific articles or reports was that they should not be older than 10 years. They had to at least handle the topic Proton exchange membrane or Solid oxide fuel cell.

Selecting data sheets for the dimension and energy density comparison was initially done by using fuel cells in the similar power range of a 100 kW. The selection was also limited to proton exchange membrane and solid oxide fuel cells. This was later changed to include both phosphoric acid and molten carbonate fuel cells. The power range was also increased.

3.4 Search words

English was the primary language during the searches while Swedish was used less frequently for searches. These are the search words that were used throughout the information gathering: shipping, marine, fuel cell, SOFC, solid oxide fuel cell, proton exchange membrane, LOHC, PEMFC, storage, hydrogen, liquid, liquefaction, compressed, methanol, HFO, MGO, PAFC, AFC, efficiency, density, cost, capex, Nasa, Apollo, Ballard, Powercell, Nedstack, Toshiba, Doosan, Sure Source, Fuel Cell Bulletin, Hyrex, Nuvera, Symbio, Bloom Energy, Swiss hydrogen, Fuel Cell Energy, Daesan, shipping and fuel cells.

3.5 Prices and currency

Fuel costs per produced kilowatt hour electric was also calculated but is not included in the literature review as method. Although it should be noted that produced kilowatt hours electric was calculated using efficiency data gathered for this report and up to date fuel prices.

If a price was gathered in euro and converted into US dollars, the conversion rate used was 1:1.116.

For cost comparisons an electricity price of 0.64 SEK/kWh, equal to 0.067 $/kWh between July and December 2018 was used in the calculations (Centralbyrån, 2019). Prices for MGO (Marine gas oil) and MFO 380 (Marine fuel oil), retrieved in April, of 740.15 $/mt and 491.97 $/mt were used to compare the traditional combustion engine with the FC technology (Bunker Index, 2019).

4 Result

Different characteristics of PEMFC and SOFC affect their potential for use onboard ships. The most important aspects will be described in this chapter. Fuel Cells sensitivity to load variations, the cost of the fuel cells, the size of fuel cells, fuel price, lifetime, fuel cost per kWh_e, electric efficiency and a comparison of both technologies.

4.1 Fuel cell costs

Fuel cell cost prices are shown as $/kW in table 1. Prices shown are divided into amount of fuel cells that are needed to be produced in order to reach that price. Where N/A is shown, price could not be associated with future, present or past production numbers. The average capex according to table 1, does not take any consideration of the number of produced units. Even if there seems to be a correlation between production volumes and capex.

In 2017 the US Department of Energy released a report of projected costs for a 80 kW PEMFC system for the automotive industry. Expected cost for 2017 depended on the amount of fuel cells produced and ranged between 50 and 45 $/kW. When looking at Battelle's report of costs we see that the modelled cost for a 100 kW stationary PEM is between 2670 and 3140 $/kW for 1000-10000 units produced. For a 250 kW PEM stationary power supply the cost decreased and landed on between 1727 and 2040 $/kW. SOFC modelled to cost range between 1544 and 1770 $/kW. Looking at larger units of 250kW SOFC the price is reduced to between 1264 and 1434 $/kW. In a more recent report from U.S Department of Energy concerning PEM fuel cells in trucks cost projections range between 96.8 and 225 $/kW depending on how many units that will be produced (US Department of Energy, 2018). Through personal communication with the fuel cell company Powercell we received the price information of a complete PEMFC could have a cost of 1500 €/kW or 1674 $/kW for maritime application (Burgren, 2019). It was explained that 2/3 of the system cost was for the fuel cell itself. Jan Froitzheim stated during our inquiry about SOFC that today's capex for SOFC is 3571 $/kW at 10MW of units shipped per year. If production volumes for SOFC increased to 50 MW shipped yearly capex can come down to 558 $/kW (Froitzheim, 2019). With capex as low as 558 $/kW for a fuel cell (FC) it is not far away from an internal combustion engine (ICE) at 700 $/kW (Brynolf, 2014). When looking at future cost between the years 2030 and 2040, maritime FC capex can range between 1695 and 2957.4 $/kW (Stephen Horvath, 2018). Here capex depends on the type of fuel cell and fuel used but doesn't take production volumes into consideration. When looking at another report (Baldi, Wang, Pérez-Fortes, & Maréchal, 2019) it can be seen that PEMFC projections for 2016 were at 1785 $/kW. The same article stated that SOFC for the same year would cost 2455.2 $/kW.

Table 1. Fuel cell cost, capex ($/kW). All values given in €, throughout the report, have been converted into $

FC System	Units produced	2015	2016	2017	2018	2019	2030	2040
PEM 80kw projected cost (Department of Energy, 2017)	100000		60	50				
	500000		53	45				
PEM 100 kW modeled cost, stationary power supply (Institute, 2016)	1000		3140					
	10000		2670					
PEM 250 kW modeled cost, stationary power supply (Institute, 2016)	1000		2040					
	10000		1727					
Medium duty truck 160 kW PEM (U. S. D. O. ENERGY, 2018)	1000				225			
	10000				135			
	100000				97			
Marine FC System Powercell (Burgren, 2019)	N/A					1674		
PEM (Baldi et al., 2019)	N/A		1786					
SOFC 100 kW modeled cost, stationary power supply (Institute, 2016)	1000		1770					
	10000		1544					
SOFC 250 kW modeled cost, stationary power supply (Institute, 2016)	1000		1434					
	10000		1264					
SOFC (Froitzheim, 2019)	10MW/year					3571		
SOFC (Froitzheim, 2019)	50MW/year					558		
SOFC 200kW (Agency, 2015)	N/A	3000						
SOFC 200kW (Agency, 2015)	N/A	4000						
SOFC (Baldi et al., 2019)	N/A		2455					
Diesel FC Capex Future Cost (Stephen Horvath, 2018)	N/A						2957	2655
Natural Gas FC Capex Future Cost (Stephen Horvath, 2018)	N/A						2655	2655
Hydrogen FC Capex Future Cost (Stephen Horvath, 2018)	N/A						1888	1695

4.2 Fuel cell dimensions and energy density

Data from 9 fuel cell manufacturers was gathered. Out of the 9 manufacturers 6 developed PEMFC, 1 PAFC, 1 MCFC and 1 SOFC. The PEMFC systems are listed to be used with hydrogen while PAFC, MCFC and SOFC have been specified for LNG. 6 out of 9 manufacturers displayed their fuel cell systems lifetime, this on either the product datasheet or their website in some form. The most common fuel cell displayed in table 2 is PEM followed by MCFC and SOFC. Out of the 14 systems 8 used H_2 and 6 natural gas as fuel.

The column "FC category" in table 2 has been made to differentiate the different fuel cell systems from fuel cells and fuel stacks:

> "1" is the energy densest and includes only the fuel cell stack. E.g. Powercell S3 is a fuel cell stack and a component of Powercell MS-100 (Burgren, 2019).
>
> "2" is the fuel cell itself, the fuel cell stack is a component of the fuel cell. It is less energy dense due to the fact that the stack is combined with other components. Powercell MS-100
>
> "3" is the least energy dens system, that includes everything, for example fuel pipes and reformers, cooling system and control system. Should be seen as complete stationary system. E.g. Sure Source 3000

Average power densities were calculated for PEMFC and SOFC according to the power densities supplied by table 2. FC Category two was used for this. The average power density for PEMFC was 226W/dm^3 and 10w/dm^3 for SOFC. (EMSA, 2017) states that there is a difference between PEMFC and SOFC where PEMFC has the higher power density. According to (Burgren, 2019) SOFC systems are 10-15 times larger than PEM. MCFCs and PAFCs have the largest size of the four, thus lower energy density (EMSA, 2017).

Table 2. Fuel cell systems, a comparison between different fuel cells, their volumes, category, power densities, mass, power, efficiency, fuel, lifetime and type. This table is not representative for how many FC manufacturers there actually are. Nor does it say that these are the only FC types. Power densities have been calculated by using manufacturers product specification sheets.

Fuel cell Systems	V (dm^3)	FC category (1-3)	W/dm^3	m (kg)	Power (kW)	Efficiency (%)	Fuel	Lifetime	Type
Powercell S3	29.1	1	3369	32.3	98	N/A	H_2	N/A	PEM[1]
Powercell ms 100	300	2	333	120-150	100	50-62	H_2	N/A	PEM[2]
Fc Velocity HD 100	528	2	190	285	100	N/A	H_2	N/A	PEM[3]
Fc Velocity XD	1980	2	51 / 101	1000	100 / 200	53	H_2	>20,000 hours	PEM[4]
H2REX Pure Hydrogen FC	N/A	2	N/A	N/A	100	N/A	H_2	80000	PEM[5]
HY-Rex100	270	2	371	98	100	50	H_2	>5000	PEM[6]
Nedstack	31	2	309	40	9.5	N/A	H2	>20000	PEM[7]
Nuvera	N/A	2	N/A	N/A	8-300	N/A	H_2	N/A	PEM[8]

Symbio, H2Motiv XL	32-128	1	2500	N/A	80 - 320	N/A	H_2	N/A	PEM[9]
ES5-YA8AAN	29962	2	10	15800	300	53-65	NG	N/A	SOFC[10]
ES5-FABAAN	23412	2	9	12600	200	53-65	NG	N/A	SOFC[11]
ES5-EA2AAN	23412	2	11	13600	250	53-65	NG	N/A	SOFC[12]
Sure source 4000	N/A	3	N/A	N/A	3700	60	NG	N/A	MCFC[13]
Sure source 3000	2217111	3	1.3	159211	2800	47 ±2%	NG	N/A	MCFC[14]
PureCell Model 400	67043	3	7	28663	440	45	NG	85848	PAFC[15]

1: (Powercell, 2018) 2: (Powercell, 2019) 3: (Ballard, 2019) 4: (Systems) 5: (Toshiba, 2019) 6: (Swiss Hydrogen, 2017) 7: (Nedstack, 2014) 8: (Renewableenergy Focus, 2013) 9: (Symbio, 2019) 10: (Energy, 2019c) 11: (Energy, 2019b) 12: (Energy, 2019a) 13: (Fuelcellenergy, 2019b) 14: (Fuelcellenergy, 2019a) 15: (Doosan, 2018)

4.3 Fuel prices

In table 3, the price for hydrogen, MGO, MFO 380 and LNG and LOHC are shown. To be noted LOHC is not a fuel itself but a fuel carrier where hydrogen is bound to an oil. As can be seen LNG has the lowest price/MJ and is followed by MFO 380. MGO is on third place and hydrogen has the highest price of the four fuels in table 3. The conversion rate between $ and € is: *$ = € * 1.116.*

An approximate cost for producing hydrogen is 4.15 $/kg, appendix B (5) & (6)

Table 3 Fuel prices for H_2, MGO, MFO 380, LNG and LOHC

	CGH_2	**MGO**	**MFO 380**	**LNG**	**LOHC**
€ / kg	9[1]	0.663	0.441	0.280	4[2]
$ / mt	10044	740.15[3]	491.97[3]	312.89	4464[2]
LHV (MJ/kg)	120.1[4]	42.7[5]	40.6[4]	50.4[4]	6.84[6]
$ / MJ	0.084[7]	0.017[7]	0.012[7]	0.006[8]	0.041[9]

1: Compressed hydrogen price: 9 €/kg in april 2019 (Burgren, 2019) 2: Hydrogenious LOHC prices: 4-5 $/kg, 4-5 €/L, <4 €/kg. A mean value of this gives 4 €/kg. This is the cost for the oil (Schneider, 2015) not the cost of hydrogenation or dehydrogenation. 3: (Bunker Index, 2019) 4: (Svein Erik Pedersen, 2015) 5: (Shell, 2012) 6: 1.9 kWh/kg LOHC = 6.84 MJ/kg LOHC (Schneider, 2015) 7: $/MJ = ($/kg) / LHV 8: The price for LNG is taken from DNVGL, they report the price on the 15 february 2019 to be 6.55 $/mmBtu. 1 mmBtu = 1055.06 MJ. This gives us 6.55 / 1055.06 = 0.00621 $/MJ.(DNVGL, 2019) 9: The calculation can be found in appendix B (16). The displayed price includes hydrogenation, dehydrogenation and the production cost of hydrogen by electrolysis.

4.4 Lifetime

Expected lifetime for PEMFC and SOFC is shown in table A3 gathered from different sources. Average lifetime for both types has been calculated at the bottom row of the table. PEMFC lifetime ranges from 5000 to 35000 hours. SOFC lifetime ranges between 30000-90000 hours. Expected lifetime of fuel cells can vary depending on its application. In the article “A review of PEM fuel cell durability” fuel cells for the automotive industry have a lifetime expectancy of 5000 hours (Wu et al., 2008). A similar lifetime expectancy is found in a company presentation (Powercell, 2017). PEMFC for buses in comparison to cars have a higher lifetime expectancy reaching 20000 hours (Wu et al., 2008) and stationary have an expectancy of 40000 hours. The lower lifetime expectancy for cars can be explained by cars being subjected to more frequent load variations which makes the lifetime shorter. According to (Burgren, 2019) lifetime of a fuel cell will increase if it is run on a constant load. Starting up and shutting down the system also decreases lifetime of a fuel cell (Wu et al., 2008). In comparison to SOFC, PEMFC can handle these load variations better, as SOFC is very sensitive to these. It is also recommended to combine FC systems with batteries to deal with load cycling (EMSA, 2017).

The average lifetime for PEMFC and SOFC according to table A3 is 21000 and 56000 hours, respectively.

4.5 Fuel cost per kWh_e

Fuel prices per kWh_e for 7 different energy conversion systems were calculated and is showed in each column of table A4. The LOHC price displayed is only based on dehydrogenation, hydrogenation and the hydrogen production cost. To be noted, the life cycle cost is not included in this price comparison.

As seen in figure 6, SOFC running on natural gas has lowest price per kWh_e followed by a 4-stroke genset on MGO. PEMFC running on compressed hydrogen has by far the highest price per produced kWh_e.

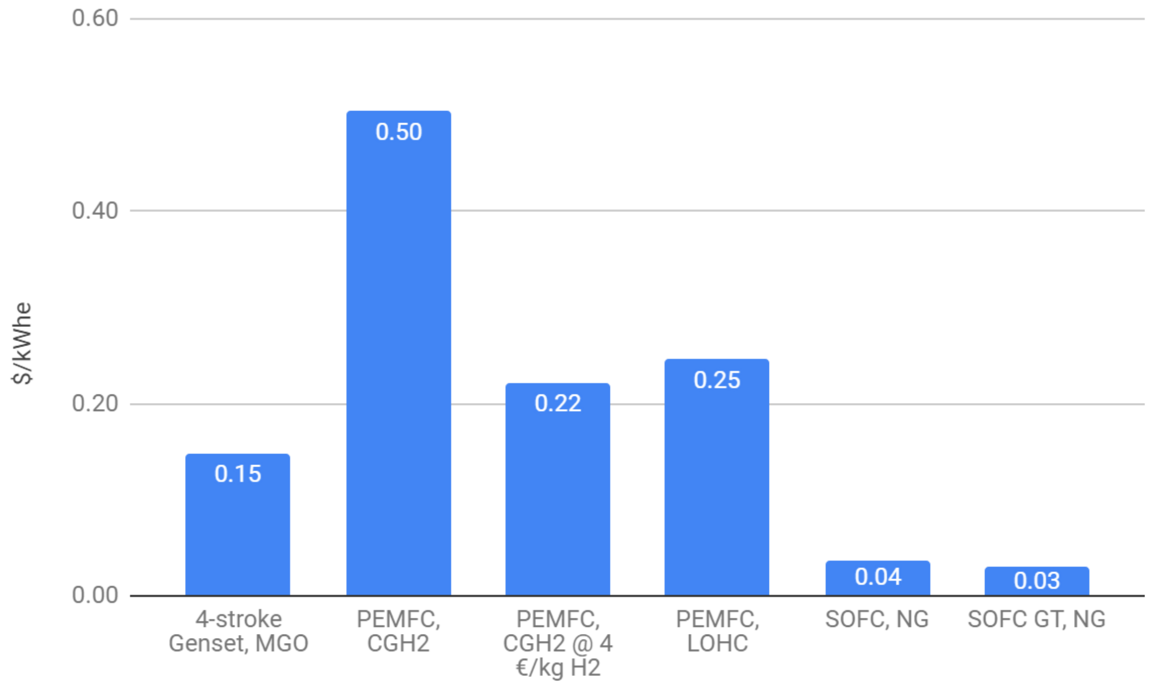

Figure 6 Fuel cost per kWh$_e$

In figure 7, a comparison where it is shown the required size of the fuel tanks depending on a certain fuel and the demand for electrical power.

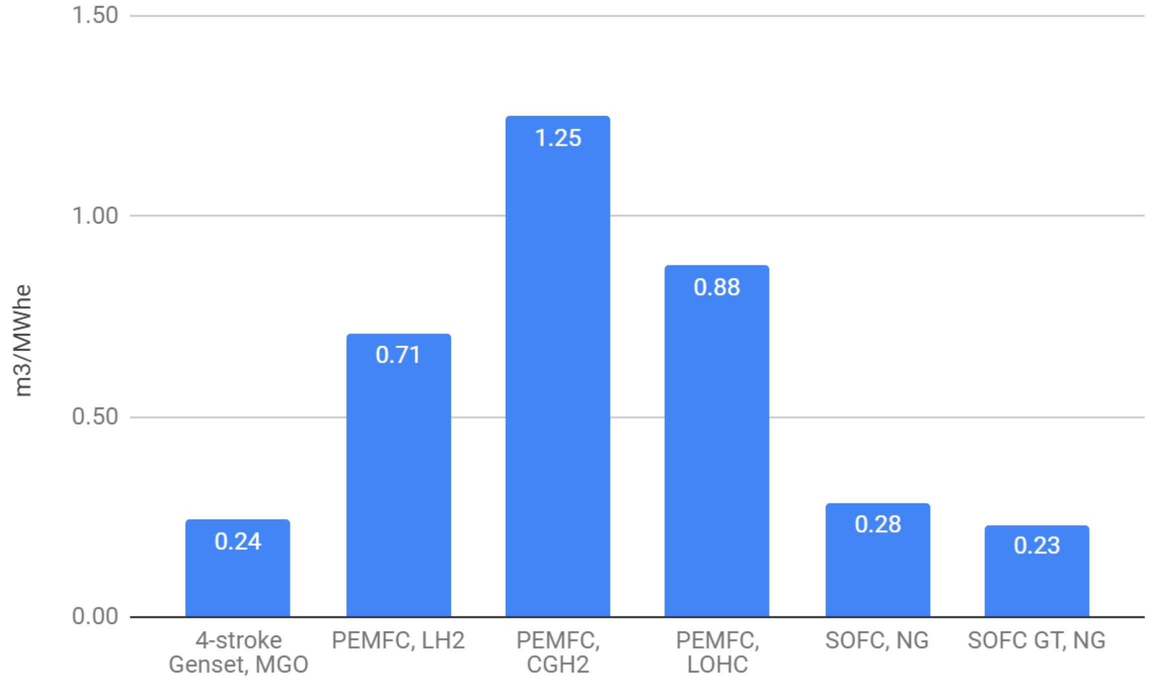

Figure 7 Fuel volume needed for producing 1 MWh$_e$

4.6 Electric efficiency comparison

In table 4 electric efficiencies for PEM and SOFC and 4-stroke internal combustion engine (ICE) was gathered from 9 sources. Average electrical efficiency for PEMFC and SOFC totalled in 60% and 59.8%, respectively. SOFC GT (SOFC with gas turbine) received an average electrical efficiency of 73.3%. Overall average efficiency for SOFC HR (SOFC with heat recovery) was 88.2%.

Table 4. Comparison of electric efficiency.

Source	4 Stroke ICE (%)	PEMFC LT, H2 (%)	SOFC, NG (%)	SOFC GT, NG (%)	SOFC HR, NG (%)
(Powercell, 2017)		50-60	50-60		
(EMSA, 2017)		50-60	60		85
(de-Troya, Álvarez, Fernández-Garrido, & Carral, 2016)			40-60	70-80	
Baldi et al. (2019)			60-61	70	85-90
(Zhang et al., 2017)			59.3		92
(Woud & Stapersma, 2002)	23-49				
(Van Biert et al., 2016)	45	70	60		
(MAN, 2019)	44.5				
(Froitzheim, 2019)			74		
Average Efficiency	**41.3**	**60**	**59.8**	**73.3**	**88.2**

4.7 SOFC and PEMFC comparison

All performance data for SOFC and PEMFC have been summarised in Table 5 for comparison. Both technologies have been tested in ships although PEMFC has been tested more times than SOFC. They can both use hydrogen as fuel but the SOFC is less sensitive to impurities and can utilize other fuels like methane, diesel and methanol. The average price/kw for PEMFC is half that of SOFC. PEMFC is the most compact of the two and has the highest energy density. In terms of $/kWh$_e$ SOFC is the cheapest when run on methane. SOFC has a higher average lifetime. PEMFC has highest electrical efficiency. SOFC can be combined with a natural gas turbine and in that way further increase its electrical efficiency. Due to its high working temperature SOFC can further increase its efficiency by utilizing heat recovery. SOFC is the only technology of the two that releases harmful emissions e.g. CO_2, nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) during operation if other fuels then hydrogen is used.

Due to high working temperature in the SOFC it is relatively slow and sensitive to load variations. It could be beneficial to use a battery to even out the load and reduce thermal stress

(EMSA, 2017). The PEMFC handles load variations well (EMSA, 2017), but will also benefit out of a lifetime perspective by using batteries, to even out the load (Burgren, 2019).

Emissions from fuel cells depends on the type of fuel. Carbon based fuel will release carbon dioxide and small amounts of NO_x, SO_x, volatile organic compounds (VOC), PM and carbon monoxide (CO) (EMSA, 2017). If hydrogen is used as a fuel, the only emission is water. This is not entirely true as it depends on how the hydrogen is produced. There are two common methods for producing hydrogen. One is by steam reforming and the second is by electrolysis. Steam-reforming is the most frequently used method (Md Mamoon Rashid, 2015). It uses carbon-based fuels and releases carbon dioxide as a by-product (Vätgas Sverige, 2019a). Electrolysis uses water and electricity to produce hydrogen by splitting the water into oxygen and hydrogen (Md Mamoon Rashid, 2015). 1 ton of produced hydrogen releases more than 10 tons of carbon dioxide (Preuster et al., 2017)

Table 5. SOFC and PEMFC comparison

Parameters	SOFC (NG)	PEM (H_2)
Maritime projects 2000-2017[1-2]	4	16
Fuel type most frequently used[1-2]	1 Methanol, 1 Diesel, 2 Various	16 Hydrogen
Fuel Cell Costs[3-10]	558-4000 $/kW	45-3140 $/kW
Fuel Cell Cost average[11]	2177 $/kW	1054 $/kW
Fuel Cell Power Density[12-26]	9-11 W/dm^3	51-371 W/dm^3
Fuel Cell Power Density Average[28]	10 W/dm^3	226 W/dm^3
Fuel[1-2]	LNG, Diesel, Hydrogen and Methanol	Hydrogen
Fuel cost per kWh$_e$[1,6-8,29-48]	0.04 $/kWh$_e$	0.5 $/kWh$_e$
Lifetime[1,6-9,18,41,49-51]	30000-90000h	5000-35000h
Lifetime Average[52]	56000h	21000h
Electric efficiency[1,7,8,40-45]	40-61%	50-70%
Average[53]	59.8%	60%
Electric efficiency with Gas turbine[7,41]	70-80%	
Average[53]	73.3 %	
Total efficiency with heat recovery[1,7,42]	85-92%	
Average[53]	88.2%	
System size[12-26]	Large	Small
Sensitivity to load variations[1]	Sensitive	Less sensitive
Potential emissions[1,27,37-38]	CO2, NOx, Sox, PM	Water
Fuel type possible to use[1]	Hydrogen, Methane Diesel, Methanol	Hydrogen

1: (EMSA, 2017) 2: (Ihonen, 2017) 3: (Department of Energy, 2017) 4: (Institute, 2016) 5: (U. S. D. O. ENERGY, 2018) 6: (Burgren, 2019) 7: (Baldi et al., 2019) 8: (Froitzheim, 2019) 9: (Agency, 2015) 10: (Stephen Horvath, 2018) 11: Table 1 12: (Powercell, 2019) 13: (Ballard, 2019) 14: (Systems, 2019) 15: (Doosan, 2018) 16: (Fuelcellenergy, 2019b) 17: (Fuelcellenergy, 2019a) 18: (Swiss Hydrogen, 2017) 19: (Energy, 2019c) 20:

(Energy, 2019b) 21: (Energy, 2019a) 22: (Toshiba, 2019) 23: (Nedstack, 2014) 24: (Renewableenergy Focus, 2013) 25: (Symbio, 2019) 26: (Powercell, 2018) 27: (Alfredsson & Swenson, 2017) 28: Table 2 29: (Vogler & Sattler, 2016) 30: (Burgren, 2019) 31: (Bunker Index, 2019) 32: (DNVGL, 2019) 33: (Schneider, 2015) 34: (Svein Erik Pedersen, 2015) 35: (Shell, 2012) 36: (Department of Energy Hydrogen and Fuel Cells Program Record, 2009) 37: (Preuster et al., 2017) 38: (Vätgas Sverige, 2019a) 39: (Centralbyrån, 2019) 40: (Powercell, 2017) 41: (de-Troya, Álvarez, Fernández-Garrido, & Carral, 2016) 42: (Zhang et al., 2017) 43: (Woud & Stapersma, 2002) 44: (Van Biert et al., 2016) 45: (MAN, 2019) 46: (ST1, 2014) 47: (Association, 2011) 48: (Chalmers Department for Mecanics and Maritime Sciencies, 2019) 49: (Nedstack, 2017) 50: (Systems, 2019) 51: (Ballard Power Systems, 2019) 52: Table A3 53: Table 4 54: Table 3

5 Discussion

There is an abundance of literature and articles on the subject. Throughout the study we found several PEMFC manufacturers but only one SOFC manufacturer. The reason for this could be PEMFC being a more mature technology than SOFC. Although few SOFC manufacturers were found, useful data was acquired through reports and scientific articles. In hindsight it would be preferable to include more SOFC manufacturers to increase the reliability of the comparison.

5.1 Discussion of result

The literature review shows that there is an interest in fuel cells in the shipping industry. Not only PEM and SOFC are being tested, but also MCFC (EMSA, 2017). Although it was chosen to focus the study on PEM and SOFC technology, we can also see that MCFC as a fuel cell technology is feasible for maritime use. Naohiro Saito concluded in his report on fuel cells, that PEM, SO and MCFC are the most feasible to use out of an economic point view (Saito, 2018).

5.1.1 Fuel cell costs

There is a large variation in the costs reported for SOFC and PEMFC in the literature as shown in table 1.

Fuel cell costs in table 1 should not be taken out of context. The average capex according to table 1, does not take any consideration to the number of produced units. Both capex for PEMFC and SOFC are cost predictions from the past and estimated costs in future. Capex ranges between 45-4000 $/kw not considering the fuel cell type or the production volumes. Prices between 45-60 $/kW should be seen from a more mature market standpoint. To achieve the prices 45-60$ production volumes of 100000-500000 units must be achieved. The fuel cells in this price range are also aimed for the automotive industry which doesn't make it an entirely fair comparison. According to the organisation Fuel Cells and Hydrogen Joint Undertaking market realizations in "a business as usual scenario" could happen between 2025-2045, with a less conservative view this could be seen in between 2025-2035 (FCH, 2019).

Looking at FC capex for the shipping industry, it can be seen from table 1, that cost predictions for stationary application is not too far apart compared to the automotive industry. Even if stationary and maritime FC predictions are quite high for now compared to internal combustion engines (Brynolf, 2014). It is not unlikely that synergy effects will be seen from the automotive industry when production volumes increase. Another factor that should be considered when analysing capex predictions is that at least in some cases a mark-up of the price is used. In Battelle's report it could be seen that capex was 1.5 times higher from the original calculated cost (Institute, 2016).

If production volumes increase significantly cost reduction could be seen for both technologies. Compared to maritime ICE both SOFC and PEM still have a higher initial capex (Stephen Horvath, 2018).

5.1.2 Fuel cell dimensions and energy density

As seen in table 2 there is a difference in size between SOFC and PEMFC in power density. PEMFC has a greater power density than SOFC. PEMFC are in general regarded as more energy dense compared to SOFC. (Vogler & Sattler, 2016) states that most FC systems of today that are in the range of 150 kW and larger are significantly less energy dense than PEMFC. This is also confirmed by EMSA's maritime study on fuel cells (EMSA, 2017). It should be noted that it would be preferable to include more SOFC systems, in order to increase the validity of the comparison.

During data gathering it was noted that fuel cells were marketed in different ways. In some cases, the fuel cell stack itself was marketed especially for the automotive industry where high-power density is demanded. When looking at stationary systems the whole system size was usually included.

5.1.3 Fuel energy density

Although fuel energy density of a fuel was not included in the research question it is an essential part of the study as it explains some of the challenges with fuels concerning fuel cells onboard ships.

Hydrogen has the highest energy density per kg compared to MGO, MFO 380, LNG and Methanol. Its volumetric energy density on the other hand shows that hydrogen in its liquid form assumes 4.7 times more volume than MFO 380 (Vogler & Sattler, 2016). Liquid natural gas requires twice the space of MGO at -162°C. This factor impairs the operational range of ships as they will need much larger bunker tanks for the same amount of energy. LOHC will need even more space compared to liquid hydrogen but has the advantage of being stored at an ambient room temperature. Hydrogen in its compressed form has lower energy density than LOHC and suffers from impracticalities from its pressure tanks. LOHC would seem to be a more convenient option compared to liquid hydrogen concerning handling and safety as it does not burn easily. Boil off from liquid hydrogen has not been investigated in this report but should be considered in future reports.

5.1.4 Fuel price and fuel cost per kWh_e

When calculating the price of hydrogen per kilo gram an assumption was made of 8766 MWh of energy usage yearly. The price of electricity during July to Dec 2018 was 0.67 $/kWh (Centralbyrån, 2019). 1 kg of hydrogen requires 50 kWh to produce (Vätgas Sverige, 2019a). Multiplying these results in a hydrogen production price of 3.33 $/kg. When adding the investment and operating cost to the production price of hydrogen will have an estimated cost of 6.66 $/kg (Vätgas Sverige, 2019a). When comparing fuel cost per kWh_e for hydrogen with natural gas and traditional marine fuels, hydrogen has the highest price of them all. If the hydrogen price decreases our result would change significantly. When looking at historical prices of the other fuels there does not seem to be any large enough change in price to affect our result.

Even if two values for the hydrogen cost was found, it was decided to use 9 €/kg H_2 throughout this thesis.

In figure 6 fuel cost per kWh_e can be seen. In the calculation, capex is not included in the final price per kWh_e.

From a shipowner's perspective it could be interesting to have capex included. If capex is added to the calculation over a time period, a difference can be seen of 4-10% on cost per kWh_e. For example, assuming a lifetime of 50000 hours and a constant price of 9 €/kg H2 the total price per kWh_e just increases from 0.50 to 0.52 $ or at a lifetime of 21000 hours the increase is 0.05

\$/kWh$_e$ equal to 10% of the total cost, table A5. If the same comparison is made with a traditional diesel genset, the fuel cost versus total cost, the increase is ~5% at 50000 hours and ~11% at 21000 hours, table A6. Even if fuel cells are considered at higher price per kW compared to the ICE, the largest cost will not be the capex but the fuel.

The reason for why capex was not added from the beginning is that capex for fuel cells varies at the moment as they have not been fully commercialized. It would be reasonable to think that shipowners would be reluctant to switch technologies if price is not competitive against current powerplant systems. Depending on the segment of shipping, capex will play an important role (Vogler & Sattler, 2016). At the same time fuel cost is as important because it governs the operational costs (Vogler & Sattler, 2016).

The numbers 17 kWh$_e$/kg H_2 (Burgren, 2019) together with the price of hydrogen, 9 €/kg H_2 results in 0.53 €/kWh$_e$ or 0.59 \$/kWh$_e$.

The calculated result 0.50 \$/kWh$_e$ for a PEMFC running on CGH_2 seems reasonable compared with the approximated cost of 0.59 \$/kWh$_e$ received from (Burgren, 2019).

Operational fuel cost as seen in figure 6 and table A4 gives the SOFC a lower cost compared to PEMFC when running on LNG.

5.1.5 Lifetime

In order to receive a general overview of PEM and SOFC lifetime, an average was calculated. PEMFC lifetime can vary between 5000-35000 hours and is categorized depending on the application. According to (Wu et al., 2008) PEMFC for stationary application has the longest lifetime followed by busses and then cars. This distinction is not made in the comparison of table A3 but is worth noting (Wu et al., 2008).

According to Johan Burgren at Powercell, to utilize the maximum lifetime of a PEM fuel cell it should run at constant medium load. EMSA states in their report “Study on the use of fuel cells in shipping” that SOFC has a low tolerance for cycling compared to PEMFC (EMSA, 2017).

What can be said about FC lifetime is that it has a strong correlation to load variation. The less load variation in a fuel cell the longer lifetime it can achieve (Alfredsson & Swenson, 2017) (Burgren, 2019). Also, the SOFC lifetime is dependent on its application. It is even more sensitive for load variations than the PEMFC (EMSA, 2017). At the same time, lifetime of PEMFC can be increased significantly if one were to use it in applications with less load cycling (Wu et al., 2008).

5.1.6 Electric efficiency comparison

Table 4 shows average efficiency for both PEM and SOFC. Efficiency values for PEM and SOFC were gathered from several sources. From the result it can be seen that both technologies have similar average efficiency. PEM efficiency varies depending on its load condition and can decrease with as much as 10% (Powercell, 2017). According to (Burgren, 2019) PEMFC has its highest efficiency at ~30% load. The efficiency of a fuel cell is higher than the internal combustion engine. The reason for this is that FC do not have to follow the Carnot-efficiency curve compared to ICE, as seen in the background (Barbir, 2005).

In chapter 4.5 and 4.6 combustion engines are compared with fuel cells. Although our research question does not support combustion engines, this comparison could give a wider perspective on how they perform against fuel cells. The columns with ICE in table 4 are not presented in table 5 since it is not a fuel cell.

5.1.7 PEMFC and SOFC technology comparison

SOFC has an average lifetime of 56000 hours based on table 5. SOFC is not yet a fully developed technology although one manufacturer was found. As for PEMFC average lifetime is shorter than SOFC. This could depend on that PEMFC are primarily used in more load driven applications, i.e. cars and buses but have also been seen in stationary applications.

As for emissions the SOFC system is the least environmentally friendly of the two as it can emit CO2, NOX, SOX, VOC and CO. This of course depends on the fuel used, if hydrogen is used in the SOFC it would mean that it would be on par with PEMFC out of an environmental perspective, where water is the only emission. This does not take into consideration from what the hydrogen is initially produced from. Hydrogen can be produced with both renewables and fossil fuels, as described in chapter 2.4.1 and 4.7.

Both SOFC and PEMFC have high electrical efficiencies over todays combustion engines.

5.2 Selection of method

The study combines both a literature review approach and consultations with representatives from the industry. Several other methods were considered. Interview and case study were also possible method candidates.

Interview as a method was considered early on but was discarded because it had possible disadvantages for the study, as finding subjects to interview could be difficult within the given timeframe. A case study was also considered for the comparison of SO and PEM fuel cells. One disadvantage with case studies is that it could be difficult to get access to the environment where the study is intended to take place (Denscombe, 2016). E.g. we could have asked permission to study PEM fuel cells in Gothenburg. This would require the permission from the specified company which we did not have. During the study there were no SOFC companies known to us in Sweden. Therefore, it was decided that a literature review approach had a higher likeliness to succeed than the other methods mentioned above.

It could be discussed if interview as a method would have produced a different result. E.g. interviews according to Denscombe (2016) are suitable for producing detailed data and could give the researcher valuable insight due to the subjects vast experience in his or her field. In hindsight the study would not have been based on the same amount of data which is also reflected by the fact that we were only able to find two representatives from the industry to consult during the study.

5.3 Literature search

Literature searches were not limited to databases found in Chalmers library's search engine. By not limiting the scope of the literature searches a broad range of data was acquired. This would not have been possible if searches had been limited e.g. to a specific database or type of article. In order to produce reliable results an age limit of ten years was set for the articles and reports reviewed. An exception to this rule was made in one case. During the comparison of fuel cell efficiency in table 4, performance data for combustion engines from 2002 was used. It was not considered that combustion engine data would affect the validity of the result as it is not likely that combustion engine efficiency has changed very much the last twenty years.

Data for chapter 4.2 was made by gathering data sheets from manufacturer's websites. In one case an exception was made concerning Nuvera fuel cells where data was gathered through a news article. This could affect reliability for that specific entry but will most likely not affect the end result if the entry would have been ignored.

The criteria given in the method states that articles must handle the topic PEMFC or SOFC. An exception to this was made during the compilation of data for chapter 4.2. Although it was not originally intended to include MCFC and PAFC in the comparison as it is not supported by research question, it was added by the fact that it exemplifies land-based fuel cell systems. These fuel cell systems require more volume in general and they provide a distinction between the different types of fuel cells.

During the data gathering of fuel cell systems, more SOFC could have been included in the comparison in order to increase the validity of the result. We believe that the main reason why so few SOFC entries were included in the study, is that PEM fuel cells are more common on the market.

5.4 Data gathering

It should be noted that the Liquid Organic Hydrogen Carrier oil cost, energy content, in table 3 derives from a company presentation. The maker Hydrogenious is a for profit organization. (Schneider, 2015). The cost for hydrogenation, dehydrogenation and hydrogen production is an approximation (Preuster et al., 2017) & (Schneider, 2015) not directly from the manufacturer, see appendix B.

One should have in mind that both persons consulted represent their own unique field within fuel cells. Johan Burgren at Powercell works for a profit company which main purpose is to promote and sell PEM fuel cells. Jan Froiztheim does research within the field of SO fuel cells.

Maritime fuel cell projects were reviewed through two sources. The bulk of maritime fuel cell data was found in EMSA's study on "maritime use of fuel cells in shipping". One project was found in (Ihonen, 2017) which was later confirmed by (Powercell, 2017). Several other articles and presentations, (Van Biert et al., 2016), (Markowski & Pielecha, 2019), (Langfeldt, 2018), (Klebanoff, Pratt, & LaFleur, 2017), (Barbir, 2005) describe the projects mentioned in EMSA's study in some way. Therefore, it was decided to use EMSA's study for the projects primarily.

6 Conclusion

By studying maritime FC projects, it can be seen that PEMFC is the most widely tested technology followed by SOFC and MCFC. The reason to why PEMFC is mostly is used could be because of the availability of the technology, more flexible performance characteristics and price.

Both PEM and SO fuel cell types have similar average electrical efficiency. When looking at the SOFC it can be noted that its average electrical efficiency is slightly lower. Although the PEMFC is favored by its slightly higher electrical efficiency the SOFC can be configured in such a way that it can further increase its efficiency. Combined with a gas turbine it can further increase its electrical efficiency. Due its high work temperature it can also utilize waste heat recovery and furthermore increase its efficiency. The overall efficiency of the SOFC can be increased up to 88% if heat recovery is utilized. This could make it a more interesting choice over the PEMFC, but it does not take into account the lower energy density of the SOFC system. The SOFC has 10-22 times the volume of PEMFC which makes it a large system. From a lifetime perspective SOFC has highest average lifetime compared to PEMFC. Load cycling decreases the lifetime of both types but SOFC is more sensitive to load cycling than PEMFC. Both PEMFC and SOFC can utilize hydrogen as fuel. PEMFC demands high purity of hydrogen while SOFC is less sensitive and can utilize other fuels like methane, methanol and diesel without using a reformer. If hydrogen is chosen as a fuel it will be the most sustainable as the only emission is water. The average calculated price for a PEM fuel cell is 1054 $/kW and the SO fuel cell has about the double of that, 2177 $/kW. As a comparison to this, a traditional diesel genset has a capex of 700 $/kW. The most expensive way the produce an electric kWh is by the use of a PEMFC running on hydrogen and most cost efficient is to run a SOFC on natural gas.

For future research it could be interesting to study how a complete fuel cell system could replace a traditional fossil fuelled one onboard ships. We know that hydrogen requires about 4.8 times the volume in its liquid form compared heavy fuel oil. Could some of the extra volume required for fuel be compensated when systems associated with heavy fuel oil operation are removed.

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References

Alfredsson, H., & Swenson, C. (2017). *Bränslecell jämfört med dieselgenerator. En fallstudie; ersättning av dieselgenerator på ett fartyg.* CHALMERS TEKNISKA HÖGSKOLA. Retrieved from http://publications.lib.chalmers.se/records/fulltext/250182/250182.pdf

Andersson, K., Brynolf, S., Lindgren, J. F., & Wilewska-Bien, M. (2016). *Shipping and the Environment*: Springer, Berlin, Heidelberg.

Association, D. M. (2011). Bio-Methanol.

Baldi, F., Wang, L., Pérez-Fortes, M., & Maréchal, F. (2019). A Cogeneration System Based on Solid Oxide and Proton Exchange Membrane Fuel Cells With Hybrid Storage for Off-Grid. *Frontiers in Energy Research*. doi:10.3389/fenrg.2018.00139

Ballard. (2019). Fuel Cell Power Module for Heavy Duty Motive Applications.

Ballard Power Systems. (2019). Heavy duty models. Retrieved from http://ballard.com/fuel-cell-solutions/fuel-cell-power-products/motive-modules

Barbir, F. (2005). *Pem Fuel Cells*: Elsevier Academic Press.

Brynolf, S. (2014). *Environmental Assessment of Present and Future marine Fuels*.

Bulletin, F. C. (2018). Doosan starts installation of hydrogen-fueled 50 MW fuel cell power plant in South Korea. *Volume 2018*(Issue 8), 1.

Bunker Index. (2019). Bunker index,. Retrieved from https://www.bunkerindex.com/

Burgren, J. (2019, 17 april 2019). [Personal Communcation].

Centralbyrån, S. (2019, 4 maj 2019). Priser på el för industrikunder 2007–. Retrieved from https://www.scb.se/hitta-statistik/statistik-efter-amne/energi/prisutvecklingen-inom-energiomradet/energipriser-pa-naturgas-och-el/pong/tabell-och-diagram/genomsnittspriser-per-halvar-2007/priser-pa-el-for-industrikunder-2007/

Chalmers Department for Mecanics and Maritime Sciencies. (2019). *Tanker Safety Liquified Gases* (T. O. Neptune Ed. Vol. 2).

de-Troya, J. J., Álvarez, C., Fernández-Garrido, C., & Carral, L. (2016). Analysing the possibilities of using fuel cells in ships. *International Journal of Hydrogen Energy, 41*(4), 2853-2866. doi:10.1016/j.ijhydene.2015.11.145

Deniz, C., & Zincir, B. (2016). Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production, 113*, 438-449. doi:10.1016/j.jclepro.2015.11.089

Denscombe, M. (2016). *Forskningshandboken* (P. Larson, Trans.).

Department of Energy Hydrogen and Fuel Cells Program Record. (2009). *Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs*. Retrieved from https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf?fbclid=IwAR0PMWYPYO0BbHyZUr9MmsLkze8BqSOOfFSvWYpy-506cUh6ae-BdINou6s

DNVGL. (2019). Current price development oil and gas. Retrieved from https://www.dnvgl.com/maritime/lng/current-price-development-oil-and-gas.html

Doosan. (2018, 04-30-2019). Pure Cell Modell 400. Retrieved from http://www.doosanfuelcell.com/download/pdf/catalog/pafc-400kw_us_en.pdf

EMSA. (2017). *MARITIME STUDY ON THE USE OF FUEL CELLS IN SHIPPING*. Retrieved from http://www.emsa.europa.eu/news-a-press-centre/external-news/download/4545/2921/23.html

Energigas, S. (2019, 26 september 2017). Svenska rederier surfar på gasvågen. Retrieved from https://www.energigas.se/publikationer/tidningen-energigas/svenska-rederier-surfar-paa-gasvaagen/

Energy, B. (2019a, 04-30-2019). ES5-EA2AAN. Retrieved from https://www.bloomenergy.com/sites/default/files/es5-250kw-datasheet-2019.pdf

Energy, B. (2019b). ES5-FABAAN. Retrieved from https://www.bloomenergy.com/sites/default/files/es5-200kw-datasheet-2019.pdf

Energy, B. (2019c, 04-30-2019). ES5-YA8AAN. Retrieved from https://www.bloomenergy.com/sites/default/files/es5-300kw-datasheet-2019.pdf

FCH. (2019). *Hydrogen Roadmap Europe A sustainable pathway for the European energy transition*, . Retrieved from https://fch.europa.eu/sites/default/files/20190206_Hydrogen%20Roadmap%20Europe_Keynote_Final.pdf

Forsea. (2019). Hållbarhet. Retrieved from https://www.forsea.se/om-forsea/hallbarhet/

Froitzheim, J. (2019, 5 february). [Personal Communication].

Fuel Cell Today. (2019). History. Retrieved from http://www.fuelcelltoday.com/history

Fuelcellenergy. (2019a). SureSource 3000

2.8 MEGAWATTS. Retrieved from https://www.fuelcellenergy.com/wp-content/uploads/2017/02/Product-Spec-SureSource-3000.pdf

Fuelcellenergy. (2019b, 04-30-2019). SureSource 4000. Retrieved from https://www.fuelcellenergy.com/wp-content/uploads/2013/11/Product-Spec-SureSource-4000.pdf

Ihonen, J. (2017). MARANDA project to develop fuel cell system for Arctic ship. *Fuel Cells Bulletin, 2017*(2), 3-4. doi:10.1016/s1464-2859(17)30072-x

ILK Dresden, M. K. (2015). Storage density of Hydrogen under certain pressure and temperature conditions. Retrieved from https://en.wikipedia.org/wiki/Hydrogen_storage#/media/File:Storage_Density_of_Hydrogen.jpg

IMO. (2014). *Third IMO Greenhouse Gas Study 2014*. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf?fbclid=IwAR2VoUCnjD_VfmMWI4AjcDRnYM0tZo4KGfbKjU5GONKY_WwRmc77GF5IiEw

IMO. (2019, 9-13 April 2018). Marine Environment Protection Committee (MEPC), 72nd session. Retrieved from http://www.imo.org/en/MediaCentre/MeetingSummaries/MEPC/Pages/MEPC-72nd-session.aspx

Institute, g. M. (2016). *Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications*. Retrieved from https://www.energy.gov/sites/prod/files/2016/07/f33/fcto_battelle_mfg_cost_analysis_pp_chp_fc_systems.pdf.

J Markowski, I. P. (2019). *The potential of fuel cells as a drive source of maritime transport*. Paper presented at the 2nd International Conference on the Sustainable Energy and Environmental Development.

Kreuer, K.-D. (2013). *Fuel Cells Selected Entries from the Encyclopedia of Sustainability Science and Technology*.

Langfeldt, L. (2018, 21 February). Maritime Fuel Cell Applications Technologies and ongoing developments. Retrieved from http://www.jterc.or.jp/koku/koku_semina/pdf/180221_presentation-01.pdf

Margaronis, S. (2018). ABB collaboration with Ballard advances fuel cell ships

Retrieved from https://www.ajot.com/blogs/full/ai-abb-collaboration-with-ballard-advances-fuel-cell-ships?fbclid=IwAR3ALzLS8Jc05bcA37hXmYPLvfvR6x-G5ua5NPFWAijbEzK41K-xnH04igI

Md Mamoon Rashid, M. K. A. M., Hamid Naseem, Mohd Danish. (2015). Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis. *International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-4 Issue-3, February 2015*.

Methanex. (2019). Methanex Methanol Price Sheet. Retrieved from https://www.methanex.com/our-business/pricing?fbclid=IwAR3BDzovuaqbiLnc5X_K1FYfJOXulHmVZlusBF5chqixVBjEqKdfAWF0RGE

Nationalencyklopedin. (2019). naturgas. Retrieved from http://www.ne.se/uppslagsverk/encyklopedi/lång/naturgas

Nedstack. (2014, 04-30-2018). PRODUCT SPECIFICATIONS OF XXL STACKS. Retrieved from http://www.nedstack.com/wp-content/uploads/2017/05/nedstack_product-specifications-of-xxl-stacks.pdf

OECD, & IEA. (2005). *PROSPECTS FOR HYDROGEN AND FUEL CELLS*. Retrieved from

Powercell. (2017). Fuel Cells-PowerCell.

Powercell. (2018). S3-Produktblad.

Powercell. (2019, 04-30-2019). PowerCell MS 100 50-100kw Pem Fuel cell system Prototype. Retrieved from https://www.powercell.se/wordpress/wp-content/uploads/2018/12/powercell-ms100-datasheet-pdf.pdf

Preuster, P., Papp, C., & Wasserscheid, P. (2017). Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy. *Accounts of Chemical Research, 50*(1), 74-85. doi:10.1021/acs.accounts.6b00474

Renewableenergy Focus. (2013, 07 November 2013). Nuvera Fuel Cells to provide Fincantieri with fuel cell technology for marine vessels. Retrieved from http://www.renewableenergyfocus.com/view/35513/nuvera-fuel-cells-to-provide-fincantieri-with-fuel-cell-technology-for-marine-vessels/

Saito, N. (2018). *The economic analysis of commercial ships with hydrogen fuel cell through case studies*. Retrieved from https://commons.wmu.se/cgi/viewcontent.cgi?article=1617&context=all_dissertations

Schneider, D. M. J. (2015). Hydrogen storage and distribution via liquid organic carriers.

Shell. (2012). Shell marine gasoil,. Retrieved from https://prodepc.blob.core.windows.net/epcblobstorage/GPCDOC_X_cbe_26724_key_140007515295_201302281447.pdf

SHELL. (2019). WASSERSTOFF. Retrieved from https://www.shell.de/energie-und-innovation/mobilitaet/wasserstoff.html

Sjofartsdirektoratet. (2019). Amendments to the Regulations on environmental safety for ships and mobile offshore units. Retrieved from https://www.sdir.no/en/shipping/legislation/directives/amendments-to-the-regulations-on-environmental-safety-for-ships-and-mobile-offshore-units/

ST1. (2014). Marine fuel oil MFO 380.

Stephen Horvath, M. F., Christian Breyer. (2018). Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040.

Svein Erik Pedersen, J. G., Svein Kaasa, Oddmund Olsen. (2015). *Teknisk formelsamling med tabeller* (7 ed.). Oslo: Gyldendal undervisning.

Swiss Hydrogen. (2017). HY-REX100 RANGE EXTENDER FOR HEAVY DUTY VEHICLES.

Symbio. (2019). *H2Motiv XL*. Retrieved from https://www.symbio.one/en/modules-2/

Systems, B. P. (2019, 04-30-2019). Fuel cells for rail applications. Retrieved from https://hydrail.appstate.edu/sites/hydrail.appstate.edu/files/11_laperche-riteau.pdf

Toshiba. (2019). An environmentally-friendly and highly efficient power generator with no CO2 emissions. Retrieved from https://www.toshiba-energy.com/en/hydrogen/product/fuel-cell.htm

US Department of Energy. (2018). *2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles*.

US Department of Energy. (2019). Types of fuel cells. Retrieved from https://www.energy.gov/eere/fuelcells/types-fuel-cells

Van Biert, L., Godjevac, M., Visser, K., & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. *Journal of Power Sources, 327*(September), 345-364. doi:10.1016/j.jpowsour.2016.07.007

Vätgas Sverige. (2019a). FAQ. Retrieved from http://www.vatgas.se/faktabank/faq/

Vätgas Sverige. (2019b). Tankstationer. Retrieved from http://www.vatgas.se/tanka/

Vogler, F., & Sattler, G. (2016). Hydrogen-fueled marine transportation. *Compendium of Hydrogen Energy, 4*, 35-65. doi:10.1016/b978-1-78242-364-5.00003-8

White, M. a. (2000). *Liquified Gas Handling Priciniples on Ships and in Terminals* (T. O. Neptune Ed. 3 ed. Vol. 1). London.

Woud, K., & Stapersma, D. (2002). *Design of propulsion and electric power generation systems*. London: nstitute of Marine Engineers.

Wu, J., Yuan, X. Z., Martin, J. J., Wang, H., Zhang, J., Shen, J., . . . Merida, W. (2008). A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies. *Journal of Power Sources, 184*(1), 104-119. doi:10.1016/j.jpowsour.2008.06.006

Zhang, L., Xing, Y., Xu, H., Wang, H., Zhong, J., & Xuan, J. (2017). Comparative study of solid oxide fuel cell combined heat and power system with Multi-Stage Exhaust Chemical Energy Recycling: Modeling, experiment and optimization. *Energy Conversion and Management, 139*, 79-88. doi:https://doi.org/10.1016/j.enconman.2017.02.045

Appendix A

Table A1. Maritime fuel cell projects.

Project	Type	Power(kW)	Fuel
FellowSHIP[1]	MCFC	320	LNG
Viking Lady, METHAPU, Undine[1]	SOFC	20	Methanol
E4Ships, Pa-X-ell, MS MARIELLA[1]	HT-PEM	60	Methanol
E4Ships, SchIBZ, MS Forester[1]	SOFC	100	Diesel
E4Ships, Toplanterne[1]	Unknown	Unknown	Unknown
RiverCell[1]	HT-PEM	250	Methanol
RiverCell –Elektra[1]	HT-PEM	N/A	Hydrogen
ZemShip -Alsterwasser[1]	PEM	96	Hydrogen
FCSHIP[1]	MCFC	N/A	Various
FCSHIP[1]	SOFC	N/A	Various
FCSHIP[1]	PEM	N/A	Various
New-H-Ship[1]	Unknown	Unknown	Unknown
Nemo H2[1]	PEM	60	Hydrogen
Hornblower Hybrid[1]	PEM	32	Hydrogen
Hydrogenesis[1]	PEM	12	Hydrogen
MF Vågen[1]	HT-PEM	12	Hydrogen
Class1 212A/2141 Submarines[1]	PEM	306	Hydrogen
US SSFC[1]	PEM	500	
US SSFC[1]	MCFC	625	Diesel
SF-BREEZE[1]	PEM	2500	Hydrogen
MC-WAP[1]	MCFC	150	Diesel
FELICITAS – subproject 1[1]	Unknown	Unknown	Unknown
FELICITAS – subproject 2[1]	SOFC	250	Various
FELICITAS – subproject 3[1]	PEM	80	Various
FELICITAS – subproject 4[1]	PEM	Unknown	Unknown
Cobalt 233 Zet[1]	PEM	50	Hydrogen
Maranda[2]	PEM	165	Hydrogen

1: (EMSA, 2017) 2: (Ihonen, 2017)

Table A2. Comparison of fuel energy density. To convert between gravimetric energy density and volumetric energy density, the formula $LHV_{volumetric} = LHV_{gravimetric} * Density$ was used.

Unit	LH_2 (-253C)	CGH_2 (700 bar)	MGO	MFO 380	LNG (-162°C)	LOHC	CH_3OH
Gravimetric energy density LHV (MJ/kg)	120.1[1]	120.1[1]	42.7[2]	40.6[1]	50.4[1]	6.84[4]	20.1[7]
Density (kg/m^3)	70.8[8]	40[5]	845[2]	991[3]	426.8[9]	1000.8	794[7]
Volumetric energy density LHV (MJ/m^3)	8503.08	4804	36081.5	40234.6	21510.7	6845.7[6]	15959.4
Energy ratio (MJ/MJ)	1	0.56	4.24	4.73	2.53	0.81	1.88
Energy ratio (MJ/MJ)	0.24	0.13	1	1.12	0.60	0.19	0.44

1: (Svein Erik Pedersen, 2015) 2: (Shell, 2012) 3: (ST1, 2014) 4: This is for kg of LOHC, Dibenzyltoluene, 1.9 kWh/kg LOHC (Schneider, 2015) 5: Figure 3 6: This is for m^3 LOHC, 57 kg H2/m^3 LOHC (Schneider, 2015) 7: (Association, 2011) 8: (EMSA, 2017) 9: (Chalmers Department for Mecanics and Maritime Sciencies, 2019)

Table A3. Expected lifetime of fuel cells.

Source	PEMFC LT, H_2 (hour)	SOFC, CH_4 (hour)
(Burgren, 2019)	35000	
(Hydrogen, 2017)	>5000	
(Nedstack, 2017)	>20000	
(Systems, 2019)	>20000	
(Ballard Power Systems, 2019)	25000	
(de-Troya, Álvarez, Fernández-Garrido, & Carral, 2016)		30000
(Froitzheim, 2019)		40000-80000
(Baldi et al., 2019)		40000
(Agency, 2015)		90000
Average Lifetime	**21000**	**56000**

Table A4. Calculated fuel cost per kWh. To convert between MJ and kWh, the formula $LHV_{MJ} = LHV_{kWh} * 3.6$ was used.

	4-stroke Genset, MGO	**PEMFC, LH_2**	**PEMFC, CGH_2**	**PEMFC, H_2[3]**	**PEMFC, LOHC**	**SOFC, NG**	**SOFC GT[4], NG**
Fuel price[1] (\$/MJ)	0.017	N/A	0.084	0.037[3]	0.041	0.0062	0.0062
Fuel price (\$/kWh)	0.06	N/A	0.30	0.13[3]	0.15	0.02	0.02
Average efficiency[2] from table 4 (%)	41.3	60	60	60	60	59.8	73.3
Fuel volume / MWh_e (m^3/MWh_e)	0.24	0.71	1.25	1.25[3]	0.88	0.28	0.23
Fuel cost / kWh_e (\$/kWh_e)	0.15	N/A	0.50	0.22[3]	0.25	0.04	0.03

1: From table 3 2: From table 4 3: If the price would be 4 €/kg H_2 4: SOFC with gas turbine

Table A5. PEMFC run time and fuel price ($/kWh$_e$). Calculated at a capex of 1054 $/kW, assuming no Opex, no degradation of the fuel cell and continuous operation at optimum efficiency. Nor does it take interest or inflation into account. The production cost without capex is 0.50 $/kWh$_e$.

Year	1	2	2.4	3	4	5	6	7	8	9	10	11
Hours	8766	17532	21000	26298	35064	43830	52596	61362	70128	78894	87660	96426
€/kg[1]												
0.25	0.134	0.074	0.064	0.054	0.044	0.038	0.034	0.031	0.029	0.027	0.026	0.0249
0.5	0.148	0.088	0.078	0.068	0.058	0.052	0.048	0.045	0.043	0.041	0.040	0.0388
1.0	0.176	0.116	0.106	0.096	0.086	0.080	0.076	0.073	0.071	0.069	0.068	0.0667
2.0	0.232	0.172	0.162	0.152	0.142	0.136	0.132	0.129	0.127	0.125	0.124	0.1224
3.0	0.287	0.227	0.217	0.207	0.197	0.191	0.187	0.184	0.182	0.181	0.179	0.1782
4.0	0.343	0.283	0.273	0.263	0.253	0.247	0.243	0.240	0.238	0.236	0.235	0.2339
5.0	0.399	0.339	0.329	0.319	0.309	0.303	0.299	0.296	0.294	0.292	0.291	0.2897
6.0	0.455	0.395	0.385	0.375	0.365	0.359	0.355	0.352	0.350	0.348	0.347	0.3455
7.0	0.511	0.450	0.440	0.430	0.420	0.414	0.410	0.407	0.405	0.404	0.402	0.4012
8.0	0.566	0.506	0.496	0.486	0.476	0.470	0.466	0.463	0.461	0.459	0.458	0.4570
9.0	0.622	0.562	0.552	0.542	0.532	0.526	0.522	0.519	0.517	0.515	0.514	0.5127

1: Fuel prices between 0.25 and 9.0 €/kg

Table A6. MGO genset cost per time. Assuming continuous optimum load. Capex 300000$ & Opex 250000$ per 10 year from (Alfredsson & Swenson, 2017). Fuel price 740.15 $/mt

Year	$/kWh_e$
1	0.187
2	0.170
2.4	0.167
3	0.164
4	0.161
5	0.160
6	0.159
7	0.158
8	0.157
9	0.157
10	0.156
11	0.156

Appendix B

Calculation of the cost of using LOHC

During this calculation it is assumed that hydrogen behave like air in terms of compression.

To compress air in a 2-stage compressor to the final pressure, X bar, with equal amount of energy going to each cylinder. The pressure in the first stage is equal to $\sqrt{X}$
We assume that we can use the same proportion as for air.
To compress hydrogen from 20 to 700 bar it takes in average 3.1 kWh/kg H_2 (Department of Energy Hydrogen and Fuel Cells Program Record, 2009)

$$\sqrt{700-20} \approx 26\ bar \tag{1}$$

$$20+26=46\ bar \tag{2}$$

46 is close to 50 and between 30 and 50. Which is the required pressure at hydrogenation (Schneider, 2015).

$$\frac{3.1}{2}=1.55\ kWh \tag{3}$$

The hydrogenation is an exothermic process 8 kWh/kg H_2 and the dehydrogenation is an endothermic process of 11 kWh/kg H_2. This gives a net power of 3 kWh. Adding the required power for compressing the H_2 give a total value of required power 4.55 kWh

$$3+1.55=4.55\ kWh \tag{4}$$

Vätgas Sverige states that it cost between 3.77 and 6.60 € to produce 1 kg H_2.
(Preuster et al., 2017) gives another number, 1.5 and 3 € / kg H_2.
Taking the average value of this gives 3.72 € or 4.15 $

$$\frac{3.77+6.6+1.5+3}{4}=3.718\ € \tag{5}$$

$$3.7175 * 1.116 = 4.149\ \$ \tag{6}$$

The price of electricity on land is 0.067 $/kWh (Centralbyrån, 2019)
The price of electricity produced by PEMFC with compressed H_2 is 0.50 $/kWh$_e$.
Total required power for compressing H2, hydrogenation and dehydrogenation is 4.55 kWh.

$$4.55 * 0.067 = 0.305\ \$_{land} \tag{7}$$

$$4.55 * 0.50 = 2.275\ \$_{PEM} \tag{8}$$

Adding the price of producing the hydrogen, 4.15 $

$$0.305 + 4.15 = 4.455\ \$_{land} \tag{9}$$

$$2.275 + 4.15 = 6.425\ \$_{PEM} \tag{10}$$

Dividing this with LHV, 120.1 MJ/kg, gives the price per Mega Joule.

$$\frac{4.455}{120.1} = 0.037\ \$/MJ_{land} \tag{11}$$

$$\frac{6.425}{120.1} = 0.053\ \$/MJ_{PEM} \tag{12}$$

To make an average of the calculation. Beginning with the price per mega joule and then calculate from the beginning again.

$$\frac{0.037 + 0.053}{2} = 0.045\ \$/MJ \tag{13}$$

$$0.045 * 3.6 = 0.162\ \$/kWh \tag{14}$$

$$4.55 * 0.162 + 4.15 = 4.887\ \$ \tag{15}$$

$$\frac{4.887}{120.1} = 0.041\ \$/MJ \tag{16}$$