The fuel cell powered superyacht

A research into the possibilities and consequences of using fuel cells to provide a superyacht in its energy demand

B.H.M. Diesveld

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by

B.H.M. (Bart) Diesveld

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	Ing. R. Kleijweg,	Oceanco
	Ir. E. de Maeyer,	Oceanco
	Ir. K. Visser,	TU Delft
	Dr. C.L. Walters,	TU Delft

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Confidentiality note

Preface

This thesis is the result of the study executed to complete the Master of Science program in Marine Technology at the Delft University of Technology. The past nine months I have been working on this thesis at the project development department of Oceanco.

Oceanco provided me with the opportunity to turn this thesis into my own work since I have been given the freedom to formulate my own research objective and thereby the direction of the project, while still maintaining critical to the decisions and developments I made. Therefore I especially would like to thank my daily supervisors at Oceanco - Ir. E. de Maeyer and Ing. R. Kleijweg - for their guidance and support during this research project, even though they had a busy schedule themselves. I also want to thank Prof. Ir. J.J. Hopman and Ir. K. Klaas Visser from the TU Delft for the pleasant and useful progress meetings we had during this period.

Finishing this project is a milestone which marks the end of my incredible study period in Delft. The past period has been a very educational and interesting period, since this research project is well aligned with my personal interests it kept me enthusiastic and motivated. This has led to a project I enjoyed working on and a result that I am proud of.

B.H.M. (Bart) Diesveld
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Abstract

One of the most important reasons to investigating fuel cells is the increased level of regulation regarding emissions in the maritime sector, while fuel cells offer the opportunity to reduce these emissions. It was not clear what the impact of these systems would be on a yacht, the aim of this project is therefore to gain more insight into these topics. The objective of this study was to investigate the impact on both the design and operation of a superyacht using fuel cells for energy supply on board. To reach this objective, first a review of different fuel cells and fuel technologies was executed. These conclusions are used to develop a decision making tool which will help in choosing between the different types of fuel and fuel cell techniques. Finally the tool is used to select the best possible fuel cell solution, for this option the impact on the design and operation of a fully fuel cell powered yacht is determined. The report is split up into two different parts, where in the first the technological review is carried out while the second part focused on the design study.

In the first part a study was conducted into the status and characteristics of different fuel cell technologies and fuel storage solutions. Seven different types of fuel cells are investigated which can divided based on their operation temperatures (Low, Medium or High). Fourteen different types of fuels which are categorised as physical-, fuel- or material based hydrogen. The density of both separate systems were analysed and merged into a combined density for comparison reasons. Other factors which have been investigated are the: storage type, maturity, safety, and emissions. To be sure that a good choice can be made despite the many variables, these review subjects are used as decision criteria for the developed tool. In addition, the time influence on the density is taken into account by the adjustable time factor which is integrated in the tool. Specific preferences for a system can be given by changing the weighting factor for the different decision criteria. When changing the weight factors the order of all options will be rearranged by the tool, showing the ranking of the most promising solutions corresponding to the preferences of by the user.

From this tool, it has become clear that a fuel cell solution should be specifically selected for any different type of application. A specific application could lead to the selection of a completely different type of technology, which is in contrast with a diesel combustion engine where only an appropriate size needs to be selected.

The second part focuses on the design study of a fuel cell powered yacht, whereby an Oceanco yacht was used as reference. The most promising fuel cell solution for this yacht was selected based on the decision making tool and selected weighting criteria, a high temperature PEM fuel cell powered by methanol turned out to be the best solution. In order to determine the influence of the conversion to fuel cells additional research has been performed towards other factors which have an impact on the design. The following subjects were considered: regulations, fuel cell characteristics, energy storage, propulsion and electrical distribution.

From these topics, several important conclusions have emerged. First of all the regulations have a substantial impact on the design of a yacht. Secondly, the fuel and fuel cells itself require more space compared to the original configuration, and the fuel cells require a larger battery system to be able to follow the fluctuating load of a yacht. Lastly, it became clear that the use of fuel cells makes it possible to have some volume and efficiency gains when switching to PODs and a DC energy distribution system. A detailed design study based on these findings made clear that the yacht needed to become longer to fit all the required systems while keeping the functional requirements for the owners the same. Additionally the system changes corresponding to the fuel cell conversion resulted in an increase in terms of weight. These changes in length and weight turned out to have negligible change on the resistance of the yacht.

There are some factors which have an impact on the operation of the yacht. One of these is the fact that the lifespan of the used fuel cell technology is lower than that of a diesel combustion engine. A well designed hybrid system and by using shore power as much as possible, could be used to stretch the expected lifetime. Another operational issue could be the fact that this fuel cell technology is not fully developed which could influence the operability of the fuel cells. In addition, the methanol used as fuel is not as widely available as diesel. Positive influences are the fact that the overall efficiency increases while reducing all emissions with 100% except for the CO_2 emissions which will be 14-20% lower compared to a diesel engine. When using green methanol, the overall emissions of the yacht will be completely reduced since it will be CO_2 neutral. Additional advantages of fuel cells are the added comfort due to low noise and operation without any vibrations as well as an increased redundancy because of the modular design of the fuel cells.

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Nomenclature

The next list describes several abbreviations and symbols that will be used later within the body of the document

Abbreviations

AC	Alternating Current
AFC	Alkaline Fuel Cells
AIP	Air independent propulsion
APU	Auxiliary Power Unit
ASC	Anode-Supported Cells, type of SOFC
avg.	Average
CCHP	Combined Cooling, Heat and Power, also known as Trigeneration
CHP	Combined Heat and Power, also known as Cogeneration
CoG	Centre of Gravity
DC	Direct Current
DME	Dimethyl ether, CH_3OCH_3
DMFC	Direct Methanol Fuel Cell
DMO	Marine Diesel Oil, a blend of gas-oil and heavy fuel oil
DoD	Depth of Discharged
DWT	Deadweight tonnage
e-motor	Electric motor
ECAs	Emmision Control Ereas
EEDI	Energy Efficiency Index
ESC	Electrolyte-Supported Cells, type of SOFC
ESS	Energy Storage System
FCHES	Fuel Cell Hybrid Electric Ship
GHG	Greenhouse Gases
HFO	Heavy Fuel Oil
HT-PEMFC	High Temperature Polymer Electrolyte Membrane Fuel Cell/ Proton Exchange Membrane Fuel Cell
IACS	International Association of Classification Societies
IGF-code	International code for ships fuelled by Gases or other low-flashpoint Fuels
LCG	Longitudinal Centre of Gravity
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LSW	Light Ship Weight
LT-PEMFC	Low Temperature Polymer Electrolyte Membrane Fuel Cell/ Proton Exchange Membrane Fuel Cell
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbonate Fuel Cells
MCR	Maximum Continuous Rating
MFCU	Marine Fuel Cell Unit
MGO	Marine Gas Oil
MOF	Metal Organic Framework
MSC	Metal-Supported Cells, type of SOFC
n/a	Not Applicable /Not Available
NFPA	National Fire Protection Association
PAFC	Phosphoric Acid Fuel Cells
PEMFC	Polymer Electrolyte Membrane Fuel Cell/ Proton Exchange Membrane Fuel Cell
PM	Particulate Matter

RPM	Revolutions Per Minute
SOFC	Solid Oxide Fuel Cells
TCG	Transverse Centre of Gravity
TRL	Technology Readiness Level
UPW	Ultra Pure Water
VCG	Vertical Centre of Gravity
Molecular formulas	
C_2H_5OH	Ethanol
$C_{21}H_20$	Dibenzyltoluene, used as LOHC by hydrogenious
CH_3OCH_3	Dimethyl ether (DME)
CH_3OH	Methanol
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate ions
e^-	Electron
H^-	Hydron/ Proton
H_3PO_4	Phosphoric acid
H_2	Hydrogen
H_2O	Water
KOH	Potassium Hydroxide
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
$MeOH$	Methanol
$NaBH_4$	Sodium Borohydride
$NaBO_2$	Sodium Boronoxide
NG	Natural Gas
NH_3	Ammonia
NO_x	Nitrogen oxides
O^{2-}	Oxigen ion
O_2	Oxygen
ODS	Ozone-depleting substances
OH^-	Hydroxide
PA	Phosphoric Acid
PA	Polybenzimidazole
S	Sulphur
SO_x	Sulphur oxides
VOC	Volatile organic compounds
YSZ	Yttria-Stabilized Zirconia
Other Symbols	
$^\circ C$	Degree Celsius
Ship propulsion and efficiency symbols	
η_E	Engine efficiency
η_H	Hull efficiency
η_O	Open water propeller efficiency
η_R	Relative rotative efficiency
η_S	Shaft efficiency
η_{tot}	Total efficiency
P_B	Engine power
P_D	Power delivered to propeller
P_E	Effective power
P_F	Power delivered trough fuel

1 Introduction

The questions dealt with during this study will be introduced by two parts. First of all an image is sketched of the relevance and context of the topics that will be discussed. Secondly the goal of this project will be introduced by defining the objective and corresponding sub questions.

1.1. Relevance and context

Over the past years more and more attention has been paid to the environment and the reduction of green house gasses in order to reduce the impact on health and environment. This has been expressed by increasing regulations and targets set by governments and international organisations regarding emissions and pollution. For this same reason there is seen an increase in rules and regulations regarding emissions in shipping which are becoming more and more strict. The following statements of regulations or strategies gives some insight in the trends of shipping emission regulations, it should be noted that it's not limited to these regulations only:

- Recently the revised MARPOL Annex VI entered into force (1 July 2010) with tightened emission limits to reduce airborne emissions from ships (SO_x, NO_x, ODS, VOC). The main changes are progressive reduction in emissions of: SO_x, NO_x and particulate matter as well as the introduction of emission control ereas (ECAs). For example: The global sulphur cap reduction will go into force in 2020, this will result in a reduction of the sulphur limits from the current 3,5% to 0,5%.[39] In addition the Energy Efficiency Index (EEDI) was made mandatory for new ships with the adoption of amendments to MARPOL Annex VI (resolution MEPC.203(62)). The EEDI is an important technical measure for energy efficiency, new ships need to meet a certain reference level depending on their ship type. This EEDI level will by adjusted every five years causing stimulated innovation and influencing to a more energy efficient design. In 2025 reduction rates of 30% with respect to ships build form 2000 till 2010 have to be met for certain ship types.[40]
- IMO recently adopted a strategy to reduce greenhouse gases (GHG) which comes down to a reduction of at least 50% of the total annual GHG emissions from the global shipping sector by 2050 compared to 2008, with a strong emphasis to 100% reduction in 2050.[41]
- Norway will get the worlds first zero emission zone at sea in the world. In order to protect its fjords Norway has acted to halt emissions from cruise ships and ferries in the Norwegian world heritage fjords as soon as technical possible and no later than 2026.[49]

With these examples it is already clearly visible that there is a need to lower or even stop using conventional combustion engines and find a more sustainable and cleaner solution in the near future to meet these regulations. For the coming years it will probably still be possible to sail with a cleaner but polluting ship according to the regulations.

There are other reasons which can make it interesting for yacht owners to reduce the harmfull emissions of it's yacht or even aim for an emission free yacht:

- Yacht owners are often famous and influential people who could be interested in a green yacht for reputational reasons.
- Yacht owners want to visit special places or nature reserves, as seen with the Norwegian fjords it is possible that these areas will be protected and will only be accessible when complying to these regulations.

The basic principle of a fuel cell is already pretty old, the discovery of the fuel cell principle is due to Christan Friedrich Schönbein, Professor at the University of Bâle from 1829 to 1868. The first fuel cell was created in 1839 by sir William Grove, a British lawyer and physicist [12]. However the technology has never really broken through and has only been used in certain niche market, lately the fuel cells again draw the attention from different markets. The increase of interest is mainly because of the green features of a fuel cells, which resulted in investments in the fuel cell technique from the automotive industry what accelerated the technological development of fuel cells. These developments have contributed to the attention of the commercial maritime industry which also sees opportunities in this technique.

Nowadays there are a number of technical solutions to store or generate power on board ships without harmful emissions. These green energy generation solutions are for example wind energy, solar energy and fuel cells, while energy storage could could be realised by batteries. In terms of energy generation a fuel cell works fundamentally different than a combustion engine, fuel cells converts chemical energy directly into electricity while an engine generates thermal and mechanical energy from chemical energy which can be converted into electrical energy. A fuel cell generally uses hydrogen (H_2) and oxygen (O_2) through a chemical reaction to generate electricity, during this chemical reaction only water (H_2O) and heat are produced as by-product. This makes an fuel cell comparable with a battery since they both produce electricity by an electrochemical reaction with heat as byproduct. Fuel cells are capable of producing electrical energy without the negative effects of combustion engine generators (emissions, noise and vibrations) while still retaining a high efficiency. Fuel cells have the potential to be very efficient, some types of fuel cells can reach an efficiency up to 60% what is a lot higher than a combustion engine which only reaches efficiencies between 35-45%.[102] When the combustion engine will be replaced by a fully electrical drive train, the biggest source of vibration and sound will disappear, this will result in a reduction of sound and vibration and inreases the comfort. This makes fuel cells a very promising technology. Compared to batteries, which is seen as an other alternative solution for zero emission vehicles, fuel cells have two big advantages which makes it more attractive for vehicles with a high energy demand like ships:

1. Both the power/weight and power/volume ratios of fuel cells are higher than batteries. This is desirable in maritime solutions since you are often dealing with high powered vessels which also need a relatively extensive range.
2. Refuelling of hydrogen can be done relatively fast and compared to charging of batteries.

Therefore, the possibility of a zero-emission super yacht will be investigated.

Obviously there are also some disadvantages with respect to fuel cells. Since fuel cells make use of H_2 as fuel, the storage of hydrogen is the biggest challenge at the moment which is mainly density and safety related. Storage of hydrogen can be divided in two different types: physical storage (storage of H_2 molecules) and chemical storage (substance containing hydrogen). The main obstacle with physical storage is the low density compared to diesel fuel, therefore it's always stored compressed and/or cooled to reduce the volume. H_2 is typically stored compressed at 350 or 700 bar in the automotive industry or cooled to a temperature of -253 °C at ambient pressure making it liquid (LH_2) this is called cryogenic. It's also possible to store the H_2 in a version in between the two options described before, than it's stored at a somewhat higher temperature and an elevated pressure (Cryocompressed). The downside of storing hydrogen compressed, cryogenic or cryocompressed is the fact that these storing processes are expensive and energy intensive. Beside the implications of storing H_2 as gas or liquid there are some other difficulties, H_2 is: highly flammable, volatile and able to react with metals making them more brittle [102].

The other storage possibility of H_2 using chemical storage could offer a good solution to store H_2, hereby high storage densities could be reached in a cheaper and safer way. However the down side of this type of storage is that these systems are mostly still under investigation, and the systems realising the uncoupling of the H_2 atoms can be quite complex.

Another point of attention is the fact that most of the fuel cell techniques are still in a prototype stage causing that the technology is often not validated. Considering that the market has not yet embraced the technology makes it still relatively costly and there is a lack of infrastructure to supply and produce hydrogen.

Taken all these mentioned facts into account it becomes clear that fuel cells have several benefits and opportunities which makes it attractive to investigate the potential of applying such a technology in the maritime sector. Some of the characteristics of fuel cells makes it even more attractive for the application on superyacht.

1.2. Objective

From the last section it became clear that the opportunities of using fuel cells on super yacht seems very promising. For this reason a feasibility study of a completely fuel cell powered super yacht will be performed. This research will investigated and compare the required installation for a fuel cell powered yacht with a conventional propulsion system. The comparison between the conventional and fuel cell arrangement will clarify the consequences of switching to fuel cells on the design and operation of a yacht. This comparison will be made using a reference yacht which will be be adjusted to enable the application of fuel cells on the same yacht, while keeping the functional requirement for the owner exactly the same.

The objective of this project is to investigate the impact on both the design and operation of a super yacht using fuel cells for energy supply on board. This objective is supported with the following sub-questions to invigorate the main objective:

1. What types of fuel cells are currently available and to what extent are these fuel cells used in the maritime sector?
2. What options are available for storage of H_2 (including reformer solutions) on board a ship? (incl. power to weight/volume ratio's)
3. What are the main design requirements (technical, operational, regulations) with respect to the propulsion power and range of a yacht?
4. What is the promising combination of fuel and fuel cell type for a integrated solution on board of a superyacht. What are the main components needed for a fuel cell powered yacht compared to a existing MGO-based solution for propulsion and energy supply?
5. What is the impact of a fuel cell powered solution on the design of a superyacht?
6. What is the operational impact of using fuel cells on a yacht?

A REVIEW OF FUEL CELL AND FUEL STORAGE TECHNOLOGY STATUS

2

Fuel cells techniques

Power for propulsion and auxiliaries on board of ships is typically generated using diesel engines, in general this is realised with different engines for the main engine(s) and auxiliaries. The main engine normally propels the ship by a mechanical coupling between the propeller and engine. While the auxiliary engines are diesel generators generating electricity for all the electrical powered systems on board. Another possible arrangement is a diesel electric propulsion, which are increasingly used for propulsion, such a solution is normally completely powered by diesel generators and sometimes supported by batteries. As seen from the introduction a fuel cell has some benefits compared to diesel engines, therefore this chapter will be discus the most important information about fuel cells. Starting with explaining the working principles of fuel cells in section (2.1): what is a fuel cell? and what are the pros and cons? The next section (2.2) will give an overview of the different types of fuel cells and subsequently a comparison overview of the most important characteristics of the different discussed fuel cells in section (2.3). The latest section (2.4) of this chapter will go into the latest developments with respect to fuel cells in the maritime sector.

2.1. Fuel cell principles

A fuel cell is principally a device which transforms chemical energy directly into electrical energy via an electrochemical reaction. The chemical energy generally comes from a fuel (mostly H_2) and an oxidant (mostly O_2) which generate: electricity, heat and water, like illustrated in equation 2.1 and figure 2.1 for a simple fuel cell.

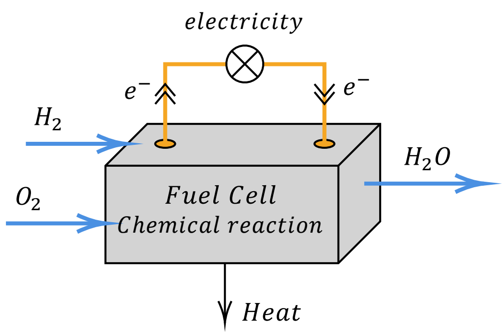


Figure 2.1: General working principle fuel cell

The electricity is generated by splitting of electrons which are than forced trough an external circuit creating an electric current. This is shown with the electrochemical half reactions showed in equation 2.2.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{2.1}$$

$$
\begin{aligned}
H_2 &\rightarrow 2H^+ + 2e^- \\
\frac{1}{2}O_2 + 2H^+ + 2e^- &\rightarrow H_2O
\end{aligned}
\tag{2.2}
$$

The fact that a fuel cell uses a electrochemical reaction makes it comparable to a battery, which also produces electricity by electrochemical reaction. The main advantage of a fuel cell compared to a battery is that it converts a fuel (chemical energy) directly into energy, while a battery needs to be charged to generate the chemical energy from electricity. A combustion engine needs some extra steps to come to electricity from chemical energy, this is done by converting heat into mechanical energy which then generates electrical energy. These different methods are graphically illustrated in figure 2.2.

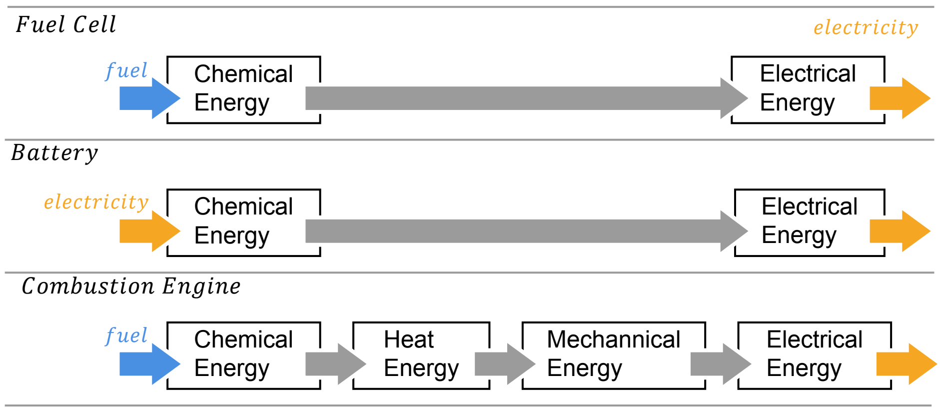


Figure 2.2: Fuel reforming process

2.2. Overview of different fuel cell types

In this section the working principle of six different fuel cell technologies are discussed. Among which: PEMFC (2.2.1), DMFC (2.2.2), AFC (2.2.3), PAFC (2.2.4), MCFC (2.2.5), SOFC (2.2.6).

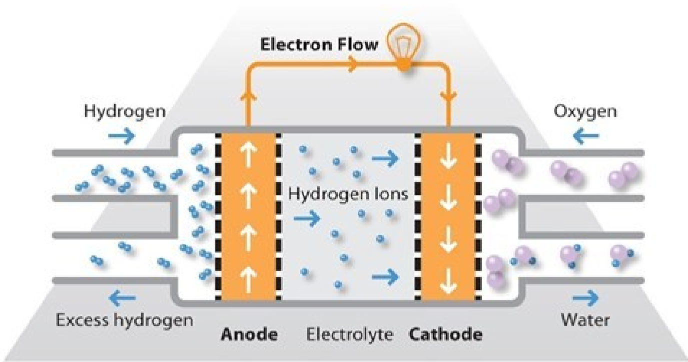
2.2.1. PEMFC

2.2.1.1. LT-PEMFC

The Polymer Electrolyte Membrane Fuel Cell (PEMFC), often called Proton Exchange Membrane Fuel Cell, uses a solid state[25] polymer electrolyte proton conducting membrane. The polymer membrane used in PEMFCs is normally a thin perfluorinated sulfonic acid polymer layer coated with a catalyst of a thin platinum layers on both sides. At the anode side the fuel (H_2) is processed, here the platinum catalyst splits the protons and electrons from each other. The protons pass to the cathode through the membrane while the electrons travel via an external carbon electrode support material to the cathode, generating the electric energy. At the cathode side the protons and electrons react with oxygen and form pure water [83]. The described anode and cathode reactions are showed in equation 2.3. This process is also schematically illustrated in figure 2.3.

$$
\begin{aligned}
Anode: 2H_2 &\rightarrow 4H^+ + 4e^- \\
Cathode: O_2 + 4H^+ + 4e^- &\rightarrow 2H_2O \\
Total\ reaction: 2H_2 + O_2 &\rightarrow 2H_2O
\end{aligned}
\tag{2.3}
$$

The operating temperature of the PEMFCs is limited to a maximum temperature of +/- 90°C because the membrane has to be constantly hydrated to retain a sufficient conductivity. Since the cell is separated by a polymer membrane film and operates at low temperatures, the sealing, assembly and handling are relatively easy compared to other type of cells [25]. The downside of this lower operating temperature is that it hinders the electrochemical reactions kinetics. To overcome this problem electrocatalysts are needed which are made of expensive precious metal (platinum or ruthenium), this is why platinum is used as catalyst.



Source: Fuel cell today: [28]

Figure 2.3: PEMFC technology, schematic explanation.

The PEMFC is currently the most developed and produced fuel cell technology [35], this is because it is seen as the best solution for vehicles. Recently there is done a lot of research in the automotive industry, as result the first fuel cell powered cars (e.g. Toyota Mirai, Hyundai Nexo, and Honda Clarity) are publicly available. It currently has the highest power density, fastest start up times and the best start-stop capabilities of all fuel cells [83]. Other benefits of this technology is that it is reasonably resistant to motions and the lack of corrosive fluid

Remarks:

- The constant need for hydration demands for an active water management system.
- Because of the low temperature the platinum catalyst is the only option, platinum catalyst are expensive and will lead to higher cost.
- This type of fuel cell is sensitive for poisoning by CO and S. CO will be absorbed at the platinum catalyst and block hydrogen from passing trough the catalyst, therefore a pure hydrogen input is essential to prevent contamination of the catalyst.
- Combined Heat and Power (CHP) difficult or impossible because of the low operating temperature

2.2.1.2. HT-PEMFC

As consequence of the problems that come with the low temperature PEM fuel cell the High Temperature PEMFC (HT-PEMFC) is being developed. The HT-PEMFC operates at temperatures around 120-200°C, other exchange membranes are needed to support this because these temperatures will cause dehydration of the membrane. Phosphoric acid (PA) (as used in PAFCs) doped in polybenzimidazole (PBI) membrane is often used as electrolyte. The platinum catalyst can be replaced by a cheaper material like nickel, instead of the platinum catalyst which is needed for the low temperature PEM fuel cells. Because of this higher temperature the cell is less sensitive for CO poisoning, CO absorption is disfavoured at higher temperatures. The point where CO becomes harmful increases from 10-20 ppm at 80°C to 1000 ppm at 130°C and even up to 30.000 ppm at 200°C, to give an idea of the temperature influence on CO poisoning [105]. This gives the opportunity to use another fuel than pure hydrogen in combination with a reformer since it better tolerates impurities. Another advantage of the higher temperature is the possibility of CHP making it possible to achieve higher efficiencies.

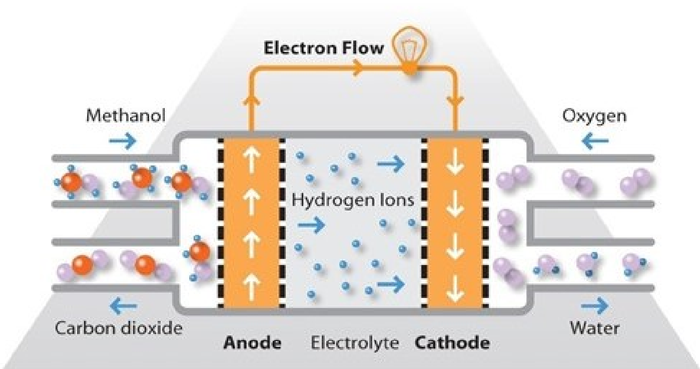
However there are also some disadvantages, the main disadvantage is the immaturity of this technique some issues with respect to durability and performance are still unsolved [89, 105].

2.2.2. DMFC

The Direct Methanol Fuel Cell (DMFC) is similar to the PEMFC as they both use a polymer membrane as electrolyte. This type of fuel cell is in fact a PEMFC that directly extracts the hydrogen molecules from liquid methanol (CH_3OH) with the use of a platinum-ruthenium catalyst [99], however a greater amount of platinum is needed to achieve the same results as with PEMFCs [21]. The chemical reaction used in a DMFC is shown in equation 2.4 and schematically illustrated in figure 2.4.

$$\begin{aligned} Anode &: CH_3OH + H_2O \rightarrow 6H^+ + CO_2 + 6e^- \\ Cathode &: \frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \\ Total\ reaction &: CH_3OH + \frac{3}{2}O_2 \rightarrow 2H_2O + CO_2 \end{aligned} \tag{2.4}$$

The operating temperature is slightly higher than with a normal PEMFC, DMFC normally operates between 50-150°C. Methanol has some advantages compared to hydrogen, it is less expensive has a relative high density and is easier to store and transport [99].



Source: Fuel cell today: [28]

Figure 2.4: DMFC technology, schematic explanation.

These fuel cells can operate in all orientations, the downside is that low temperature cells which don't operate on H_2 like DMFCs are still in development stage with a lot of challenges to solve[21]. The DMFCs are most suitable for small portable solutions like computers and mobile phones[25].

Remarks:

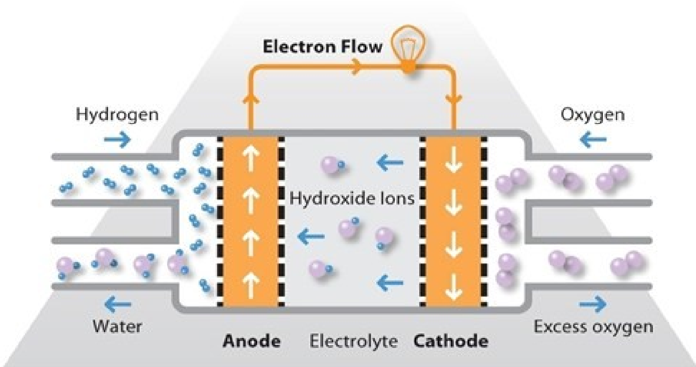
- Use expensive platinum catalyst.
- DMFCs have a relatively low efficiency and power density.
- DMFCs emits not only H_2O but also CO_2, so zero emission configuration is not possible.

2.2.3. AFC

The Alkaline Fuel Cell (AFC) is one of the first developed fuel cell technologies, and where used by NASA for their space shuttles. As the name suggest these cells use an alkaline electrolyte, generally a potassium hydroxide (KOH) solution. The early adopted AFCs operated between 100-250°C, nowadays these cells normally operate at temperatures around 70°C [28]. More metal-based catalyst are stable in an alkaline environment, this is why AFCs can use other metals as catalyst while still operating at relatively low temperatures. A nickel catalyst is typically used in AFCs which is cheaper compared to platinum catalysts as used in PEMFCs. This fuel cell transfers hydroxide (OH^-) through the alkaline electrolyte and has an opposite direction compared with the PEMFC and DMFC. The hydroxide passes through the cathode towards the anode where it reacts with hydrogen [83]. The chemical reactions used in a AFC are shown in equation 2.5 and schematically illustrated in figure 2.5.

$$\begin{aligned} Anode &: 2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \\ Cathode &: O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \\ Total\ reaction &: 2H_2 + O_2 \rightarrow 2H_2O \end{aligned} \tag{2.5}$$

As seen in equations 2.5, the cathode consumes water which is produced at the anode. The anode produces water twice as fast as the cathode consumes water, so the excess water has to be expelled from the electrolyte to prevent dilution of the KOH solution.



Source: Fuel cell today: [28]

Figure 2.5: AFC technology, schematic explanation.

These types of fuel cells have a relative high reaction speed and hereby offering a high electric efficiency.

Remarks:

- AFCs suffer from CO_2 poisoning because CO_2 will react with the alkaline electrolyte forming solid carbonates causing lower efficiencies. Therefore AFCs need pure H_2 and O_2 to keep the cell in good shape, therefore fuel reformers can't be used for this type of fuel cell and air need to be purified before it can be used as O_2 source.
- The needs to remove water from the electrolyte demands additional systems.

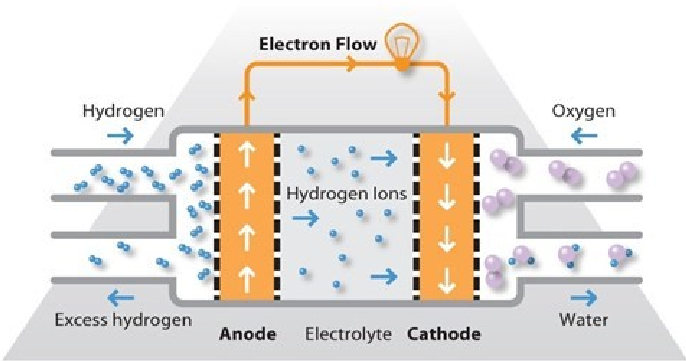
2.2.4. PAFC

The Phosphoric Acid Fuel Cell (PAFC) uses a liquid phosphoric acid (H_3PO_4) electrolyte contained by a silicon carbide matrix. This fuel cell uses a platinum catalyst like the PEMFCs. The working principle is about the same as for PEMFCs but they work at higher temperatures. The chemical reactions for this fuel cell are exactly the same as with PEMFC. The reactions used in PAFCs are showed in equation 2.6. This process is also schematically illustrated in figure 2.6.

$$\begin{aligned} Anode &: 2H_2 \rightarrow 4H^+ + 4e^- \\ Cathode &: O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \\ Total\ reaction &: 2H_2 + O_2 \rightarrow 2H_2O \end{aligned} \tag{2.6}$$

PAFCs normally operate at 180-210°C because of these higher operating temperatures the platinum catalyst is slightly less sensitive for CO and S poisoning compared with PEMFCs [83].

These fuel cells have a somewhat lower efficiency than other fuel cells, however because of the relatively high operating temperature a CHP efficiency of over 85% can be reached [28].



Source: Fuel cell today: [28]

Figure 2.6: PAFC technology, schematic explanation.

Remarks:

- PAFCs has a relatively low power density resulting in a large and heavy system.
- Catalyst is made of a expensive platinum material
- The electrolyte has to be replenished during operation because it slowly evaporates.

2.2.5. MCFC

The Molten Carbonate Fuel Cell (MCFC) uses carbonate ions (CO_3^{2-}) as charge carrier. If H_2 is used as fuel the only output this cell generates is heat and water, CO_2 and O_2 are needed to generate CO_3^{2-} at the cathode. The system will produce exactly the same amount of CO_2 as needed at the cathode, so with internal recirculation of CO_2 it will be possible to have no CO_2 emissions. This is clearly visible in equations 2.7 where the chemical reactions used in MFFCs are shown, in the total reaction only H_2O is left at the end of the reaction. This process is also schematically illustrated in figure 2.7.

$$\begin{aligned} Anode &: 2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^- \\ Cathode &: O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-} \\ Total\ reaction &: 2H_2 + O_2 \rightarrow 2H_2O \end{aligned} \tag{2.7}$$

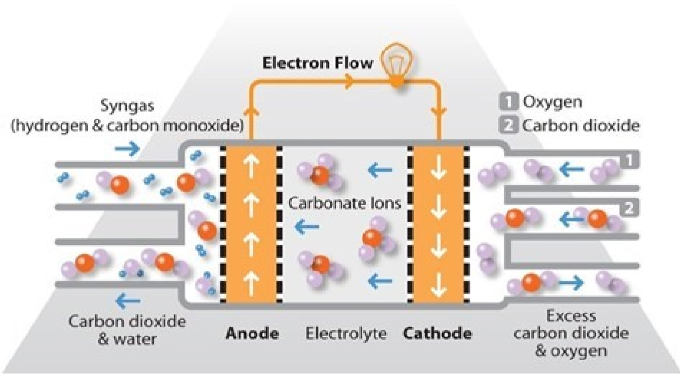
This cell operates at a relatively high temperature, normally around 600-700°C. In contrast with a lot of other fuel cells CO doesn't act as poison but as fuel because of the different working principle of this high temperature fuel cell. At the anode CO can react with CO_3^{2-} forming CO_2 as illustrated below (2.8):

$$Anode : CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^- \tag{2.8}$$

Hereby the cell has some more flexibility and can run on different type of fuels like: coal-derived fuel gas, methane (CH_4) or natural gas without the need of external fuel reformers. The possibility of using (Liquefied) Natural Gas ((L)NG) is a big advantage since there is already a widely adopted logistical system for NG in the form of LNG in the marine sector. The electrical efficiency of this fuel cell is between 50-60%, with CHP the efficiencies could reach about 85% because of the high operating temperature.

Remarks:

- High temperature corrosion and the corrosive electrolyte can result in problems.
- Lifetime and degradation of the fuel cell can be an issue.
- Bad on-off cycling capability
- This type of cell uses relatively expensive materials.



Source: Fuel cell today: [28]

Figure 2.7: MCFC technology, schematic explanation.

2.2.6. SOFC

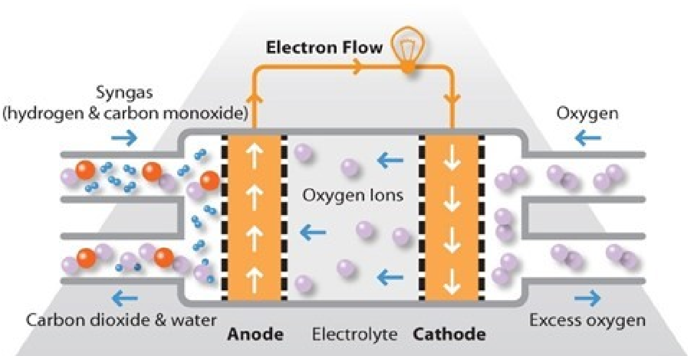
Solid Oxide Fuel Cells (SOFC) work at the highest temperature of all the discussed fuel cells. SOFCs work at temperature of 500-1.050°C, currently most of the SOFCs operate at the higher side of this range about upward of 800°C but most of the time >900°C because of the used electrolyte. As electrolyte a solid ceramic is used, often yttria-stabilized zirconia (YSZ), which conducts oxygen ions (O^{2-}). The chemical reactions used in a SOFC are given in equation 2.9. This process is also schematically illustrated in figure 2.8.

$$
\begin{aligned}
Anode &: 2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^- \\
Cathode &: O_2 + 4e^- \rightarrow 2O^{2-} \\
Total\ reaction &: 2H_2 + O_2 \rightarrow 2H_2O
\end{aligned}
\tag{2.9}
$$

The high operating temperatures of this cell give some challenges and benefits. The main advantages are: fuel flexibility (can use CO as fuel), since it can be oxidised at the anode as illustrated in the equation below (2.10):

$$Anode : CO + O^{2-} \rightarrow CO_2 + 2e^- \tag{2.10}$$

Further more these type of fuel cells could operate at a high electrical efficiency with an even higher efficiency when using cogeneration. The electrical efficiencies are around 50-65% with the use of CHP an efficiency up to 90% is possible. Compared to MCFCs this type of fuel cell has a relatively high power density.



Source: Fuel cell today: [28]

Figure 2.8: SOFC technology, schematic explanation.

Remarks:

- Material problems because of high temperature.
- Sealing issues because of high temperature.
- Startup is slow because of the high temperature
- Bad on-off cycling capability
- High cost of components and manufacturing

Developments of SOFC technologies:
The solid ceramic supported (YSZ) SOFC is the most used electrolyte, however this ceramic is the reason for the high temperatures in these types of cells. The high temperature ensures high transport kinetics of the oxygen ions, with lower temperatures large ionic transport resistances will occur which lower the performance of the cell. As seen in the remarks mentioned before, the high temperature is the main source of problems related to the SOFC. Therefore research has been executed to lower the operating temperatures of these cells to cope with problems like: start-up times and sealing issues.

At the moment there are four types of SOFC: tubular, electrolyte-supported cells (ESCs), anode-supported cells (ASCs) and Metal-supported cells (MSCs) [14]. The main differences are mentioned in table 2.1, it can be seen that the MSC technology seems very promising since it solves issues related to the high temperatures like on-off cycling capabilities and cost. However the life time capability is still relatively low, this is mainly because it is a very new technology with limited demonstrator cases.

Type of SOFC	Operating Temperature	Life capability (Demonstrated)	On off cycling capability	Cost prediction
Tubular	900-1000	High	Very Low[1]	High
ESC	850-1000	High	Low	Medium-High
ASC	700-800	Medium-High	Medium	Medium-Low
MSC	500-800	Low-Medium	High	Medium-Low

[1] *Very long start-up times*

Source: N.P. Brandon, Solid Oxide Fuel Cell Lifetime and Reliability [14]

Table 2.1: Different types of SOFC technology

2.3. Comparison overview of different types of fuel cells

An overview of characteristics of the earlier discussed fuel cells, is given in this section. Based on the temperature the fuel cells can grouped, this is often done by three different group: low, medium and high temperatures. The most common distinction is shown next:

- *Low temperature*, generally operate at temperature around 80°C.
  Fuel cells: LT-PEMFC, DMFC and AFC.
- *Medium temperature*, generally operate at temperature around 130-180°C.
  Fuel cells: HT-PEMFC and PAFC
- *High temperature*, generally operate at temperature between 650-1000°C.
  Fuel cells: MCFC and SOFC

Each type of fuel cell has its own pros and cons, however based on the different temperature groups a general distinction of characteristics can be made. In general low temperature fuel cell are very sensitive to poisoning by fuel or oxygen impurities, therefore its necessary to use pure H_2 and in case of AFC even pure O_2. Because of the low temperature its often not possible to use the waste heat for cogeneration, causing these fuel cells to have a relative low overall efficiency compared to medium or high temperature fuel cells. When heat is increased the fuel cell becomes less sensitive to poison, therefore medium temperature fuel cells can tolerate higher levels of CO and S making them more suitable to use these cells in combination with reformers. With high temperature fuel cells CO will act as fuel since they can internally reform fuel or oxidise CO directly. Because of this there is a higher flexibility in using other types of fuel. It must be said that using other fuels then H_2 always result in emissions of CO_2 and in some cases also in a small amount of NO_x[(1)]. The very high temperatures give the possibility of reaching very high efficiencies up to 90% when CHP is used.

The temperature of the fuel cell has a big influence regarding the start up time, the startup time significantly increases when the temperature of the cell is higher. Besides the startup time also the response time by load changes decreases with higher temperatures. Broadly speaking can also be said that power density declines with increasing heat level, while the efficiency increases (mainly because of the possibility to use CHP).

An extensive overview of the main characteristics of each type of fuel cell, based on literature, is shown in table 2.2, some new specifications are brought to attention.

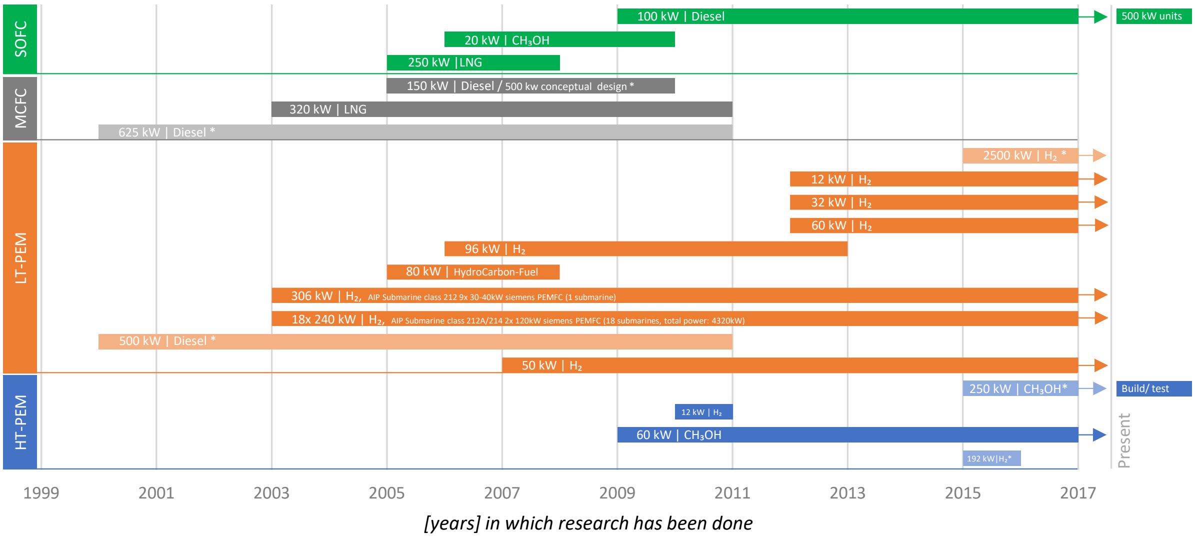
[(1)]The emission for different types of fuel and fuel cells will be covered in more detail during section 5.1

2.4. Projects and applied fuel cell technology in the maritime sector

Fuel cell are already an old technology, as described before the first fuel cell was developed in 1839. From that moment on a lot of research is done with respect of fuel cells.

The first maritime projects that deployed fuel cell technology where naval projects. The first project was executed by the United States navy, their research and development program started with investigation and implemented the technology on warships from the 1960s. Germany discovered the possibility of implementing fuel cells to produce energy on board of submarines in the 1970s. Hereby Germany succeeded to produce the first submarine powered by fuel cells while complying with the power requirements of the ship. During the 1980s the Canadian Department of Defence also did research into fuel cells, but this time for power production on board of floating units.

The last two decades an increased interest in fuel cell for the maritime sector has been seen, during this period at least 23 projects were carried out[99] from what 10 projects are still ongoing. These project are sorted on fuel cell type and time of execution and plotted in a graph shown in figure 2.9. Within this overview only projects with a decent amount of information about fuel cell type and power capacity are listed. The colours indicate the different type of fuel cells: the green bars are the SOFC projects (3x), in grey the MCFC projects are shown (3x), the orange indicate the LT-PEMFC (10x) and HT-PEMFC are shown in blue (4x). The light coloured bars indicate an conceptual project, the others are real integration's or test setups of fuel cells on a ship. All projects together represent a total capacity of just less than 10.5 MW, including the 4.6 MW of conceptual studies. Without these concepts the total amount of installed/tested fuel cells is only 5.9 MW divided over 15 projects with a total of 32 vessels, which comes down to a average of 183kW per ship.



Data source: EMSA study on fuel cell in shipping[99], complete data list is given in appendix: A.1.
*The lighter coloured bars indicate that the project was a conceptual design instead of a real life test.

Figure 2.9: Overview of recent maritime research project in the field of fuel cells.

In figure 2.10 a subdivision based on power of different types of fuel cell used in the non conceptual projects is given. The LT-PEMFC is with 85% clearly the most used fuel cell, this is mainly because of the submarine class 212A/214 of which many have been build and uses a LT-PEMFC. When the subdivision without the submarines is shown (figure 2.11) it gives a better represented image for fuel cell in surface ships. This demonstrates that with respect to power MCFC (2 projects) is the most used type of fuel cell while LT-PEMFC (6 projects) and SOFC (3 projects) are almost the same. So LT-PEMFC (avg. 55kW) is still the most deployed technique but both SOFC (avg. 123kW) and MCFC (avg. 235kW) surpass in power because of the higher power ranges per project.

Type of Fuel Cell	LT-PEMFC	HT-PEMFC[1]	DMFC	AFC	PAFC	MCFC	SOFC
Temperature (°C)	40-90	120-200	60-130	60-250[2]	130-220	600-700	500-1.050
Electrical efficiency	40-60%, 40%[3]	45%	32-40%	50-60%	36-45%	50-60%	50-65%
Efficiency CHP	n/a	<85% [104]	n/a	n/a[2]	<85%	<85%	≤90%
Power density grav.[4] (W/kg)	1020	76.9	14.7	16.2	59.3	39.15	55.6
Power density vol.[4] (W/L)	406.9	60.2	7.6	6.56	46.2	2.71	17.8
Life time, up to (hours)	50.000	Limited	Limited	2.500-5.000	40.000	40.000	70.000
Startup time	Fast	Medium	Fast	Fast	Slow	Very-Slow	Medium-Very-Slow
Fuel type	$Pure\ H_2$	H_2	$CH_3OH + H_2O$	$Purest\ H_2$	H_2	H_2, CO, HC[5]	H_2, CO, HC[5]
Poison	S, CO(≥10-20 ppm)	S, CO (> 3-5 %)	CO	S, CO, CH_4, CO_2	S, CO (>3-5%)	S	S
Emission	-	-	CO_2	-	-	CO_2[6], NO_x[6]	CO_2[6], NO_x[6]
Advantages	•Low operating temperature •Good start/stop durability •Fast start up •Non corrosive materials are used •Proven long life time •Current designs show high possible densities over 2000 kW/m^3	•Higher CO tolerance than LT-PEMFC, this makes it more suiteble for fuel reforming •Could use cheaper non precious metal catalyst •CHP is possible because of higher temperature	•Low operating temperature •Fast start up •Use relatively cheap and dense methanol fuel •Compact	•Relatively cheap non precious metal catalyst, inexpensive electrolyte and cell materials •High electrical efficiency •Low operating temperature	•Mature technology •Reliable •Low electrolyte cost	•Fuel flexibility •Non precious metal catalyst •High quality waste heat for cogeneration	•Fuel flexibility •Non precious metal catalyst •Completely solid state electrolyte •High quality waste heat
Disadvantages	•Expensive platinum catalyst •High cost membrane and cell components •Sensitive for poisoning by CO en S •The constant need for hydration requires an active water management system	•Immature technology •Limited lifetime •Currently only one manufacturer	•Has a low power densities •Low efficiency •Emits CO_2 •Complex stack •Limited life time •Low power output	•The need of a water removal system to remove excess water out of the electrolyte •Requires pure H_2 and O_2 •Limited life time	•Expensive platinum catalyst •Electrolyte has to be replenished during operation because it slowly evaporates	•Complex system because of CO_2 recycling •Corrosive electrolyte •Relative expensive materials	•Complex system because of high temperature •Cell sealing difficulties because of high temperature •Relatively expensive components and manufacturing
	LT-PEMFC	**HT-PEMFC**	**DMFC**	**AFC**	**PAFC**	**MCFC**	**SOFC**

[1] Little information available (immaturity of technique), efficiency based on Serenery. [2] Modern AFCs typically operate at 70°C. [3] Efficiency using reformed fuel (CH_4). [4] Limited information available, scattered information. Upper limits from figure 2.18 are used in table. [5] Hydrocarbon fuels, some can directly be used with internal reforming [6] When using carbon fuels

Based on literature, sources: [25, 28, 50, 83, 99]

Table 2.2: Overview of the main characteristics from different types of fuel cells.

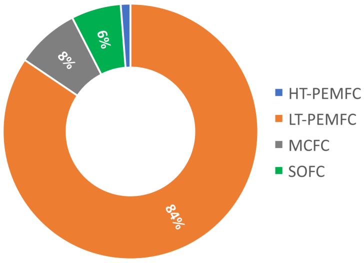


Figure 2.10: Projects subdivision, submarines included

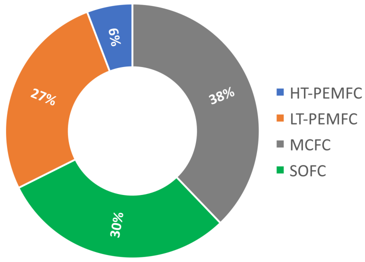


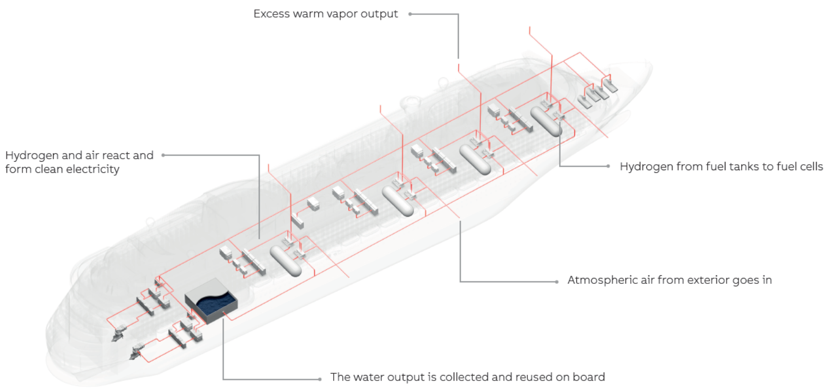
Figure 2.11: Projects subdivision,submarines not included

Some of these projects are described in more detail in sections 2.4.2. But first the most recent relevant announcements about fuel cell deployment in the maritime sector will be discussed in section 2.4.1.

2.4.1. Recent announced projects

Fuel Cells Bulletin(2) made some announcements about fuel cell developments in the maritime sector within the issues of 2018. The most interesting news is summed up bellow:

ABB and Ballard started a collaboration to produce a MW maritime PEMFC solution. ABB and Ballard signed a Memorandum of Understanding to develop a scalable PEMFC for ships. Hereby they will first focus on cruise ships, and realise a fuel cell solution capable of generating 3MW in a single module which is about the same size as a comparable marine engine. The eventual goal will be the development of a commercial ready scalable megawatt containerised PEMFC solution. The multiyear collaboration will include: system design, development, system testing and validation. [8, p.4-5]



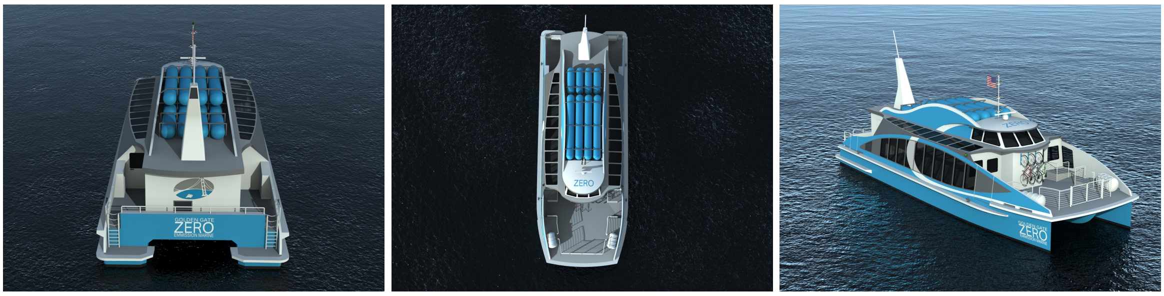
Source: ABB.com

Figure 2.12: ABB and Ballard concept of MW scale cruise ship fuel cell solution.

HySeas III consortium has been granted with EU funding to produce the first emission free seagoing ferry, this ferry will be powered by PEM fuel cells of Ballard and use hydrogen of renewable sources.
The Horizon 2020 programme of the EU provides a €9.3 million fund of the total cost of €12.6 million for the project. This project will in 2019 first do onshore tests to prove the modular drive train under data from existing vessels. After successful testing the the ROPAX ferry will be build and used in the Scottish coast. For fuel the renewable hydrogen of the Surf 'n' Turf hydrogen project will be used, which provides a hydrogen refuelling facility. As fuel cells 100kW Ballard FCveloCity®-HD fuel cell modules will be used to generate power for the propulsion. [8, p.5]

(2)The journal Fuel Cells Bulletin is the leading source of technical and business news for the fuel cells sector.

California Air Resources Board awards $20 million to accelerate the shift to zero-emission in different sectors, including the waterborne mass transit sector. The project includes a hydrogen-powered passenger ferry in San Francisco Bay
A hydrogen fuel cell powered ferry will provide a passenger service between the Ports of San Francisco, Oakland, Redwood City and Martinez in the San Francisco Bay Area. The ferry will be a 21m high speed catamaran powered by 360kW of Hydrogenics PEMFC power modules combined with a 100kWh li-ion battery pack. The hydrogen (264 kg) is stored compressed at 250 bar on the roof, it should reach a top speed of 22 knots and the project will be launched mid 2019. This project is called "THE WATER-GO-ROUND" and will be managed by Golden Gate Zero Emission Marine which is set up by the manager of the SF-BREEZE project. [8, p.14], [54]



Source: watergoround.com [54]

Figure 2.13: Renders of the water-ground project.

Dutch project FELMAR[3] focuses on a zero-emission fuel cell solution for inland and coastal shipping.
The FELMAR consortium is a cooperation of six Dutch companies to optimise the PEM fuel cell in electric propelled ships. The goal of the project is to have a scalable zero-emission solution for inland and short-sea shipping by the end of 2019.[9]

PowerCell and German industrial group Siemens team up by signing a memorandum of Understanding, to develop a marine fuel cell power generating system.
Siemens is a leading company in terms of integrated propulsion and power systems for marine applications. Siemens developed the Blue Drive system which optimises the diesel electric propulsion system leading to a more efficient system resulting in less fuel usage and lower emission. The next step is to integrate fuel cells in this system, hence the cooperation between Siemens and PowerCell [10]

Lloyd's Register, siemens and Viareggio Super Yachts singed an agreement on MYS[4] 2018 to develop a hydrogen fuel cell solution for one of their yachts (VSY 65).
The main goal of this project is to asses the specific safety and technical requirements of providing energy for the stern electric engine by fuel cells. VSY will focus on both the technical and economical feasibility of a hydrogen fuel cell, Siemens will support them with their technical know-how and solutions they already developed. Lloyd's Register will do an assessment with respect to certification of such a system. [6]

ABB starts collaboration with SINTEF for testing the viability to use fuel cells for ship propulsion.
SINTEF Ocean's laboratory in Trondheim will do scaled down lab test with two 30kW PEM fuel cell from the company Hydrogenics, to simulate diesel fuelled batteries and load profiles. This should give them more knowledge about the operation and control of a MW-scale fuel cell power system. [7]

[3] First ELement MARine power
[4] Monaco Yacht Show

2.4.2. Selection of executed and ongoing maritime projects

HT-PEMFC

E4Ships, Pa-X-ell | MS Mariella
The Pa-X-ell project is a part of E4Ships programme, a joint industry project focusing on fuel cells in maritime application. This project is part of the lighthouse project from e4ships, where two demonstration projects are executed (Pa-X-ell and SchIBZ).

This project will test the application of multiple 30kW HT-PEM fuel cell in parallel generating a total electric power of 120 kW. Besides electricity also the waste heat of the fuel cells will be used for both heating and cooling (CCHP). This project was led by the Meyer Werft and put to the test on a passenger vessel.

The modular HT-PEM fuel cell are a commercially ready solution developed by SerEnergy, containing of 8 standard 5kW fuel cells combined in one 19" rack of 30kW. The HT-PEMFC ran on methanol during phase one, which was internally converted into H_2. Because methanol is toxic, NG will be used in the second phase of the project.

During this project first a onshore test was executed, where after onboard tests took place including the demonstration onboard MS Mariella which is still ongoing.[24, 99]

The main result of this project is that it showed that the use of HT-PEMFC's for supporting the electrical and heat systems, substantially lowered the noise and emission levels. The decentralised placed energy systems also increased the redundancy while there were also benefits like small energy flow within the system and low material and energy demand.

Rivercell
Rivercell is a feasibility study for a fuel cell powered inland passenger ship. This project is like the Pa-X-ell part of the E4Ship program and reviews different type of fuel cells to find the best suitable solution for a decentralised energy network.

The final design consist of three diesel generators, two HT-PEM fuel cell racks and two battery packs. The batteries are used for peak shaving, and depending on the power demand there can be switched to a fully electrical or hybrid propulsion using fuel cells.

As part of this project the impact of different fuel types where examined and compared to diesel. In the final concept there was chosen for methanol which requires 2.5x more space than comparable diesel solution. This is a lot better than other investigated options like LNG, LPG and $cryogenic\ H_2$ which all need a storage space of ten times the volume compared to diesel while the effective volume is reduced by 5%. For gasious NG the effictive storage was reduced by 20%. The use of methanol has some problems with respect to regulations since this is not regulated yet. The final version of this ship design will be build in 2020.[99]

LT-PEMFC

US SSFC
The U.S. Ship Surface Fuel Cell (US SSFC) project was launched in 1997 and has gone through three different research phases. The goal of this project was to design and demonstrate that fuel cells in combination with carbon fuels are a viable solution for surface ships.

During the first phase conceptual design of a 2,5MW fuel cell solution was created for both MCFC and PEMFC fuel cell type. The second phase focused on testing, a 625 kW MCFC module and a 500 kW PEMFC module with diesel fuel reformer where tested. The third phase only focussed on testing the MCFC module at sea.

The tested MCFC module reached a efficiency of 53%, it was found that fuel processing is a important factor to reach efficient operation. A general conclusion for both fuel cells was that the large volume and complexity of the systems limited the possibility to develop a large scale solution.[34, 99]

SF-Breeze
SF-BREEZE (San Francisco Bay Renewable Energy Electric vessel with Zero Emissions) was

the precursor of the recent project called ”The Water-Go-Round”. This new project is managed by the former project leader of the SF-Breeze project. A feasibility study for a high speed hydrogen powered fuel cell passenger ferry was started in 2015. For this project a concept of a 33m catamaran was made, consisting of 41x 120 kW PEM fuel cells to power two 2.5 MW electric engines. On top of the boat 1200kg hydrogen is stored as liquid, the hydrogen is stored on top of the ship because of safety and regulations. [53, 99]

FELICITAS Subproject 3

The FELICITAS(5) project focussed on the development of fuel cell systems for the heavy-duty transport industry (road, rail and marine applications). The requirements asked for this type of industry acording to the FELICITAS project are: power above 200 kW, power density of 200 kW/t, system efficiency of about 60%, fueled by H_2 and/or hydrocarbon, robustness and long lifetime, improved environmental impact and price competitiveness.

Subproject 3 focussed on improving the reliability and power level of PEMFC solutions. [46, 99]

DESIRE

This project investigated the technical and economical possibilities of using F76 marine diesel in combination with a reformer as fuel for different type of fuel cell on naval surface ships. During this research the following fuel cell are evaluated in combination with different fuel processing options: SOFC, PEMFC, SOFC + PEMFC, SOFC + gas turbine and gas turbine (as stat-of-art system). The focus was to create a system with an electrical output of 2.5MW by 2010. The scoring of the different trade-off rules for the evaluated setups were influenced by this deadline, because of the limited development status of SOFC the availability was not ensured. This resulted in a low scoring of the SOFCs development status. For diesel processing systems three systems have been considered: partial oxidation, autothermal reforming and steam reforming. From these three systems the steam reforming sytem was suggested as most promising system, mainly because of the high efficiency.

Eventually a steam reformer and PEMFC where chosen as best option especially the time schedule led to this decision. Because of the higher efficiency potential of a SOFC it is strongly recommended that these systems should be reconsidered, mainly on availability, for future projects. Next to the conceptual design of a 2,5 MW diesel fueled PEMFC system also a 25 kW demonstration setup for fuel processing was tested.

The sulphur removal out of the F76 diesel seemed the only problematic issue, the desulphurization unit did not meet the requirements during the tests. Instead of F76 a low sulphur fuel was used to meet the requirement for the PEM fuel cell.[48]

MCFC

US SSFC

As described before, the SSFC project also developed and tested a PEMFC with diesel reformer, here the large volume and complexity also limited the development of a large scale solution. The tested DMFC module with diesel reformer reached a efficiency of 35%, here the fuel processing was also an important part for the performance of the fuel cell. [34, 99]

FellowSHIP

The FellowSHIP project was set up design, build and test an integrated fuel cell system that would meet the maritime industrial requirements. During this project a 320 kW prototype MTU fuel cell (HM400 adapted for marine operation) was developed and tested in a containerised solution both on land and onboard the offshore supply vessel Viking Lady. This ship was powered by LNG due to its dual fuel engines, this made it an attractive platform to test the MCFC on LNG fuel. The total fuel efficiency at 100% load, including internal power consumption losses.

(5)Fuel-cell Powertrains and Clustering in cell Powertrains and Clustering in cell Powertrains and Clustering inHeavy-duty Transports duty Transports duty Transport

Like all fuel cells this type delivers a direct current (DC) voltage, depending on its load condition and age this varies between 380 and 520V. The electrical system had to be designed for stable stable conditions because this type of fuel cell can only handle slow load changes. No major additional implications were revealed within this project, however the investment cost was high. [99]

MC-WAP
Molten-Carbonate fuel cell for Waterborne Application (MC-WAP), was supported by the EU with 17 partners from 7 countries. The project focused on MCFC as the project name indicates, the goal was to develop a benchmark of a real life MCFC solution for maritime industry. A concept study of a 500 kW MCFC system and an onboard test of a 150 kW MCFC system were executed, fuelled by diesel with the use of a reformer. [99]

SOFC

FELICITAS Subproject 2
FELICITAS Subproject 2 looked at the marinisation of a 1MW Rolls-Royce fuel cell (SOFC), which was developed for stationary power generation, to a 250 kW marine APU. A detailed investigation to integrate such a fuel cell on a yacht was carried out by Lürssen. As part of this project the following subjects were investigated: a marinised 60kW sub-system and stationary power 250kW generator module are tested, fuel processing (incl. supply, storage and exhaust piping), SOFC power management, controller design and simulation.

The main conclusion of this project was that the Rolls-Royce SOFC design would require substantive modification before successful use in a marine environment is possible.

As result a better understanding on the impact of the operation and application of SOFC technology on a yacht was achieved. Some of the conclusions regarding the design of a SOFC system for a yacht are:

- The marine environment will impact the cell and stack performance, an increased use of coating should be investigated to ensure durability.
- Marine diesel is challenging to process into a use-able fuel for the SOFC, mainly because it contains sulphur, NG is quite easy to process for a SOFC. The fuel processing solutions are still in development stage, NG can be reformed internally at the catalyst.
- The SOFC startup is a long process, a SOFC should run constantly in contrast with a diesel engine to be able to provide energy when necessary.
- Special attention needs to be paid to bunkering because this is the most critical step related to safety.
- Standardisation of a fuel cell module for shipping is needed to provide a competetive price due to mass production.
- A flywheel or a comparable energy storage solution could compensate energy fluctuations resulting in the delivery of the same amount of energy with a smaller fuel cell.

E4Ships, SchIBZ | MS Forrester
Like the Pa-X-ell, this project is part of the lighthouse project from e4ships, the SchIBZ projects focuses on a SOFC based APU for merchant shipping. The scope of this project is to test a APU system consisting of a combined low sulphur diesel powered SOFC and Li-Ion battery which provide 50-500 kW.

This concept is tested by a 100kW research prototype tested on land and thereafter on board of the ship ”MS Forrester” for 12 months. Sunfire delivered the 50kW prototype SOFCs with integrated reformer which runs on low-sulphur diesel. Öl-Wärme-Institut developed the recirculating exhaust gases and integrated reforming process, reaching a electrical efficiency of more than 50% and and efficiency over 90% for overall performance.

2.5. Current fuel cell market development

In this section the worldwide fuel cell market developments are analysed. During this analysis the annual number of shipments and total annual produced amount of megawatts are compared by fuel cell type and application. Next to the shipments by type and application also an overview of the power densities of commercially available fuel cells is given.

The main conclusions which can be drawn when comparing figure 2.14 (annual shipments) and 2.15 (annual produced megawatt) by the different fuel cell types are:

- The PEM fuel cells are the most produced fuel cells and experienced the most rapid growth rates. The last couple of years the shipment growth flattened while the annual produced amount of power grew extensively, showing that the amount of power per fuel cell raises over the years.
- The SOFC's have experienced an opposite development compared to the PEMFC, the annual amounts of shipped SOFC's grew faster than the annual power. This indicates a decrease in power per shipped fuel cell, which can be explained because of the development in small powered CHP SOFC's for household usage with low power requirements.
- MCFC can't be seen on the shipment graph while the megawatt graph shows roughly the same amount as seen with the SOFC fuel cell. This is because of the MCFC is only been used for large land based power plants, with a few exceptions for other applications. This same story also applies to PAFC.
- DMFC is typically used for small electronic devices like: phones, laptops, camera's, etc. That is the reason for a relatively large number of DMFC's while there is a very low amount of total combined power.
- AFC is only used for special applications, this is due to its limited life time and the requirement of very pure hydrogen and oxygen.

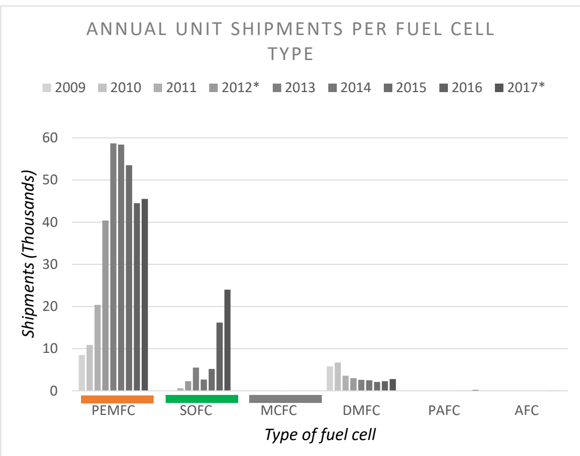


Figure 2.14: Annual Unit Shipments per fuel cell type

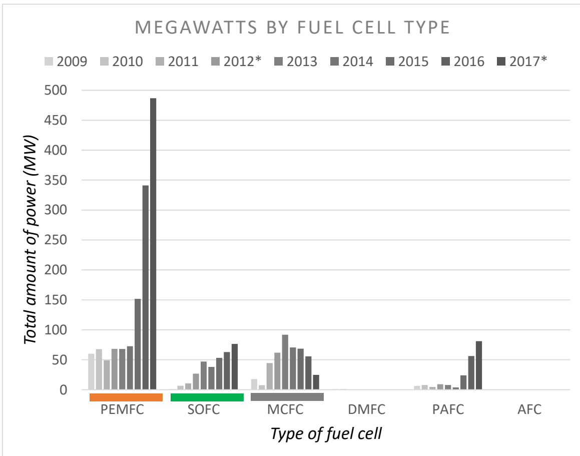


Figure 2.15: Megawatts by fuel cell type

Data source: Fuel Cell Today (2009-2013)[17] and E4Tech (2014-2017)[35]. Overview of used data in appendix A.2 and A.4.

The main conclusions which can be drawn when comparing figure 2.16 (annual shipments) and 2.17 (annual produced megawatt) by application are:

- Portable applications are mainly represented by the DMFC type, these fuel cells are typically operating at very low powers.
- Stationary applications generally use MCFC or SOFC fuel cells, sometimes even large stacks of PEMFC's are used for stationary power generation. The rapid growth of the stationary market is related to the market success of smaller residential CHP fuel cells due to governmental support in different countries.

- The transport sector has experienced rapid growth with respect to fuel cell applications, especially when looking at megawatt growth rate. This has to do with the automotive investments in this technology (PEMFC), Toyota, Honda and Hyundai together represent more than 50% of the 455 MW shipped in the transport sector, the +/-3,000 vehicles account for approximately 350 MW.

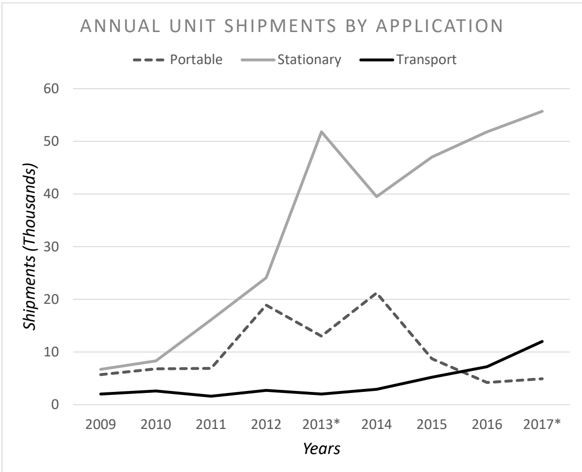


Figure 2.16: Annual Unit Shipments by application

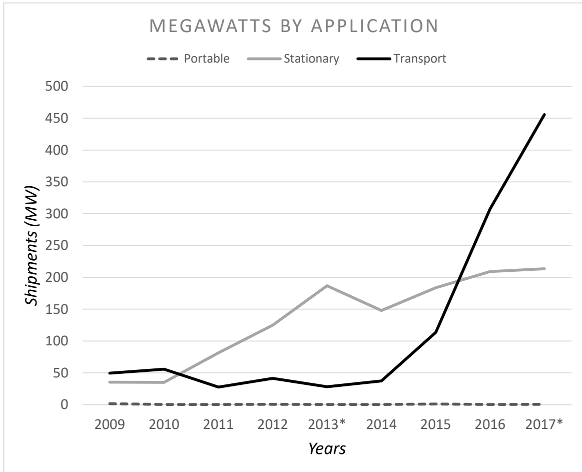


Figure 2.17: Megawatts by application

Data source: Fuel Cell Today (2009-2013)[17] and E4Tech (2014-2017)[35]. Overview of used data in appendix A.3 and A.5.

Figure 2.18 gives an overview of different types of fuel cells for both gravimetric and volumetric energy densities. The diesel engines, represented in black circles, are actual installed main engines on Oceanco yachts. Its clearly visible that the diesel engine surpasses almost all types of fuel cells with respect to energy density. However some PEMFC are capable of outperforming diesel engines on energy density, it has to be said that the right top of the PEMFC's are prototypes. An other remark with respect to the volumtric density is that this graph is based on nominal power, when a same graph is made for partial load cases the fuel cell will perform a lot better compared to the diesel engines because of the flat load vs efficiency characteristics.

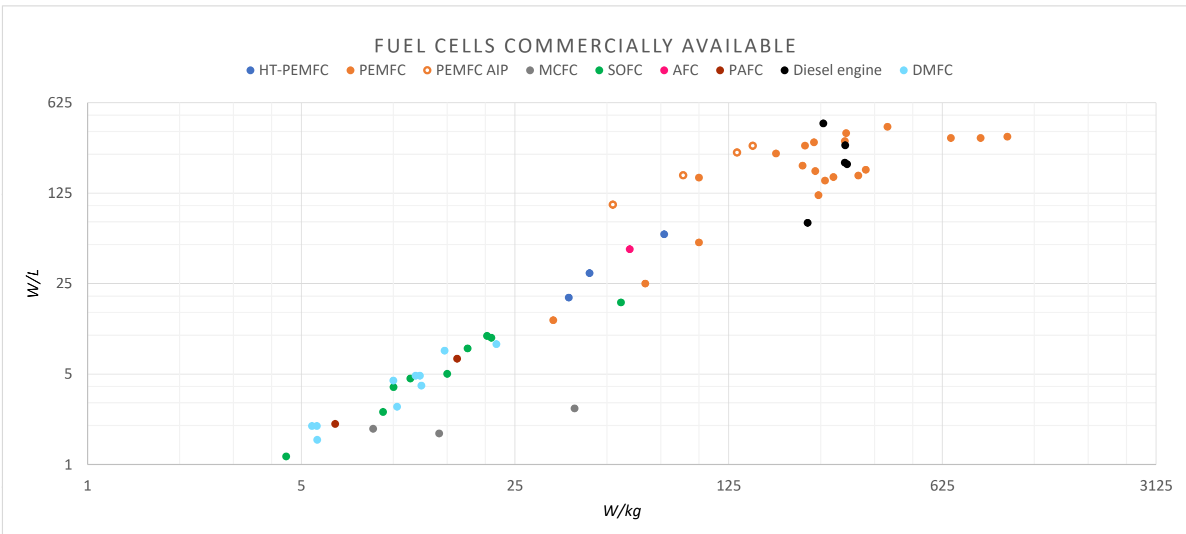


Figure 2.18: Volumetric and gravimetric density of different commercially available fuel cell solutions and diesel engines used in oceanco yachts, based on data of manufacturers.

2.6. Choice of fuel cells for further comparison

Based on the market research a selection of most promising fuel cell candidates for usage on a yacht or maritime sector in general will be made.
The main decision drivers on which the fuel cells are assessed are:

- Power density
- Power levels
- Efficiency
- Fuel sensitivity and poison
- Start-up time/ cycling
- Usable waste heat (CHP)

Each fuel cell is ranked for these factors with a: ++, +, - or - - which respectively indicates the most positive to most negative ranking. A overview of the ranked fuel cells are shown in table 2.3.

	Low temperature			*Medium temperature*		*High temperature*	
	LT-PEMFC	**DMFC**	**AFC**	**HT-PEMFC**	**PAFC**	**MCFC**	**SOFC**
Power density:	++	- -	- -	+	+	-	+/-
Power levels:	++	- -	-	-	++	++	++
Electrical efficiency:	+	- -	++	-	- -	++	++
Fuel sensitivity/poison:	-	-	- -	+	+	++	++
Start-up time/ cycling:	++	++	++	+	-	- -	+/- -[1]
Usable waste heat:	- -	- -	- -	+	+	++	++
Maturity[2]:	++	- -	- -	+/++	-	+	+
Total score:	+6	-9	-5	+3/4	+1	+6	+6/11

[1] *The start-up time and life cycle capability of a SOFC strongly depends on the used technology as explained in section 2.2.6*
[2] *Maturity is based on number of project in the maritime sector and total number of shipments*

Table 2.3: Comparison different fuel cell technologies

The overview of the different fuel cells mentioned above (table 2.3), shows the positive outliers for each fuel cell temperature category. These are: the LT-PEMFC for the low temperature fuel cells, the HT-PEMFC for the medium temperature fuel cells and the SOFC for the high temperature fuel cells.
These fuel cells (LT-PEMFC, HT-PEMFC and SOFC) will be furher investigated. In the following sections of this report only these fuel cells will therefore be mentioned.
A selection of fuel cells which will be used for comparison overviews later in this project is made from the fuel cells shown in figure 2.18. The densities of these chosen fuel cells are shown below in figure 2.19.

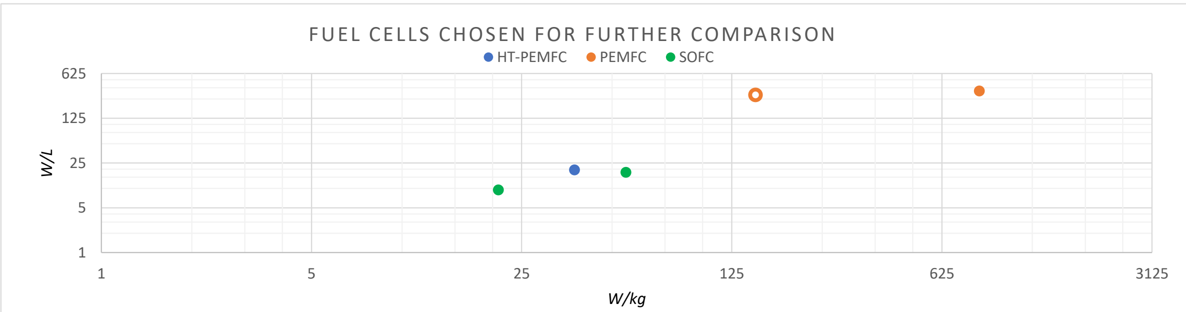


Figure 2.19: Volumetric and gravimetric density of chosen full cell solutions.

The main characteristics, brand and type information of these different fuel cells are summed up in table 2.4:

	LT-PEMFC		HT-PEMFC	SOFC	
	Power Cell MS100 [84]	**Siemens FCM NG 135 [3]**	**Serenergy H3 30kRack [92]**	**Bloomenergy ES5-YA8AAA [26]**	**Redox Power Cube [97]**
Power (kWe):	100	135	30	300	25
Dimensions:	300 l	0.5x0.53x1.76 m	2.2x0.7x1 m	5.6x2.6x2.1 m	1x1x1.4 m
Weight (kg):	120	900	800	14333	450
Efficiency (%):	50	54	45	65	55
W/kg:	833,0	150,0	37,5	20.9	55.6
W/L:	333,3	289,5	19,5	9.5	17.9
Refered to as:	LT-PEMFC	LT-PEMFC_AIP	HT-PEMFC	SOFC_Low	SOFC_High

Table 2.4: Characteristic of chosen fuel cells.

These five fuel cells represent the upper limit of the commercially available fuel cells in terms of density while still having a descend level of power. Since all fuel cells include a complete balance of plant a fair comparison between fuel cells as well as other energy converters can be made. The dimensions and complexity of the balance of plant can differ for each type of fuel cell.

For all types of fuel cells, except for the HT-PEMFC, two different options are mentioned in table 2.4. The HT-PEMFC is only produced by one manufacturer therefore there is only one fuel cell of this type mentioned in the table. The main differences between these two options are discussed for each type of fuel cell.

With the low temperature pem fuel cells two options each made by a different manufacturer (PowerCell and Siemens) are taken into account. Power Cell is world leading in terms of density for these types of fuel cells, however the solution from Siemens has about the same volumetric density. The main difference is the weight which is approximately five times as heavy, which is normally no issue since these cells are used for air independent propulsion (AIP) on submarines. Beside the weight the efficiency differs as well, this is slightly better for the AIP solution from Siemens.

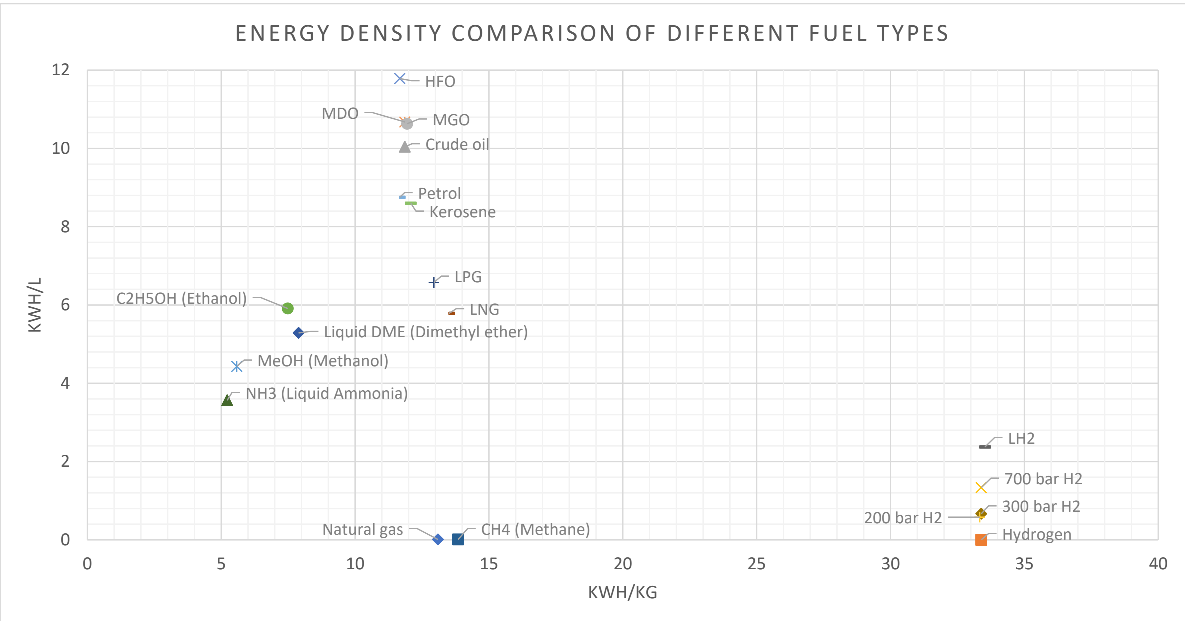
For the SOFC type the Redox is the one with the highest density, however it is quite small in power output. The other one is from Bloom-energy which has a higher power output but a lower density. Both these SOFC's focus on land based applications and are equipped to work on natural gas, but other fuels would be theoretically possible when some small adjustments are made to the system.

3
Fuel storage solutions

Most fuel cells work on hydrogen or a hydrogen rich gas (as discussed in section 2), with exception of high temperature fuel cells which can run directly on chemicals like methanol, methane or ammonia. In this chapter the different possible types of fuel which can be used in fuel cells are discussed. The focus will be on the storage of hydrogen and associated systems to subtract the hydrogen from other storage mediums. The storage of hydrogen is divided in three sections, physical based, fuel based and material based hydrogen storage. Where physical based only focuses on direct hydrogen storage while material and fuel based include several indirect storage methods of hydrogen using a hydrogen carrier.

3.1. Physical based hydrogen storage

Hydrogen is a chemical element with symbol H, hydrogen is the lightest and most abundant chemical in the universe. It has the second lowest boiling and melting point of all substances, helium is the only element which has a lower boiling and melting point [16]. Figure 3.1 shows the density of hydrogen in comparison with other fuels.



Data sources: [13, 27, 31, 33, 51, 52, 98, 101]. Overview of used data in Appendix: B.1

Figure 3.1: Energy density comparison of different fuel types, gravimetric/volumetric density based on LHV

Hydrogen at ambient conditions is a colour- and odorless gas with a very low flash point temperature of -253°C

As a result of the low weight of hydrogen it scores high in terms of gravimetrical density, 33.3 kWh/kg, as visible in figure 3.1. On the other hand the volumetric density of hydrogen is very low, the density of hydrogen at ambient conditions is 0.08 kg/m^3 compared to 1.2 kg/m^3 for air. Because of the low volumetric density it is impractical to store hydrogen at ambient condition, therefore hydrogen is typically stored in compressed or liquid state which will be discussed in section 3.1.1 and 3.1.2.

3.1.1. Compressed hydrogen

Compressed hydrogen (CH_2) is at the moment still the most common storage method of hydrogen, and is widely adopted in the automotive industry. In automotive industry compressed hydrogen is typically stored in carbon fibre cylindrical tanks at pressures of 300 to 700 bar. The density of compressed hydrogen is respectively 20 to 40(6) kg/m^3. Although the density is increased by compressing the hydrogen it is still an impractical storage solution for storing a large amount of energy, the volumetric density without storage vessel is still very low. Including storage tank(7) the density of a 700 bar hydrogen storage solution is in the range of 0.7 kWh/L (51 vol%) and 1.25 kWh/kg (3.73 wt%). This means that only about 50% of the volume and 4% of the weight is covered by the hydrogen, all the rest is added because of the storage tank.

In addition pressurising hydrogen is an energy intensive process, approximately 10% of the energy content is needed to compression hydrogen to 300bar. [16, 83]

3.1.2. Liquid hydrogen

The boiling point of hydrogen lies at -252.9°C, this is the point where hydrogen becomes liquid. To store hydrogen in a liquid state it has to be stored at cryogenic temperature, like LNG only at an even lower temperature (the boiling point of LNG lies at -162°C). To store liquid hydrogen (LH_2) at these temperatures cylindrical vacuum isolated tanks are used. These tanks are insulated to minimise the evaporation losses, comparable with LNG tanks (section 3.2.5). Liquid hydrogen has to be cooled or slowly evaporated to maintain its cryogenic temperature. The LH_2 is initially stored at atmospheric pressure, when the temperature of hydrogen increases there will be boil-off gas. This gas will cause a pressure increase inside the pressure vessel, therefore the gas must be released at a certain point to regulate the pressure. If there is less gas used than evaporated, for example when a ship isn't used for a certain time, the boil off gas causes an energy loss.

The tanks used for storing liquid hydrogen are quite big and heavy resulting in a limited benefit of the increased density by liquefaction. Besides the storage tank volume and weight the system also becomes complex and a lot of energy is lost during the liquefaction process (+/- 30% of the energy content).

The density of liquefied gas is 2.4 kWh/L while the density including storage tank(8) is in the range of 1.3 kWh/L (54 vol%) and 2.4 kWh/kg (7.11 wt%). There are already several companies (like: Linde and MAN Cryo) which offer liquid hydrogen storage solutions.

(6) Hydrogen deviates from the ideal gas law, in practice lower densities are reached than one would expect by using the ideal gas law.

(7) Based on MAHYTEC 700 bar hydrogen tank, information obtained on mahytec.com [17-03-2019]. Appendix B.2.1 gives an more extensive overview of compressed hydrogen storage tanks.

(8) Based on Liquid hydrogen storage systems from Linde, Source: [31]. Appendix B.2.2 gives an overview of some Linde's LH_2 tanks.

3.2. Fuel based hydrogen storage

From the previous section it can be concluded that hydrogen is not a very energy dense solution with respect to the volume. Even if it is stored at high pressure or cryogenic temperature (to store more energy in the same volume) the maximum amount of energy per litre is still a lot lower than MGO as visible in figure 3.1. This density however drops very rapidly when storage tanks are taken into account to about 54 vol% and 7.11 wt%. Other fuels which contain hydrogen can be used for powering fuel cells are shown in figure 3.1. During this section these hydrogen carrying fuels (3.2.1 Methanol, 3.2.2 Ethanol, 3.2.4 DME, 3.2.5 LNG, 3.2.6 Diesel) are discussed in more detail.

3.2.1. Methanol

Methanol or methyl alcohol with chemical formula CH_3OH or abbreviation $MeOH$ is a colourless and flammable organic liquid at ambient temperature and pressure. Methanol is the simplest form of all alcohols and most importantly contains hydrogen. Methanol has a molecular weight of $32.04 g/mol$ since the molecular weight of hydrogen (H_2) is $2.016 g/mol$ it contains $12.6 wt\%$ hydrogen.[56]

Methanol can be directly used in DMFC's or in high temperature fuel cells like HT-PEMFC's, MCFC's or SOFC's since these fuel cells can reform methanol internally. When methanol is used to provide hydrogen for low temperature fuel cells like LT-PEM's methanol has to be reformed, fuel reforming will be further elaborated in section 3.3.

Methanol is completely soluble in water and biodegradable, resulting in small environmental risk compared to diesel. However there are some hazards associated with methanol like: a very low flash point temperature, highly flammable, toxic, it's hazardous to health and it is slightly heavier than air what causes it to gather at low points by spills. Methanol can be corrosive to some metals and mainly for rubber (eg. in fuel delivery systems like gaskets). Except of the corrosive properties methanol could be used in the existing fuel infrastructure like tankers and fuel stations. Currently methanol is mainly produced from fossil fuels, however it is possible to produce a renewable methanol by using biomass or by hydrogenation of CO_2 from green energy.[18]

- For detailed safety information and chemical compatibility of methanol see appendix B.5 and B.7.

3.2.2. Ethanol

Ethanol (C_2H_5OH) is a clear, colourless alcoholic liquid which normally used as "drinking alcohol". It is less toxic than methanol and more energy dense. With a molecular weight of $46.07 g/mol$ ethanol contains $13.1 wt\%$ hydrogen. Ethanol is biodegradable and completely miscible in water, making it save for the environment.

Ethanol can be produced using conventional petrochemical processes, but it is mostly produced from food-stock like sugar or corn wherefore it can be seen as a completely renewable fuel. It seems to be a promising fuel, however it is a lot harder to oxidise and more problematic to reform compared to fuels like methanol or natural gas because of carbon coking. Ethanol could be reformed to hydrogen as fuel for PEMFC's, internal reforming of ethanol is investigated but doesn't seem feasible because of carbon coking.[18, 82]

Since ethanol is produced from stock as raw material, it is dubious if this would be a good pathway as fuel choice. The growing world population will create an increasing demand for food which will already become a challenge on it own. When agricultural land is used to produce crops for fuel, this problem becomes even more difficult to solve.

- For detailed safety information and chemical compatibility of ethanol see appendix B.5 and B.7.

3.2.3. Ammonia

Ammonia with chemical formula NH_3 is a gaseous substance at ambient temperature and atmospheric pressure since the boiling point lies at -33°C. To store ammonia in liquid state it should be stored at -33°C under atmospheric conditions or pressurised to around 10bar at ambient temperature. The ammonia gas is: colourless, intensely irritating, a serious health

hazard, a hazard to environment and very toxic to aquatic life. The gas has an ammoniacal odour so it can be detected in case of leakage. From flammability perspective ammonia is very safe compared to other types of fuel.
- For detailed safety information and chemical compatibility of ammonia see appendix B.5 and B.7.

From density perspective ammonia is slightly less energy dense than the fuels discussed before, the amount of hydrogen in ammonia is quite high. The molecular weight of ammonia is $17.03 g/mol$ of which $1{,}5 mol\ H_2$ so it contains $17.7 wt\%$ hydrogen. One of the big advantages of ammonia is the fact that it does not contain any carbon molecules, so it can be used directly in high temperature fuel cells or reformers to produce H_2 without the risk of carbon coking and forming any CO or CO_2. Ammonia can also be used as hydrogen carrier for low temperature fuel cells by reforming ammonia into hydrogen.
Another big advantage of ammonia is the fact that it is already one of most produced chemicals mainly because the fertilisers which used in the agriculture sector. About 80% of the ammonia is used in the agricultural sector. In total 159 million tonnes of ammonia is produced worldwide, due to this large scale industry the production, handling and storing of ammonia is already well known. However since it has to be stored cooled or pressurised to keep it in a liquid state it needs to be stored in a special tank(9). [2, 18]

3.2.4. Liquid DME

Dimethyl ether with chemical formula CH_3OCH_3 can be produced from different sources like: methanol, methane or bio-fuels. It can by used as hydrogen carrier or directly be used for fuel in high temperature fuel cells. DME is commonly used to replace fossil fuel like LPG and can be directly used in diesel engines in contrast with methanol. DME has a slightly higher density than methanol, however additional steps are required to produce DME from methanol making it more expensive than methanol.
[18, 42]

DME is a gaseous substance at ambient temperature and atmospheric pressure with a boiling point of -24.8°C, pressurised DME will become liquid at 5bar and therefore needs to be stored in a special tank(10). DME has a very low flaspoint, is marked as extremely flammable and hazardous concerning health but does not seem to have concerns with respect to the environment.
- For detailed safety information and chemical compatibility of ammonia see appendix B.5 and B.7.

3.2.5. LNG

LNG stands for liquefied natural gas, LNG has recently gained more attention in the shipping industry. LNG is adopted increasingly in the maritime sector as a solution to reduce the green house gas emissions of ships. Since LNG is liquefied natural gas, it consists for almost 90% out of methane (CH_4), and needs to be stored at a cryogenic temperature of -162°C to become liquid. This introduces a lot of implications like: insulation, material compatibility and regulating boil off gasses. These reasons make it a complex and bulky solution compared to a conventional diesel solution.

Aside the negative sides of LNG it also has some benefits compared to MGO. Combustion of LNG will decrease the emission of: SO_X with 90-95%, CO_2 with 20-25% compared to diesel combustion and is also expected to be less costly than MGO.[90]

Natural gas can be converted into a hydrogen or a hydrogen rich gas by fuel reforming, this makes it suitable for different fuel cells. Depending of the overall system efficiency even bigger gains can be reached, for example a SOFC powered on NG only produces approximately 60% of the CO_2 emissions with almost zero NO_X, SO_X and PM emissions. [55]

(9)Appendix B.2.3 shows an example of a possible ammonia/DME storage tank
(10)Appendix B.2.3 shows an example of a possible ammonia/DME storage tank

3.2.6. Diesel

Diesel is still the most used fuel in the maritime sector, with MGO as most used fuel in the yachting industry. As clearly visible in figure 3.1, these diesel fuels (HFO, MDO and MGO) are the fuels with the highest possible fuel density from volumetric perspective.

It is currently only used as fuel for combustion engines, but since it is the fuel with the most wide spread infrastructure in the marine industry and very energy dense it has been investigated to use as hydrogen carrier for fuel cells. Different studies did research into the possibilities to use diesel as fuel for different types of fuel cells. As described in section 2.4 the following projects all investigated diesel as fuel for fuel cells: US SSFC, FELICITAS, MC-WAP, E4Ships - SchIBZ, FCSHIP and DESIRE.

It seemed that the sulphur levels in diesel gave problems in combination with fuel cells since this sulphur needs to be removed from the fuel. This sulphur removal process was an issue since the desulphurization unit did not meet the requirements during the tests with a PEMFC in the DERSIRE project. During the SSFC project the complexity also limited the development of a large scale solution of a diesel reformer in combination with a PEMFC. Also the process to reform diesel into a useable fuel for SOFC seemed problematic during the FELICITAS project. The overall conclusion is that it is very difficult to remove the sulphur from diesel resulting in problems with poisoning the fuel cell, to overcome this problem low sulphur diesel could solve this problem.

3.3. Fuel processing

For all fuel based solutions described in section 3.2 some kind of fuel reforming is required, either internal (in case of high temperature fuel cells) or external (for low temperature fuel cells) and sometimes a combination of both for difficultly reformable fuels. The goal of reforming is to process a fuel containing hydrogen into a hydrogen rich gas which can be used in a fuel cell.

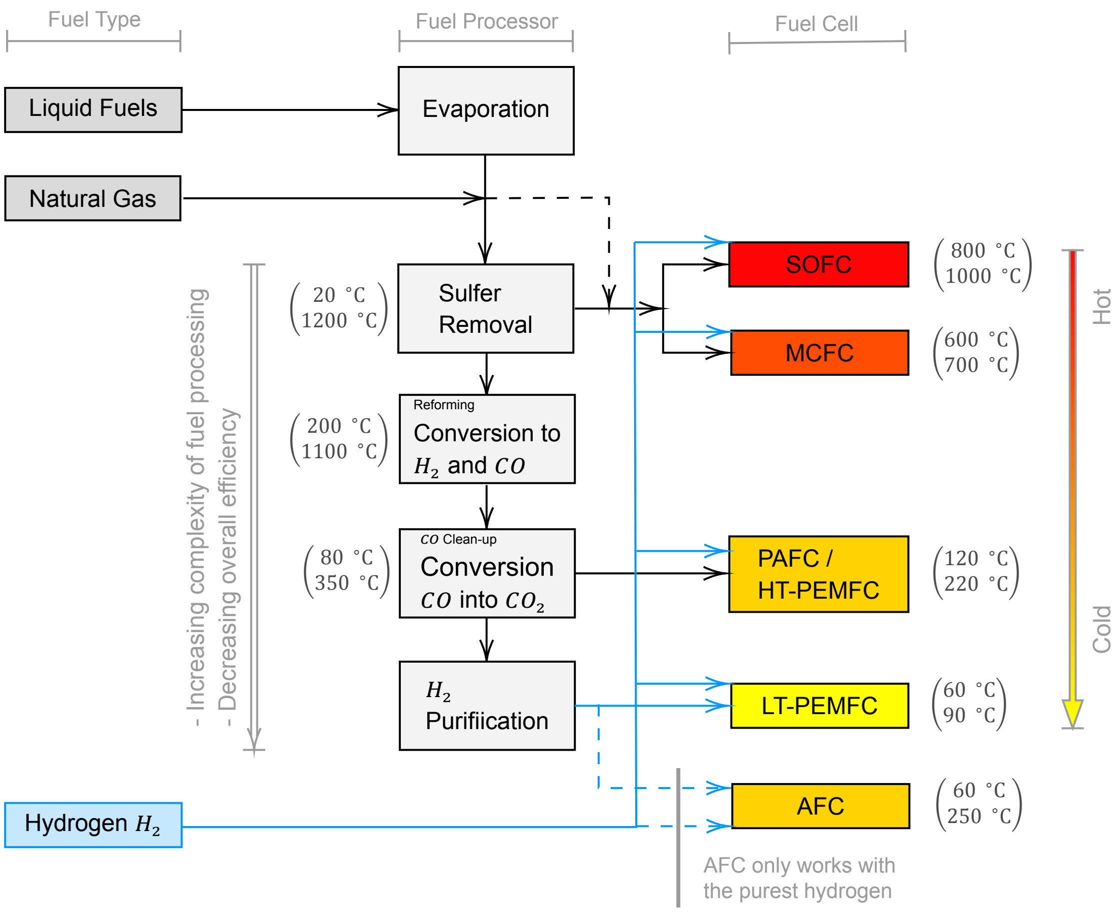
Figure 3.2 gives a general overview of the fuel processing steps needed to process different types of fuel to use in the earlier discussed types of fuel cells (section 2.2). The different reforming steps and working principles will be discussed during this section.

In this diagram the fuel cells on the right are ranked from high temperature (top) to low temperature (bottom) and therefore represent the required purity of the fuel at the same time. Prior to discussing the different fuel reformer solutions it is important to keep in mind that every step adds complexity to the system and will lower the overall efficiency since most steps require energy. In general, it can be said that the lower a solution is located in the diagram (figure 3.2) the lower the efficiency will become with simultaneously increasing complexity.

3.3.1. Sulphur removal

Since sulphur is a poison to all anode catalysts of fuel cells and catalysts in fuel processing steps, sulphur has to be removed from sulphur containing fuels. When the traces of sulphur in the fuel cell feed gas are to high the lifetime of the fuel cell and/or catalyst in fuel reforming installations will be lowered drastically. So sulphur containing fuels (fossil fuels) like natural gas or diesel need to be processed first removing sulphur compounds from the fuel.

There are different sulphur removal processes available with there own characteristics. These are processes such as: scrubbing, Merox mercaptan removal process, hydrodesulfurization, etc. The latest developments focus on solid sulphur sorbets, which desulfurize the fuel during the gas- or liquid-phase. These sorbent-based processes are the main contenders for a compact processor for fuel cells. In principle each installation needs a special approach, depending on the type of fuel and the sulphur tolerance of the fuel cell.[93]



Note: Dashed lines are optional are special cases.

Figure 3.2: Fuel processing steps

3.3.2. Reforming

Reforming is the first step in creating a hydrogen rich gas from hydrocarbon fuels if the fuel doesn't contain traces of sulphur. During the reforming process the hydrocarbon fuel is converted into hydrogen and carbon monoxide. There are three principles of reforming: Steam Reforming, Partial Oxidation and Auto-thermal Reforming.

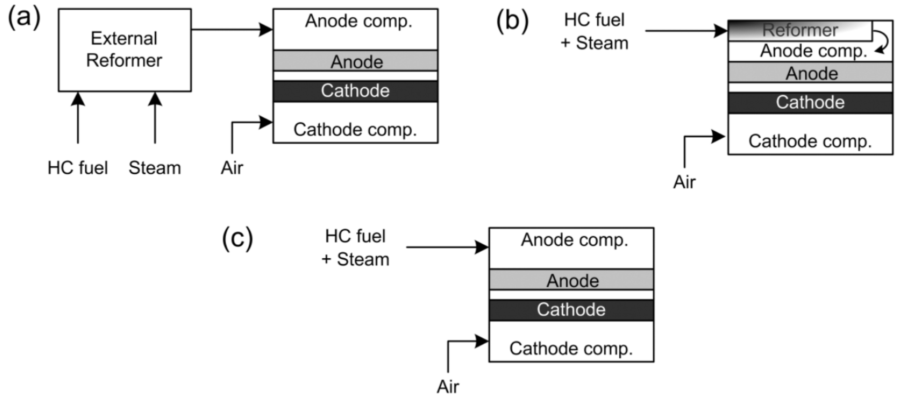
3.3.2.1. Steam Reforming

Steam Reforming (SR) is a endothermic process (requires energy) where a hydrocarbon fuel reacts with steam into H_2 and CO according to the reaction illustrated in equation 3.1[83].

$$C_xH_y + xH_2O \leftrightarrow xCO + (\frac{1}{2}y + x)H_2 \tag{3.1}$$

If a overcapacity of water/steam is added the CO can react simultaneously whereby the CO is formed into CO_2 and H_2, known as water gas shift reaction (section 3.3.3.1). Steam reformers typically operate at high temperatures (240-1000 °C), since it is an endothermic reaction this reaction has to be maintained by adding heat. This is typically done by burning fuel either from the input gas or the anode exhaust gas or by recovering heat in case of high temperature fuel cells like SOFCs. The amount of heat/energy needed for such a reaction depends on the type of fuel, varying from 240-260°C (49.7 kJ/mol) for methanol [43] up to 700-1000°C (206.4 kJ/mol) for methane[83].

There are three types of steam reforming solution as illustrated for a SOFC in figure 3.3: external, indirect internal or direct internal reforming. External reforming (a) is mostly used in large scale land based applications while indirect or direct steam reforming are mostly used in small scale portable applications. This because the size and complexity of the overall system can be reduced by integrating the reformer in the fuel cell. Direct internal reforming provides the simplest, most compact and efficient system, however there can be some issues regarding temperature gradients and carbon coking. At the moment the internal reforming within a SOFC is only limited to methane. [18] It must be taken into account that internal re-



Source: Cimenti, M. and Hill, J.M., Direct Utilization of Liquid Fuels in SOFC for Portable Applications: Challenges for the Selection of Alternative Anodes[18]

Figure 3.3: Types of steam reforming: (a) external reforming, (b)indirect internal reforming and (c) direct internal reforming.

forming is only possible for high temperature fuel cell since the heat needed for the reforming process must be available in the fuel cell.

3.3.2.2. Partial Oxidation

A Partial OXidation (POX) reforming process converts hydrocarbons into CO and H_2 like steam reforming, but in contrast with steam reforming partial oxidation is a exothermic reaction (releases energy). During partial oxidation the hydrocarbon fuel reacts with oxygen often in combination with a catalyst as illustrated with equation 3.2[83].

$$C_xH_y + \frac{1}{2}xO_2 \leftrightarrow xCO + \frac{1}{2}yH_2 \tag{3.2}$$

This process has some advantages over steam reforming: it starts and responds faster because of the exothermic reaction and doesn't require a thermal management. Therefore this system is more compact and simpler compared to the steam reforming reformer, however it has a lower hydrogen yield. The temperatures of POX have a broad range in possible operating temperatures, this type of reforming ranges from 870 °C for catalytic POX up to 1400 °C for non-catalytic POX reactors.[25]

Like with the steam reforming process, the CO produced during the reforming process can be further processed into CO_2 and H_2 via water gas shift reaction (section 3.3.3.1).

3.3.2.3. Auto-thermal Reforming

Auto-thermal Reforming (AR) is a combination of both steam reforming and partial oxidation, by combining these two reactions the overall reaction becomes energy neutral. The energy released from the exothermic POX reaction drives the endothermic SR reaction. Resulting in the reaction as can be seen in equation 3.3.

$$2C_xH_y + xH_2O + \frac{1}{2}xO_2 \leftrightarrow 2xCO_2 + (x+y)H_2 \tag{3.3}$$

The advantages of this type of reforming is the fact that its relatively compact and the thermal management is less complicated because of the combination of the endo- and exothermic reaction. The downside of this system is that it requires a well balanced design to regulate these two reactions during start-up and dynamic loads.[83]

3.3.3. CO clean-up

The goal of the CO clean-up process is to process the carbon monoxide trace in the hydrogen rich gas into other harmless gasses like H_2, CO_2 or CH_4. This process is only executed when the fuel has to be processed to low or medium temperature fuel cells since CO will poison the catalyst. The different methods of CO cleanup are: water gas shift reaction, preferential oxidation and selective methanation.

3.3.3.1. Water Gas Shift reaction

Water Gas Shift reaction (WGS) is an exothermic reaction of carbon dioxide with steam, which forms additional hydrogen and converts carbon monoxide into carbon dioxide. The water gas shift reaction is as follows (equation 3.4):

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad | \ \Delta H_{298} = -41.2 \ kJ/mol \tag{3.4}$$

The balance and kinetics of the WGS reaction depends on the temperature of the reaction, with a low temperature the reaction speed is slow while having a high hydrogen yield (reaction shifts to the right). A high temperature, on the other hand, has a fast reaction with a lower hydrogen yield, meaning less CO will be converted.

Because of these reaction characteristics often both the high temperature and low temperature WGS reaction are used. The high temperature will be executed first, because of the high kinetics a large amount of CO will already react. Secondly a low temperature WGS reaction will follow to clean up a part of the remaining CO which will simultaneously increase the hydrogen yield.

This process will still leave traces of CO, even with high and low temperature WGS reaction, typically around 0.2% of the gas will be CO (2000 ppm) which is still to much for a LT-PEMFC. [83]

3.3.3.2. Preferential Oxidation

Preferential Oxidation (PrOX) could be used as final cleaning step after a WGS reaction. The PrOX reaction is a exothermic reaction where CO is selectively oxidised with the use of a catalyst. During this exothermic reaction CO together with O_2 form CO_2. The down sight of this reaction is that some of the hydrogen is also oxidised resulting in H_2O which actually is a loss of fuel. Both oxidation reactions are presented in equation 3.5[83].

$$\begin{aligned} CO + \frac{1}{2}O_2 \leftrightarrow CO_2 \qquad & | \ \Delta H_{298} = -284 \ kJ/mol \\ H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O \qquad & | \ \Delta H_{298} = -286 \ kJ/mol \end{aligned} \tag{3.5}$$

3.3.3.3. Selective Methanisation

Selective Methanisation (SMET) as the name implies is an exothermic reaction which selectively methanises CO (equation 3.6) over CO_2 (equation 3.7) to lower the amount of CO in the gas flow. The methanisation reaction can occur both on CO as on CO_2, but as shown in equation 3.6 and 3.7 both reactions consume H_2. Therefor these reactions are regulated with the use of a catalyst which encourages the CO methanation over the CO_2 methanation.[83].

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad | \ \Delta H_{298} = -206.1 \ kJ/mol \tag{3.6}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad | \ \Delta H_{298} = -165.2 \ kJ/mol \tag{3.7}$$

This reaction is in fact the reverse reaction of steam reforming, since this reaction consumes H_2 it will only be used for gasses with a small amount of CO otherwise the fuel H_2 will be reduced too much.

3.3.4. Purification

For the most LT-PEM fuel cells the CO clean-up steps are not sufficient to lower the CO to an acceptable level. So, most of the time an additional step is necessary to reach a hydrogen gas which is clean enough to fuel a LT-PEMFC without the risk of excessive degradation because of CO membrane poisoning. To realise this last purification step the two following techniques can be used: Membrane Separation and Pressure Swing Adsorption.

3.3.4.1. Membrane Separation

With Membrane Separation (MS) often a palladium-silver alloy membrane is used to separate hydrogen molecules from other element. This membrane is highly selective towards hydrogen and will permeate at a faster rate than other elements. The hydrogen flow strongly depends on the design of the membrane and system, the hydrogen yield is dependant of the pressure difference, operating temperature and thickness.

The hydrogen flow will increase when the pressure difference is higher. Increasing the operating temperature also improves the hydrogen yield since it will increase the kinetics. Lastly the hydrogen yield can be increased by a thinner membrane since hydrogen can pass through more easily, however leakage can then become a problem when using a thin membrane.

Lastly the hydrogen yield will be lower after time since the non-H_2 elements will be blocked by the membrane and therefore block the passage of hydrogen. Therefore the system needs to be purged once in a while to release the impurities from the membrane. The purity of the release gas can degrade when holes in the membrane occur.

3.3.4.2. Pressure Swing Adsorption

Pressure Swing Adsorption (PSA) presses a hydrogen rich gas trough a high-surface-area adsorbent bed inside a pressurised chamber, where only H_2 molecules can pass through the bed because of their low molecular weight. All other impurities are adsorbed to the surface of the bed because of the higher molecular weight, by this process a 99.99% pure hydrogen gas can be produced.

The adsorption bed used to adsorb impurities will be saturated after using it for a certain amount of time, when this is the case the bed needs to go trough a desorption process called pressure swing. During this pressure swing mechanism the pressure will be lowered what causes to lower the adsorption capabilities of the bed where after the bed will be purged, removing all the non-H_2 matters from the bed. When this purging process is completed and the system can be pressurised again, this completes the pressure swing mechanism. Because this system needs to go through this pressure swing cycle every once in a while such a system is often equipped with two PSA pressure vessels in parallel, making it possible to run continuously by alternating the usage of the PSA systems.

3.4. Material based hydrogen storage

Lastly the material based storage solutions of hydrogen are discussed. These types of fuel storage store the hydrogen by bonding the hydrogen to a hydrogen carrying material. The hydrogen will be released when necessary, these storage solutions can carry pure hydrogen with some advantages over the storage of pure hydrogen.

3.4.1. Formic Acid

Formic acid (or methanoic acid) is a colourless, clear and corrosive liquid with a pungent odor. The chemical formula of formic acid is $HCOOH$ or HCO_2H, and can be converted into H_2 (contains 53 g_{H_2}/L) and CO_2 after which the H_2 can be utilised in a fuel cells.

The main production method is based on the methyl formate process and is responsible for roughly 90% of all produced formic acid. The methyl formate process used industrially is based on methanol, the process is illustrated with equation 3.8

$$\begin{aligned} Methanol\ to\ methyl\ formate: CH_3OH + CO \rightarrow HCOOCH_3 \ {\scriptstyle (\Delta H_r = -29kJ/mol)} \\ Hydrolysis\ to\ formic\ acid: HCOOCH_3 \rightarrow HCOOH + CH_3OH \ {\scriptstyle (\Delta H_r = +16.3kJ/mol)} \end{aligned} \tag{3.8}$$

An other method to produce formic acid is hydrogenation of carbon dioxide when this process is maintained with green energy a CO_2 neutral formic acid can be produced. [37]

The density of formic acid without tank and reformer is 1.8 kWh/L and 1.5 kWh/kg (4.3 wt%). The energy loss for reforming is around 15%, and formic acid is a liquid which can be stored in conventional tanks with some restriction with respect to material usage since it is corrosive to some materials [Aerts, M and Swinkels, T. pers. comm.]. Besides the toxicity and corrosion limitations of this liquid hydrogen carrier, formic acid decomposes to CO and H_2O when temperatures are above 50°C. Carbon monoxide (CO) is highly toxic and could lead to dangerous situations, therefore the tanks should be placed in a well ventilated location and tank temperatures should be management [37].

DENS (Dutch Energy Solution) is a company which is working on the commercialisation of formic acid as fuel for fuel cell by developing a fuel reformer suitable for LT-PEMFC's, its not used as fuel (on large scale) before.

3.4.2. Liquid Organic Hydrogen Carrier

Liquid Organic Hydrogen Carriers (LOHC) are unsaturated organic compounds which can store/carry hydrogen. The hydrogenated LOHC can be dehydrogenated whenever the energy is needed, without energy loss in the meantime, by an endothermic catalytic reaction. By using a LOHC the hydrogen can be stored in a liquid medium at atmospheric pressure and broad range of temperature. This makes it very easy to implement since the fuel infrastructure is similar to the conventional diesel infrastructure. The only big difference is that after the fuel is used, there is still the dehydrogenated LOHC left which needs to be stored on board for later re-hydrogenation at the factory.

During hydrogenation a catalytic exothermic reaction bonds hydrogen molecules to the used/ dehydrogenated LOHC after which it can be used again. Liquid organic hydrogen carriers have a gravimetric storage density of about 6 wt%

At the moment there are at least two companies which have a LOHC storage solution including hydrogenation and dehydrogenation units, these companies are $Hydrogenious$ and $H_2 - Industries$.

Hydrogenious uses Dibenzyltoluene ($C_{21}H_{20}$) as LOHC with an density of $1040kg/m^3$ [59], and can uptake $53kg_{H_2}/m^3$ ($5.1wt$%) at ambient pressure with a temperature range of -39 to 390°C. The hydrogenation process is a exothermic catalytic reaction, the process releases 8 kWh/kg_{H_2} with a temperature of >200°C. The dehydrogenation process occurs also via a catalytic reaction but endothermic, requiring 11 kWh/kg_{H_2} at a temperature of 300°C.[76]

3.4.3. Sodium Borohydride

Sodium borohydride ($NaBH_4$) is stored in a white crystal/ powder form, and can be used for hydrogen storage. Hydrogen can released from its storage material ($NaBH_4$) on two different ways, either with use of a catalyst or hydrochloric acid as activator. With both methods the sodium borohydride need to be mixed with ultra-pure water (UPW / $2H_2O$), this UPW combined with the activator triggers the reaction which releases the hydrogen from both the $NaBH_4$ and UPW. During this reaction the same amount of hydrogen is released from both substances delivering in total $8H$ and leaves a residual product "spend fuel" sodium boronoxide ($NaBO_2$). With this process 98% of the theoretical maximum hydrogen is released. The remaining substance also consist of water and strongly diluted acid if a hydrochloric acid acelerator is used. The acid and water is removed from this substance, the sodium boron oxide can be recycled into sodium borohydride which could then used again as hydrogen storage. This technology is developed by H2Fuel-Systems B.V. which is owner of the intellectual property (IP) concerning H2Fuel, the company does not intend to produce, sell and distribute H2Fuel or associated systems but only market the IP. [67]

At this moment there is no company which exploits the IP of H2Fuel-systems, as consequence there is no available solution at the moment.

The main advantages of this storage solution is that the production, storage and consumption is clean (if created with green energy) and happens under atmospheric conditions without harm for people and environment.

For storage and handling of this fuel there are multiple solutions each with their pros and cons. The Sodium borohydride can be stored in several conditions from dry to solved in water (could be completely liquid or a slurry condition). Dry sodium borohydride can generate $1kg_{H_2}$ from $4.7kg_{NaBH_4}$ ($21.3wt$%) and wet fuel30 containing 30% fuel can generate $1kg_{H_2}$ from $16.2kg_{Fuel30}$ ($6.2wt$%). As activator there are also different solutions: hydrochloric acid, catalyst or by elevated temperature (decrease in reaction speed from left to right). Ultra-pure water is needed as well to trigger the reaction, this can be stored on board what results in a lower overall system density or it can be produced on board by adding an extra filter between the drink water generators currently used on yachts. The last variable is the spend fuel, spent fuel is +/- 3.2x as heavy and 2.2x as big compared to dry $NaBH_4$. When the spent fuel is stored dry after filtering out the water it is +/- 1.74x as heavy and 0.73x as big compared to dry $NaBH_4$. This shows a big disadvantage of $NaBH_4$, namely the fuel gets heavier when used even if its stored in dry form. The complete system based on catalytic reaction can differ from $3.1wt$% to $8.1wt$% according to choices made in the variables discussed before. The most auspicious density of such a system will be $1.1kWh/L$ and $1.0kWh/kg$ for 30% fuel solved in water and unfiltered spent fuel stored in separate tanks on board, and $4.3kWh/L$ and $2.7kWh/kg$ for most dense solution were the ultra-pure water is produced on board while using the same tank for storing the fuel and spent fuel [103].

3.4.4. Metal Hydrides

Metal hydrides form a group of rechargeable hydrates, metal hydrides are alloys which can be re- and dehydrogenated at moderate pressure and temperature. This type of hydrogen carrier has some benefits with respect to safety and volumetric density, however they often lack in gravimetrical density.

There are a lot of metallic hydrides with varying: storage capacities, de- and re-hydrogenation characteristics. The most promising type of metal hydrides can be found in the magnesium based hydrades, MgH_2 has a storage capacity of 7.7 wt% which is a lot higher compared to other metal hydrides. However, there are some drawbacks which makes this hydride less attractive: unfavourable desorption temperature of 300 °C for hydrogen discharge, slow desorption kinetics and a high reactivity toward air and oxygen. [81, 91]

The development state of metal hydrides is limited, commercially available solutions have a substantially lower density than the potential density of MgH_2.

3.4.5. Metal-Organic Frameworks

Metal-Organics framework (MOFs) is an adsorptive hydrogen storage solution. Adsorption of hydrogen occurs by the interaction of the hydrogen gas with a surface, this leads to higher storage densities than pure gas. There are a number of different solutions which use this principle,of which one is the MOF. This type of storage depends on the surface area of the material, so the material with the biggest surface area can theoretically store the most hydrogen. MOFs are porous coordination polymers which form three-dimensional networks, forming a porous solid structure with a large surface area. MOFs is the most promising storage solution in the group of adsorptive hydrogen storage solutions. Currently a maximum density of 10,3 wt% is reached with project SNU-70 where 7.3 wt% of the hydrogen is usable. However there are some practical limitations, the interaction energy with most surfaces is low, therefore only a significant amount of hydrogen can be stored at low temperatures and high pressures. [94]

Like the metal hydrides the metal-organic frameworks are also still under development and need to overcome some issues before it could be a viable solution.

3.5. Overview and comparison of fuel storage solutions

As described in the previous sections there are three types of hydrogen storage possible with in each category numerous solutions.

These different possible fuels are listed below:

Group	Fuel Type
Physical based hydrogen storage	Liquid hydrogen and Compressed hydrogen
Fuel based hydrogen storage	Methanol, Ethanol, Ammonia, Liquid DME, LNG and Diesel
Material based hydrogen storage	Formic Acid, Liquid Organic Hydrogen Carrier, Sodium Borohydride, Metal Hydrides and Metal-Organic Frameworks

These fuels will be compared on both volumetric and gravimetric density during this section. For both densities the pure fuel without storage system and the fuel including system are shown for comparison. For the fuel without storage system the values shown in figure B.1 and Appendix B.1 are used, these values are based on the lower heating value of the fuels.

For the fuel including storage system a distinction is made between fuels which can be stored in a conventional steel tank(11) and fuels which need to be stored in a special tank. Special tanks are needed for the storage of pressurised or cooled fuels. The fuels which can be stored in conventional tanks a factor to estimate the weight and volume of a tank according to S.C. Misra [57] is used to determine the density including storage system. The volume/weight of the tank can be calculated by 0.072x volume/weight of the MGO fuel. This ratio is assumed to be the same for the following fuels: MGO, Methanol, Ethanol, Formic Acid and LOHC since they all are liquid fuels under normal conditions and can be stored in approximately the same kind of tanks.

All the other fuel storage systems are based on actual commercially available storage systems. These are mentioned in Appendix B.2 for: compressed hydrogen B.2.1, liquefied hydrogen B.2.2, ammonia/DME B.2.3, LNG B.2.4 and metal hydrides B.2.5. For sodium borohydride the values mentioned in section 3.4.3 are used.
Based on these values (summarised in Appendix B.3) the bar charts displayed in figure 3.4 and 3.5 are generated. The graphs show the gravimetrical and volumetrical densities of the the fuel itself and including storage system, both graphs show a horizontal line which represent MGO (blue line) and LNG (grey dotted line). These two lines are displayed as baseline for the marine industry where MGO is used as fuel within superyachts and LNG is seen as a ”clean” alternative to diesel and is currently more and more adopted and infrastructure becoming more widely available.

Ammonia, DME and LNG are all stored in cylindrical pressure vessels, since these tanks are often in-practical to store, therefor a box volume is taken into as well (light coloured bars). This box volume is the space the tank would occupy when a box is drawn around the tank, these spaces can often not be used for other applications.

(11) Possibly with coating or build from stainless steel when the fuel is not chemical compatible, for chemical compatibility see chapter 5.3 and Appendix B.7

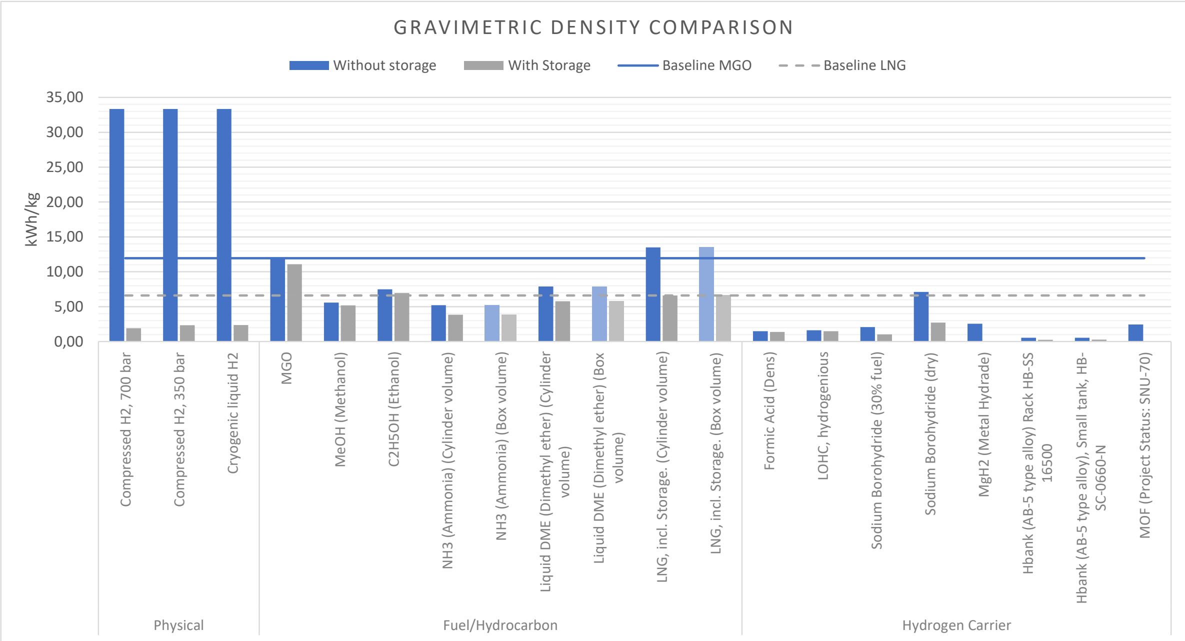


Figure 3.4: Energy storage solutions, gravimetric density comparison

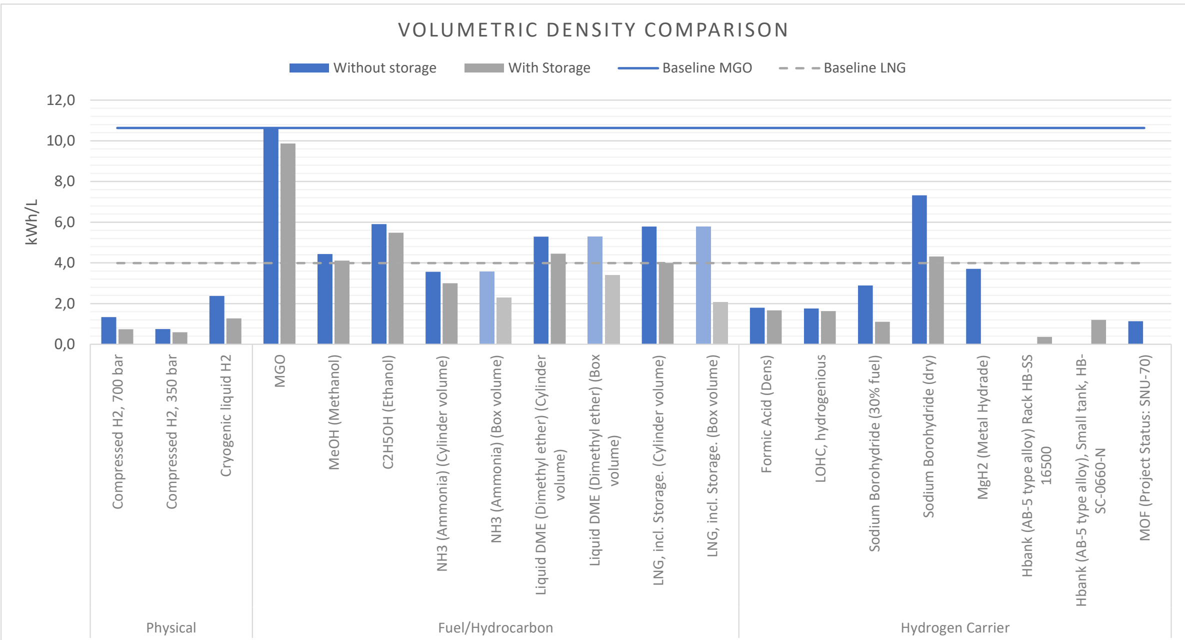


Figure 3.5: Energy storage solution, volumetric density comparison

4

Combined Fuel Cell and Fuel system density

This section will discus the densities of the combined fuel cell and storage system. After this section it will be clear what type of fuel in combination with what type of fuel cell will be the best solution for different applications in terms of energy density.

4.1. Effective Density

To make a comparison of the total density of a fuel cell system a ragone chart is used, this type of plot is a commonly used way to make a performance comparison of different energy storing devices. With this type of chart the effective energy density (Wh/kg or Wh/L) is plotted versus the effective power density (W/kg or W/L) on a logarithmic scale.

The formulas for the effective power and energy are formulated according to the method used in the paper written by van Biert et al. [102] as follows:

$$\begin{aligned} P_{effective} &= \frac{P}{1 + t\frac{P}{\eta \cdot W}} \\ W_{effective} &= t \cdot P_{effective} \\ \\ P &= Power\ Density \\ W &= Energy\ Density \\ \eta &= Efficiency\ energy\ converter \end{aligned} \tag{4.1}$$

The effective power ($P_{effective}$) as written in equation 4.1 is the power density corrected for the energy density of the fuel storage and efficiency of the energy converter. Since this overview should give an indication of the density of the total system the power density (P) and efficiency (η) is the combination of both the fuel cell and fuel processing system as illustrated in equation 4.2.

$$\begin{aligned} P &= \left(\frac{1}{P_{fuel\ cell}} + \frac{1}{P_{fuel\ processing}}\right)^{-1} \\ \eta &= \eta_{fuel\ cell} \cdot \eta_{fuel\ processing} \end{aligned} \tag{4.2}$$

To check this formulation the limits of the $P_{effective}$ and $W_{effective}$ can be calculated, which give the limits $P_{effective} \approx P$ for $t = 0$ and $W_{effective} \approx \eta W$ for $t = \infty$ [102].

4.2. Ragone charts

For the fuel cells defined in section 2.6 and the fuels defined in section 3.5 ragone charts are made. The reformers and fuel converters used for these calculations are described in Appendix B.4, for a overview of the used fuels see Appendix B.3.

To increase readability of the following graphs the number of examples within the ragone charts are limited, therefor not all options are shown. For the same reason the low temperature fuel cells and medium/high temperature fuel cells are split-up into separate graphs. Although, not all possible combinations are mentioned within these graphs, all options have been calculated and compared later in this report during chapter 6. The ragone charts shown below are presented to illustrate the way to read a ragone chart as well as the relevance and importance of using a method like this. The first two graphs (figure 4.1 and 4.2) show some of the possible fuel options combined with the LT-PEMFC.

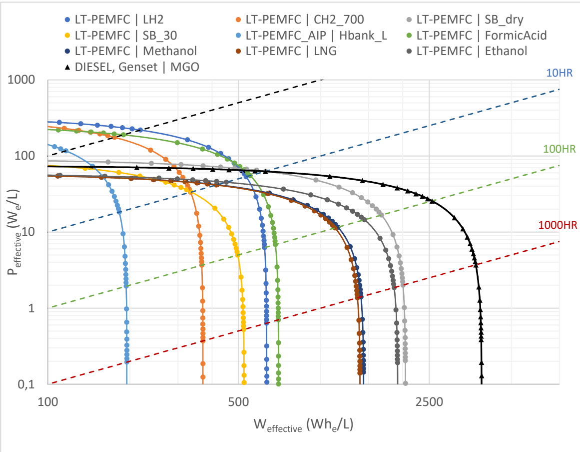


Figure 4.1: Volumetric density LT-PEMFC

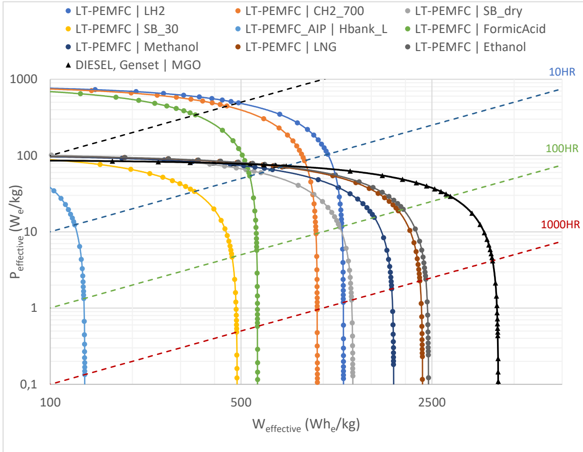


Figure 4.2: Gravimetric density LT-PEMFC

For the medium and high temperature fuel cells (HT-PEMFC, SOFC_Low and SOFC_High) some options are plotted in figure 4.3 for the volume density and in figure 4.4 for the weight density. As reference a diesel generator is added to the ragone chart for both plots, which can be recognised by the black line with triangles.

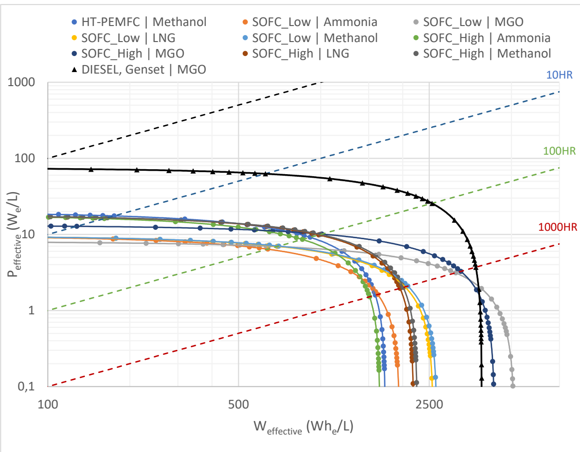


Figure 4.3: Volumetric density HT-PEMFC/ SOFC

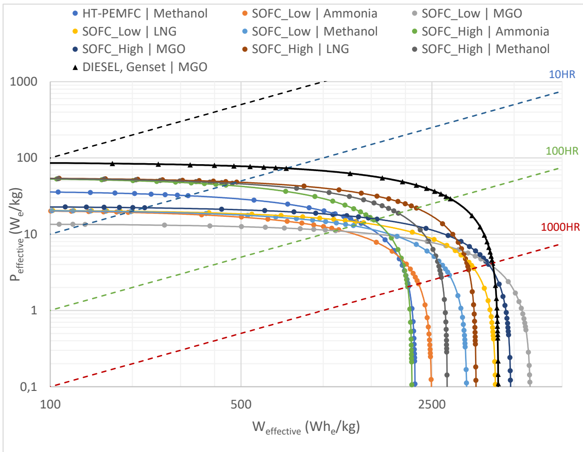


Figure 4.4: Gravimetric density HT-PEMFC/ SOFC

Explanation ragone chart

The four figures presented before show both the effective power density and effective energy density in one plot. These two values W_{eff} and P_{eff} are plotted for a certain time range, as earlier explained. The mentioned time (t) indicates the continuous amount of time a ship could sail without having to fuel in between. This time range is illustrated within the graph by the parallel coloured dashed lines, varying from 1 hours (black line left top) to 1000 hours (red line at the bottom). An intersection of the plotted ragone curves with a diagonal time line will give the effective density and power for that specific time frame. This means that the higher you intersect a time line the denser this solution will be. In other words as long as a graph is diagonally above an other combination this solution is more energy dense than the other.

4.3. Conclusion

Volumetric densities:

It can be seen that the LT-PEMFC (figure 4.1) are better or very close to the power density of a diesel engine for some combinations. However even for these options the energy density of the diesel engine can no longer be met with a LT-PEMFC from about 10 hours. The limit of the effective energy density is defined by the efficiency and fuel density ($\lim_{t\to\infty} W_{effective}(t) \approx \eta W$). The reason that the energy density can not be met has to do with the energy density of the alternative fuels used for fuel cells, since these are all substantially less energy dense compared to diesel. The maximum effective energy density will therefore be lower than a diesel fuelled engine (even with the higher efficiency and density for some of these fuel cell solutions). So from the volumetric point of view, it seems only interesting to use LT-PEMFC for applications which operate for relatively short time periods up to approximately 7 hours.
For the HT-PEMFC and SOFC (figure 4.3) it can be seen that the system never reaches the density of a diesel engine except of the MGO powered SOFC upward of 2000 hours. However, all fuels combined with a SOFC are less energy dense for the lower time ranges but have a crossing point at a time raging from about 200 hours (and 2000 hours for Sodium Borohydride) where the SOFC becomes more energy dense than the LT-PEMFC for the options shown in figure 4.5. This can be explained by the fuel cell characteristics a LT-PEMFC is more power dense than a SOFC but, a SOFC generally has a higher efficiency which will compensate the lower power density by requiring less fuel over time. These crossing points are visible in figure 4.5, this figure shows all types of fuel cell in one graph so they can easily be compared. It can be seen that the HT-PEMFC has a lower density than the LT-PEMFC with a crossing point where it performs better than the LT-PEMFC as seen with the SOFC, however the methanol powered SOFC is better compared to the HT-PEMFC for a earlier point in time. So in terms of volumetric density there doesn't seem to be a operating point where this type of fuel cell would be the best solution.

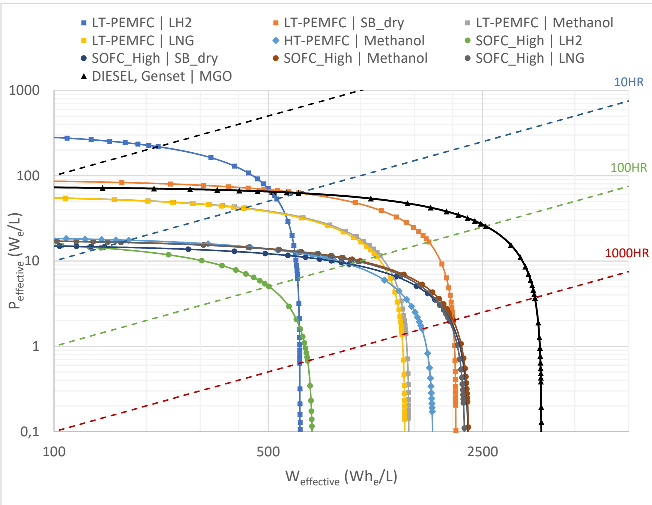


Figure 4.5: Volumetric density all three types of fuel cells

Gravimetric densities:
From gravimetrical point of view, the LT-PEMFC solutions (figure 4.2) show a numerous of options which are lighter than a diesel engine. This however is only up to about 16 hours in case of liquefied hydrogen and formic acid, for the other fuels its a sorter time frame which is depending on the type of fuel. For the higher temperature fuel cells (figure 4.4) the MGO powered SOFC's surpaces the diesel engine for long continuous operations as seen for the volumetric density. Other fuels never reach the gravimetrical density of the diesel engine, while LNG comes very close for the SOFC_Low. As seen with the volumetrical density the diesel engine is more energy dens for longer operating times. The SOFC is more dens than the PEM fuel cells with respect to the weight from approximately 50-60 hours for non hydrogen based fuels mentioned in the ragone chart shown in figure 4.6. These crossing points can be seen in this graph as well (figure 4.6) since all types of fuel cells are combined in one graph. For the HT-PEMFC the same conclusions as seen with the volumetric densities can be drawn, meaning that the LT-PEMFC and SOFC perform better than the HT-PEMFC for different time ranges. For the gravimetrical density point of view the SOFC even outperforms the HT-PEMFC for all time ranges.

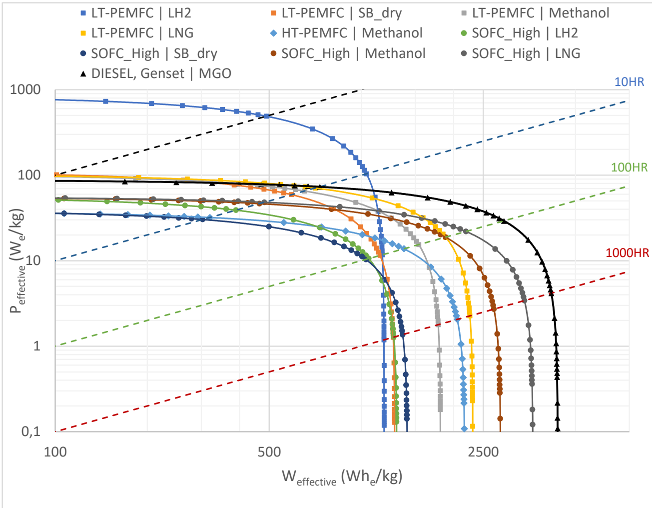


Figure 4.6: Gravimetric density all three types of fuel cells

Overall:
Form the previous comparisons it can be concluded that LT-PEM fuel cells are an excellent solution for short time periods between refuelling. In case of a LT-PEM fuel cell in combination with liquefied hydrogen this solution will even outperform the diesel generator set for both the volumetric density (up till 7 hours) and the gravimetrical density (up till 16 hours). Such a system would be perfect for ships with a short sailing time like ferries or inland ships which are able to tank during stops. For the same time range other types of fuels in combination with a LT-PEM fuel cells are very close to the diesel engine for the volumetric point of view. The gravimetrical density is almost always better for the diesel engine when other fuels are used, however depending on the design requirements (weight or volume driven) the LT-PEMFC could probably still be a good solution even with other fuels. The turning point is at a time of approximately 16 hours, from this point on all types of fuel cells and fuel combinations except of the diesel powered SOFC are worse for both weight and volume than the diesel engine which is used as reference.

When a fuel cell is chosen for other reasons (like: emissions, vibration or noise) the LT-PEM fuels cells seem to be the best solution up to a certain time where the SOFCs cross the LT-PEMFCs within the ragone chart. This point varries per type of fuel and is different for the volumetric or gravimetrical density. For the volumetric point of view this crossing point is about 200 hours and 50 hours for the gravimetrical density. For the HT-PEMFC it turns out that there is no optimal operating point since the LT-PEMFC and SOFC are more energy dense for shorter operating times and longer operations in respectively order.

5

Decision parameters fuel and fuel cell

Next to the density of the fuel cell system including the fuel, other parameters are also important for a decision making overview. These other parameters like emissions, regulations and safety are discussed during this chapter.

5.1. Emissions

5.1.1. Fuel cell system emissions

5.1.1.1. Carbon dioxide emissions

All three fuel cells considered during this research (LT/HT-PEMFC and SOFC) basically work on hydrogen and have the same overall reaction as shown with equation 5.1.

$$2H_2 + O_2 \rightarrow 2H_2O \tag{5.1}$$

As earlier discussed in section 2.2 the main difference between the low and high temperature fuel cell is the fuel flexibility, this is because CO can be oxidised so it works as fuel instead of poison. When CO is oxidised it forms electrons and CO_2 as shown in equation 2.10 during section 2.2.

During this section the CO_2 emissions are based on the fuel reforming as discussed in section 3.3. Theoretically all CO is converted into CO_2 for all reforming processes since it's practically always combined with a water gas shift reaction. In reality the fuel will always contain some pollution in the form of CO, however in case of SOFC this will be oxidised as discussed before. In case of low temperature cells it will be removed with additional steps.

Therefore the steam reforming and water gas shift reaction is used to calculate the amount of CO_2 emission per fuel type. Below, in equations 5.2, the combination of these two reactions are given.

$$\begin{aligned} Methane &: CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \\ Methanol &: CH_3OH + H_2O \rightarrow 3H_2 + CO_2 \\ Ethanol &: C_2H_5OH + 3H_2O \rightarrow 6H_2 + 2CO_2 \\ DME &: CH_3OCH_3 + 3H_2O \rightarrow 6H_2 + 2CO_2 \end{aligned} \tag{5.2}$$

For formic acid the reaction according to DENS occurs within their reactor, illustrated by equation 5.3.

$$Formic\ Acid:\ HCOOH \rightarrow CO_2 + H_2 \tag{5.3}$$

For fuels that do not contain carbon or hydrogen carriers, which only release hydrogen no CO_2 will be emitted. These fuels or carriers are:

- Hydrogen (Also compressed or liquefied)
- Ammonia (NH_3)
- LOHC
- Sodium Borohydride
- Metal hydrides

Based on the mol ratio CO_2 versus fuel the amount of CO_2 per kilogram fuel can be calculated, with this and the energy density of the fuel in Appendix B.1 the amount of CO_2 emission per kilowatt hour of fuel can be calculated. The results are shown in table 5.1.

Fuel	Formula	Molecular weight (g/mol)	kWh/kg_{fuel}	$nr.CO_2/molfuel$	kg_{CO_2}/kg_{fuel}	g_{CO_2}/kWh_{fuel}
Methane	CH_4	32,04	13,095	1	2,743	209.5
Methanol	CH_3OH	46,069	5,582	1	1,374	246,1
Ethanol	C_2H_5OH	17,031	7,487	2	1,911	255.2
DME	CH_3OCH_3	46,069	7,889	2	1,911	242.2
Formic Acid	CH_2O_2	46,025	1,537	1	0,956	622.3

Table 5.1: CO_2 emission different fuels

For the amount of CO_2 emission of MGO the emissions are based on the calculation method according to the lecture notes WB4408B [95]. The mass ratio of carbon dioxide can be obtained using equation 5.4.

$$mr_{CO_2}^{g-out} = \frac{M_{CO_2}}{M_C} \cdot x_C^f \quad [kg_{CO_2}/kg_{fuel}]$$

$$\begin{aligned} M_{CO_2} &= mol\ mass\ of\ CO_2 \\ M_C &= mol\ mass\ of\ C \\ x_C^f &= carbon\ content \end{aligned} \tag{5.4}$$

A carbon content of 85,7% [73] the $mr_{CO_2}^{g-out}$=3,140 and a fuel density of 11,944 kWh/kg this leads to the emission of 262,906 g_{CO_2}/kWh_{fuel}. This same method has been used to compare the values from table 5.1, it gives exactly the same values for all other fuels. For LNG it is found that around 230 g_{CO_2}/kWh_{fuel} is emitted [72]. In table 5.2 a overview of the CO_2 for the different discussed fuels is shown.

	MGO	LNG	Methanol	Ethanol	DME	Formic Acid	Hydrogen	Ammonia	LOHC	Sodium Borohydride	Metal Hydride
Emission (g_{CO_2}/kWh_{fuel})	262,9	230	246,1	255.2	242.2	622.3	0	0	0	0	0

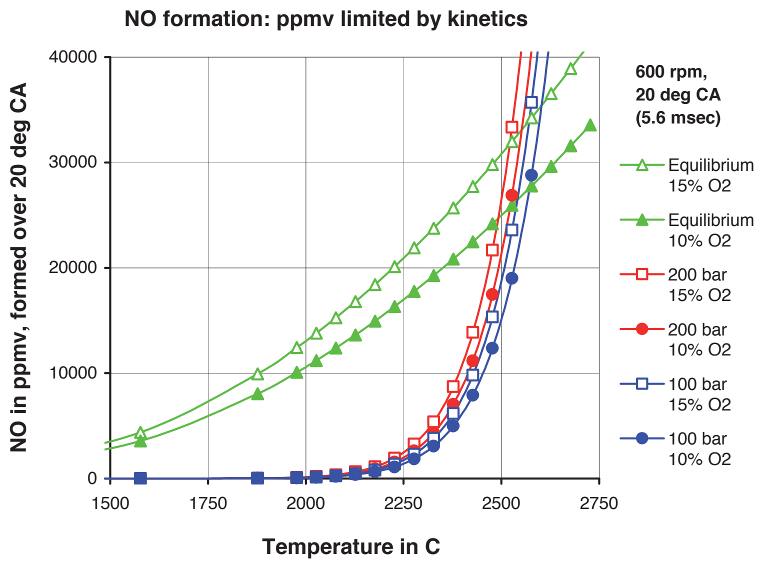
Table 5.2: Total overview of CO_2 emission per type of fuel

5.1.1.2. Other non carbon emissions

Next to the carbon emissions there are also other emissions with combustion fuel like for example: NO_x, SO_x and PM. Since the regulations for these emissions are becoming increasingly strict these emissions can not be ignored. Therefore this section will discuss these emissions for fuel cells as far as possible.

When a fuel cell is powered on hydrogen the fuel cell operates completely emission free, as a fuel cell then only emits heat and water.

For fuel cells powered by other fuels like Ammonia (NH_3) or LNG, the fuel can contain sulphur or nitrogen which can result in NO_x or SO_x emissions. The gas delivered to the fuel cell has to be practically sulphur free because of it's poisonous for all types of fuel cells, therefore any sulphur traces should be removed in advance. This fact ensures that emission of SO_x by a fuel cell can be neglected.
Nitrogen oxides (NO_x) are typically formed by the reaction of nitrogen and oxygen. The most relevant formation of NO_x occurs under high temperature (thermal NO_x) in the form of NO. NO_x consists of NO, NO_2 and N_2O where NO is normally the largest contributor in the total amount of NO_x. NO_2 only contributes 5-10% and 1% consists of N_2O in a diesel engine. Figure 5.1 shows the amount of NO formation in a typical diesel engine. [96].



Source: Diesel Engines Volume 4 Emissions and Heat transfer [96]

Figure 5.1: NO formed in time available in typical medium speed diesel engine

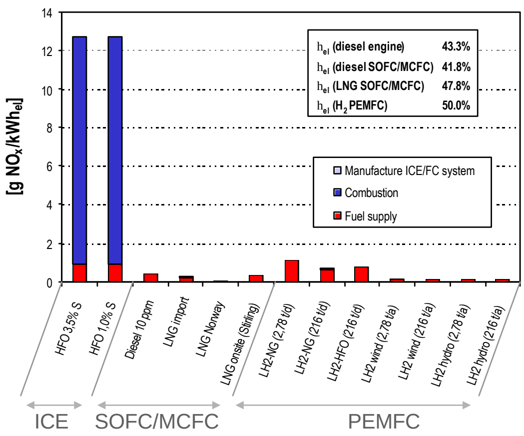
From this figure can be concluded that for temperatures below 2000°C basically no NO is formed. All types of fuel cells and fuel reformers practically operate below this temperature which ensures that hardly any NO_x will be formed if the main contributor (NO) will be eliminated.

These statements made above can be supported by the findings from the study of FCSHIP [4] which made a life cycle analysis of fuel cell ships. The life cycle emission for on board energy generation with fuel cell was investigated for two case ships. Below the emissions are showed for one of the case ships[12] which best matches the power demand of a super yacht. The different type of emissions are mentioned for different types of fuels and energy converters.

Figure 5.2,5.3, 5.4 and 5.5 show the life cycle emissions of air pollutants like SO_x and NO_x.

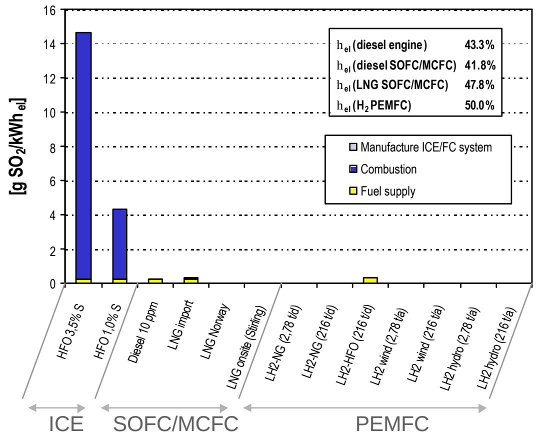
From these figures can be concluded that the fuel cell systems only emit a negligible amount of pollutant emissions except for CO_2. An important point to notice is that over a lifetime there are some pollutants emitted however they are substantially lower than emissions from a diesel combustion engine. Another fact is that the emissions are generated during the fuel supply instead of during combustion.

[12]Case ship 1, a large passenger ferry where the auxiliary power should be produced by fuel cells (about 2MW).



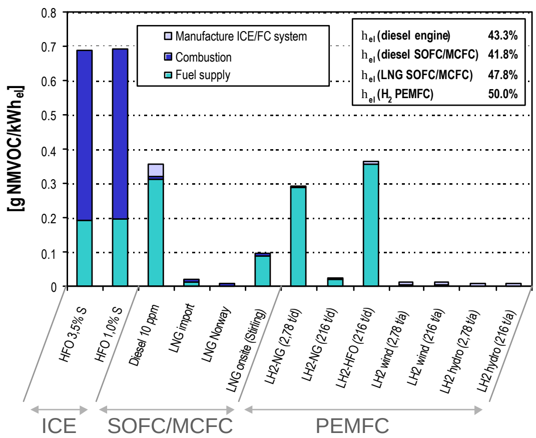
Source: FCSHIP – Fuel Cell Technology in Ships [4]

Figure 5.2: Life cycle NO_x emissions



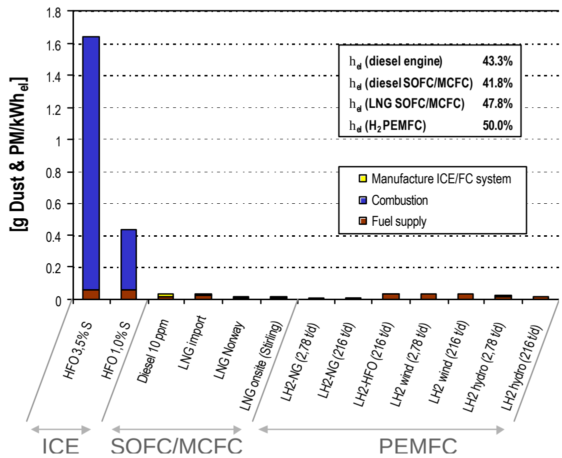
Source: FCSHIP – Fuel Cell Technology in Ships [4]

Figure 5.3: Life cycle SO_2 emissions



Source: FCSHIP – Fuel Cell Technology in Ships [4]

Figure 5.4: Life cycle $NMVOC$ emissions



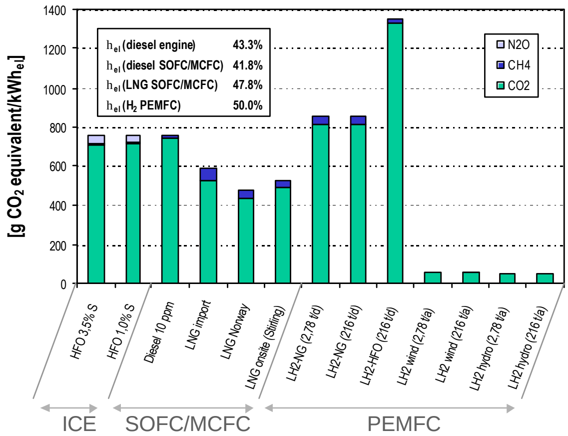
Source: FCSHIP – Fuel Cell Technology in Ships [4]

Figure 5.5: Life cycle PM emissions

5.1.2. Well to shaft emissions

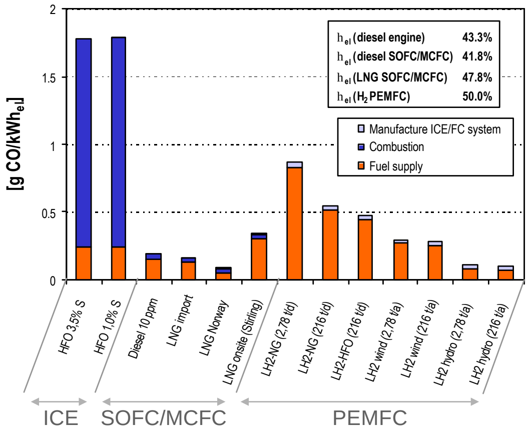
Next to the emissions on board the ship it self, the production and supply of the fuel requires energy as well and therefore contributes to the life cycle emissions of a yacht, although it is not a significant amount.

For CO_2 equivalent emissions the FCSHIP study [4] made a life cycle assessment as well, figure 5.6 and 5.7 respectively show the CO_2 equivalent and CO life cycle emissions for different fuel cells. Figure 5.6 shows the life cycle CO_2 emissions, this figure emphasises the fact that well to tank emissions should not be ignored. The on board CO_2 emissions of a hydrogen fuel cell are zero, while the production of liquefied hydrogen from natural gas or HFO emit overall more CO_2 than an HFO diesel engines. Nowadays nearly 90% of the hydrogen is produced from fossil fuels [81]), when such a type of hydrogen will be used the overall CO_2 emissions will increase. This increase in pollution has mainly comes from the energy intensive process of creating and liquefying process of hydrogen. Figure 5.8 shows the same results the total energy amount (kWh_{PE}) needed per kWh of electric energy (kWh_e) is a lot higher for LH_2 than for the other mentioned solutions.



Source: FCSHIP – Fuel Cell Technology in Ships [4]

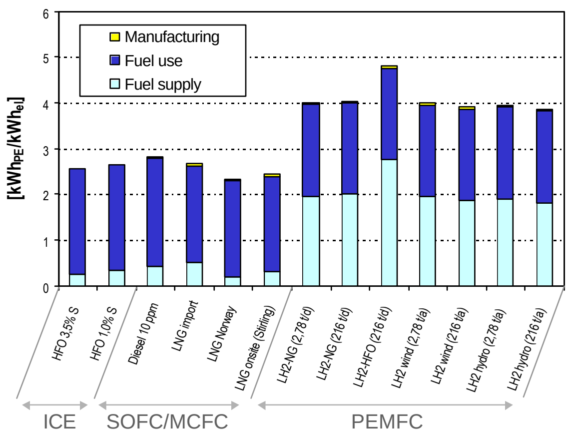
Figure 5.6: Life cycle CO_2 emissions



Source: FCSHIP – Fuel Cell Technology in Ships [4]

Figure 5.7: Life cycle CO emissions

The production method of hydrogen is very important for the overall emissions from source to electricity, since it can negatively influence the result of 'green' designed ship into an even worse solution for the environment. Theoretically almost all types of alternative fuels are possible to produce in a renewable way. Another option would be to capture the carbon emissions when producing the fuel. This way the footprint of the fuel production can be lowered. However, limited information is available about this subject and since it is outside the scope of this research, therefore this topic is not discussed in more detail. The remainder of this study will therefore only look at on-board emission.
Though this subject should be considered when further research into fuel cell powered ships or other solutions is executed, so that a well-considered decision can be made. It can for example been decided to accept a fuel from non renewable source as a stepping stone to a completely renewable solution, since time is required to develop a sufficient infrastructure for new sort of alternative fuels.



Source: FCSHIP – Fuel Cell Technology in Ships [4]

Figure 5.8: Life cycle analysis energy usage (kWh_{in}/kWh_{out})

5.2. Regulations

Fuel cells have the potential to limit emissions from ships, the amount of reduction is dependent of the type of fuel and the fuel cells. There are a lot of promising fuels like for example hydrocarbons and hydrogen as fuel, which are capable of substantially lowering the emissions, these carbon fuels all have a low flash-point what brings some concerns regarding storage and use on board of ships. The regulations regarding fuel for ships state that fuels used on board should have a minimum flash point temperature of 60°C with exception of fuels for emergency generators and lifeboats (SOLAS Convention [19]).

The international Code of Safety for Ships Using Gases Or Low Flashpoint Fuels (IGF Code) went into force on the first of January 2017, it covers the requirements for constructing and operating ships with natural gas as fuel. The IGF code is mandatory for all gases and other low flashpoint fuels, however only natural gas (CNG/ LNG) is covered in the current version of the IGF code. For other gasses or low flashpoint fuels an alternative design method, as prescribed in SOLAS Regulations II-1/55, should be followed according to part A of the IGF Code to demonstrate a sufficient level of safety is applied.

Currently IMO is working on revisions for the IGF Code due to take place within the 4-year cycle for SOLAS revisions. The Sub-Committee on Carriage of Cargoes and Containers (CCC) keeps the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) under review. The CCC has a yearly session of one week in September where the progress and direction of different codes among which the IGF Code will be discussed. During the latest sessions (up to CCC5 which took place at 10-14 september 2018) the progress for the revision of the IGF Code where discussed and noted. The following quotes and aspects noted during the CCC sessions up till CCC5 (according to IMO) give an indication of the revision status of the IGF code that are relevant for this investigation:

- **According to IMO, CCC 2nd session [38]**
  ”*IMDG Code 2016 amendments agreed*
  The Sub-Committee began developing draft text of technical provisions for the safety of ships using methyl/ ethyl alcohol as fuel, for further consideration by a correspondence group.”

  ”*Draft amendments to MARPOL Annex V developed*
  The Sub-Committee developed draft amendments to the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), regarding fuels cells, which will be further considered by a correspondence group, with a view to being finalized at the next session of the Sub-Committee.”

- **According to IMO, CCC 4th session [38]**
  ”*Safety provisions for ships using fuel cells developed*
  Further progress was made in developing safety provisions for ships using fuel cells, including the proposed new part E on fuel cell power installations to IGF code. Part E would cover installation, fire safety and other relevant matters.”

- **According to IMO, CCC 5th session [38]**
  ”*Interim guidelines for ships using methyl/ ethyl alcohol as fuel*
  The Sub-Committee agreed, in principle, to draft interim guidelines for the safety of ships using methyl/ ethyl alcohol as fuel. The MSC was invited to refer specific paragraphs to other technical sub-committees for consideration and advice to CCC 6.

  The detailed interim guidelines are intended to provide requirements for the arrangement, installation, control and monitoring of machinery, equipment and systems using methyl/ ethyl alcohol as fuel to minimize the risk to the ship, its crew and the environment, taking into account to the nature of the fuels involved.

Specific sections/paragraphs to be referred to other sub-committees for consideration concern: location of cargo and methyl/ethyl alcohol fuel tanks (Sub-Committee on Pollution Prevention and Response (PPR); limit for safe location of fuel tank(s) (Sub-Committee on Ship Design and Construction (SDC)); fire safety (Sub-Committee on Ship Systems and Equipment (SSE)); ventilation, for review regarding control and monitoring of fire detection system in machinery spaces containing methyl/ethyl alcohol engines (SSE); and drills and emergency exercises (Sub-Committee on Human Element, Training and Watchkeeping (HTW))."

"*Safety provisions for ships using fuel cells*
The Sub-Committee agreed to develop safety provisions for fuel cells as interim guidelines, to cover installation, fire safety and other relevant matters and instructed the correspondence group on safety of ships using low-flashpoint fuels to develop relevant draft interim guidelines."

"*Use of low flashpoint diesel as marine fuel*
The correspondence group was also instructed to discuss a proposal to carry out a formal safety assessment study for ships fuelled by low-flashpoint diesel (i.e. diesel fuel with a flashpoint of less than 60°C) and report back to CCC 6."

Next CCC session, CCC6 will be held on 9-13 september 2019.

Currently the only fuel covered by the IGF code is natural gas, however according to the notes of the CCC meetings up to CCC5 held in 2018 it seems very likely that the next revision (begin 2021) will include fuel cell regulations in a new part E as well as additional fuels next to LNG. The additional fuels added will probably only be methanol and ethanol. These additional regulations will become the first official rules for fuel cells and methyl/ethyl alcohols within the shipping industry. These developments will certainly help in accelerating the adaptation of these type of techniques since it will probably become easier to class such a ship.
At the moment there are only guidelines from classification societies like: Bureau Veritas, DNV GL (rules for classification), Korean Register of Shipping and Lloyds Register [99]. Besides these rules there are some standards for fuel cell applications produced by IEC (International Electrotechnical Commission) and ISO (International Organization for Standardization) which are not specifically for the maritime industry but could be used for guidance. These rules are IEC 62282 and ISO 16110 for respectively fuel cell technology and hydrogen generation [99].

5.3. Safety

Previous section captured that fuels need a flash point temperature of at least 60°C according to the Solas convention, for lower flash point temperatures the IGF code has to be followed. Due to these regulations the flash point temperature is one of the safety factors which at least needs to be considered.
Besides the flash point temperature, which covers the fire hazards, other factors should be considered concerning safety: health hazards, environmental hazards, instability hazards and chemical compatibility with materials.

The basic health, fire and instability hazards are all covered in a systematic way by the NFPA 704. This is a standard system of the National Fire Protection Association of the U.S. which was created to give emergency personal the possibility to quickly asses the hazards of certain materials in case of an emergency situation. The different hazards are illustrated in a fire diamond divided in four sections which all cover a different safety hazard as illustrated in figure 5.9. All hazards, exept the (white) special hazards, are indicated with a number from 0-4 where 0 is a minimal hazard and 4 is a severe hazard. A more detailed explanation of the NFPA 704 and sings for all different fuels can be found in Appendix B.5 and B.5 which gives an overview of the important safety aspects for all different fuels. Next to the NFPA 704

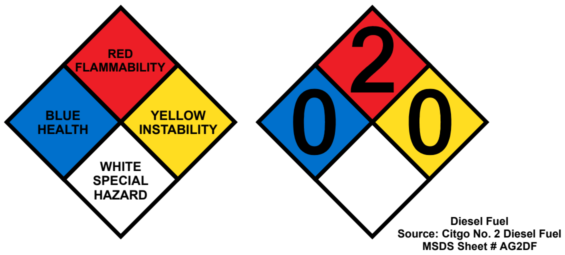


Figure 5.9: NFPA 704 signs [80]

the flash point temperature, auto ignition temperature, explosive limits and boiling points are mentioned for each fuel giving extra information with respect to the fire safety.

In appendix B.5 and B.5 the GHS(13) sings which are used to classify hazards during transport like the NFPA 704 are shown as well. The main difference between these two systems is the fact that GHS is globally harmonised. In principle both systems indicate the same hazards in a different way and could herefor both be used.

To conclude on safety the chemical compatibility is presented in Appendix B.7 as far as this is known for the different fuels.

Remarks based on safety details provided

The table below (table 5.3) gives a recapitulation of some of the conclusions which can be drawn from the fuel safety aspects shown in appendix: B.5, B.5 and B.7.

State of matter under normal conditions	
Gaseous fuels:	Ammonia, DME, LNG, Hydrogen
Liquid fuels:	Methanol, Ethanol, MGO, LOHC, Sodium Borohydride (Fuel30), Formic acid
Dry fuels:	Sodium Borohydride, Metal Hydride, MOF
Flash point conditions	
Above 60°C [1]:	Ammonia, MGO, LOHC, Sodium Borohydride, Metal Hydride, MOF
Below 60°C:	Methanol, Ethanol, DME, LNG, Hydrogen, Formic Acid
Health hazard	
Limited:	Methanol, Ethanol, DME, MGO, LOHC , MOF
High:	Ammonia, LNG, Hydrogen Sodium Borohydride, Formic Acid
Hazardous to environment	
High:	Ammonia, MGO
Material Incompatibility	
Aluminium:	Formic Acid
Carbon steel:	Formic Acid

[1] Or equivalent or higher fire safe.

Table 5.3: Recapitulation of fuel safety aspects

(13)Globally Harmonised System of Classification and Labelling of Chemicals

6 Decision Making Tool

The choice of which fuel and fuel cell combination should be used depends on a lot of different factors and can vary from project to project. Most of the important topics which can influence the choice are discussed separately earlier in this report, however since there are a lot of factors to take into account it is hard to make a well considered decision. For this a decision making tool is created to help make a decision on which fuel cell technique and fuel type should be used. This tool can be used as guidance to make a quick assessment to find the best cell solution, based on the needed time range and preferences regarding the fuel and fuel cell characteristics.

The tool uses a multi criteria analysis to distinguish between different fuel and fuel cell combinations. This chapter highlights the decision criteria (section 6.1.1) and the way these are used within the tool (section 6.1.2). Furthermore the tool will be demonstrated with the use of three example cases.

6.1. Tool development

6.1.1. Decision criteria

As decision criteria the following topics are included: density, storage type, maturity, safety and emissions. The meaning of these criteria and the way they have been calculated are discussed below.

Density: With regards to the density criteria, both the effective volumetric and effective gravimetric densities, as discussed during chapter 4, are taken into account. The effective density varies a lot depending on the expected operation time of the system, therefore a different decision should be made for different continuous operating hours (t). For this reason the time-factor (t) for the effective density is implemented as a variable. The effective density is calculated according to equation 4.1 and 4.2, where variable ”t” can be defined in the decision tool. Therefore the densities for that specific time factor (one line in the ragone chart) are calculated for all different fuel and fuel cell combinations. The input for the fuels, energy converters and reformers are listed in appendix B.4.

Storage type: With the current yachts of Oceanco the diesel fuel has always been stored inside the double bottom, therefore the amount of space and weight which needs to be added for the construction of tanks is minimal fuel that can be stored in at that location as well. A distinction is made between a fuel which could be stored in the conventional double bottom tank and a fuel wherefore this is not possible. It is assumed that all fuels which are liquid or a powder under normal conditions could be stored in the double bottom. These fuels are: MGO, Ethanol, Methanol, Sodium Borohydride, Formic acid and LOHC.

Maturity: To determine the maturity of the different technologies the technological readiness level (TRL) is used, the TRL system is developed by NASA in the 70’s and from then on used by a lot of different parties.
Below in table 6.1 the nine different levels used in the TRL system are described:

Discovery	
TRL 1:	Basic principles observed
TRL 2:	Technology concept formulated
TRL 3:	Experimental proof of concept
Development	
TRL 4:	Technology validated in lab
TRL 5:	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6:	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
Demonstration	
TRL 7:	System prototype demonstration in operational environment
TRL 8:	System complete and qualified
Deployment	
TRL 9:	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Source of information: `https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf`

Table 6.1: Description of the nine different technological readiness levels

The TRL status is determined for all different fuel and fuel cell combinations[(14)], the result is listed in appendix C.1. Next to the TRL there is another factor taken into account, which is the existance of relevant companies for this type of technology. This is done by introducing four different distinction levels: active company for the marine sector (1), active manufacturer in another sector (0.75), active company in the past/ very limited activity (0.25) and lastly no active company (0). For the maturity level, the tool uses the TRL status which is corrected for level of company activity with the values mentioned in parentheses.

Safety: Safety is based on the information discussed during section 5.3. The safety decision criteria are split up into three categories (fire hazard, health hazard and instability) which are based on the raking according to the NFPA 704 which is provided for each fuel in appendix B.5 and B.6. The NFPA 704 has four diamonds from what three are: fire hazard, health hazard and instability hazard. These diamonds are all rated from 0 to 4 which go from safe (0) to dangerous (4), the same ranking is used within the multi criteria analysis.

Emission: Since fuel cells are considered for sustainability reasons the emission from fuel cells can not be ignored. For the amount of emission, only the CO_2 emissions are tanken into account since other emissions can be neglected for fuel cells (section 5.1). The amount of CO_2 is presented in table 5.2 for all different fuels, this is shown as the amount of CO_2 emissions per kWh of fuel (g_{CO_2}/kWh_{fuel}). For the comparison in the decision tool these values are corrected for the efficiency of the fuel cell and reformer combined, which in fact gives the amount of CO_2 per kWh electric as follows: $\frac{g_{CO_2}}{kWh_{electric}} = \frac{g_{CO_2}}{kWh_{fuel} \cdot \eta_{combined}}$.

6.1.2. Raking of the solutions

For various designs different criteria could be more or less important than another. Therefore, a a weight factor is added to all different decision criteria. These weight factors are variables in the decision matrix so the weight factors can be entered by the preference of the user, by changing the weight factors certain characteristics can by emphasised.

All values for the decision criteria are normalised, so for each criteria a maximum of 1 and a minimum of zero can be can be achieved. This type of ranking is made with the thought that the results should be easy to compare. The overall result is calculated for the sum product of the weight factors times the normalised decision criteria, these total scores are corrected for a maximum score of 10. The variables which can be changed are the time and the weight

[(14)]The ranking of the TRL values is based on the author's assessment by knowledge acquired during the research.

factors: weight density, volume density, storage type, maturity, safety and emission. For safety the internal weight of the different safety categories can be changed as well.

Finally the different solutions can be ranked on the total scores, which will output the list of options sorted from best to worst possible solution. Based on the value of the total score the user can asses the value of the position where a particular option is listed. For example if there is a big gap between two options then it's likely that this is the best solution, while when different options are very close to each other or get similar scores then perhaps more extensive research needs to be done to make a choice.

6.2. Tool demonstration

The decision making tool will be demonstrated with three different example cases to illustrate the importance of selecting a fuel cell system case by case.

6.2.1. Examples for different applications

The different example cases are described below:

Example case 1: Fast passenger ferry with a very short range
In this case there will be looked at a short distance fast ferry. The speed and range characteristics are shown below:

- Route: Calais, France ↔Dover, United Kingdom
- Distance: +/-25 nm
- Cruising speed: 20 knots
- Sailing time: 1.25 hours

Since it is a fast sailing vessel the weight is an important factor, volume however is of less importance because it only has to transport people for a short time so a seat per person should do the job. The safety aspects are quite important when transporting people.

Example case 2: Yacht with a medium range
The second example case is closer to the scope of this project and looks at a super yacht with a range which should be more than sufficient for a ocean crossing. The speed and range characteristics are shown below:

- Route: unknown
- Distance: 5000 nm
- Cruising speed: 14 knots
- Sailing time: 357 hours

For a yacht other decision criteria are important than seen with the fast passenger ferry. For a yacht the biggest selling point is the luxury space, this should be maximised therefore the volume density is very important. Further, the weight is also quite important since yacht are generally design for high maximum speeds. As earlier discussed the fuel is always stored in the double bottom, so a fuel which could be stored in the double bottom is preferable. Lastly, the safety is important as well.

Example case 3: Slow steaming bulk carrier with a long range
The last example case will cover a slow steaming bulk carrier with a long distance trade route, as specified below:

- Route: Santos, Brazil ↔Hechuan, China
- Distance: 12300 nm
- Cruising speed: 12 knots
- Sailing time: 1025 hours

For such a ship the volume density is important since the payload need to be maximised. As the speed is relatively low and the ship is transporting heavy goods the weight is not seen as an important factor. Storage type is important from the volume point of view because this can safe space for cargo, last the safety factor is less important compared to the other types of ships since limited people are on board combined with the fact that only a small part of the ship is an accommodation.

6.2.2. Input and results

Based on the information of the different example cases the input variables for the decision making tool are determined. These input variables are shown in table 6.2. The emission weight factor is kept the same for all cases, this factor is set relatively high since the reduction of emission is the main reason to look into the possibilities of fuel cells. The internal weight factors of the different safety categories vary from 1 to 3 indicating the importance of the different type of hazards, however the overall weight factor is determined by the safety factor.

	Weight Factor									
	Weight density	**Volume density**	**Storage type**	**Maturity**	**Safety**	*Fire Hazard*	*Health Hazard*	*Instability*	**Emission**	**Time factor (t) in hours**
Example case 1, Ferry:	4	1	0	1	3	*3*	*3*	*1*	3	1.25
Example case 2, Yacht:	1.5	3	1.5	1	2	*3*	*2*	*1*	3	357.14
Example case 3, Bulk carrier:	1	4	2	1	1	*3*	*1*	*1*	3	1025

Table 6.2: Input of variables for decision making tool for the different example cases

The top ten results for all three example cases are presented in appendix C.2. The results shown here are in line with the conclusions from chapter 4 for case 1 and 3, however for case 2 the evaluation of all criteria results in some different conclusions.

For example case 1 only LT-PEM fuel cells with different types of fuels are been brought forward in the top ten results. For the other two examples the SOFC becomes increasingly attractive from case 2 to 3 since the sailing time increases.

For example case 2 it can be seen that all different types of fuel cells end up in the top ten results, while there was still a big spread with respect to the density as seen in chapter 4. The HT-PEMFC's represent the first two best solutions after the diesel engines, however the result of methanol powered SOFC's are very close. According to the conclusions in chapter 4 the SOFC would be the best solution for this time range, the same result can now be seen at the density part of the decision tool. However the density is now not the only parameter which is taken into account any more, this is the reason that the HT-PEMFC came at the top of the list. The substantially higher degree of development for this type of operation, is the main reason that the HT-PEMFC ended up higher in the decision tool. Further on, its a bit surprisingly that the dry sodium borohydride is suggested as tenth option while it scores the lowest on the maturity. The reason is that a LT-PEMFC combined with sodium borohydride is very energy dens solution for this time factor as seen in figure 4.5, while it still operate without emissions.

For the last example case 3 the SOFC and HT-PEMFC are the only solutions besides the diesel engines suggested by the decision making tool. The SOFC is on top of the results is again in line with the conclusions of chapter 4.

II

DESIGN STUDY, FUEL CELL POWERED YACHT

7

Basic System Selection and Design

In the second part of this study, the results from Part 1 will be used to design a fuel cell powered yacht based on an existing Oceanco design. During this chapter a basic system design is made for a particular yacht with certain assumptions. First the reference yacht and energy requirements are discussed, where after a decision for the best type of fuel cell will be made.

7.1. Reference yacht

7.1.1. Dimensions and characteristics

The reference yacht used for this design study is a [redacted]. The main dimensions and characteristics are shown below, in table 7.1.

General specification:	
Length overall:	[redacted]
Length waterline:	[redacted]
Beam:	[redacted]
Design displacement:	[redacted]
Cruising speed:	[redacted]
Maximum speed:	[redacted]
Range:	[redacted]
Power generation:	
Genset:	[redacted]
Main engine:	[redacted]
Battery pack:	[redacted]

Table 7.1: Generall specifications reference yacht

There are two speeds mentioned, cruising speed and maximum speed, the cruising speed is the speed for which the specified range must be achieved. The ship is propelled by [redacted]
The hotel load and thrusters [redacted]

The power and propulsion arrangement of the reference yacht is summarised in the diagram shown in figure 7.1.

7.1.2. Energy requirements

The energy requirements of the yacht strongly depend on the operational condition of the yacht. There are four operating modes considered: sailing at cruising speed, sailing at top speed, harbour and anchoring/dynamic positioning. The different modes mainly change

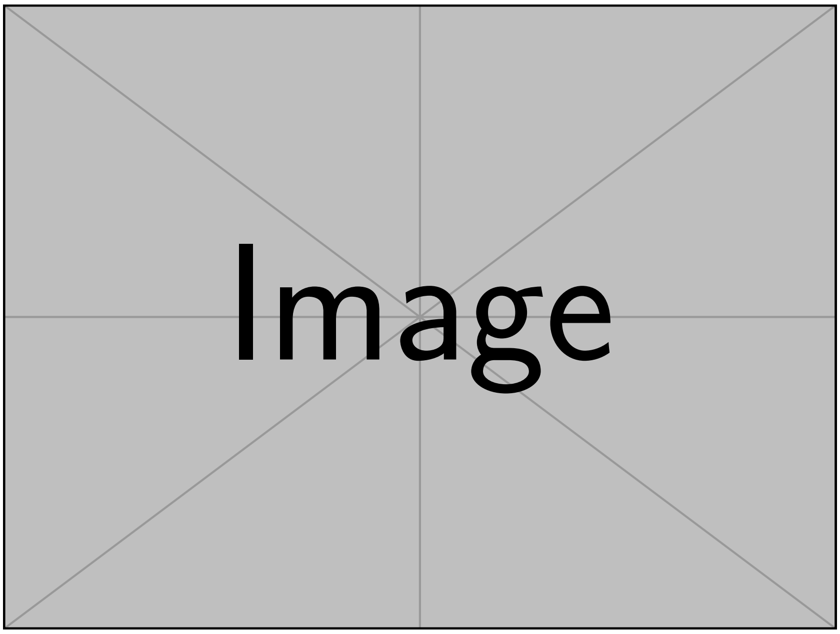


Figure 7.1: Propulsion/power configuration diagram

in propulsion load, the hotel load is more or less constant with a slightly lower hotel load during sailing conditions. These different operating modes are used for two conditions: crew only and crew + guest, which result in a different hotel load. For the energy and power requirements only looked at the crew + guest condition is considered, as these situations will cover the most power demanding circumstances.

[redacted]

The used operating modes and power requirements are summarised in table 7.2. The

[redacted]

Table 7.2: Different operating modes

maximum load for crew + guests is used for mode 1 and 4, which represent the maximum load condition for sailing and non-sailing operation. Operating mode 2 is are the requirements for the range, which has to be sailed [redacted]. Finally mode 3 represent the absolute minimum possible load which is for crew only while in harbour.

These different operating modes are important to determine the needed amount of energy and power on board. The total installed power on the reference yacht, including gen-sets and main engines, is [redacted]. However these engines have different task, the gen-set will provide energy for the hotel load and thrusters while the main engines drive the propellers directly. With a fuel cell powered yacht all power is delivered electrically and can be designed as one integrated electrical system. So, the total amount of power used with the reference yacht would result in an overdimensioned system for an all electric vessel. For designing the fuel cell system the amount of power and total energy is not based on the reference yacht, but on actual operating requirements as presented in table 7.2.

The power and energy required are derived from mode 1 (sailing cruising speed) and mode 2 (sailing maximum speed). Mode 1 is the only mode with a range requirement, it will be used to determine the minimum amount of electrical available energy, for the range of [redacted] with a speed of [redacted]. This comes down to a total continuous sailing time of about [redacted], the power consumed at cruising speed is [redacted]. Sailing with this electrical load for [redacted] results in a total amount of energy of about [redacted].

Mode 2 requires the most power and therefore defines the minimal amount of power what need to be installed, this turns out to be [redacted].

7.2. Fuel cell selection

Based on the findings described in part I, a decision making tool is developed and explained in chapter 6. With this tool the most promising fuel cell system can be found for the reference yacht.

Suggested solutions based on selection tool:
For selecting the right type of fuel cell for the reference yacht the selection criteria for the yacht example mentioned in section 6.2.1 were discussed with Oceanco and slightly changed to their preference. According to their preference the maturity should be emphasised more, by increasing this weight factor. Therefore the volume density, storage type, safety and emissions were all slightly lowered in favour of the maturity. The reasons for the change in maturity is because its more relevant for Oceanco to find a solution which has the prospect to become commercially available within a reasonable time. This is logical considering the main target of Oceanco, which is to sell high quality custom superyachts. At the moment a increasing amount of potential customers are becoming more aware and interested in 'green' solutions for their yachts. So itegrating such a solution in their yachts could help them to improve there competitiveness with respect to other yards. By this change the maturity factor has become a very important decision factor, and shifted from emission and volume density to maturity as most determining factor. The emissions and volume are also seen as important and are therefore the second most important criteria.

The new criteria weight factors are shown in table 7.3. [redacted]

	Weight Factor									
	Weight density	**Volume density**	**Storage type**	**Maturity**	**Safety**	*Fire Hazard*	*Health Hazard*	*Instability*	**Emission**	**Time factor (t) in hours**
Reference yacht weight factors:	1.5	2.5	1	3,5	1	*3*	*2*	*1*	2,5	[redacted]

Table 7.3: Input of variables for decision making tool for reference yacht

The weight factors as shown in table 7.3 are filed into the decision tool. The results and ranked results of the fuel and fuel cell options for these criteria are shown in appendix C.4 and C.5. The top 10 results as shown in table 7.4 consists of the following energy converters and fuel types:

- Energy converters: Diesel engine, HT-PEMFC and LT-PEMFC
- Fuels: Diesel, Methanol, LOHC and Metal Hydride

Nr.	Fuel cell:		Type of technology:	SCORE:
1	DIESEL engine		Diesel engine, Engine (MTU 16V4000M73L)	8,84
2	DIESEL engine		Diesel engine, Genset (16V2000M41A)	8,35
3	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC	7,38
4	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC, MFCU	7,30
5	HT-PEMFC		Methanol, HT-PEMFC	6,56
6	HT-PEMFC		Methanol, HT-PEMFC, MFCU	6,47
7	LT-PEMFC_AIP		LOHC, LT-PEMFC_AIP	6,38
8	LT-PEMFC		LOHC, LT-PEMFC	6,35
9	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Small tank)	5,94
10	LT-PEMFC		Metal Hydride, LT-PEMFC (Small tank)	5,91

Table 7.4: Top 10 Results

Next to the defined weight factors, a sensitivity analyses is executed for the different options with a constant time factor of [redacted] hours. This sensitivity analysis the criteria weight factors of the raking tool are filled in for 700 random values between 0 and 1. These 700 weight factors are used to calculate a scoring based on random input, with this approach the result should be independent of any personal or project orientated preference. The 700 different scores are compared based on the geometric mean, average and median, this overview can be found in appendix C.6. With the scoring data from these random factors a box plot is made (appendix C.1) where the different options are ranked from high to low based on the scoring median to give an indication of the scatter in the results.

Comparison calculations top10 results:
During these comparison calculations the amount of fuel, fuel cells and fuel reformers for the different top 10 results are calculated. These three elements add up to a total weight and volume. Besides the volume and weight calculations the local CO_2 emissions are calculated as well. However it should be noted that for green methanol the net CO_2 emissions are zero, therefor a zero CO_2 emission is used in cases where green methanol is used. Green methanol has a zero net emission since already emitted CO_2 is withdrawn from the air for the production of methanol. The data for this comparison is based on the findings discussed in Part I of this report and used in the selection during section 7.2.

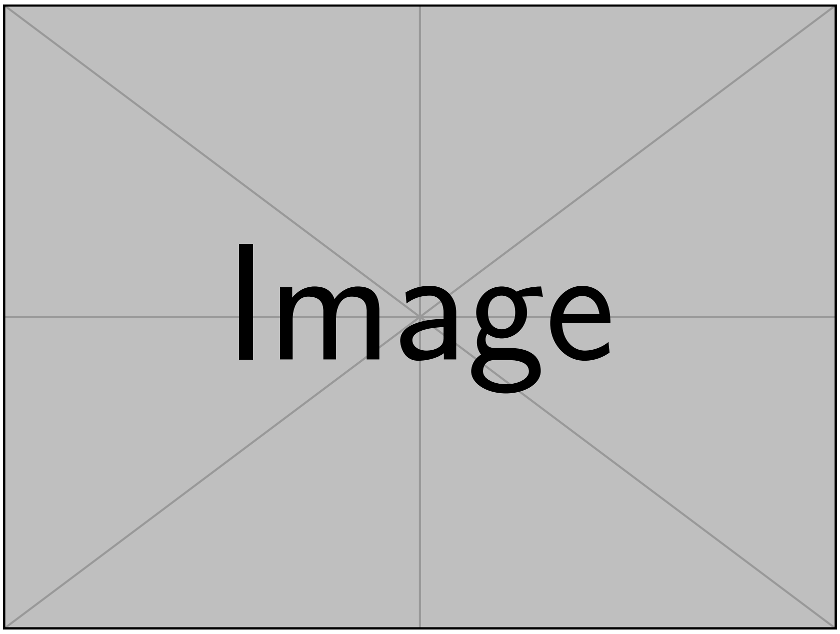


Table 7.5: Fuel cell comparison calculations

Calculations explained:

- Since methanol and LOHC can be stored in the double bottom of the yacht the amount of fuel has been calculated without the additional fuel storage solution, in other words only the pure fuel.
- The amount of fuel needed is based on total required amount of energy [redacted] corrected for the efficiency of the fuel cell and fuel reformer divided by the fuel density.
- The number of fuel cells and fuel reformers are calculated by dividing the total amount of installed power [redacted] by the maximum power output of the fuel cell.

The results of these calculations are shown in table 7.5 and in the form of a graph within figure 7.2.

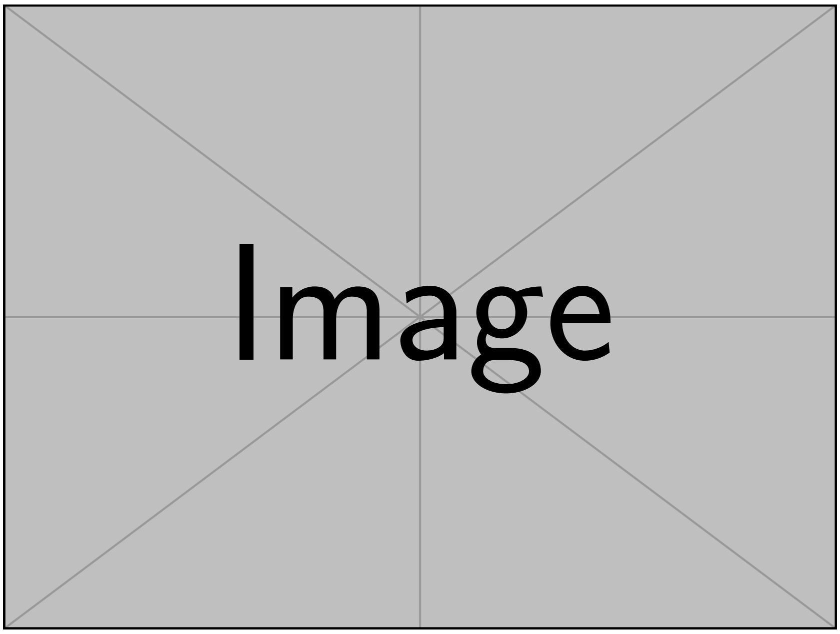


Figure 7.2: Fuel cell comparison calculations graph

To compare the result in the same way these calculations are used to rank the options again, this ranking is done in the same way as was done within the ranking tool. So all weight factors as used in section 7.2 were kept the same, the only things which were changed are the weight and volume density values. These values are replaced by the normalised total weights and volumes as calculated and shown in table 7.5. The results of these ranked values based on the new calculations are shown in table 7.6. The HT-PEMFC is shown in combination with methanol in both a renewable and non-renewable methanol, what can be seen in the difference of the CO_2 emission values.

		Density				Safety hazards			Emission		
		Weight	*Volume*	*Storage*	*Maturity*	*Fire*	*Health*	*Instability*	*CO_2*		
						Overall Safety ranking: 1					
Option	Energy Converter	1,5	2,5	1	3,5	3	2	1	2,5	Total	Ranking
MTU	MTU 16V2000M41A, Genset	1,00	1,00	1,00	1,00	0,50	1,00	1,00	0,55	8,9	1
HT-PEMFC_1	Serenergy MCFU (300kW)	0,55	0,43	1,00	0,89	0,25	0,75	1,00	1,00	7,6	2
HT-PEMFC_1_R	Serenergy MCFU (300kW)	0,55	0,41	1,00	0,89	0,25	0,75	1,00	0,60	6,7	3
LOHC	Power Cell MS100	0,19	0,21	1,00	0,78	0,75	0,75	1,00	1,00	6,5	4
MetalHydride	Power Cell MS100	0,04	0,26	0,00	0,89	1,00	1,00	1,00	1,00	6,1	5

Table 7.6: Fuel cell comparison calculations ranked

When comparing these results with the initial values from the ranking matrix (appendix C.5) it can be concluded that the results are still almost identical. This confirms that the estimate, which is made based on the effective density made in the ranking tool, gives a good picture of the actual dimensions and weights.

Conclusion:
The ranking tool gives a good representation of the actual weight and size as concluded with the comparison calculations, for this reason the final decision will be purely based on the results of the ranking tool. As seen in the top 10 results (table 7.4) A diesel engine still scores the best overall, even with the high weight factor for the CO_2 emissions. This is because a diesel engine scores high on all other criteria, this underlines once again why the diesel engine is such a great solution and why it's still used on the majority of ships. However, a very big disadvantage of a diesel engine is the burden on the environment due to harmful emissions. For that reason the possibility to use fuel cell technology to lower this impact is researched within this report, the diesel engines are purely added for reference.

The best four fuel cell solutions after the diesel engine are all HT-PEMFC's, interesting to see that the HT-PEMFC both with and without renewable methanol stands out of the rest. Hereby it appears that the HT-PEMFC with methanol is the best solution based on the criteria preferences regardless of the origin of the fuel. It should be noted from the score that the renewable option is clearly better than non renewable methanol.

Apart from the methanol powered HT-PEMFC, a number of other solutions are mentioned in the top 10 results, two different types of LT-PEMFC in combination with LOHC and Metal Hydride. When comparing these options in more detail with the HT-PEMFC solution it can be seen that the non renewable methanol options are very close to the LOHC option. When looking at the individual criteria results for the LOHC solution its clear that the positive points are the low safety risks and no local CO_2 emissions, however from the density perspective it has less than half of the density compared to the methanol powered HT-PEMFC solution.

Hereby it can be concluded that methanol in combination with a HT-PEMFC is one of the most dense solutions and easy to store. When the methanol is produced renewable the net emissions are CO_2 neutral and therefore set to zero. This combined makes methanol one of the best alternative fuels to use in combination with a fuel cell for applications with a high energy demand such as a yacht, and which is available at the moment.

When this result is compared with the ranked median score of the random weight factors shown in appendix C.6, the HT-PEMFC with renewable methanol is still suggested as second best after the diesel engines. In this comparison the SOFC with diesel and methanol is suggested again, probably because the maturity is weighted not as high on the average random values. But it is very interesting to see that the renewable methanol HT-PEMFC is still the best from the sensitivity study, which indicates that this is probably the best solution for this time range independent of the project or preferences. When looking at the boxplot (appendix C.1) this presumption is confirmed once more, since these two options clearly stand out of all the other fuel cell solutions.

Based on these observations, it can be concluded that the methanol powered HT-PEMFC is the best possible solution for this reference yacht. For this reason the methanol powered HT-PEMFC is the only fuel cell solution which will be used and investigated in more detail for the in the continuation of this report.

Remarks:
The maturity was of great influence when the fuel cell solution was selected in the last section, despite that the selected option is one of the most developed solutions even this technology isn't fully developed. Some other remarks should be kept in mind during the continuation of this report. These remarks are listed below:

- It's important to keep in mind that most of the technologies are still in development, despite of the development status some of these solutions seems to be very promising. Therefore the developments with respect to fuels cells and alternative fuels should be followed very closely, any breakthrough or sudden development within one of these solutions could change the conclusion. For example the SOFC's are mainly penalised for the state of maturity but most of the other characteristics seems very promising. The current SOFC fuel cells are build for shore based power plants which operate at a constant rate all the time. These cells have a maximum on off thermal cycling capability of about 50-100 times, which is a limitation of these fuel cells to implement them in a yacht[14].However there are still developments with respect to SOFC's, for example the MSC (Metal substrate as support for thin ceramic layers) SOFC technology where Ceres Power is working on at the moment. This type of fuel cell combines some of the benefits of the HT-PEMFC and the SOFC, making it possible to handle more on off cycles. The main benefit of SOFC's is that they typically have a higher electric efficiency. The operating temperature and efficiency is relatively low for this particular SOFC but still higher than that of a HT-PEMFC which means a higher quality waste heat with the potential to reach high efficiencies when CHP is used.

- An other interesting technology is Sodium Borohydride which has some promising characteristics, in particular when the spent fuel will be filtered afterwards. The combined fuel cell and fuel density of sodium borohydride in dry form is very high, in particular the volumetrical density which offers the highest density compared with both the HT-PEMFC and SOFC in combination with methanol. However the downside of this fuel is that it leaves a liquid substance remnant (spent fuel) which needs to be stored and returned so it can be recycled. This spent fuel has a volumetric density which theoretically still could be very high in the most optimistic filtered scenario. This spent fuel however will always be a lot heavier in comparison with methanol which is considered as the optimal fuel to use with fuel cells for the moment. The big advantage of this solution is that there are zero local emissions, while still offering a dense solution compared to other solutions which offer zero local emissions. When it's important that no local emissions are emitted, sodium borohydride should be seriously considered. Currently there are still a lot of challenges with respect to this fuel, even when the development of the on board fuel system and reformer will be neglected there are a lot of other factors which are influncing the probability of succes. For example: There is no infrastructure available to bunker and/or to recycle this fuel type. In addition to this, this type of fuel needs to be stored, transported and fuelled in powder form, which is quite a big change to the current infrastructure. Besides the logistics this type of fuel is a very specific type of fuel, with a relatively limited production (thousands of tons annually[(17)]) compared to methanol (over 70 million tons annually [56]).

- Considering the fact that methanol is produced on large scale, has a completely developed and ready to use infrastructure, 80% of the methanol is shipped overseas to different continents, it is stored and transferred locally by: train, barge or truck and it's a lot easier to obtain this type of fuel. Methanol is an emerging fuel since its seen as a possible renewable solution for different types of transports, already some ships use it as marine fuel. In addition methanol can and is already produced 100% renewable by combining captured CO_2 and green hydrogen.[56] From regulational point of view methanol will be added in the IGF code, which now only contain LNG as alternative fuel. LNG was the first fuel to be adopted in the IGF code begin Januari 2017, natural gas is already used as fuel on 165 ships and has grown rapidly the latest years as seen in figure 7.3.

  A small methanol bunkering unit can be build for a fraction of the cost of a LNG terminal (€0,4 Million vs €50 Million), further more this methanol can be burned in an combustion engine as well as in fuel cells. These facts form the expectation that this type of fuel will be more rapidly adopted in the maritime sector compared to other alternative fuels. And therefore this type of fuel will likely be more rapidly available and investments in infrastructure and green production will get into gear rather soon. Not all methanol will be produced 100% renewable but this type of fuel can also be seen as an enabler to get towards a greener type of propulsion. For the mean time when no green methanol can be required the local CO_2 emissions of a methanol powered HT-PEMFC are still at least 12%[(18)] lower than a conventional diesel powered gen-set and it already has zero PM, NO_X and SO_X emissions.

(17)Source: `https://deepresource.wordpress.com/2019/02/12/production-of-nabh4/`

(18)This is based on the optimal efficiency of the Diesel engine, in practice these engines don't operate at there optimal working

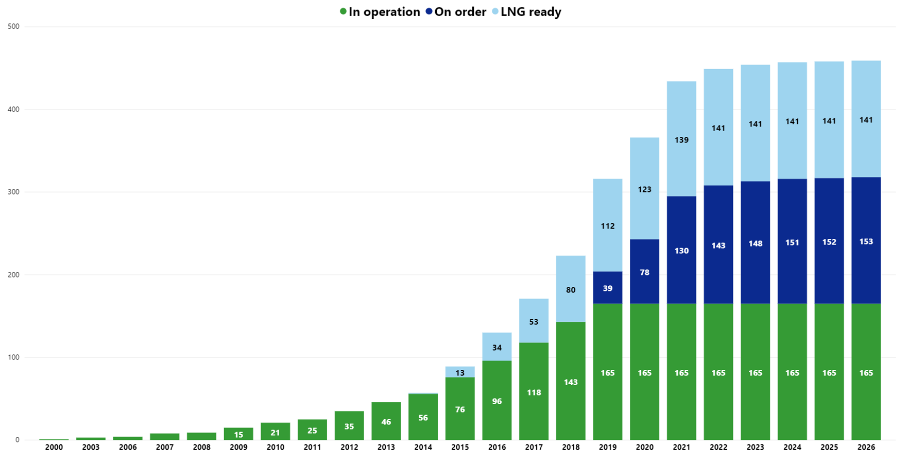
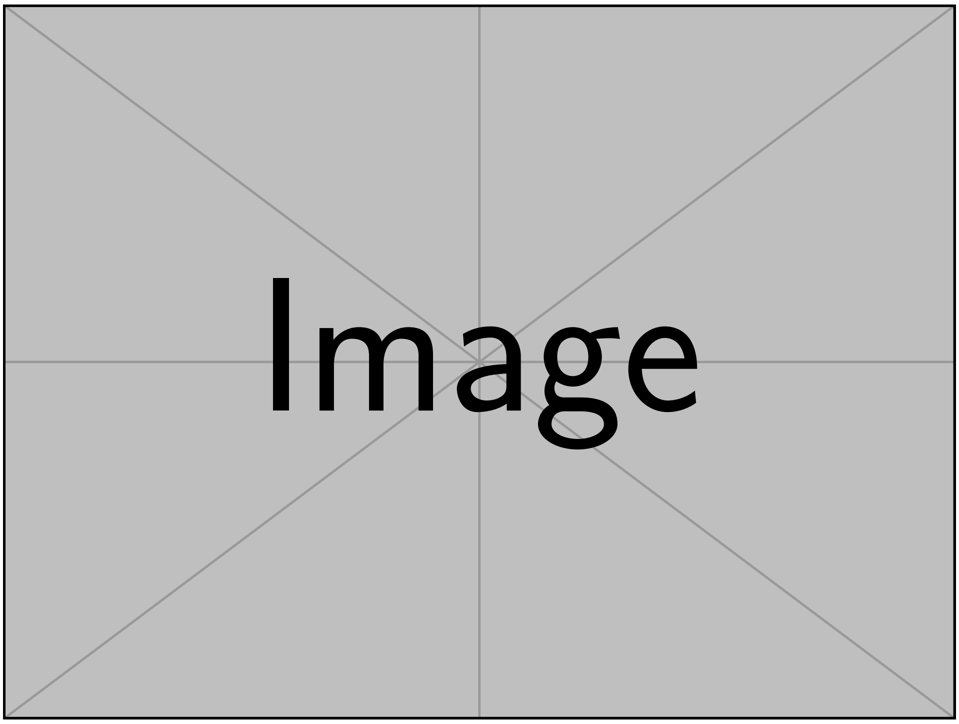


Figure 7.3: Yearly development of LNG fuelled fleet [22]

7.3. Basic Design Assesment

7.3.1. Initial Rough Design

In the latest section it has been calculated how many fuel cells and fuel reformer are needed for the different considered options. These numbers are used to make a quick graphical comparison by drawing the system blocks for the HT-PEMFC inside the ships contour. Figure 7.4 shows the original arrangement of the yacht, the engine room [redacted]



Machine room

highlighted in blue

Figure 7.4: Original arrangement

For the comparison the block arrangement of the HT-PEM marine fuel cell unit of Serenergy is used, the fuel cell systems are drawn from the most aft part of the engine room

point. This results in a higher fuel consumption and more emissions, making the difference with the fuel cell even bigger since these have generally a higher efficiency in part loaded conditions.

forward. This directly shows if the sytems will fit inside the existing machinery space. The colours used in these drawings indicate the different type of equipment: cyan blocks indicate fuel cells and magenta highlight the minimum required service space.

For these drawings it's assumed that all the needed fuel will fit in the double bottom, therefore only the fuel cells are drawn in the comparison. The reference yacht has around [redacted] of fuel tank space in the double bottom, besides this there is an additional space of about [redacted] for other fluids that belong to the engines. In total there is about [redacted] of fuel space available inside the double bottom. The fuel space could probably be extended with another [redacted] within the surplus of ballast tanks available or within some of the voids in the double bottom. This makes it presumable that all needed methanol could fit in the tank space that is currently available in the double bottom. The tank space arrangement will be investigated more detailed within section 8.3.1.1.
As concluded in last section and illustrated in table 7.5 there are at least 19 HT-PEM MFCU's necessary to fulfil the power requirements of the reference yacht. Figure 7.5 shows the size of these 19 fuel cell within the contours of the yacht, the two horizontal lines indicate the watertight bulkheads which demarcate the limits of the engine room/machinery space where both the main engines and generators are placed. It can be seen from this figure that all fuel cells fit within these boundaries. The machinery space where these fuel cell systems are drawn includes more machinery and components than the engines, however these fuel cell systems as drawn in figure 7.5 almost completely fill the space. Next to the fuel cell units there are some additional systems required to keep the cells cool and running, these relatively small additional components are not taken into account yet. Knowing that the fuel cell system already occupies the complete machinery space while there are other components which still need to be fitted it can be concluded that the reference yacht as it is now will be to small to install fuel cells while keeping exactly the same requirements of the yacht.

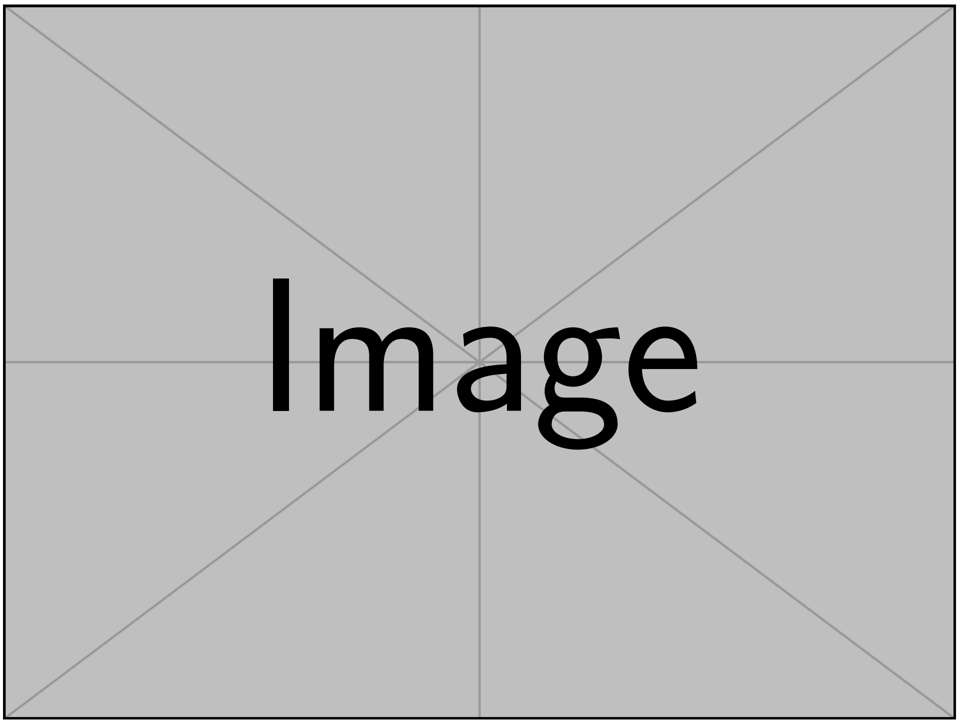


Figure 7.5: Block arrangement option 7, Serenergy MFCU

7.3.2. Needed system changes because of the use of fuel cells

Now the type of fuel and fuel cell which are going to be used are known as well as the rough design illustrated in figure 7.5, it's becoming more clear what the impact of a change from diesel engines to a fuel cell system will be.

Based on the comparison calculations (table 7.5) it became already clear that the system will become bigger and heavier compared to a diesel engine. By the sketches made during the rough design it became clear that the fuel cell systems require more space than available in the reference yacht. Since the functional requirements of the owner must be kept the same, a larger system will inevitably lead to another design which will probably come down to a larger yacht.

What is the impact on the design of a super yacht using fuel cells for energy supply on board? For the fuel cells some additional systems are required like the cooling and a fuel management system are needed for the operation. Therefore some additional research has to be executed, how much additional space is needed to fit all the systems? In addition the fuel used for this type of fuel cell is methanol which is a low flash-point fuel, therefore additional rules concerning low flashpoint fuels will certainly have some impact on the design.

The reference yacht will be converted from a diesel direct propulsion system to a fully electric system, this implicates that next to the fuel cell systems the energy distribution and propulsion system will be changed as well. All these different aspects will be reviewed in the next section.

8

Design impact

During last chapter it has been concluded that a methanol powered HT-PEMFC is the best possible solution for the reference yacht this moment. From the basic design assessment (section 7.3) it became clear that the technical available spaces are to small to fit all the fuel cells needed to keep the same requirements regarding speed. To make sure that all needed systems for a fuel cell powered yacht will fit in the ship, this chapter will go into the details regarding the change from diesel engines to fuel cells and all implications. Therefore this chapter will first of all focus on the regulations. Whereafter the technical details and characteristics of the selected fuel cell system will be discussed, based on the fuel cell characteristics a more specific energy storage plan will be made. This energy storage plan includes the needed methanol fuel and the electrical storage systems. The final technical details like propulsion type and energy distribution will be shortly mentioned.

8.1. Impact of regulations

The impact of regulations, by a change in design like this, needs to be taken into account. These changes can influence the decisions during the design of the yacht. During this chapter the regulations that are different from the regulations which apply to the reference yacht are investigated in more detail. There are two new factors which are a quite radical change compared to the reference yacht, these are the new type of fuel and the fuel cell as main power source. Diesel will be replaced by methanol, with this different type of fuel there are some new risks involved regarding to safety since this fuel has a substantially lower flash point. For low flash point fuels there are some mandatory regulations which are covered by the IMO with the IGF code as discussed before. Next to the change in fuel the power will come from fuel cell instead of a diesel engine, which will involve a new type of rules from classification.

The regulatory impact for using methanol and fuel cells on board of a yacht will be discussed during this section.

8.1.1. Methanol

During the assessment of the regulations with respect to methanol, there are a few different regulation documents from different parties consulted. For the assessment of the regulatory impact on the design of a yacht regarding methanol as fuel the regulations from IMO[20], Lloyd's Register[88] and DNV-GL[23] where used. The most relevant regulations which could have influence on the design of a ship powered by methanol are noted. Some rules have been omitted since these are not of big relevance now because of the high level of detail. However these rules should be used during any final or more detailed design phase. The most relevant regulations which are quoted one on one and included in the appendix D for reference.

Based on these documents it can be concluded that despite of the rules which are provided by three different regulatory parties, the rules are almost identical for storing and using methanol as fuel on ships. During this section the most important rules based on the regulations provided in appendix D.1 are summarised.

Fuel storage and handling:

- The methanol tanks can be both integral or independent tanks, which are not allowed to be placed within accommodation or machinery spaces of category A.
- The fuel storage tanks must be placed at least 800mm from the boundaries of ships the ship with the exception of integral tanks, integral tanks are allowed to be bound by bottom shell plating and should always be surrounded by cofferdams unless its bound by the bottom shell plating or a fuel pump room.
- The fuel tanks must be placed within the fore peak/collision bulkhead and the most after placed bulkhead.
- All tanks should be fitted with a system to inert the fuel tanks at all times, as well as a tank venting system to be able to make the storage tanks free of gasses.
- The fuel tanks should be accessible from open deck, for tanks without direct access from open deck the entrance shall be arranged in such a way that the tank space can be freed for dangerous gasses before opening the hatch. Its not allowed to access a tank from an: accommodation space, service spaces and machinery spaces of category A. The entry space needs to be well ventilated and the space around the entry hatch should be sufficient for an evacuation and rescue mission.

Fuel preparation:

- The fuel preparation spaces or pump room shall be placed in a dedicated space outside a machinery space of category A, this space should be gas and liquid tight to surrounding spaces.
- A fuel preparation or pump room is seen as an hazardous area and is not allowed to be directly accessed from a non hazardous area, therefor this room shall be entered from open deck, when this is not possible an air-lock between these two spaces is required.

Piping:

- All piping should be located at least 800mm from the ships side.
- Fuel piping must be separated from all other piping and should not pass through accommodation, service spaces and control stations.
- All fuel supply piping within enclosed spaces including machinery spaces shall be enclosed in gas- and liquid tight enclosure, either by a double walled piping or a cofferdam. The annular space in double walled piping should be ventilated or alternatively pressurised with an inert gas.
- Double walled piping is not necessary within: fuel tanks, fuel preparation spaces, fuel pump rooms, tank hold spaces or other hazardous fuel treatment systems since these spaces allready have secondary boundary.
- All piping should be equipped for gas freeing and inerting.

Airlocks:

- An airlock is a gas tight space between two bulkhead provided with two gas tight doors.
- The doors of an airlock need to be at least 1.5m and not more than 2.5m apart from each other.
- The deck area of such an airlock should be minimum 1.5m^2.
- The airlock should maintain a pressure difference so no fuel could be leaked to a non hazardous area in case of any leakage.

Ventilation:

- All hazardous areas which are enclosed need to be ventilated with a capacity of at least 30 air changes per hour, the only exception here is a cofferdam which is not needed to be ventilated.
- The ventilation air should be provided in addition to the combustion air.
- Ventilation exhaust needs to be at least 3m away from the nearest air intake, open deck accessible for people, openings to accommodation or any source of ignition.
- An air lock should be mechanically ventilated from a non hazardous area.

- The storage tanks should be fitted with a controlled venting system, the venting system should be equipped with a pressure relief valve. This relief valve should be at least B/3 or 6m (whichever is larger) above the weather deck and gangways. This exit should be at least 10m away from air intakes, openings to accommodations and non-hazardous zones or decks accessible to people.
- Outlets for gas-freeing need to be at least 3m above deck level.
- The annular space within the double walled fuel pipes should be vented with at least 30 air changes per hour which needs to be ventilated to open air.
- Fuel preparation spaces should be ventilated by mechanically forced ventilation.

Inert gas system:

- Provisions need to be made to supply inert gas to all systems which need to be inerted, like fuel tanks and pipes.
- The nitrogen purging gas can be either generated on board or stored in a dedicated system, while being refuelled from shore.
- The inert gas system should be permanently on board and be equipped for the maximum expected trip length and staying in port for two weeks.

Most important conclusions based on methanol rules

First of all tanks must be placed 800mm from the ships side and bound by cofferdams, for the reference yacht the diesel tanks are placed directly to the ships side. This directly influences the available fuel space. Next to the location the tanks should be accessed from open deck or with some special arrangements from the inside of the ship if access from the outside is not possible, however this is not allowed from accommodation, service and machinery spaces category A. Reading this rule it seems that the tanks are only allowed to be accessed from the ship if it's a cargo space, access from open deck in case of a tank in the double bottom would mean that one should decent from the gangway down to tank. Such an access arrangement will lead to very dangerous situations if a evacuation missions is required since the person inside the tank will be located far from the access hatch. On the tank deck of the reference yacht there are no real accommodation spaces, there are mainly technical spaces as well as the laundry room and crew gym located. So it needs to be discussed with classification if it will be allowed to access the tanks on a yacht from service/machinery spaces. If this would not be allowed it will become practically unfeasible to build a yacht powered by an alternative low flash point fuel.
In addition, such a methanol fuel system requires a separated fuel preparation space which is only accepted to be accessed from the ship when there is an airlock available. There are regulations about the ventilation of the rooms and tanks containing methanol. All tanks should be double walled and innerted or ventilated unless it's located inside the tank space or fuel preparation space.

8.1.2. Fuel Cell

For the regulations regarding fuel cells there is quite limited available at the moment, DNV-GL is one of the leading classification societies in this region. Normally Oceanco uses Lloyd's Register to class their ships, however until now they don't offer standard regulations for fuel cells. DNV-GL however offers regulations for fuel cells at the moment and are like Lloyd's Register a member of the IACS (International Association of Classification Societies) which offers a standard for classification where all different organisations need to comply with. For this reason the regulations from DNV-GL are probably to the same level of standards as Lloyd's Register would use, and could for this reason be used to form the conclusion for the fuel cell part.

The most important rules are listed in appendix D.2 in the same way as done during the latest section.

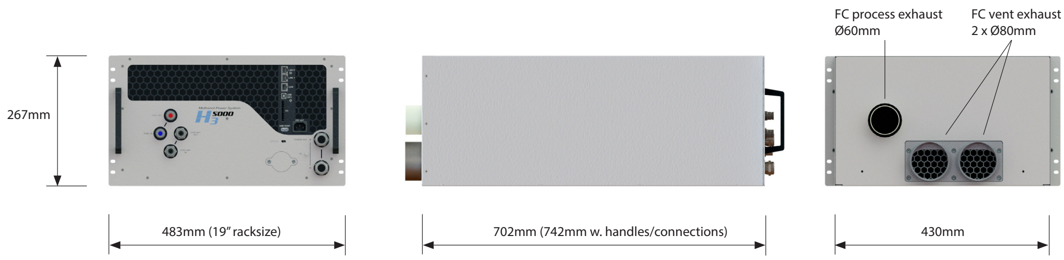
A lot of rules regarding ventilation and fuel piping are the same for fuel cells as seen in the previous section regarding methanol. The space arrangement of a fuel cell room is substantially different from current systems and requirements as seen with methanol rules.

Fuel cell spaces which contain reformers should comply with the regulations as required with the original fuel, in this case the fuel cell system has a reformer which is integrated in the system so the room needs to be equipped for both regulations. For this reason only the rules which differ from the requirements seen during the latest section for methanol will be mentioned.

- All boundaries of the fuel cell space should be gas tight towards enclosed spaces, with a special ceiling to capture any gas leakage. This comes down to a ceiling which needs to be smooth and sloping to one single point where any gas leakage will be led to the ventilation outlet. A thin plated secondary ceiling installed to cover this rule will not be accepted.
- Two ventilation fans for mechanical ventilation of the fuel cell space shall be installed which both have a 100% capacity and need to be connected through a separate circuit in terms of redundancy.

8.2. Power source and characteristics

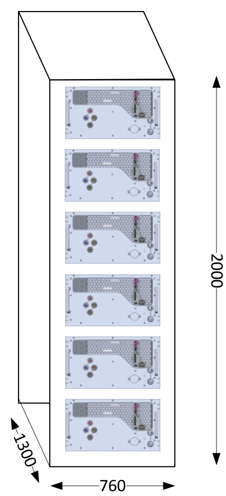
During this chapter the characteristics of the main power source (the fuel cells) are discussed. As concluded in chapter 7, there are 19 marine fuel cell units (MCFU) from Serenergy needed to comply with the energy requirements of the reference yacht. These marine fuel cell units make use of the HT-PEM fuel cell technology and work on 60/40 methanol/water mixture. The systems from Serenergy are modular build up from standard fuel cell modules of 5kW (H3-5000), figure 8.1 shows the dimensions of this module.



Source: SerEnergy A/S [92]

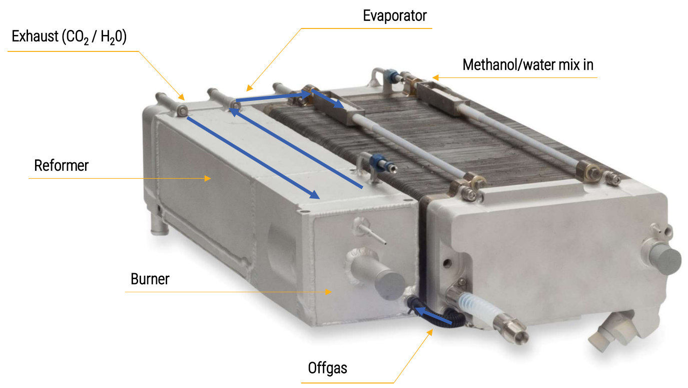
Figure 8.1: Fuel cell module, H3-5000

Inside the fuel cell module box, there is a HT-PEM fuel cell stack and methanol reformer combined. The methanol is reformed to a hydrogen rich gas inside the reformer which works on the steam reforming principle (section 3.3.2.1). The fact that the reforming works on the basis of steam reforming is the reason that the fuel is an methanol/water mixture, since this water is necessary to generate the steam during the reforming process. This reforming process is powered by the waste heat from the fuel cell and burning of the offgas. Since this is a HT-PEM fuel cell the stack has a way higher tolerance to gas impurities, making gas purification superfluous so the reformate gas can directly be used in the fuel cell. At the end of the process the exhaust gas of this fuel cell only consists of CO_2 and water vapour [5]. The fuel cell stack and reformer is shown in figure 8.3. A single module could work as stand alone unit and consists of all necessary components next to the fuel cell stack and reformer like: power electronics, blowers, system control, internal air cooling and external liquid cooling interface. The modules are build in such a way that it should be compatible with the regulations set-up by DNV-GL using alternative design. Six of these modules are used to form a rack of 30kW, such a fuel cell rack with the corresponding dimensions



Source: SerEnergy A/S [5]

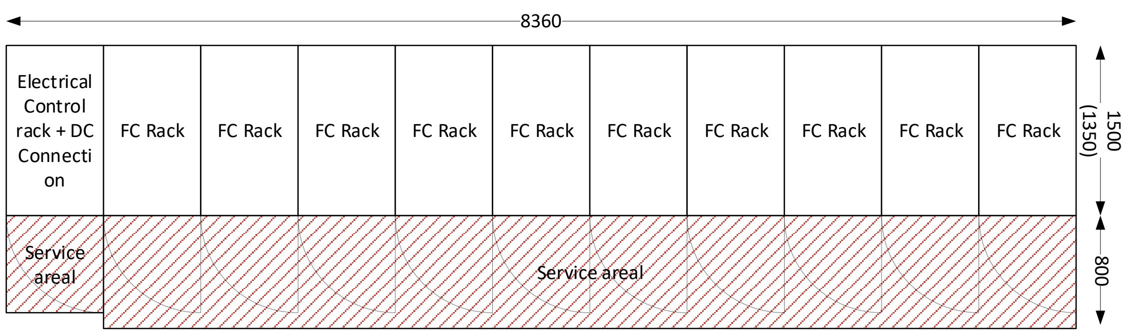
Figure 8.2: Serenergy fuel cell rack



Source: SerEnergy A/S [5]

Figure 8.3: Serenergy H3-5000 inside the module

in millimetres is shown in figure 8.2. The connections from the individual modules are combined to a centralised connection, in total there are five connections for each fuel cell rack: one exhaust outlet, a fuel in- and outlet, ventilation air and liquid cooling.
These fuel cell racks can then again be used to form a MFCU which is build up from multiple fuel cell racks. A MCFU can vary from a system with 1-10 racks which form a system from 30 to 300 kWe. Next to the fuel cell racks such a MCFU consists of one additional electrical cabinet which couples all the racks together to one integrated system. The layout and minimum required service space of a 300kW MCFU is shown in figure 8.4, if preferred the system can be arranged in a different layout for example placing the fuel cell racks back to back reducing the width of the system. This Marine Fuel Cell Unit (MCFU) was specially designed for the marine industry and has already been tested during several projects in the maritime industry as mentioned in section 2.4.2. This type of fuel cell works on a methanol



Source: SerEnergy A/S [5]

Figure 8.4: Serenergy Marine fuel cell unit

mixture of 60% vol methanol and 40% vol pure water, since PEM fuel cell produce water (section 2.1,2.2) it was assumed based on calculations that this water could be reused to mix the methanol which is stored pure. When methanol would be stored as mixture this would reduce the power density drastically and thereby this solution would not be as attractive as it is now. This water percentage is required for the steam reforming reaction which reforms the methanol into a hydrogen rich gas as mentioned before.

During the previous chapters it was checked if the amount of released water is enough to mix the methanol to a 60% methanol mixture. This was evaluated by using the reforming and the fuel cell reaction (equation 8.1 as discussed in section 3.3.2 and 2.2.1:

$$\begin{aligned} Methanol\ reforming &: CH_3OH + H_2O \rightarrow CO_2 + 3H_2 \\ Fuel\ cell\ reaction &: H_2 + \frac{1}{2}O_2 \rightarrow H_2O \\ Total\ reaction &: CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O \end{aligned} \tag{8.1}$$

There is 1.5 mol H_2O per mol $MeOH$ needed to get a 40/60% vol fuel mixture. From equation 8.1 it's clear that there is 1 mol H_2O is released for every H_2 so 3 mol H_2O for every mol of methanol. So according this calculation the reaction should generate twice the amount of water which is needed for the mixture. This has been checked with Serenergy, they confirmed that this is possible by condensation of the water in the exhaust gas. With their system its possible to get 150% water from the exhaust compared to the input.

From contact with Serenergy, it became clear that the efficiency of the fuel cell at nominal power is less than the efficiency mentioned at their website, which is 42% instead of 45% which is the maximum possible efficiency. Furthermore, the specified power of the fuel cell is higher than the nominal load, a 30/300 kW system has a nominal power of 22,5/225 kW. When the fuel cell is run at maximum power the efficiency drops to about 30% and the lifetime reduces with a factor five. Another factor which influences the life span of this type of fuel cell is when the system is run through a on-off cycle, such a procedure will count for 5 hours of normal operation.

As mentioned, there is a separate system required to recover the water from the exhaust gasses to be able to reuse the water to mix the methanol. Next to the water system some other additional systems like: fuel pumps, ventilation and exhaust fans are needed to operate a system like this. A complete overview of such a fuel cell system including water recovery and fuel mixing system is illustrated with figure E.1 in appendix E. This appendix E also shows the efficiency graph of this fuel cell unit by figure E.2.

8.3. Energy storage

The amount of needed energy storage will be now investigated in more detail, and will cover the energy storage in the form of electrical energy and methanol as fuel.

8.3.1. Methanol

8.3.1.1. Methanol storage

For this specific design the chosen fuel cell will run on a methanol mixture (40% water and 60% methanol). The methanol is stored in its pure form and will be mixed with water before entering the fuel cell to keep the overall density of the system as high as possible. As explained in section 8.2, the fuel cells produce more water than actually needed for mixing the methanol. During section 7, a rough estimation showed that the methanol would probably fit within the double bottom when some small adjustments would be made. However section 8.1, indicated the most important regulations regarding methanol, involving some additional rules regarding the fuel storage.

The most important rule regarding the impact on the fuel storage is, that in case of integral fuel tanks, the tanks should be placed at least 800mm from the ships side and allowed to be bound by bottom shell plating. This impacts the fuel storage quite a lot since both on port and starboard the tanks are reduced with 800mm over the height and length of the tanks. Besides the loss of tank space because the tanks need to kept free from the ships shell, there is also tank space lost because of the cofferdam which needs to be placed in fort and aft of the fuel tanks.

A cofferdam has to be minimal one frame in length, in case of this yacht this minimum will be [redacted]. So, in addition to the 800mm at the sides of the tank the tank will also become [redacted] shorter.

All tanks in the double bottom should be surrounded by shell plating or cofferdams, to prevent a lot of voids because of mandatory cofferdams, for this all tanks will be centralised and bound by two cofferdams (one in front and one aft of the tanks). Most of the fuel tanks are currently already placed next to each other, therefor this place (with some changes) will be the location of the methanol tanks.

The new central location of the fuel tanks is marked by the pink border (as indicated in figure 8.5), these pink borders show the additional space needed because of the regulations for methanol storage. This space is 800mm from the sides and [redacted]mm for- and afterwards of the fuel tanks. This comes down to a loss of tank space of about 35.3 m^3.

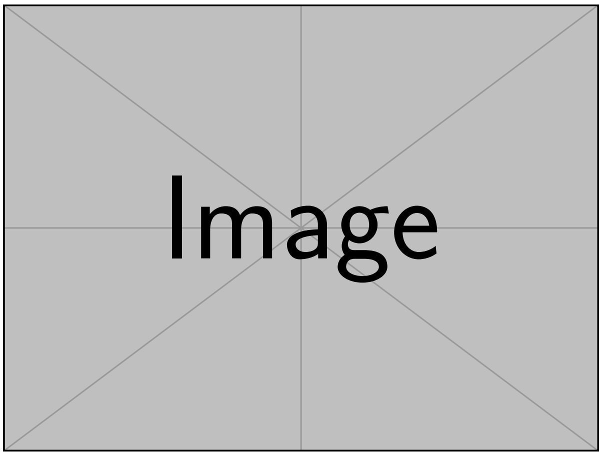


Figure 8.5: Changes in tank plan

The lost space because of keeping the sides of the tanks free from the ships shell is calculated based on a number of cross sections. One of the cross sections is shown in figure 8.6, the grey marked triangle in the chine is the area which needs to be kept clear in this example. For the cofferdam the total tank area (indicated with crosses) of the first and last section adjacent to the fuel tanks are used to calculate the loss of tank space.

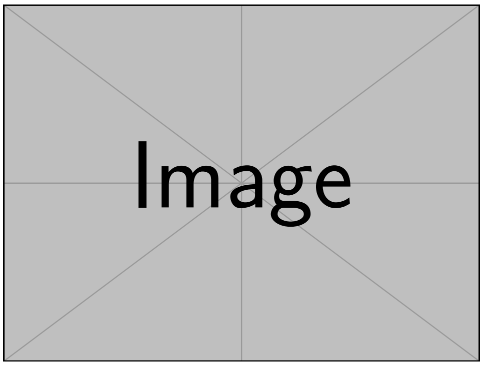


Figure 8.6: Cross section example

The yellow and blue marked tanks in figure 8.5 are existing fuel tanks of which only the yellow tanks will be preserved to store fuel in the new design. The orange tanks where ballast and grey water tanks and indicate the tanks which need to be relocated to make place for fuel storage tanks to have all fuel centralised and bound by cofferdams. The new fuel tank space, including the lost space because of the regulations for the new situation is [redacted] which is slightly less than the original fuel space of [redacted]. When the loss of tank space is taken into account the tank space comes down to approximately [redacted], while +/-550m^3 is needed as concluded in section 7.2.

Within these tanks the fuel service tanks are included as well, however in this case the fuel service tanks will be situated afther the fuel treatment system and filled with the methanol mixture instead of pure methanol. This will have a influence on the amount of energy that a tank can hold, for this reason the tank should be compensated for this loss in energy. Two service tanks of [redacted] are equivalent to a storage tank of [redacted] containing pure methanol, so another [redacted] should be added. Within the current available space a equivalent of about $380m^3$ pure methanol could be stored, so this means that $170m^3$ of additional fuel space should be added.

To solve this issue several solutions or a combination of solutions are possible like: make the ship longer/wider, increase the height of the double bottom, completely rearrange the tank plan and add tanks to other decks.
By rearranging the tank deck some additional space can be made free, for example the green marked tanks in figure 8.5 are used for engine and gearbox oil which aren't needed anymore. These tanks together have a capacity of 21.8 m^3, however a rearrangement has a influence on the parent decks as well since the systems connected to these tanks are located on these decks. During section 7.3, it was already concluded that the current available space for fuel cells is to small to fit all the systems. For this reason, it chosen to increase the length of the ship with a number of frames to tackle the space problem regarding both the fuel and the fuel cell. Therefor it has been calculated how much additional length is needed to fit the required amount of methanol (except of the service tanks) inside the double bottom. For this calculation the cross section of the frame which is located at the most rear placed fuel tank [redacted] is used to calculate the transverse tank area, this transverse tank area covers a surface of about [redacted]. When the needed amount of tank space is divided by the cross sectional area of the tank it becomes clear how much additional length is needed. This number rounded up to a integer amount of frames, which comes down to a minimum of 16 frames equal to [redacted] additional length. The total amount of pure methanol equivalent capacity is $555m^3$ which is almost $3m^3$ to less than the required $546.7m^3$ of methanol when a filling range of 98% is taken into account. One extra frame space of [redacted]mm will add 10.9 m^3 which increases the the capacity including filling range to $554.8m^3$ which provides a margin of $8m^3$.

This latest option has a capability of $566.1m^3$ pure methanol in the double bottom, this is obtained by lengthening the hull from the engine room forward with 10,2m. This extended arrangement is shown in figure 8.7, the additional fuel tanks are marked in yellow and the total fuel cell space is outlined by the pink outline which again represent the minimum required space around the fuel cells because of regulations.

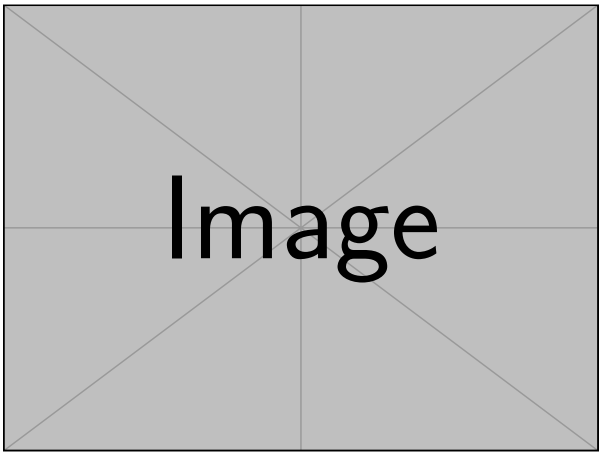


Figure 8.7: Extended lenght of yacht for fuel storage

8.3.1.2. Purging system

According to the regulations, provisions need to be made to supply inert gas to fuel tanks and fuel piping. This is also called a purging system and is used to enhance the fire safety by mixing the flammable/explosive hydrocarbon vapours with nitrogen (inert gas) to bring the fumes below the ignitable range and/or reduce the oxygen levels.

This can either be done by installing a nitrogen tank and store the gas on board or by producing the nitrogen with a nitrogen generator. The tanks should be inerted in all cases and the system should be capable of generating or storing enough for the maximum expected voyage and for staying in port for two weeks. When the system will be equipped for the maximum voyage it means that all fuel tanks of in total 566,1 m^3 need to be filled with nitrogen, when one should choose for storing the nitrogen on board this same amount of nitrogen needs to be stored on board. Nitrogen can be stored compressed or liquid, when using the ideal gas law, the needed gas volume for different pressures can be calculated by the following formula: $P_1 \cdot V_1 = P_2 \cdot V_2$. The specific volume of nitrogen at 20°C is 0.861 m^3/kg[87], so 566.1 m^3 of nitrogen has a weight of 657.5 kg without storage tank and independent of the state it's stored. When using compressed nitrogen at a pressure of 200bar the volume of 566.1m^3 can be compressed to 2,86m^3 on top of this a storage tank need to be included. Liquefied nitrogen has a expansion ratio 694 to gas, so when storing nitrogen in liquid form only a volume of 0.82m^3 is needed for nitrogen excluding the storage tank.

There are a number of disadvantages of storing the nitrogen among which the need to fill the nitrogen tanks when methanol will be bunkered as well as the safety issues regarding pressurised or cryogenic storage.

Another solution is on board generation of nitrogen, for on board generation the system needs to be designed to be able to handle the maximum needed flow of nitrogen. If the nitrogen generation can follow the maximum fuel consumption this will be enough to purge the fuel tanks since they will not be drained faster than this rate. The maximum fuel consumption of one MFCU is 300 l/h, in total there are 19 fuel cell systems installed which comes down to an overall maximum fuel consumption of 5700l/h. GENERON® is one of the companies which sells systems like this from small scale to very large systems. In their range of products, they have nitrogen generators as well for low to medium flow rates, which are specially designed and certified for the marine environment. The 4001 Marine Cabinet nitrogen generator [29] is the smallest generator and is and capable of delivering 3x the needed flow rate of about 5.7m^3/h. Such an system can deliver a nitrogen flow rate of 37m^3/h and weighs 112 kg and has a volume of 0,9 m^3, to generate 17m^3/h nitrogen the system requires an air input of 37m^3/h with a pressure of 6.9 bar. On the reference yacht there is already a compressed air system installed, when it's needed to make it an individual system an additional compressor could be added in the design, such a compressor is about 0.5m^3 and 170kg. Compared to compressed nitrogen it's already lighter without including the storage tank, hereby the on board generation system has the additional advantage that it's not needed to refill the nitrogen since its generated on demand. Therefor in this design the on board generation system is included.

8.3.2. Electrical storage for peak shaving

Fuel cells are not capable of following rapid load changes, especially with high temperature fuel cells since these systems have a relatively low ramp-up/down response. The power generation system on board of a yacht has to endure load changes which can vary depending on the usage and location of the yacht. For this reason the power configuration should be designed in such a way that the ship can still be used as required despite of the slower response of the main energy converter.

Currently, only the hotel load and thrusters are electrically powered. The hotel load of a yacht varies over time as well, this hotel load is very dependent of the location of the yacht since the majority of the needed energy is for the HVAC system. The HVAC power requirements vary over time as well since the outside temperature changes over the day, this variation is well known and could be used to estimate the energy load requirements over time. The remainder of the hotel load will vary over time as well, however this is mainly dependent on the user of the yacht and is therefor very difficult to estimate. When the hotel load will become to high for one generator a secondary generator will be started, however a fuel cell can not be started as quick as a diesel engine. As discussed in section 8.2 the used fuel cell has a startup time of 30-45 minutes. During this startup period a secondary system should be able to provide the necessary power this can for example be a battery system, this means that the system should be a hybrid configuration consisting of fuel cells as main energy source and a electrical energy storage system.

One could imagine that the thrusters are only used for short moments during manoeuvring or dynamic positioning while anchoring. Such an operation involves short peaks where a lot of power is required, normally all generators are online for these types of operations. Using a hybrid system can be used to reduce the number of active fuel cell systems.

Next to the thrusters and hotel load the main propulsion will also become electric in case of an all electric ship, and should be powered from the same type of fuel cells. For this reason the load fluctuation for the propulsion should be covered as well, either by the fuel cell or the energy storage system. This propulsion power is estimated to be constant a relatively long period of time since yachts will be sailed at a steady speed, the power fluctuations because of waves or wind will be neglected during this research.

To determine the required size of an energy storage for such a hybrid solution, the different hotel load scenarios (Appendix **??**) are used to obtain inside in the load characteristics of the yacht.

8.3.2.1. Hybridisation

When a hybrid system is mentioned it refers to a fuel cell hybrid electric ship (FCHES) with a HT-PEMFC as main power source. This HT-PEMFC will be supported by a energy storage system (ESS) to form a fuel cell hybrid electric ship (FCHES). The main reason of a hybrid solution in this case is to tackle the variable load characteristics, a well designed hybrid solution could allow for an overall smaller energy system with the following advantages: reduced size, lower capital cost, improved power response, improved lifetime of main energy converter and an improved efficiency [45]. Since this reference yacht has the requirements to sail at a maximum speed of [redacted] knots the amount of batteries can unfortunately not be reduced because these are needed to generate enough power. However the efficiency, power response of the total system can still be increased as well as the lifetime of the fuel cells if designed for this.

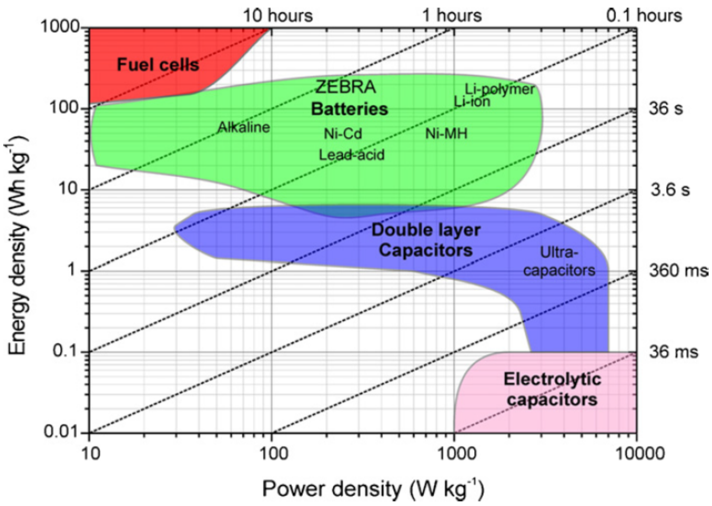
Below in figure 8.8 a general ragone chart is shown where different electrical storage systems (fuel cells, batteries and capacitors) are merged in one graph [15]. From this graph it can be seen that fuel cells clearly have the highest energy density of all, they also have a relatively low power density for shorter operational periods. From 9 hours and less other solutions than fuel cells become more power and energy dense, for example capacitors have a high power density but only for short periods of time these should for that reason only be used for very short energy spikes. The batteries are located between the capacitors and fuel cells in terms of density.

From this graph it can be concluded that no individual energy storage technology has both a high energy and power density. When designing a well balanced FCHES with a fuel cell system as primary power and using a batter/capacitor system as buffer, all positive characteristics can be combined in such a way that the negative properties will be neutralised.

In order to achieve a perfect integrated FCHES the load profile should be well known in order to select the appropriate technologies and system sizes, in a corresponding method like done for the fuel cells but than for the load fluctuations. Next to the selection of systems and size of the system, the electrical integration, interconnection and control strategy of these systems should be well known to reach the required goal. Therefor the goal one would like to reach with designing a hybrid system should be known, as different design target could be reached with a hybrid system as discussed during the begin of this section.

8.3.2.2. Degree of hybridisation

Fuel cells have an expected lifetime of 5.000-6.000 hours at the time of writing this report, and it is expected that this will increase to around 10.000-15.000 hours within 3 years. When a system is operated continuously, which is the case with generators at the moment, this system has a lifetime of 208-250 days now and 416-625 days in the near future. This comes down to a operational life time of 0.57-0.68 to 1.14-1.71 years in case of continuous



Source: Q. Cai et al. 2010 [15]

Figure 8.8: Ragone plot of different energy storage systems

operation. In reality just a small amount of the fuel cells will be operated continuously, the majority of the fuel cell will be used for a short or relatively short time for example when sailing. When these systems go through an on-off cycle this will represent 5 hours of normal operation in terms of their lifespan. Since the lifespan of the fuel cell is already relatively limited, it would be very use-full to have a hybrid system which is able to cover peak loads so the fuel cells have to run through a minimum number of on-off cycles. By this type of operation the lifespan of the fuel cell will be extend as much as possible.
Another possibility is to design the system in such a way that the system is the most efficient, to achieve a maximum efficiency the fuel cells have to run at a lower rate of approximately 50-60% since the efficiency curve has a very flat profile up to 100% load as can be seen in the efficiency graph appendix E. When designing the hybrid system with as goal reaching the maximum efficiency there are 1,7-2 times as much fuel cells needed to deliver the same amount of power. The efficiency gain is only 3% since it only rises from 42% to 45%, while the expected lifetime of the same amount of energy drop with almost a factor two.
A system would be designed for maximum efficiency to lower the impact on the environment and lower the fuel cost, however in case of this system the efficiency gain is very limited while the system lifespan is reduced significantly. Therefore the gain in efficiency will probably not be able to compensate the environmental impact of the production as well as the purchase costs.
For this reason the hybrid system will be designed with the goal to extend the lifetime of the fuel cells. The reference yacht has already a battery pack of [redacted]kWh installed for peak shaving, to limited the impact of a hybrid system the system will be optimised up to a certain battery size. Therefore the battery system should be limited to a maximum of [redacted] the capacity of the current battery system which comes down to [redacted]kWh.

There are four load scenarios used to get an indication of the needed battery power and the influence of such a system on the life time of the fuel cell. These scenarios are based on hotel load only and cover two different temperatures (35°C and 25°C) for two cases, namely crew only and crew + guests. For these different options the non hybrid fuel cell solutions are calculated first, these results are shown in appendix **??**. This scenario simulation is used as benchmark although it should be kept in mind that this solution as indicated isn't possible in real life since the fuel cells are to slow to follow the energy fluctuations. In practice the small fluctuations should always be covered by at least a small battery pack, or the fuel cells should run constantly at a higher load to cope with these fluctuations. The start-up time of a fuel cell is 30-45 minutes, so a fuel cell should be started up this time it before it is actually needed. These small issues are for now diminished in the non hybrid solution since it will only be used as benchmark to compare the influence on the expected lifetime when a hybrid solution is applied to the fuel cell system. As hybrid solution there are two options simulated, the first one is a relatively conventional solution of peak shaving where the load is spread out over the day so the main power system can run at a constant rate the whole day (appendix **??**). The second hybrid solution is optimised for the lowest possible running hours while the battery capacity is still limited to 800kWh (appendix **??**).

These optimised situations are found by a GRG nonlinear solving method, GRG stands for Generalised Reduced Gradient and is a basic and fast solving method which most likely converges to a local optimum solution. This means that this method probably will not find the optimal solution, but it will give you a solution relatively fast and is locally optimal. Since these results are only used to give a indication of the required degree of hybridisation substantiated by a calculation it will be sufficient for an initial design. Apart from the question if this method will give a good solution, the yacht will probably never encounter the same circumstances twice so the system should be developed to cover a relatively wide range of possible load profile. The objective for the optimisation was set to minimise the total amount of hours per day, including the equivalent life time hours of an on/off cycle, the variables where the number of switched on fuel cells per hour of the day (in total 24 variables). The problem was subjected to three types of constraints: the variables (nr. of fuel cells) are integer, the battery should not be greater than 800kWh and the overall battery load should be greater or equal to 0 kWh (to be sure there is an equal amount of energy generated as has been used). The results are shown in appendix **??**.

When comparing these results it showed that the optimisation for the lifetime of the fuel cell can lead to a reduction in operating hours of 6-20% compared to the fuel cell system without a hybridisation. This difference between the optimised hybrid solution and the non hybrid solution will become bigger when the start-up times are taken into account as well since the system should be started up 30-45 minutes in advance. The hybrid system designed to run on a constant average load, has a bigger spread compared to the optimised solution which can have exactly the same amount of running time or having up to 25% extra running hours. The case where both the average and lifespan optimised hybrid systems come down to the same amount of running hours (35°C crew only, figure **??** and **??**) indicate the importance of a well developed fuel cell management system. The running hours are exactly the same however in this case the average loaded system runs at a lower load which increases the efficiency and has approximately the same amount of the batteries usage.

Such an fuel cell management system must assess and predict the situation maybe even based on the weather forecast to come up with the optimal use of the fuel cells, batteries and fuel. Since this is quite a complicated task which is depending on a lot of different parameters it should be fully automated what makes it probably to difficult for people to make a good interpretation. For the four scenarios used during this section it already showed that an optimised system could extend the lifetime of the fuel cells up to 20-25%.

For the optimised hybrid solution the minimum needed battery capacity varies from 270 kWh to 625 kWh. The current system uses a li-ion battery system, which are allowed to have a depth of discharged (DoD) of 80% for specified life cycles. This comes down to a battery system of at least 780 kWh. Since the goal of this research was to find out what the impact of a fuel cell system will be compared to a reference yacht, it's chosen to keep the battery technology approximately the same as with the reference yacht. Therefore the current battery technology and options for a larger battery system was discussed within Oceanco. After this discussion it became clear that there are two possible options which are either to double the battery space currently installed on the reference yacht, which currently holds a battery pack of 400 kWh at 80%DOD for peak shaving, to get a total system of 800kWh or to use the battery pack of another project. This project used an battery system which has a capacity of 852 kWh resulting in 682 kWh at 80%DOD. Both these battery systems are shown in figure 8.9 and 8.10.

To keep the influence of the changed battery pack on the ship design as small as possible

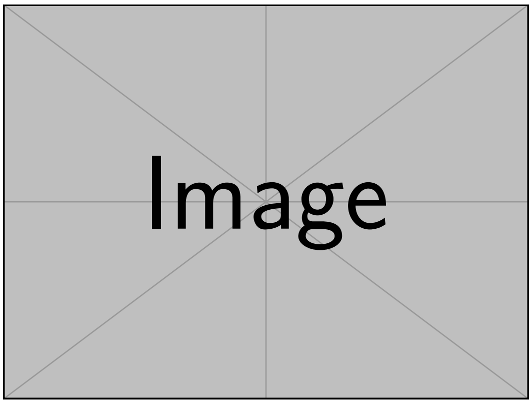


Figure 8.9: Battery system -kWh, - @80%DOD

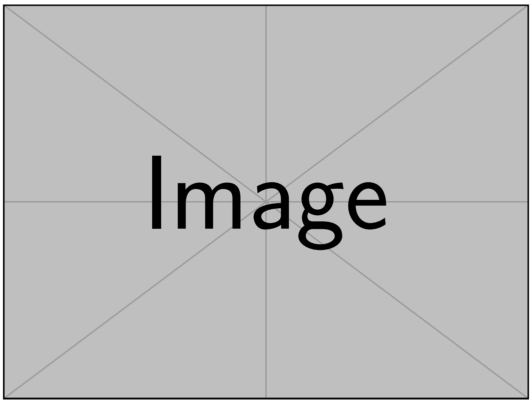


Figure 8.10: Battery system -kWh, - @80%DOD

Source: Provided by Oceanco

it has been decided to use the same battery system as originally was used in the design of the reference yacht. Since the calculations showed that for one of the investigated situations a battery back of at least 625kW is required, and in reality a lot more use cases will occur it will be very likely that there will be a situation which requires more battery capacity.

8.4. Propulsion

Now the yacht will be provided of energy by a completely electric source the ship now requires to be propelled by an electrical drive. When considering an electric propulsion, there are a few different types of solutions possible:

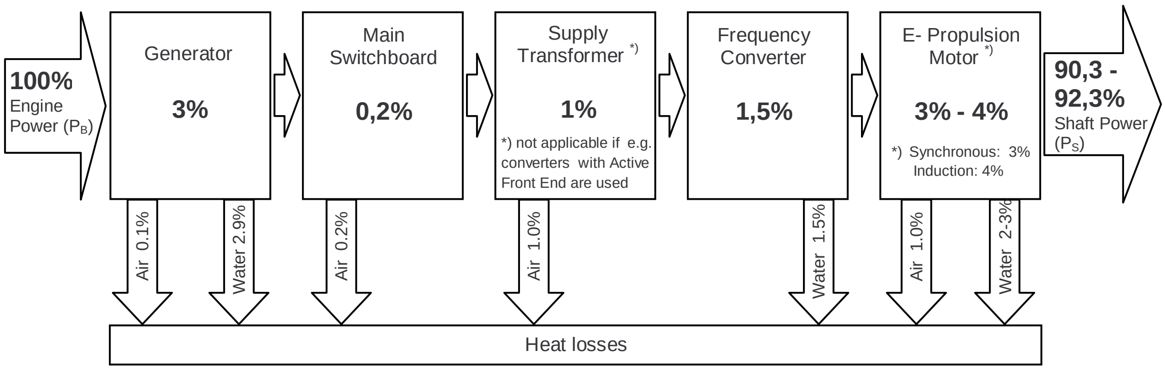
- Keep the drive system complete the same as the reference yacht while changing the main engine for an electric motor and matching gearbox.
- Steerable thrusters, with two different engine/motor arrangement possibilities as mentioned below:
  - L-Drive, e-motor place above the thruster by this type of thruster the height is often the limiting factor.
  - Z-Drive, engine or e-motor is placed in front of the thruster this type of arrangement makes it possible to have a more compact arrangement compared to shaft lines.
- Podded propulsors, this is a steerable thruster where the e-motor is placed under water inside the pod.

The goal of this design study is to investigate the impact of implementing fuel cells on a yacht compared to conventional diesel direct arrangement as used on the reference yacht. Therefore it seems the most fair to compare both designs with the same propulsion type system, to keep the influence of a different type of propulsion system out of the comparison. The diesel direct propulsion is the most efficient in case of using a diesel engine, however this does not have to be the most efficient in case of an electric power source.

To keep the comparison as fair as possible there will be looked at different propulsion systems if this will add advantages which where not specifically the case with the reference yacht.

When using the same propulsion arrangement the only difference will be the type of engine, which will change from a diesel engine to a electrical engine. Thereby the overall efficiency will become lower because of additional electrical losses including the: propulsion motor, transformers and frequency converter. Below in figure 8.11 the efficiencies for a diesel electric power plant by MAN [77] are given, for a fuel cell configuration all losses are the same except from the generator loss.

Which comes down to an increase in needed propulsion power of about 4.7-6.7% compared to a diesel direct shaft line arrangement. Depending on the speed of the e-propulsion motor a gearbox as used in the reference yacht can be removed as well which could save around



Source: MAN, Diesel-electric Propulsion Plants [77]

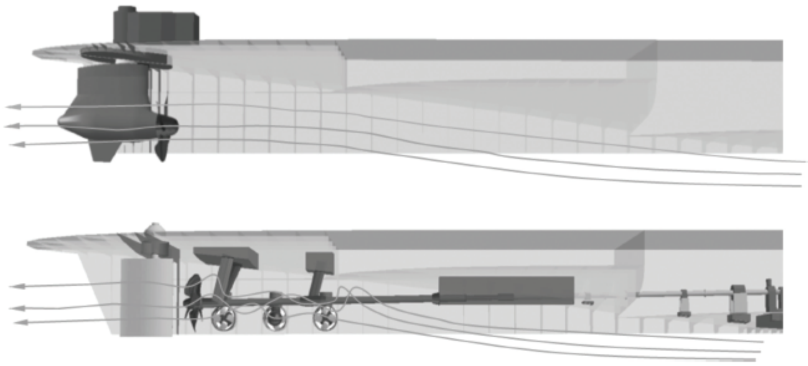
Figure 8.11: Electric loss diesel electric propulsion plant

2% of losses compared to diesel direct.
The other option is to use a steerable thruster in either a L- or Z- drive, this is mainly attractive in special cases where manoeuvrability/ dynamic positioning are important and/or when a compact machinery spaces is needed. However, there are no specific benefits for a electric powered steerable thruster compared to a diesel powered steerable thruster, so for fair comparison reasons this option will not be taken into account.
Lastly, the podded propulsors, mentioned to as POD's in the remainder of this report, will be discussed. This type of propulsion has an electric motor located inside the pod which is directly coupled to the propeller. With an arrangement like this the gearbox and shaft lines are not needed any more, this affects the losses which are reduced by 3% (1% shaft losses and 2% gearbox losses). Comparing this to the conventional option used in the reference yacht, the efficiency will be reduced this same amount bringing it to 1,7-3,7%. On top of the mentioned reduction in losses because there are no shafts and reduction gears any more, there are some other factors which also apply in case of a diesel electric system and should be taken into account to get a complete picture of the benefits. First of all, when using POD's instead of shaft-lines there will be a reduction in resistance because the appendages belonging to the shaft line type of propulsion will be replaced by pods. Secondly pods can be used in a pulling arrangement without the obstruction of appendages what results in a better inflow to the propeller (illustrated in figure 8.12), resulting in less noise and vibration which lead to an improved passenger comfort. Next to this, the hull efficiency could be better as well, however this will depend on the hull of the ship [32]. Finally this system will result in a more flexible machinery space placement and the manoeuvrability as well as the DP capability of this propulsion arrangement will be a lot better when compared to the twin shaft line with rudder used in with the reference yacht.

Now it's known that an arrangement of fuel cells in combination with PODs is guaranteed for at least a saving of 3% compared to the conventional shaft line because there are no longer shaft and reduction gear losses. In case of a fuel cell powered arrangement, POD's will be as well 3% more efficient compared to a diesel electric POD arrangement since there are no generator losses. Next to these efficiency benefits there are some other benefits of POD's which lead to an even more improved efficiency.
Therefore the complete efficiency of a POD arrangement compared to the reference arrangement is investigated, this efficiency depends on the change in propulsion efficiency and resistance. To express this difference the needed power delivered to propeller (P_D) is expressed in the effective power (P_E) which is the needed to power to propel the yacht at a certain speed, as shown in equation 8.2 [60].

$$P_D = \frac{R \cdot V_S}{\eta_O \cdot \eta_H \cdot \eta_R} = \frac{P_E}{\eta_D} \tag{8.2}$$

This expression is used for both types of arrangements: twin screw shaft lines as shown in figure 8.13 with equation 8.3 and two pods as illustrate with figure 8.14 and mentioned in



Source: ABB, Azipod study summary [71]

Figure 8.12: Water flow of a shaft line arrangement compared with POD's

equation 8.4 [32]. As shown in equation 8.14 and 8.3 the propulsion efficiency of the shafts is $\eta_{D_{Shaft}} = 0.607$[32] while the efficiency of the PODs vary a bit depending on the hull efficiency $\eta_{D_{Pod}} = 0.581 - 0.614$[32], this comes down to a difference in propulsion efficiency between -2.6% and +0.7%. Both ABB[71] and J. Grevink[32] claim that shaftlines have 10% added resistance compared to pods because of the additional appendages. When considering the additional benefit of the reduced resistance of the POD arrangement this comes down to a reduced need in power delivered to the propeller which can vary between 5.4 to 10.3%.

Source: Course slides MT44005 Marine Propulsion Systems [32]

Figure 8.13: Twin screw shaft line

$$Twin\ screw/shaft : P_D = \frac{1.0 \cdot P_E}{0.69 \cdot 0.88 \cdot 1.0} = \frac{1.0 \cdot P_E}{0.607} = 1.65P_E \tag{8.3}$$

Source: Course slides MT44005 Marine Propulsion Systems [32]

Figure 8.14: Podded propulsion

$$Podded\ propulsor : P_D = \frac{0.91 \cdot P_E}{0.66 \cdot (0.88 - 0.93) \cdot 1.0} = \frac{0.91 \cdot P_E}{0.581 - 0.614} = 1.48 - 1.56P_E \tag{8.4}$$

Finally, the needed engine power can be calculated by $P_B = P_D/\eta_S$, where η_S is the shaft efficiency which in case of POD can be seen as electrical efficiency as mentioned in figure

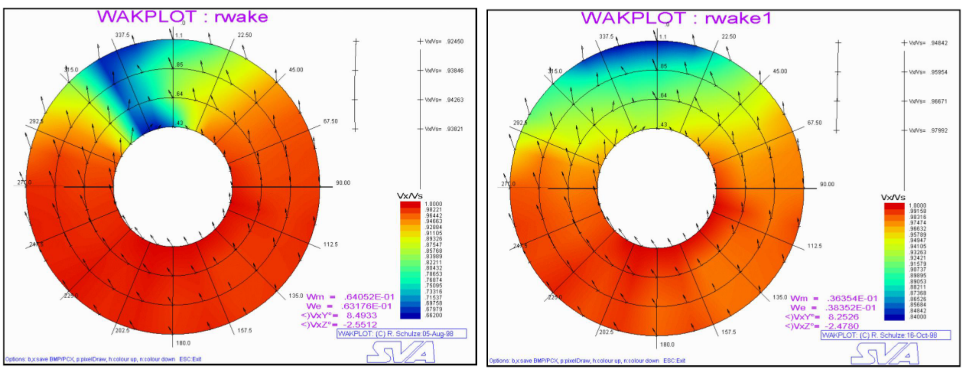
8.11. Again there will be no generator in case of a fuel cell, resulting in an electrical efficiency of 93.3-95.3%. When comparing this to the reference case the shaft efficiency consists of the shaft- and gearbox losses as well as the electrical losses and have a efficiency of 90.3-92.3%, which indicate a reduction of 3% due to the earlier mentioned shaft efficiency.

$$
\begin{aligned}
P_B &= \frac{P_D}{\eta_S} \\
\textit{Twin shaft reference diesel}: P_B &= \frac{1.0P_E}{0.607 \cdot 0.97} = 1.70P_E \\
\textit{Twin screw/shaft electric}: P_B &= \frac{1.65}{0.943} - \frac{1.65}{0.903}P_E = 1.75 - 1.82P_E \\
\textit{Podded propulsor electric}: P_B &= \frac{1.48}{0.953} - \frac{1.56}{0.933}P_E = 1.55 - 1.68P_E
\end{aligned} \tag{8.5}
$$

Compared to the diesel powered reference situation the electric powered twin shaft configuration needs +2.9% to +7.1% extra power (P_B), while the PODs require less additional power for all situations and even save 1.2% to 8.5% compared to the diesel direct shaft line arrangement. This comes down to saving 3.9-14.8% on power when changing from twin shafts to two pods in case of electrical propulsion.

The conclusions of ABB [71] where the same comparison was made for a 200m RoPax slightly differ from the results as shown before, this is because different propulsion efficiencies were used for the two different options. The propulsion efficiency of the POD arrangement used by ABB is 2.2% more efficient than the conventional arrangement compared to a maximum of 0.7% more efficient with the example given before. At the end of the line this comes down to possible reduction in deliver power (P_D) of 12% and 11.2% to 16.4% for the propulsion power (P_B) compared to the shaft lines powered by a diesel engine. This is a slightly higher maximum reduction, however the lower limit of the reduction has increased about 7% which indicates that the system will be even more interesting.

As mentioned before taking away the shaft lines including the corresponding appendages like the struts and mount the POD in a pulling arrangement ensures that the water inflow to the propeller is less disturbed as illustrated in figure 8.15. Figure 8.15 shows the wake field of the conventional twin shaft arrangement on the left and the double pod arrangement on the right. It's visible that the inflow is much more consistent at the right figure and is only disturbed because of the ships boundary. This will make it possible for propeller designers to optimise the propeller and there will be less chance of cavitation or vibrations because of more uniform water inflow to the propeller. These mentioned improvements will increase the comfort on board, which is one of the key points of attention for super yachts.



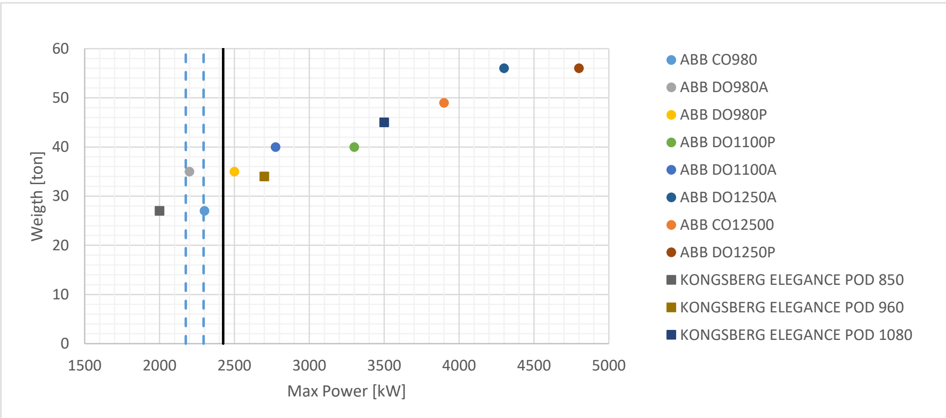
Source: Course slides MT44005 Marine Propulsion Systems [32]

Figure 8.15: Propeller inflow twin shafts (left) vs pods (right)

If PODs will be more energy efficient when using diesel generators is not completely clear however the results weigh more to an increase in efficiency since these vary from an increase

in power of 1.3% up to a decrease in power of 6.6%.
However, when looking to an electric propulsion with a fuel cell as energy source it became clear that it will be a lot more efficient to use a double POD propulsion arrangement instead of shaft lines. Next to the increase in efficiency this type of propulsion has the potential to increase the on-board comfort as well as the available machinery space since there will be less machinery inside the ship. Because of the efficiency gains which are possible when using pods in case of using PODs for an all electric fuel cell powered ship, this type of propulsion will be used for the final design of the yacht.

For choosing a POD the needed propeller thrust P_D is the most important factor, as concluded earlier the needed power delivered to the propeller can be reduced with 5,4-10-3% while being capable to reach the same speed. Originally the yacht needed [redacted]kW of engine power (P_B) to reach a speed of [redacted]kn, by $P_D = P_B * \eta_S$ where $\eta_S = 0.97$ the original [redacted]. [redacted]



Source: ABB [1] and KONGSBERG [47]

Figure 8.16: Comparison of different POD's

[redacted]
To make sure the speed will be reached the right dashed line will be used as minimum needed power. Looking at the possible POD solutions from ABB and KONGSBERG, the [redacted] is the smallest suitable solution which delivers [redacted] at maximum power which gives both PODs a margin of 64kW. In section 7.3 and 3.2.1 it has been concluded that both for the fuels cells as for the methanol storage the current available space is not sufficient to store the needed amount of fuel/fuel cells. For this reason the yacht needs to be enlarged which will increase the weight and wetted surface of the yacht which will probably result in a need for more propulsion power, for this reason the first next possible POD solution (ABB DO980P) will be used in the design of a fuel cell powered yacht.

8.5. Electrical Energy Distribution

Currently all Oceanco yachts are executed with an AC electrical distribution since electricity is mainly used for hotel load and the thrusters. Next to the main AC electrical distribution it's becoming more frequent that battery packs for peak shaving are being installed, for these configurations an separate DC system will be installed next to the main AC grid.

In case of an all electric fuel cell and battery hybrid yacht all energy suppliers deliver a DC power. When considering this it seems logical to provide such a yacht with an main DC power distribution system, since this will involve less power transformations. This section will discuss the advantages and disadvantages of a DC- compared to an AC energy distribution system in case of a fuel cell and battery hybrid system.

A DC power distribution system is nothing new, it already was used in the 1880's with the

SS Columbia which had a DC distribution system for electric lamps [44]. However for a long time the AC system has been in favour of the DC system because the AC transformers where simpler, smaller and more efficient making them more economical than the DC converter. Besides the benefits with respect to the transformers the circuit breakers of an AC system where a lot easier since AC has a zero crossing periodically depending on the frequency which helps with protection during interruption [11]. Due to the major development of: power electronics, energy storage devices and renewable energy sources of the recent year as well as the demand for more efficient ships the DC energy distribution sytem is slowely making a comeback [44, 86].

A DC grid is typically used to improve the fuel efficiency of the diesel generators in case of an electric powered ship. With an AC distribution these gensets have to run at fixed RPM to keep a constant frequency, however with the use of a DC distribution these gensets can run at their optimal RPM to obtain the best specific fuel consumption. As mentioned before both fuel cells and batteries generate DC power already, whereby this biggest benefit with diesel electric propulsion doesn't comply anymore. However, there are additional benefits which need to be considered.
With an AC distribution the speed control of both an induction or a synchronous drive is regulated by a frequency controller. A frequency controller in an AC network first rectifies the AC signal where after it's inverted back to AC, these steps are as follows: AC/DC/AC/Frequency conversion [86].

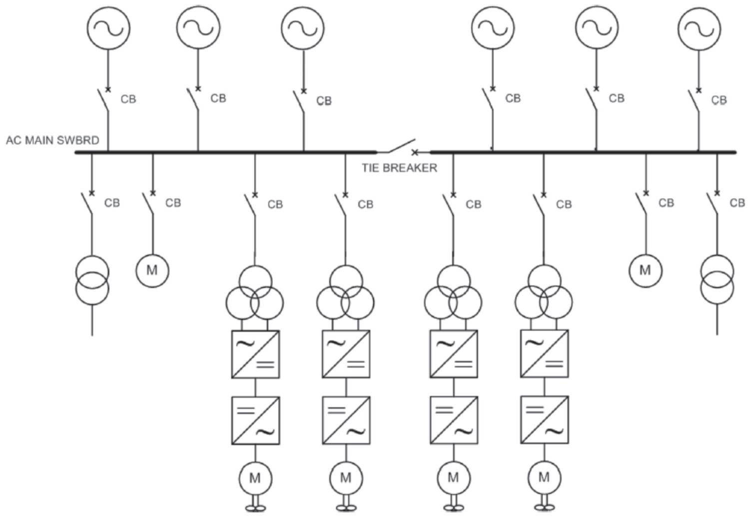
In case of a DC distribution system the first rectifying step (AC/DC) is replaced to the generator in case of a diesel electric system, however when using a DC system in combination with a DC power supply a DC-DC converter is needed instead of the rectifier. When the DC output would be fed into a conventional AC grid the signal should first be inverted where after it will be rectified. This will lead to unnecessary conversion steps and additional loss of efficiency and space while increasing the weight of the system. So simply said a DC grid is just an expansion of the DC hubs which are already used with most well known AC systems like for example the AC motor. In addition to the benefits with respect to the number of conversions and corresponding efficiencies of a DC grid, there is no need for an AC main switchboard and thruster transformers. These omitted systems could lead to considerable savings with respect to weight and space [64]. In case of an all electric ship 80% of the electrical power is for the propulsion [86], looking to the different operation modes of the reference yacht (section 7.1.2) it is even 90% when sailing at max speed.

When considering this, it makes no sense to use an AC distribution when the energy source delivers a DC signal and 80-90% of the consumers are powered by frequency converters which require a rectified input signal. Based on these conclusions it would be most logical to change the distribution system to a DC system.

Figure 8.17 and 8.18 show the difference of the same propulsion configuration executed with an AC or DC distribution shown in a one line diagram.
As seen with the DC distribution system there is no switchboard anymore, the electric DC power is directly supplied to the DC-bus which than distributes it to consumers which are all fed by separate inverters. The hotel load is provided by a specially designed island inverter which will be located close by the AC consumers. So there is no need to install these systems in a dedicated switchboard room anymore because there are no AC switches and relays anymore. With such a approach the energy can by distributed around the yacht by a DC bus, all electrical systems like inverters are distributed over the yacht and installed where they are actually needed.

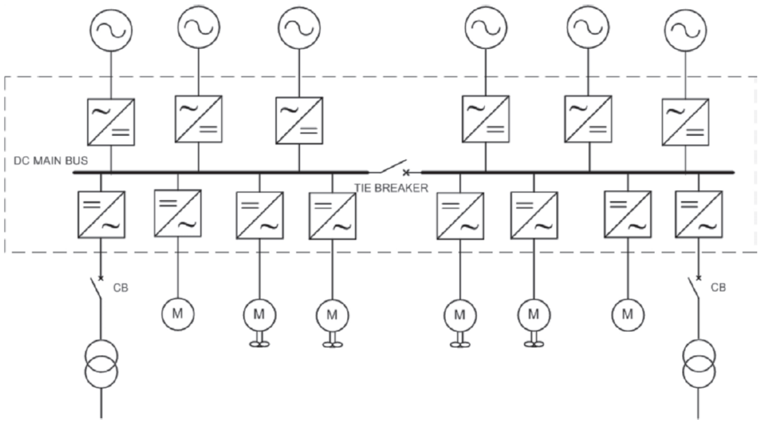
The benefit of such an approach with a fully distributed DC system is the reduction systems in the switchboard room, since these systems are placed locally next to the end consumer. This gives more flexibility in the design of the yacht, in this way the electrical systems are adjusted to the yacht instead of the conventional approach where dedicated electrical spaces where made in the design. An example of such a fully distributed DC system for a fully electric hybrid configuration is shown in figure 8.19.
Other DC related benefits are [86]:

- There are only two conductors needed (a plus and minus pole) versus a three phase AC



Source: Advantages of using a DC power system on board ship [86]

Figure 8.17: AC Distribution configuration (diesel-electric)



Source: Advantages of using a DC power system on board ship [86]

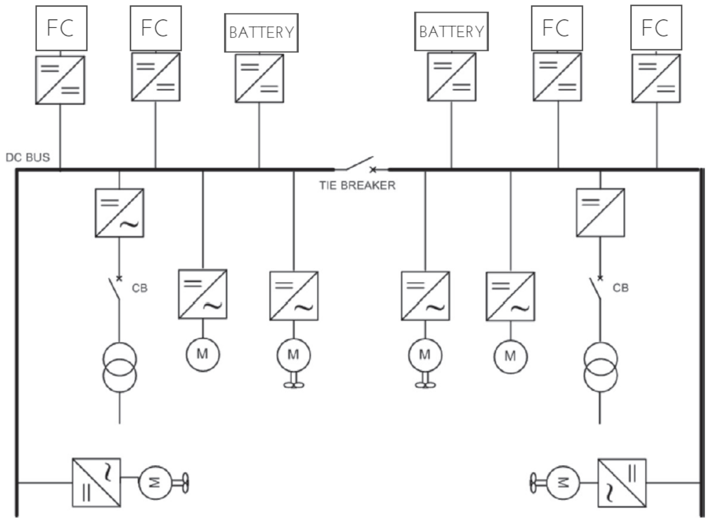
Figure 8.18: DC Distribution configuration (diesel-electric)

system which requires three conductors, this can save weight and volume. However, especially with a fully distributed arrangement, a DC bus needs to be led through the entire ship which are typically bars surrounded by a duct. This type of installation is relatively new but has some advantages, one of the main advantages is improved fire resistance. A study executed by ABB showed that the overall weight savings on the electrical system of a 93m 5000 DWT offshore supply vessel was around 30ton (original 115ton; DC grid 85ton).

- A DC distribution has unlike with an AC distribution no frequency, because of this there is no skin effect in the cables resulting in a lower transmission loss. For the same reason a DC distribution doesn't distribute reactive power which results in lower current and thereby lowers the Joule losses, in addition this could even result in smaller required cables.

- A DC energy distribution ensures easier implementation of energy storage devices since these practically have a DC electrical output, this is one of the main reasons the AC and DC distribution systems were reviewed for a fuel cell powered yacht.

Remarks concerning DC distribution challenges:



Customised image based on following source: Advantages of using a DC power system on board ship [86]

Figure 8.19: DC Distribution fully distributed configuration (fuel cell - battery - hybrid electric)

- Safety aspects of DC electricity have always been the main concern, since the lower losses in the cables any short circuit will have higher currents compared with a same short circuit for an AC power circuit. So any short circuit will effect every system connected to the DC bus. This effect combined with the fact that DC currents don't have zero crossing periods makes it very hard to break a connection, since there is a high chance of forming an electrical arc when opening a breaker. However this problem seems to be solved, ABB claims to have managed to build a protection which works faster (40 ms) than a traditional AC protection circuit (1 s) and is fully compliant with regulations.

Conclusion
Now all new electrical components are known it's possible to draw a new power/propulsion configuration diagram as shown in figure 8.20. This figure can be compared with the original diagram of the reference yacht shown in section 7.1, figure 7.1.

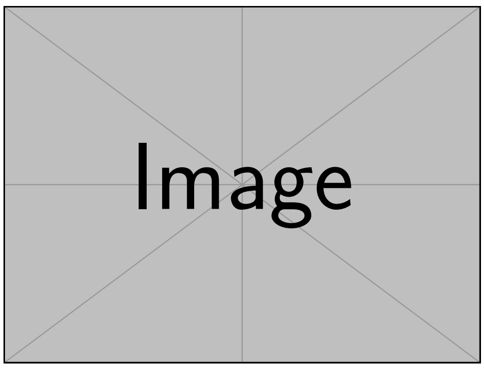


Figure 8.20: New propulsion configuration

III

CONCLUSIONS AND RECOMMENDATIONS

9 Conclusion

The most important findings to answer the objective of this study will be discussed using the research questions. These questions will all be answered and have been formed in such a way that the objective is answered after this as well.

Objective: The objective of this project is to investigate the impact on both the design and operation of a superyacht using fuel cells for energy supply on board.

Research questions:
1. What types of fuel cells are currently available and to what extent are these fuel cells used in the maritime sector?

Below the different types of fuel cells are shown divided by the temperature categories:

catergory	Fuel Cell	Description
Low temp.	LT-PEMFC:	Low Temperature Polymer Electrolyte Membrane Fuel Cell
	DMFC:	Direct Methanol Fuel Cell
	AFC:	Alkaline Fuel Cell
Med temp.	HT-PEMFC:	High Temperature Polymer Electrolyte Membrane Fuel Cell
	PAFC:	Phosphoric Acid Fuel Cell
High temp.	MCFC:	Molten Carbonate Fuel Cell
	SOFC:	Solid Oxide Fuel Cell

In the marine sector there are three of these seven types of fuel cells used for either demonstrator cases or even in some cases for actual fuel cell powered ships. The PEMFC is the most used type of fuel cell this is the same case for the maritime sector, numerous projects have been executed for both LT-PEMFC and HT-PEMFC. Some of these projects are ships that are operational using these fuel cells as energy source. Further both the SOFC and MCFC are used in the marine sector mainly for test or demonstrator cases, however this technology has never been used as primary energy source in a maritime environment.
The different fuel cell types were compared on seven different characteristics: power density, power levels, electric efficiency, fuel sensitivity, start-up time, waste heat recovery and maturity. Based on these characteristics, it appeared that for each temperature category one type of fuel cell clearly stood out of the rest. It was concluded that the best possible option per category are the: LT-PEMFC, HT-PEMFC and SOFC. Therefore these three types of fuel cells are seen as most suitable options for the application in a maritime environment like a superyacht.

2. Which options are available for storage of H_2 (including reformer solutions) on board a ship? (incl. power to weight/volume ratio's)

There are numerous fuel solutions possible, these options are categorised in three different group as shown below:

Group	Fuel Type
Physical based hydrogen storage	Liquid hydrogen and Compressed hydrogen
Fuel based hydrogen storage	Methanol, Ethanol, Ammonia, Liquid DME, LNG and Diesel
Material based hydrogen storage	Formic Acid, Liquid Organic Hydrogen Carrier, Sodium Borohydride, Metal Hydrides and Metal-Organic Frameworks

Not all fuels are directly usable in all types of fuel cells. Depending on the the type of fuel and fuel cell it's most often needed to process the fuel to a certain extend. Typically, all fuel based hydrogen solutions need to be reformed to some extend, this is executed internally for some high temperature fuel cells or otherwise an external fuel processor is needed. Next to fuel based hydrogen storage formic acid, LOHC and sodium borohydride all need a reforming process as well. The other fuel storage solutions can be used directly in most types of fuel cells.

The volumetric and gravimetric densities of all these fuels are compared in two different bar charts (figure 3.4 and 3.5) which show a comparison of all fuels with and without the required storage tank. From this comparison, it can be concluded that depending on the type of fuel the storage tank could have a big influence on the overall density of the fuel storage.

It must be mentioned that for a well-founded choice the decision can be made based on the fuel type or fuel cell only. The fuel (including any reformer) and fuel cell must be seen as one system which should be selected/optimised for every new design. Therefore another comparison is made which combines the density of the fuel, fuel cell and reformer in one (ragone) chart as explained in chapter 4. This graph shows the density of a fuel and fuel cell combination for different time scales in one graph, with this graph it's possible to find the most dense solution for any specific case based on the time it will be used. These results have been used to answer another research question to find the most promising type of fuel cell for a specific super yacht.

3. What are the main design requirements (technical, operational, regulations) with respect to the propulsion power and range of a yacht?

The technical and operational requirements of the yacht should be kept the same for the owner, therefore the range and required speed of the yacht need to be the same as for the reference yacht. The original requirements of the reference yacht mentions that the yacht will have a range of at least [redacted] nm with a cruising speed of [redacted] kn, next to this she should be capable of reaching a top speed of at least [redacted] kn.

Since a different type of energy converter and fuel type will be used, regulations according to these different systems on board will change as well. The most important requirement from regulations for fuel cells is that these need to be placed in a separate liquid and gas tight space which preferably is only accessible from open deck, if the fuel cell space is accessible from the inside an airlock should be placed between the fuel cell space and adjacent spaces. These fuel cell spaces should be well ventilated. The arrangement for the fuel storage and supply have to comply with the IGF code in case of low flash point fuels in most of the cases. The IGF code currently has only established rules for LNG but will probably add regulations for methyl and ethyl alcohols in 2021. Fuels which have to comply with the rules of the IGF code are typically required to have double walled or ducted fuel pipes and special arrangements for purging the fuel lines and storage tanks have to be made. Additionally to MGO fuel there are stricter requirements regarding location and ventilation of the fuel tanks.

4. What is the most promising combination of fuel and fuel cell type for a integrated solution on board of a superyacht. What are the main components needed for a fuel cell powered yacht compared to a existing MGO-based solution for propulsion and energy supply?

For the reference yacht used during this research, the methanol powered HT-PEMFC turned out to be the most promising solution at the moment. The selection of this type of fuel cell was based on different criteria (weight density, volume density, type of fuel storage, maturity, safety and emissions) and compared to all different solutions which where taken into consideration during this study.

The biggest change from changing a MGO-based yacht to methanol powered fuel cell yacht obviously is the change of propulsion train as well as the energy storage. Both these two factors have the biggest impact on the design of the yacht. A fuel cell system does not only consist of the fuel cell itself but also requires: ventilation fans, exhaust fans, water cooling, a water recovery system, fuel mixing system and fuel pumps. Due to the characteristics of the fuel cells it's needed to install a larger battery system to handle peak loads and variation in the fuel cell load as well as for increasing the lifespan of the fuel cells. Apart from the fuel cell related changes, regulations require arrangements for a fuel venting and purging system which is not required with a conventional diesel arrangement.

Although it's not essential to do, it was decided to change the propulsion arrangement from a twin-shaftline to a twin POD arrangement. Besides this the energy distribution system was changed from a AC system to a DC distribution with a main DC bus which is locally inverted to AC where this is required. These two changes were more efficient and safe space compared to the original arrangement in case of an all electric fuel cell powered yacht.

5. What is the impact of a fuel cell powered solution on the design of a superyacht?

The biggest impact on the design of such a fuel cell powered yacht while keeping the requirements of the superyacht the same is the fact that both the fuel storage and fuel cells take up more space than was initially available. To overcome this problem the yacht had to be lengthened by [redacted] frames which is 10.2m.

With all system changes taken into account it appeared that the full loaded yacht only became 244.95 ton heavier with a lower centre of gravity. This relatively limited increased weight combined with the hull extension resulted in a new draft which is 28.2cm less than the reference yacht. This combination led to a new ship design which has approximately the same resistance, and will presumably have an improved stability because of the lowered centre of gravity.

6. What is the operational impact of using fuel cells on a yacht?

Fuel cells have a limited lifespan this is therefore one of the most important impacts on the operation of a yacht using fuel cells. The crew of such a yacht always needs to keep in mind that the fuel cells are not be used unnecessarily to expand the lifetime of the fuel cells as much as possible. Ways to expand the lifespan of the fuel cell are: optimal usage of the battery system to reduce the number of on-off cycles of the fuel cell, reduce the speed and preferably use a maximum top speed 16 kn instead of [redacted] kn and increase the time in port so shore power can be used instead. A calculation estimated that it should be possible to increase the lifespan by 95% without serious impact in the way the yacht is used for the owner.

Positive impact of this change is that the overall efficiency of the yacht has increased and the emissions except of CO_2 have been have been reduce to zero emission, the CO_2 emissions have been reduced by 14-20%. When using green methanol, it is even possible to sail completely CO_2 neutral. Other advantages are: reduction of noise and vibrations, reduced maintenance and an increased energy security because of the modular design.

The challenge of such a design change would be the reason that the technology is relatively new and not completely developed. This can be a challenge for crew since they will have to learn how to operate such a yacht, and it can lead to teething problems because of the limited operation experience of the cells. The fuel itself can also lead to some challenges since methanol is not yet available as marine fuel.

10

Recommendations

10.1. Follow technical developments

The fuel cell technological development should be followed closely and used to constantly update the decision making tool to keep this relevant and up to date. A lot of mentioned fuel cell or fuel storage solutions mentioned in this report are not net fully developed or even didn't left the laboratory setting. Since these developments will continue it is important keep up to date the status of the technology, any development or break through could make significant changes in the conclusions as drawn during this study.

For example the SOFC or Sodium Borohydride technology showed some interesting features for application on a superyacht, however the biggest drawback at the moment was the technical readiness of these solution. However if these technology will be further developed this could become a viable or even a better solution than the HT-PEMFC which was seen as the best option for this application at the moment.

10.2. Steps to build up experience

At the moment, it can be noticed that a lot of companies are following the developments in the fuel cell technology to check if the technology is ready to implement on ships. However by this approach the technical development is very slow because there is no market for fuel cells in the maritime environment. Most of the developments are due to large investments of the automotive industry.

For this reason, it would be good if an actual project would be initiated because the best way to speed up the technological development is by putting them into use, making it also interesting for companies to invest in development.

Apart from this statement it would be good for Oceanco to build up their knowledge around fuel cells, for example by building a demonstrator or test setup, which could be onshore, to become more familiar with this technology. This would increase the confidence to sell a yacht with fuel cell technology on board if this would be requested by a customer.

Next to practical experience it would be good for Oceanco to develop a design including fuel cells which would be more applicable for an early adoption this technology. It became clear that implementing fuel cell even on large scale is technological feasible, but it has quite a lot of impact on the yacht. Such a design could for example use the same methanol fuel cells for auxiliaries only, in this way the complicated fuel cell spaces stay relatively compact and the investment cost will be a lot smaller. A study like this should focus on topics that were just briefly or haven't even been discussed during this research like the fuel cell spaces and venting arrangement as well as cost involved by such a fuel cell installation.

An interesting option to consider when thinking about the application of methanol HT-PEMFC's is the combination of a methanol combustion engine for main propulsion combined with fuel cell auxiliaries. This offers a more environmentally friendly solution than diesel while having less impact on the design compared to fuel cells. Such an arrangement will allow a single type of fuel, making the tank plan less complex and probably smaller compared to a dual fuel plan.

Another idea is providing a lease construction for the fuel cell, hereby clients won't have to worry about the uncertainties of fuel cells like: lifetime, expensive price, etc. In this way, the fuel cell technology could become more interesting and perhaps earlier applicable, and could even be a unique selling point to environmentally clients. Such a construction would probably be executed in collaboration with a fuel cell manufacturer.

10.3. Alternative Design

10.3.1. Changing the operational requirements

The functional requirements of the yacht are kept the same to have a clear overview of the impact. However, when designing a 'green yacht' speed can make a big difference on the actual fuel consumption and thereby the environmental impact. To realise this there is looked at two different options: the reduction of maximum power (which reduces the amount of fuel cells) and optimising the cruising speed for minimum fuel consumption (hereby the amount of fuel consumption can be reduced). These two principles are combined and used to give an indication what the impact would be if speed would no longer be a strict requirement.

Impact on Fuel Cell Systems and Fuel Storage:
As seen with the generic operational profile (section **??**, table **??**) the maximum speed is only used 1,5% of time while sailing. A yacht typically only sails 10% of the time which means that the maximum speed is only used for 0.15% of the year. However the complete propulsion arrangement is designed in such a way that the design speed [redacted] can be met, this has a big influence on the required installed power and thereby the needed number of fuel cell systems.

When considering this, it would make sense to optimise the power for cruising speed since the yachts will be sailed at cruising speed for 66.5% of the time at sea. The required propulsion power when sailing at 14 kn is only [redacted] kW which is less than 50% of the power required at maximum speed. In this situation, there are only 14 fuel cells required, calculated for sailing at 14 kn with 100% fuel cell load (225kW). When comparing this to the design arrangement made while retaining this maximum speed, [redacted] at 130% fuel cell load (300kW), it required 19 fuel cells. With these 14 fuel cells the yacht can still reach a speed of approximately 16kn when using 130% load of the fuel cells.

During transit, the speed could be optimised for fuel consumption by lowering the speed. Hereby, the propulsion power will decrease while keeping a constant hotel load during a longer transit period, this will give an optimum point at 7 kn where the required energy is at a minimum (figure 10.1).

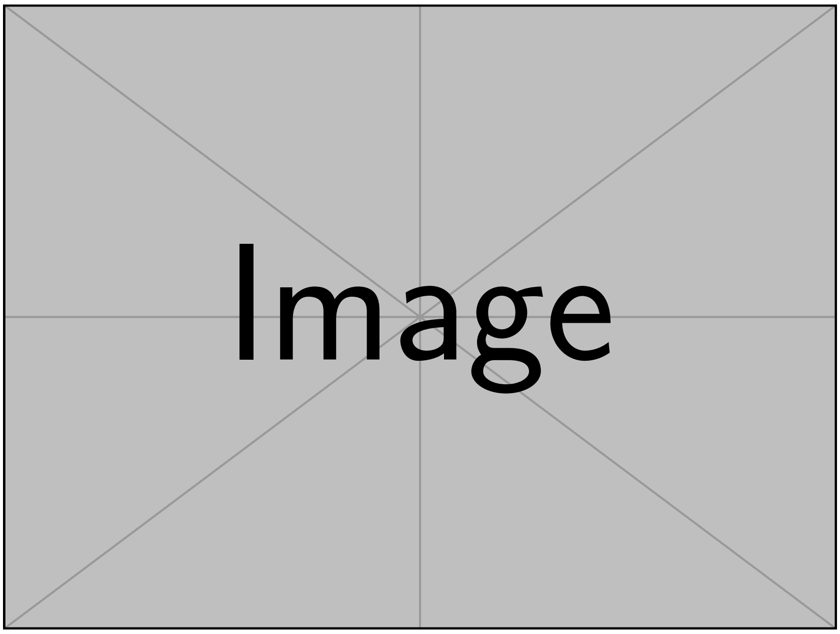


Table 10.1: Comparison energy requirements for range of - nm at different speed

Dropping the speed from 14kn to 7kn means that the transit time will be doubled, looking at the figure above it shows that the reduction is getting smaller with every knot the speed is lowered. For this reason, 10kn seems a good balance between energy reduction and transit time, therefore this speed will be used to calculate the needed energy instead of the 14kn used in the other design. Hereby the required fuel can be reduced from 546.8 to 372.8 m^3 which now will fit within the original available tank space without the need of enlarging the yacht.

Impact on Design:
These changes already showed that the fuel will fit within the original available space, probably the fuel cells will fit in the original yacht as well (it maybe requires some small changes to the yacht arrangement). After calculating the new weight changes while keeping the dimensions of the ship the same it turns out that the yacht became lighter for both the light ship and the deadweight of the yacht.

Because the yacht became lighter than the original the draft decreases with 6.5 cm, the resistance for the alternative yacht design including these changes was calculated again with PIAS. This showed that the ship now has a lower resistance as shown in table 10.3.

[redacted]

Table 10.2: Weight changes alternative design

[redacted]

Table 10.3: Resistance calculations PIAS for the alternative design compared to the previous design and reference yacht resistance calculations by MARIN

Conclusion:
By only changing the requirements for the speed of the yacht it showed that the impact on the design of the yacht could already be reduced enormously while at the same time having a yacht with less impact on the environment. This shows that it's important to always critically look at the design requirement of a yacht, particularly if the target is to design a yacht with a lower impact on the environment.

10.3.2. Zero emission

Because of the scope of this project, there has been searched for a solution that would be suitable for a fully fuel cell powered yacht. During this study the choice of fuel cell was based on the decision tool which was discussed in the first part of this report. In consultation with Oceanco, it was decided that the maturity was one of the most important factors, since it was most interesting for Oceanco to investigate a solutions which has a prospect of becoming commercially available within a reasonable time. For this reason the maturity weight factor was set relatively high, next to the volumetric density and emissions which were the second most important factors. With these decision factors, the methanol powered HT-PEMFC seemed to be the most suitable solution at the moment.

This HT-PEMFC has some clear benefits compared to diesel engines regarding for example comfort and emissions. The CO_2 emissions with this solutions will be approximately 12% lower than a diesel engine when both are run on nominal power, with the possibility to be CO_2 neutral when using green methanol. For various reasons it could be that one would like to have a completely zero emission yacht, for this reason these options will be discussed briefly.

From the comparison of the top 10 results shown in table 7.5 (section 7.2) it became clear that the zero emission solutions are substantially bigger and heavier than the HT-PEMFC solution. The two zero emission solutions shown in the top 10 are LOHC or Metalhydride in combination with the LT-PEMFC. For such a fully fuel cell powered yacht with LOCH the fuel cell system becomes 2.9x heavier and 2x larger compared to the HT-PEMFC MFCU, when using metalhydride the total system will become 13.1x heavier and 1.7x larger. For the new made design (using HT-PEMFC's) it's already known that this solution has a serious impact on the size of the yacht. When one of these two zero emission options would be used, the impact will even be large compared to the methanol HT-PEM solution which will result in a design which will probably not be practically/economically feasible.

For this reason it would be more interesting to look at the possibility to power the hotel load by a zero emissions fuel cell solution. Since yachts only sail approximately 16% of time superyachts are mostly used in auxiliary mode. By swapping the diesel auxiliaries for a zero emission fuel cell solution, a yacht can operate emission free for the majority of the time while the impact on the size of the yacht will be minimised.

To find the best zero emission solution the decision making tool is used again but this time filtered on completely emission free solutions[19]. The filtered options now only consist of one fuel cell type (the LT-PEMFC) combined with different types of fuels, namely: LOHC, Metalhydride, SodiumBorohydride, Compressed hydrogen and Liquid hydrogen.

These filtered options are ranked using exactly the same weight factors but this time without the decision criteria of emissions (because only zero emission solutions are compared) and a time span of two weeks (336 hours). The results are shown in Appendix G (figure G.1). The same comparison has been made but this time without the influence of the maturity of the fuel cell or fuel solution, hereby the technical readiness level will not influence the ranking. The results of the zero emission solution without the TRL influence is shown in Appendix G as well (figure G.2). When comparing these two results, it shows approximately the same ranking except for Sodiom Borohydride which has clearly the lowest score when maturity is included. However when the TRL levels are being disregarded this Sodium Borohydride ends

[19] Hereby is only mentioned to the local emission of the yacht as done during the rest of the report. Since CO_2 neutral options have local emissions these options are filtered out as well.

up as the best option in the comparison.

Finally all mentioned zero emission solutions are compared on their weight and volume, this is done for a hotel load of 670 kW which should be maintained for 336 hour (2 weeks). These results are shown in Appendix G (figure G.3). From these calculations, it becomes clear that a zero emission solution will a have a serious bigger impact on the yacht compared to the HT-PEMFC. All solutions except of the Sodium Borohydride are at least two times bigger and heavier, with an outlier to a solution which is 15.4x as heavy and 6.4x larger. The Sodium Borohydride solution seems again very promising as it will probably be smaller compared to the methanol powered HT-PEMFC. However the spent fuel will in all cases be substantially heavier. The downside is that this technology is not yet ready to be applied, since there are still a number of issues that need to be further developed (like for example the reactor which regulates the release of hydrogen).

Concluding when aiming for a zero emission solution there should now be looked at LOHC, Hydrogen or Metal hydrates because these are the solutions which will be technical ready to use. One of these solutions should be selected depending on the preference on weight and volume for the specific solution where it will be used. The weight and volume of these currently available solutions (according to Appendix G, figure G.3) are summarised and compared to a methanol HT-PEMFC and a diesel engine in table 10.4.

			vs. Diesel		***vs. Methanol***	
	Weigth [tons]	**Size [m^3]**	**Weigth**	**Size**	**Weight**	**Size**
Diesel, Combustion engine	60	79	1x	1x	0.5x	0.4x
Methanol, HT-PEMFC	118	196	2x	2.5x	1x	1x
LH2, LT-PEMFC	191	357	3.2x	4.5x	1.6x	1.8x
LOHC, LT-PEMFC	429	461	7.2x	6x	3.6x	2.4x
Metalhydride, LT-PEMFC	1816	1249	30.8x	16x	15.4x	6.4x

Table 10.4: Most promising currently available zero emission solutions

From this table it can be concluded that the impact of a zero emission solution will be substantially larger compared to both a diesel engine and a HT-PEMFC, even when the fuel cells will be used for hotel load only. As it looks now Sodium Borohydride will probably be the best solution for zero emission applications when this technology will become commercially available. The weight and size of the spent fuel will be the bottle neck when designing such a solution since it will be larger and heavier than the original fuel.

Until more suitable zero emission solutions become available, such as for example sodium borohydride, an emission neutral solution like a HT-PEMFC (or maybe SOFC in the future) powered by green methanol will be the most promising solution. This will be a good transition solution when for example CO_2 emissions from factories will be used to produce methanol in combination with renewable hydrogen as long as factories are not emission (CO_2) free. No additional emissions will be generated by the use of the yacht itself, since the CO2 that has already been emitted by the factory released delayed. When the technology of capturing carbon from the air will be further developed, this could be used to produce methanol without any burden to the environment. As already indicated before and briefly repeated by these statements, it is very important to take the entire process (from fuel production to usage of the fuel) into account to get a clear picture of the actual influence on the environment. A (local) zero emission hydrogen powered fuel cell, where the hydrogen is made from fossil fuels will be more polluting than burning the fossil fuel directly in a combustion engine.

If it is considered very important not to emit any emissions locally for a specific design, this would be possible already, however the influence on the design will be much larger. To come up with a feasible design it will probably not be possible to use the same design requirements, by adjusting the technical requirements of the vessel (for examples by reducing the required power or available operating time) current available solution would probably be more realistic, however hereby the impact on the operation of the yacht will become larger.

Bibliography

[1] ABB. Azipod® propulsors for open water, n.d. URL `https://new.abb.com/marine/systems-and-solutions/azipod`. Last accessed 1 August 2019.

[2] A. Afif, N. Radenahmad, Q. Cheok, S. Shams, J.H. Kim, and A.K. Azad. Ammonia-fed fuel-cells:acomprehensivereview. *Renewable and Sustainable Energy Reviews*, 2016(60), 2016.

[3] Siemens AG. Sinavy pem fuel cell, n.d. URL `https://www.industry.siemens.com/verticals/global/de/marine/marineschiffe/energieverteilung/Documents/sinavy-pem-fuel-cell-en.pdf`. Last accessed 22 January 2019.

[4] M. Altmann, M. Weinberger, and W. Weindorf. Life cycle analysis results of fuel cell ships recommendations for improving cost effectiveness and reducing environmental impacts. Technical report, L-B-Systemtechnik GmbH and MTU Friedrichshafen GmbH, 2004.

[5] Serenergy A/S. E-mail and phone call conversation with s. kildedal, 2019.

[6] S. Barrett. Lloyd's register teams up on marine fuel cell tech, lohc storage. *Fuel Cells Bulletin*, 2018(11):5–6, 2018.

[7] S. Barrett. Abb, sintef testing viability of fuel cells for ship propulsion. *Fuel Cells Bulletin*, 2018 (12), 2018.

[8] S. Barrett. Fuel cell bulletin issue 7. *Fuel Cells Bulletin*, 2018(7), 2018.

[9] S. Barrett. Fuel cell bulletin issue 8. *Fuel Cells Bulletin*, 2018(8):7, 2018.

[10] S. Barrett. Fuel cell bulletin issue 9. *Fuel Cells Bulletin*, 2018(9):4, 2018.

[11] M. Belkhayat. Ship electrification: dc versus ac and the rise of digital power. *IEEE Electrification Magazine*, 2017(17):83–86, 2017.

[12] A. Boudghene Stambouli and E. Traversa. Fuel cells, an alternative to standard sources of energy. *Renewable and Sustainable Energy Reviews*, 6:297–306, 2002.

[13] B. Boundy, S.W. Diegel, L. Wright, and S.C. Davis. Biomass energy data book, appendix a: Lower and higher heating values of gas, liquid and solid fuels. Technical report, U.S. Department of energy, 2011.

[14] N. Brandon and P. Boldrin. *Solid Oxide Fuel Cell Lifetime and Reliability*. Elsevier Ltd., first edition edition, 2017.

[15] Q. Cai, D.J.L. Brett, D. Browning, and N.P. Brandon. A sizing-design methodology for hybrid fuel cell power system and its application to an unmanned underwater vehicle. *Journal of Power Sources*, 2010(195):6559–6569, 2010.

[16] R. Carriveau and D. Ting. *Methane and hydrogen for energy storage, Chapter 1 Hydrogen storage and compression*. The Institution of Engineering and Technology, London, 2016.

[17] D. Carter and W. Jonathan. The fuel cell industry review 2013. Technical report, FuelCellToday, 2013.

[18] M. Cimenti and J.M. Hill. Direct utilization of liquid fuels in sofc for portable applications: Challenges for the selection of alternative anodes. *energies*, 2009(2):377–410, 2009.

[19] International Maritime Organization. Maritime Safety Committee. *SOLAS : International Convention for the Safety of Life at Sea, 1974 : 1996 amendments, effective July 1998*. International Maritime Organization, 1998.

[20] Sub committee on carriage of cargoes and containers. Ccc 5, agenda items 3 and 8. Technical report, IMO, 2018.

[21] J.J. de Troya, C. Álvarez, C. Fernández-Garrido, and L Carral. Analysing the possibilities of using fuel cells in ships. *International Journal of Hydrogen Energy*, 41(4):2853–2866, 2016.

[22] DNV. Dnv alternative fuels insight, n.d. URL https://afi.dnvgl.com/. Last accessed 1 July 2019.

[23] DNV-GL. Part 6 additional class notations chapter 2 propulsion, power generation and auxiliary systems. Technical report, DNV-GL, 2018.

[24] E4Ships. E4ships, n.d. URL http://www.e4ships.de. Last accessed 4 February 2019.

[25] Inc. EG&G Technical Services. *Fuel Cell Handbook*. National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161, seventh edition edition, 2014.

[26] Bloom Energy. Energy server 5, es5-ya8aan, n.d. URL https://www.bloomenergy.com/sites/default/files/es5-300kw-datasheet-2019.pdf. Last accessed 6 February 2019.

[27] MAN energy solutions. Hfo, n.d. URL https://powerplants.man-es.com/fuels/hfo. Last accessed 20 March 2019.

[28] FuelCellToday. Technologies, n.d. URL http://www.fuelcelltoday.com/technologies. Last accessed 30 January 2019.

[29] GENERON. Marine nitrogen generator, n.a. URL https://www.generon.com/product_type/nitrogen-generator-marine-offshore/. Last accessed 7 August 2019.

[30] WS Reformer GmbH. Flox®reformer compact, fpm-c10, n.d. URL http://www.wsreformer.de/index.dhtml/325cc98f6b35b645921q/-/enEN/-/CS/-/Prod/reformerPEM#. Last accessed 2 April 2019.

[31] A. Godula-Jopek, W. Jehle, and J. Wellnitz. *Hydrogen Storage Technologies: New Materials, Transport, and Infrastructure*. Wileyy-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2012.

[32] J. Grevink. Marine propulsion systems mt44005, 2018. URL https://brightspace.tudelft.nl/d2l/le/content/66997/viewContent/1043228/View. Last accessed 29 July 2019.

[33] H2Tools. Basic hydrogen properties, n.d. URL https://h2tools.org/hyarc/hydrogen-data/basic-hydrogen-properties. Last accessed 25 March 2019.

[34] J. Han, J.F. Charpentier, and Tang T. State of the art of fuel cells for ship applications. Technical report, French Naval Academy Research Institute, 2015.

[35] D. Hart, F. Lehner, R. Rose, J. Lewis, and M. Klippenstein. The fuel cell industry review 2017. Technical report, E4tech, 2017.

[36] A.M. Helmenstine. What is nfpa 704 or the fire diamond?, 2019. URL https://www.thoughtco.com/what-is-nfpa-704-or-the-fire-diamond-609000. Last accessed 24 March 2019.

[37] J. Hietala, A. Vuori, P. Johnsson, I. Pollari, W. Reutemann, and H. Kieczka. Formic acid. Technical report, Ullmann's Encyclopedia of Industrial Chemistry, 2016.

[38] IMO. Sub-committee on carriage of cargoes and containers (ccc), 2015-2018. URL http://www.imo.org/en/MediaCentre/MeetingSummaries/CCC/Pages/Default.aspx. Last accessed 1 April 2019.

[39] IMO. Prevention of air pollution from ships, 2018. URL http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx. Last accessed 8 January 2019.

[40] IMO. Energy efficiency measures, 2018. URL http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx. Last accessed 8 January 2019.

[41] IMO. Un body adopts climate change strategy for shipping, 2018. URL http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx. Last accessed 8 January 2019.

[42] Methanol Institute. Dme: An emerging global fuel, n.d. URL http://www.methanol.org/wp-content/uploads/2016/06/DME-An-Emerging-Global-Guel-FS.pdf. Last accessed 24 April 2019.

[43] A. Iulianellia, P. Ribeirinha, A. Mendes, and A. Basile. Methanol steam reforming for hydrogen generation via conventional and membrane reactors: A review. *Renewable and Sustainable Energy Reviews*, 29(29):355–368, 2014.

[44] Z. Jin, G. Sulligoi, R. Cuzner, L. Meng, J.C.V. Quintero, and J.M. Guerrero. Next-generation shipboard dc power system. *IEEE Electrification Magazine*, 4(2):45–57, 2016.

[45] VKR Kasimalla, NS G, and V. Velisala. A review on energy allocation of fuel cell/battery/ultracapacitor for hybrid electric vehicles. *Journal of Energy Research*, 42(14):4263–4283, 2018.

[46] M. Klingner. Fuel cell power trains and clustering in heavy-duty transports. Technical report, Fraunhofer Institute for Transportation and Infrastructure Systems, 2009.

[47] Kongsberg. Elegance pod system, n.d. URL https://www.kongsberg.com/maritime/products/propulsors-and-propulsion-systems/thrusters/podded-azimuth-propulsors/elegance-pod-system/. Last accessed 1 August 2019.

[48] S. Krummricha, B. Tuinstra, G. Kraaij, J. Roes, and H. Olgun. Diesel fuel processing for fuel cells —desire. *Fuel Cells Bulletin*, 2006(160), 2006.

[49] M. Launes. Norwegian parliament adopts zero-emission regulations in the fjords, 2018. URL https://maritimecleantech.no/2018/05/03/norwegian-parliament-adopts-zero-emission-regulations-fjords/. Last accessed 8 January 2019.

[50] Z. Liu. *Fuel Cell Performance*. Nova Science Publishers, Inc., 2012.

[51] A. Lundgren and A. Wachsmann. The potential of methanol as a competitive marine fuel. Technical report, Chalmer, 2011.

[52] MABANAFT. Net calorific value & gross calorific value, 2015. URL https://www.mabanaft.com/en/news-info/glossary/details/term/calorific-value.html. Last accessed 20 March 2019.

[53] Golden Gate Zero Emission Marine. Projects: Golden gate zero emission marine, n.d.. URL https://ggzeromarine.com/projects/. Last accessed 5 February 2018.

[54] Golden Gate Zero Emission Marine. Water go round project, n.d.. URL https://watergoround.com/. Last accessed 1 February 2019.

[55] S.J. McPhail, L. Leto, and C. Boigues-Muñoz. The yellow pages of sofc technology. Technical report, IEA Energy Technology Network, 2012-2013.

[56] E. Medina, G. Wellon, and F. Evegren. Methanol safe handeling manual. Technical report, Methanol institute, 4th edition.

[57] S. C. Misra. *Design Principles of Ships and Marine Structures*. CRC Press, 2015.

[58] N/A. Safety data sheet, formic acid. Technical report, Thermo Fisher Scientific, 2009.

[59] N/A. Dibenzyltoluene, dibenzyltoluene. Technical report, Arkema innovative chemistry, 2010.

[60] N/A. Basic principles of ship propulsion. Technical report, MAN Diesel & Turbo, 2011.

[61] N/A. Liquefied natural gas, material safety data sheet. Technical report, Linde Gas North America LLC, 2011.

[62] N/A. Safety data sheet marine gas oil. Technical report, Oylieum Ghana Ltd, 2012.

[63] N/A. Safety data sheet, sodium borohydride. Technical report, Sigma-Aldrich, 2013.

[64] N/A. The step forward onboard dc grid. Technical report, ABB, 2014.

[65] N/A. Safety data sheet, magnesium hydride. Technical report, Santa Cruz Biotechnology, Inc., 2015.

[66] N/A. Safety data sheet, ethanol, 2016. URL https://www.sigmaaldrich.com/MSDS/MSDS/DisplayMSDSPage.do?country=NL&language=en&productNumber=16368&brand=SIAL&PageToGoToURL=https%3A%2F%2Fwww.sigmaaldrich.com%2Fcatalog%2Fproduct%2Fsial%2F16368%3Flang%3Den. Last accessed 22 March 2019.

[67] N/A. H2fuel: carrier of hydrogen energy. Technical report, H2Fuel-systems BV, 2016.

[68] N/A. Hydrogen, refrigerated liquid. Technical report, Praxair, Inc., 2016.

[69] N/A. Safety data sheet ammonia. Technical report, Air Liquide, 2017.

[70] N/A. Dimethyl ether, safety data sheet p-4589. Technical report, Praxair, Inc., 2019.

[71] N/A. Abb azipod study summary: Faster, safer, cleaner azipod® propulsion for ferries, n.d. URL https://resources.news.e.abb.com/attachments/published/24879/en-US/B43C4875A59F/Azipod_study_summary.pdf. Last accessed 29 July 2019.

[72] N/A. Carbon content of common fuels, n.d. URL https://www.gasinfocus.com/en/indicator/carbon-content-of-common-fuels/. Last accessed 1 May 2019.

[73] N/A. Oil fuel properties, n.d. URL http://www.globalcombustion.com/oil-fuel-properties/. Last accessed 11 April 2019.

[74] N/A. Clp pictograms, n.d. URL https://echa.europa.eu/regulations/clp/clp-pictograms. Last accessed 26 March 2019.

[75] N/A. Metal hydride hydrogen storage for h_2 fuel cells, n.d.. URL http://www.hbank.com.tw/fc/fpe.html. Last accessed 4 April 2019.

[76] N/A. Hydrogenious-technology, n.d.. URL https://www.hydrogenious.net/. Last accessed 4 April 2019.

[77] N/A. Diesel-electric propulsion plants, a brief guideline how to engineer a diesel-electric propulsion system, n.d.. URL https://marine.mandieselturbo.com/docs/librariesprovider6/marine-broschures/diesel-electric-drives-guideline.pdf. Last accessed 29 July 2019.

[78] N/A. Nfpa 704, n.d. URL https://en.wikipedia.org/wiki/NFPA_704. Last accessed 22 March 2019.

[79] N/A. Gas tanks for anhydrous ammonia, n.d. URL http://www.eurotainer.com/containers/products-list/gas-tanks-for-anhydrous-ammonia. Last accessed 25 April 2019.

[80] NFPAsigns. Nfpa 704 hazmat diamonds, 2019. URL https://www.compliancesigns.com/nfpadiamonds.shtml?utm_source=cmarketing&utm_medium=CRB. Last accessed 25 March 2019.

[81] S. Niaz, T. Manzoor, and A.H. Pandith. Hydrogen storage: Materials, methods and perspectives. *Renewable and Sustainable Energy Reviews*, 2015(50), 2015.

[82] U.S. Department of energy. Ethanol fuel basics, n.d. URL https://afdc.energy.gov/fuels/ethanol_fuel_basics.html. Last accessed 17 April 2019.

[83] R.P. O'Hayre, S-W. Cha, W.G. Colella, and F.B. Prinz. *Fuel cell fundamentals*. John Wiley & Sons Inc., Hoboken, New Jersey, third edition edition, 2016.

[84] PowerCell. Powercell ms100, n.d.. URL https://www.powercell.se/wordpress/wp-content/uploads/2018/12/powercell-ms100-datasheet-pdf.pdf. Last accessed 22 January 2019.

[85] PowerCell. Powercell ms30, n.d.. URL https://www.powercell.se/wordpress/wp-content/uploads/2018/12/powercell-ms-30-datasheet-18-11-26.pdf. Last accessed 16 May 2019.

[86] R. Prenc, A. Cuculić, and I. Baumgartner. Advantages of using a dc power system on board ship. Technical report, University of Rijeka, Faculty of Maritime Studies, 2016.

[87] Air Products. Gaseous nitrogen, 2014. URL http://www.airproducts.com/~/media/Files/PDF/company/safetygram-2.pdf. Last accessed 7 August 2019.

[88] Lloyd's Register. Rules for the classification of methanol fuelled ships. Technical report, Lloyd's Register Group Limited, 2019.

[89] R.E. Rosli, A.B. Sulong, W.R.W. Daud, M.A. Zulkifley, T. Husaini, M.I. Rosli, E.H. Majlan, and M.A. Haque. A review of high-temperature proton exchange membrane fuel cell (ht-pemfc) system. *international journal o f hydrogen energy*, 42:9293–9314, 2017.

[90] P.C. Sames, N.B. Clausen, and M.L. Andersen. Costs and benefits of lng as ship fuel for container vessels. Technical report, GL and MAN Diesel & Turbo, 2011.

[91] F. Schüth. Challenges in hydrogen storage. *The European Physical Journal*, 2009(176), 2009.

[92] Serenergy. Reformed methanol fuel cell h3 30k rack, datasheet, n.d. URL http://serenergy.com/wp-content/uploads/2017/11/H3-30k_datasheet_v1.0-1117.pdf. Last accessed 6 February 2019.

[93] D. Shekhawat, J.J. Spivey, and D.A. Berry. *Fuel Cells: Technologies for Fuel Processing*. Elsevier B.V., 2011.

[94] D.J. Siegel, A. Ahmed, Y. Liu, A. Matzger, J. Purewal, S. Seth, M. Veenstra, and A. Wong-Foy. Iv.c.15 hydrogen adsorbents with high volumetric density: New materials and system projections. Technical report, University of Michigan, 2018.

[95] D. Stapersma. *Diesel Engines Volume 3 Combustion*. NLDA & Delft UT, 2010.

[96] D. Stapersma. *Diesel Engines Volume 4 Emissions and Heat transfer*. NLDA & Delft UT, 2010.

[97] Redox Power Systems. Redox cube datasheet, n.d. URL https://www.redoxenergy.com/docs/Redox%20Cube%20Datasheet.pdf. Last accessed 6 May 2019.

[98] Engineering ToolBox. Fuel gases heating values, 2015. URL https://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html. Last accessed 20 March 2019.

[99] T. Tronstad, H.H. Åstrand, G.P. Haugom, and L. Langfeldt. Emsa study on the use of fuel cells in shipping. Technical report, DNV-GL, 2017.

[100] MAN Diesel & Turbo. Product specification, vacuum insulated tanks, n.d. URL https://sweden.man-es.com/docs/librariesprovider16/cryo-files/6-2-product-specification-vacuum-insulated-tank.pdf?sfvrsn=bd7fda2_2. Last accessed 19 March 2019.

[101] A. Valera-Medina, H. Xiao, M. Owen-Jones, W.I.F David, and P.J. .Bowena. Ammonia for power. *Progress in Energy and Combustion Science*, 69(69):63–102, 2018.

[102] L. van Biert, M. Godjevac, K. Visser, and A. Purushothaman Vellayani. A review of fuel cell systems for maritime applications. *Journal of Power Sources*, 327:345–364, 2016.

[103] F.M. van Nievelt. Maritime application of sodium borohydride as an energy carrier. Technical report, TUDelft, 2019.

[104] M. Wei, T. Lipman, A. Mayyas, S.H. Chan, D. Gosselin, H. Breunig, and T McKone. A total cost of ownership model for high temperature pem fuel cells in combined heat and power applications. Technical report, Lawrence Berkeley National Laboratory (LBNL), 2014.

[105] J. Zhang, Z. Xie, J. Zhang, Y. Tang, C. Songa, T. Navessin, Z. Shi, D. Songa, H. Wang, D.P. Wilkinson, Z-S Liu, and S. Holdcroft. High temperature pem fuel cells. *Journal of Power Sources*, 160:872–891, 2006.

A

FuelCells

A.1. Overview of recent maritime fuel cell research project.

Project	Begin research	End research	Type of fuel cell	Capacity (kW)	Stack Size (kW)	Fuel
HT-PEMFC						
RiverCell - Elektra	2015	2016	HT-PEMFC	192	-	Hydrogen
E4Ships - Pa-X-ell MS Mariella	2009	2022	HT-PEMFC	60	2x 30	Methanol
MF Vagen	2010	2010	HT-PEMFC	12	-	Hydrogen
RiverCell	2015	2022	HT-PEMFC	250	-	Methanol
LT-PEMFC						
CoBalt233 Zet	2007	Present	LT-PEMFC	50	-	Hydrogen
US SSFC	2000	2011	LT-PEMFC	500	-	Diesel
Class 212A submarines	2003	Present	LT-PEMFC	306	9x 30-40	Hydrogen
Class 212A/214 sub. 18x	2003	Present	LT-PEMFC	240	2x 120	Hydrogen
FELICITAS Subproject-3	2005	2008	LT-PEMFC	80	-	Hydro-Carbon
ZemShip - Alsterwasser	2006	2013	LT-PEMFC	96	-	Hydrogen
Nemo H2	2012	Present	LT-PEMFC	60	-	Hydrogen
Hornblower Hydrogen	2012	Present	LT-PEMFC	32	-	Hydrogen
Hydrogenesis	2012	Present	LT-PEMFC	12	-	Hydrogen
SF-Breeze	2015	Present	LT-PEMFC	2500	120	Hydrogen
MCFC						
US SSFC	2000	2011	MCFC	625	-	Diesel
FellowSHIP	2003	2011	MCFC	320	-	LNG
MC-WAP	2005	2010	MCFC	150	-	Diesel
SOFC						
FELICITAS Subproject-2	2005	2008	SOFC	250	60	LNG
Viking Lady METHAPU Undine	2006	2010	SOFC	20	-	Methanol
E4Ships - SchIBZ	2009	2017	SOFC	100	-	Diesel
Not used in figure 2.9 because of lack on information or irrelevance.						
E4Ships - Toplanterne	2009	2017	-	-	-	-
DESIRE	2001	2004	SOFC/ PEMFC	-	-	F76 Diesel
FCSHIP	2002	2004	MCFC/ SOFC/ PEMFC	-	-	Various
New-H-Ship	2004	2006	-	-	-	-
FELICITAS Subproject-1	2005	2008	-	-	-	-
FELICITAS Subproject-4	2005	2008	LT-PEMFC	-	-	-

Source: EMSA Study on the use of Fuel Cells in Shipping [99], except project DESIRE[48].

Table A.1: Overview recent maritime research project in the field of fuelcells.

A.2. Fuel cell market development data

Annual Unit Shipments per fuel cell type

	2009	2010	2011	2012	2013*	2014	2015	2016	2017*
PEMFC	8500	10900	20400	40400	58700	58400	53500	44500	45500
SOFC	100	100	600	2300	5500	2700	5200	16200	24000
MCFC	0	0	0	0	0	100	0	0	0
DMFC	5800	6700	3600	3000	2600	2500	2100	2300	2800
PAFC	0	0	0	0	0	0	100	100	200
AFC	0	0	0	0	0	0	0	100	100

Data source: Fuel Cell Today (2009-2013)[17] and E4Tech (2014-2017)[35].
*Data from 2013 and 2017 are market forecast respectively done by Fuel Cell Today and E4tech.

Table A.2: Annual Unit Shipments per fuel cell type.

Annual Unit Shipments by application

	2009	2010	2011	2012	2013*	2014	2015	2016	2017*
Portable	5700	6800	6900	18900	13000	21200	8700	4200	4900
Stationary	6700	8300	16100	24100	51800	39500	47000	51800	55700
Transport	2000	2600	1600	2700	2000	2900	5200	7200	12000

Data source: Fuel Cell Today (2009-2013)[17] and E4Tech (2014-2017)[35].
*Data from 2013 and 2017 are market forecast respectively done by Fuel Cell Today and E4tech.

Table A.3: Annual Unit Shipments by application.

Megawatts by fuel cell type

	2009	2010	2011	2012	2013*	2014	2015	2016	2017*
PEMFC	60	67,7	49,2	68,3	68	72,7	151,8	341	486,8
SOFC	1,1	6,7	10,6	26,9	47	38,2	53,3	62,9	76,4
MCFC	18	7,7	44,5	62	91,9	70,5	68,6	55,7	24,7
DMFC	1	1,1	0,4	0,3	0,2	0,2	0,2	0,2	0,3
PAFC	6,3	7,9	4,6	9,2	7,9	3,8	24	56,2	81
AFC	0	0,1	0,1	0	0,3	0	0,2	0,5	0,5

Data source: Fuel Cell Today (2009-2013)[17] and E4Tech (2014-2017)[35].
*Data from 2013 and 2017 are market forecast respectively done by Fuel Cell Today and E4tech.

Table A.4: Megawatts by fuel cell type.

Megawatts by application

	2009	2010	2011	2012	2013*	2014	2015	2016	2017*
Portable	1,5	0,4	0,4	0,5	0,3	0,4	0,9	0,3	0,5
Stationary	35,4	35	81,4	124,9	186,9	147,8	183,6	209	213,5
Transport	49,6	55,8	27,6	41,3	28,1	37,2	113,69	307,2	455,7

Data source: Fuel Cell Today (2009-2013)[17] and E4Tech (2014-2017)[35].
*Data from 2013 and 2017 are market forecast respectively done by Fuel Cell Today and E4tech.

Table A.5: Megawatts by application.

B

Fuel Storage

B.1. Fuel Densities

		LHV				*Density*
		MJ/kg	**kWh/kg**	**MJ/m3**	**kWh/m3**	**kg/m3**
Gas	Natural gas	47,1	13,1	36,6	10,2	0,78
Gas	Hydrogen	120,2	33,4	10,1	2,8	0,08
Gas	CH4 (Methane)	49,9	13,8	33,9	9,4	0,67
Compressed	700 bar H2*	120,2	33,4	4808,4	1335,7	40,00
Compressed	300 bar H2	120,2	33,4	2404,2	667,8	20,00
Liquid	Crude oil	42,7	11,9	36141,0	10039,2	846,67
Liquid	MeOH (Methanol)*	20,1	5,6	15956,7	4432,4	794,10
Liquid	C2H5OH (Ethanol)*	27,0	7,5	21274,5	5909,6	789,35
Liquid	LPG	46,6	12,9	23676,5	6576,8	508,00
Liquid	LNG*	48,6	13,5	20825,3	5784,8	428,22
Liquid	LH2*	120,7	33,5	8545,3	2373,7	70,80
Liquid	HFO	42,0	11,7	42420,0	11783,3	1010,00
Liquid	MDO	42,7	11,9	38430,0	10675,0	900,00
Liquid	MGO*	43,0	11,9	38270,0	10630,6	890,00
Liquid	NH3 (Liquid Ammonia)*	18,8	5,2	12832,9	3564,7	682,60
Liquid	Petrol	42,0	11,7	31500,0	8750,0	-
Liquid	Kerosene	43,5	12,1	30960,0	8600,0	-
Liquid	Liquid DME (Di-methyl ether)*	28,4	7,9	19028,0	5285,6	670,00

Data sources: [13, 27, 31, 33, 51, 52, 98, 101].
*Fuels used in comparison overview of appendix B.3

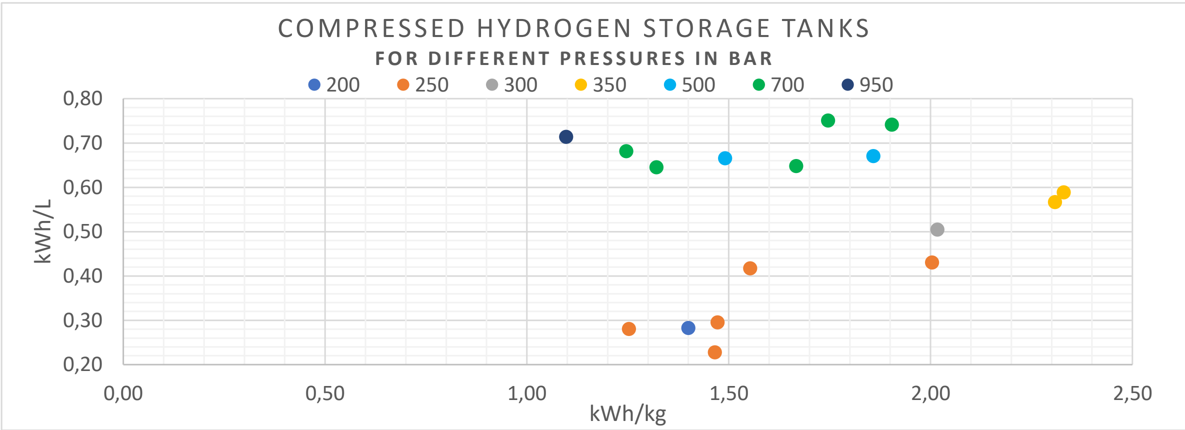
Table B.1: Fuel Densities

B.2. Storage Tanks

B.2.1. Compressed hydrogen storage tanks

Source: hexagongroup.com

Figure B.1: Example of a large scale compressed hydrogen solution (Hexagon TITAN® XL)



Used data shown in table B.2

Figure B.2: Storage tanks for compressed hydrogen at different pressures

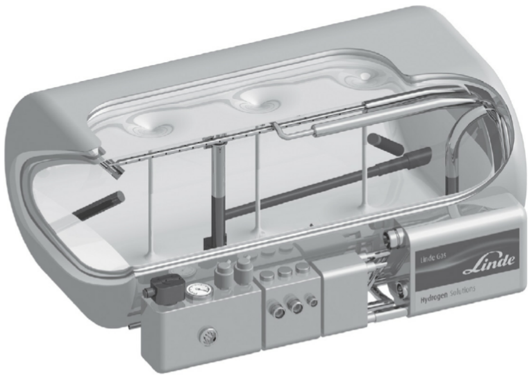
	Pressure	Weight	Outer volume	Hydrogen Cap		Density	
	Bar	**kg**	**L**	**kg**	**kWh H_2**	**kWh/L**	**kWh/kg**
HEXAGON A	200	16	82,6	0,7	23,4	0,28	1,40
HEXAGON X-STORE®[1]	250	9415	46865,2	415,0	13857,6	0,30	1,47
HEXAGON TITAN®4[2]	250	16259	72574,4	610,0	20368,9	0,28	1,25
HEXAGON TITAN® XL[3]	250	20165	129761,3	885,0	29551,6	0,23	1,47
HEXAGON B	250	164	639,7	8,0	267,1	0,42	1,55
HEXAGON C	250	94	465,4	6,0	200,4	0,43	2,00
HEXAGON D	300	112	476,6	7,2	240,4	0,50	2,02
HEXAGON E	350	101	442,0	7,5	250,4	0,57	2,31
*HEXAGON F**	*350*	*112*	*476,6*	*8,4*	*280,5*	*0,59*	*2,33*
HEXAGON G	500	280	821,6	16,5	551,0	0,67	1,86
HEXAGON H	500	229	536,8	10,7	357,3	0,67	1,49
MaHytec 700	700	54	98,0	2,0	13857,6	0,68	1,25
HEXAGON I	700	34	72,4	1,4	46,7	0,65	1,32
HEXAGON J	700	29	71,2	1,6	53,4	0,75	1,75
*HEXAGON L**	*700*	*43*	*117,1*	*2,6*	*86,8*	*0,74*	*1,90*
HEXAGON L	700	59	159,7	3,1	103,5	0,65	1,67
HEXAGON M	950	365	579,7	12,4	414,1	0,71	1,10

*Tank used in comparison overview of appendix B.3 | Data obtained from MaHytec.com and hexagonlincoln.com

[1] *DOT HL23 20ft* [2] *40ft container module* [3] *Truck Trailer*

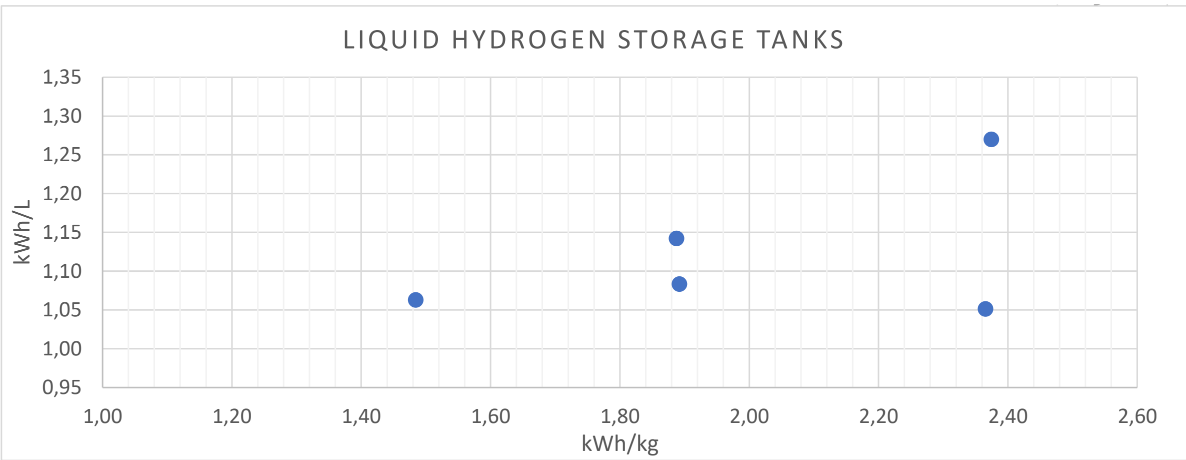
Table B.2: Storage tanks for compressed hydrogen at different pressures

B.2.2. Liquid hydrogen storage tanks



Source: Hydrogen storage technologies : new materials, transport, and infrastructure [31]

Figure B.3: Linde liquid hydrogen storage tank



Used data shown in table B.3

Figure B.4: Storage tanks for liquid hydrogen

Type	70L	120L	115LF	600LF	*500L**
H2 (kg)	4	6,8	6,5	34	*32*
Length (mm)	1000	915	1080	5500	*2125*
Diameter (mm)	400	540	400x560	500	*710*
m^3	0,13	0,21	0,19	1,08	*0,84*
Weight (kg)	90	120	115	480	*450*
Weight %	4,4%	5,7%	5,7%	7,1%	*7,1%*
kWh/L	1,06	1,08	1,14	1,05	*1,27*
kWh/kg	1,48	1,89	1,89	2,37	*2,37*

*Tank used in comparison overview of appendix B.3
Data source: Hydrogen storage technologies : new materials, transport, and infrastructure [31]

Table B.3: Storage tanks for liquid hydrogen

B.2.3. Ammonia/ DME storage tank

Source: eurotainer.com (Europtainer T50)[79]

Figure B.5: Storage tank for lightly pressurised gasses, eq. storage of liquid Ammonia or liquid DME.

THE EUROTAINER T50 TYPE		
Inner Volume	24600	liter
Length	6,058	m
Width	2,438	m
Height	2,591	m
Empty weight	6000	kg
Max weight	34000	kg
Outer Volume (Cylinder)	29,20734	m^3
Outer Volume (Box)	38,26753	m^3

	DME	Ammonia	
Grav. energy density fuel	670	682,6	kg/m^3
Vol. energy density fuel	5285,6	3564,7	kWh/m^3
Weight fuel	16482	16792	kg
Energy fuel	22482,0	22792,0	kWh
Total Weight (tank+fuel)	22482	22792	kg
Total Energy Density			
Vol. energy density (Cylinder)	2,29	3	kWh/L
Vol. energy density (Box)	3,4	4,45	kWh/L
Grav. energy density	5,78	3,85	kWh/kg

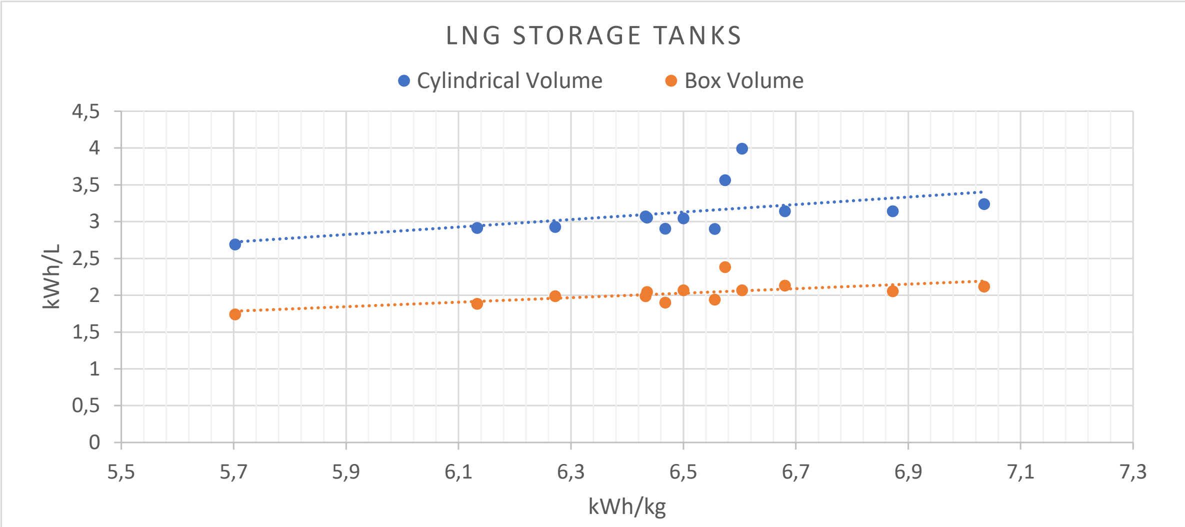
Source: eurotainer.com (Europtainer T50)[79]
This tank is used in the comparison overview of appendix B.3

Table B.4: Storage tank for lightly pressurised gasses, eq. storage of liquid Ammonia or liquid DME.

B.2.4. LNG storage tanks

In both figure B.6 and table B.5 a cylindrical volume and box volume is mentioned for the different storage tanks. The cylindrical tank is the tank volume in its pure cylindrical form. Because the volume around the cylinder is practical useless for other applications a box volume is mentioned as well. This box volume indicates the volume needed if a box is drawn around the cylindrical tank.

For this overview the tank specification of MAN Cryos vacuum insulated tanks are used [100].



Used data shown in table B.5

Figure B.6: Storage tanks for LNG

	Volume		*Weight*		*Amount of LNG*		*Density*		
Type	**Total box volume** (m^3)	**Total cylindrical volume** (m^3)	**Total empty weight**	**Total full weight**	**Ton LNG**	**kWh LNG (full-empty)**	**kWh/kg**	**kWh/L (Cylinder)**	**kWh/L (Box)**
T76	225,2	145,7	38,2	68,7	29	391758	5,70	2,69	1,74
T100	272,5	176,2	44,2	83,7	38	513338	6,13	2,91	1,88
T124	319,7	206,8	50,2	98,7	47	634918	6,43	3,07	1,99
T142	376,9	246,5	56,2	110,7	53	715972	6,47	2,91	1,90
T175	440,4	288,0	63,2	131,7	67	905096	6,87	3,14	2,06
T209	504,0	329,6	71,2	151,7	79	1067203	7,03	3,24	2,12
T249	655,0	438,0	98,2	193,7	94	1269837	6,56	2,90	1,94
T300	754,0	504,2	120,5	239,3	114	1540015	6,44	3,05	2,04
T352	754,0	504,2	135,5	273,3	133	1796684	6,57	3,56	2,38
T385	985,8	669,3	162,5	312,3	145	1958790	6,27	2,93	1,99
T450	1110,8	754,1	178,5	353,3	170	2296513	6,50	3,05	2,07
T516	1235,7	838,9	194,5	394,3	195	2634235	6,68	3,14	2,13
*T600**	*1484,2*	*768,6*	*232,5*	*464,3*	*227*	*3066520*	*6,60*	*3,99*	2,07

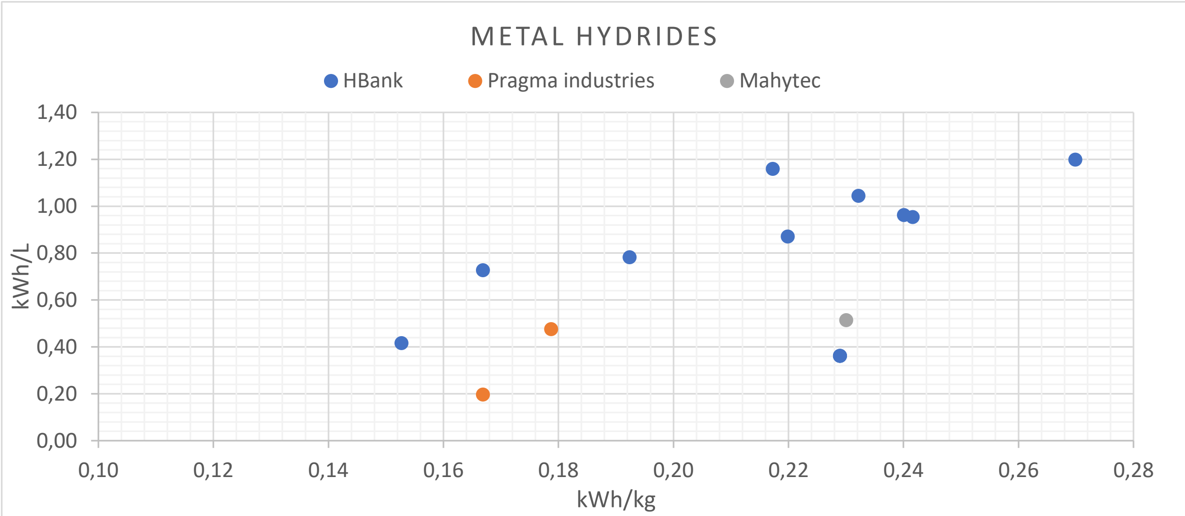
*Tank used in comparison overview of appendix B.3

Table B.5: Storage tanks LNG, MAN Cryo

B.2.5. Metal hydride storage tank

Source: www.hbank.com[75]

Figure B.7: Examples of HBank metal hydride storage tanks



Used data shown in table B.6

Figure B.8: Storage tanks for metal hydrides

Brand	Type	Volume (L)	Storage Weight (kg)	Hydrogen Weight (kg)	kWh/kg	kWh/L
HBank	HB-SC-0010-Q	0,03	0,15	0,0008	0,17	0,73
HBank	HB-SC-0050-Q	0,16	0,65	0,0042	0,19	0,78
HBank	HB-SC-0100-Q	0,22	1,15	0,0084	0,22	1,16
HBank	HB-SC-0220-Q	0,64	2,5	0,0184	0,22	0,87
HBank	HB-SC-0300-N	0,79	3,1	0,0251	0,24	0,95
HBank	HB-SC-0375-N	0,98	3,9	0,0314	0,24	0,96
HBank	HB-FR07-0500-B	3,02	8,2	0,0419	0,15	0,42
HBank	*HB-SC-0660-N**	*1,39*	*6,1*	*0,0553*	*0,27*	*1,20*
HBank	HB-SC-0660-N-L	1,59	7,1	0,0553	0,23	1,04
HBank	HB-SS 3300	22,99	36	0,2764	0,23	0,36
HBank	*HB-SS 16500**	*114,95*	*180*	*1,3819*	*0,23*	*0,36*
HBank	HB-SS 16500-L	114,95	180	1,3819	0,23	0,36
Pragma industries	MH10M	128,24	150	0,8375	0,17	0,20
Pragma industries	MH7000	37,01	98	0,5863	0,18	0,48
Mahytec	MHT-Magnum	10,28	22,8	0,1759	0,23	0,51

*Tank used in comparison overview of appendix B.3
Data obtained from www.hbank.com[75]

Table B.6: Storage tanks for metal hydrides

B.3. Fuel storage density comparison overview.

	Volumetric Density (kWh/m^3)		**Gravimetric Density (kWh/kg)**	
Fuel type	*Pure Fuel*[11]	***With Storage system***[11]	*Pure Fuel*[10]	***With Storage system***[10]
Compressed H2, 700 bar[1]	1335,7	**741,6**	33,33	**1,90**
Compressed H2, 350 bar[1]	750,0	**588,6**	33,33	**2,33**
Cryogenic liquid H2[2]	2373,7	**1270,1**	33,33	**2,37**
MGO[3]	10630,6	**9865,2**	11,94	**11,08**
MeOH (Methanol)[3]	4432,4	**4113,3**	5,58	**5,18**
C2H5OH (Ethanol)[3]	5909,6	**5484,1**	7,49	**6,95**
NH3 (Ammonia) (Cylinder volume)[4]	3564,7	**3002,4**	5,22	**3,85**
NH3 (Ammonia) (Box volume)[4]	3564,7	**2291,5**	5,22	**3,85**
Liquid DME (Dimethyl ether) (Cylinder volume)[4]	5285,6	**4451,8**	7,89	**5,78**
Liquid DME (Dimethyl ether) (Box volume)[4]	5285,6	**3397,8**	7,89	**5,78**
LNG, incl. Storage. (Cylinder volume)[5]	5784,8	**3989,7**	13,51	**6,60**
LNG, incl. Storage. (Box volume)[5]	5784,8	**2066,0**	13,51	**6,60**
Formic Acid (Dens)[3]	1800,0	**1670,4**	1,48	**1,37**
LOHC, hydrogenious[3]	1761,8	**1635,0**	1,61	**1,49**
Sodium Borohydride (30% fuel)[6]	2885,7	**1105,0**	2,06	**1,02**
Sodium Borohydride (dry)[6]	7324,3	**4314,2**	7,10	**2,71**
MgH2 (Metal Hydrade)[7]	**3708,8**	n/a	**2,56**	n/a
Hbank (AB-5 type alloy) Rack HB-SS 16500[8]	n/a	**361,3**	0,55	**0,25**
Hbank (AB-5 type alloy), Small tank, HB-SC-0660-N[7]	n/a	**1199,0**	0,55	**0,27**
MOF (Project Status: SNU-70)[9]	**1135,3**	n/a	**2,44**	n/a

Storage tank size and weight based on data of:

[1] appendix B.2.1 [2] appendix B.2.2 [3] S.C. Misra, Design Principles of Ships and Marine Structures (MGO factor)[57] [4] appendix B.2.3 [5] appendix B.2.4 [6] section 3.4.4 [7] section 3.4.4 [8] appendix B.2.5 [9] section 3.4.5

[10] Pure fuel densities are based on appendix B.1
[11] The storage densities with storage system are used during Chapter 4, Combined Fuel Cell and Fuel system density. With the exception of MgH_2 and MOF where the Pure fuel is used since there is no tank data available at the moment.

Table B.7: Fuel storage density comparison overview.

B.4. Fuel reformers and fuel cells used for effective density calculations

Reformer type		W/kg	W/L	Efficiency
SB_30	*SodiumBorohydride Fuel30 [103]:*	128,4	128,7	0,95
SB_100	*SodiumBorohydride Dry Fuel [103]:*	126,3	124,4	0,95
Flox	*FloxReformer (FPM-C10) [30]:*	200,7	89.7	0,82
FA	*Formic Acid*[1]*:*	-	1166,7	0,84
LOHC	*LOHC (ReleaseBOX 250) [76]:*	-	9,7	0,78
Diesel	*Diesel SR [102]:*	40,0	50,0	0,8

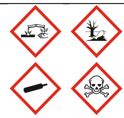
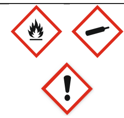
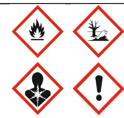
[1] *received by discussion with DENS (dens.one)*

Table B.8: Fuel reformers used for density calculations

Reformer type		W/kg	W/L	Efficiency
LT-PEMFC	*Power Cell MS100*	833,0	333,3	0,5
LT-PEMFC	*Power Cell MS30*[85]	207,0	171,9	0,427
LT-PEMFC_AIP	*Siemens FCM NG 135*	150,0	289,5	0,54
SOFC_Low	*Bloomenergy ES5-YA8AAA*	20,9	9,5	0,65
SOFC_High	*Redox power Cube*	55,6	17,9	0,55
DIESEL, Main Engine	*MTU 16V 4000 M73L*	300,0	215,4	0,388
DIESEL, Genset	*MTU 16V2000M41A, Genset*	226,5	73,7	0,39
HT-PEMFC	*Serenergy H3 30kRack*	37,5	19,5	0,42
HT-PEMFC	*Serenergy Marine Unit (300kW)*	41.1	12.0	0,42

Table B.9: Energy converters used for effective density calculations

B.5. Safety aspect overview different fuels.

Fuel	**Methanol** [56]	**Ethanol** [66]	**Liquid Ammonia** [69]	**DME**[70] Dimethyl ether	**LNG**[61] Liquefied Natural Gas	**MGO**[62] Marine Gas Oil	**Hydrogen** CH_2/LH_2 [68]
Formula	CH_3OH	C_2H_5OH	NH_3	CH_3OCH_3	$\pm 95\%\ CH_4$	MGO	H_2
Molucalar weight (g/mol) [1]	32.04	46.069	17.031	46.069	-	-	2.016
Flash point (°C)	11 °C	14 °C	N/A	-41.1 °C	-188 °C	60 °C	N/A
Autoignition temperature	455 °C	363.0 °C	651.0 °C	350 °C	580.0 °C	257 °C	566 °C
Explosive limits	6-36%	3.3-19%	15-28%	3.4-27%	5-15%	0.7-5%	4-75%
Boiling point (°C)	65 °C	77 °C	-33 °C	-24.8 °C	-162 °C	154-372 °C	-252.9 °C
GHS[2] safety indication:							
NFPA[3] 704 Hazmat Diamond [80]:							

Symbol explanation [74]

 = Flammable, extremely flammable

 = Acute toxicity, Fatal if: swallowed/contact with skin/inhaled

 = Serious health hazard

 = Health hazard/Hazardous to the ozone layer

 = Hazardous to environment: very toxic to aquatic life.

 = Corrosive: May be corrosive to metals.
Causes severe skin burns and eye damage.

 = Gas under pressure: may explode if heated.
Refrigerated gas: may cause cryogenic burns.

NFPA 704 explanation: [36, 78]

HEALTH HAZARD
4 = Very short exposure can be lethal
3 = Can cause serious temporary or moderate permanent injury
2 = Can cause temporary incapacitation or residual injury
1 = Can cause significant irritation and only minor residual injury
0 = No health hazard

FIRE HAZARD
4 = Flashpoint < 22.8 °C.
3 = Liquid: Flashpoint < 22.8 °C and boiling point ≥37.8 °C. Or flashpoint > 22.8 °C
2 = Flashpoint above 37.8 °C
1 = Flashpoint above 93.3 °C
0 = Will not burn when exposed to a temperature of 820 °C for a period of 5 min.

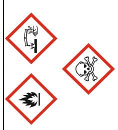
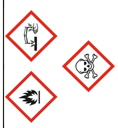
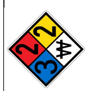
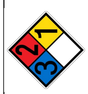
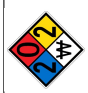
INSTABILITY HAZARD
4 = Readily capable to explode at normal temperatures and pressures
3 = May explode, requires a strong initiating source like high temperature or shock
2 = Violent chemical change at high temperatures or pressures
1 = Normally stable. High temperatures and pressure can make it unstable
0 = Stable, even under fire conditions

SPECIAL NOTICE
~~W~~ = Reacts with water in an unusual or dangerous manner

[1] *Source: https://pubchem.ncbi.nlm.nih.gov/* [2] *Globally Harmonised System of Classification and Labelling of Chemicals*
[3] *NFPA 704: System for Identification of Hazards of Materials from the National Fire Protection Association of United stated*

Table B.10: Safety aspect of different fuels

B.6. Safety aspect overview different hydrogen carriers.

Fuel	**LOHC** Dibenzyltoluene [59]	**Sodium-Borohydride** [63, 67]	**Formic Acid** [58]	**Metal Hydride** MgH2 [65]	**Metal Hydride** Hbank	**MOF** Metal Organic Framework
Formula	$C_{21}H_2O$	$NaBH_4$	$CHOOH$	MgH_2	AB_3type	-
Molucalar weight (g/mol) [1]	182.261	37.83	46,03	26.32	No information available	No information available
Flash point (°C), closed cup	212 °C	70 °C	50 °C	No information available	No information available	No information available
Autoignition temperature	500 °C	220 °C	520 °C	No information available	- °C	- °C
Explosive limits	0%	>3.02%	10-45%	No information available	No information available	No information available
Boiling point (°C)	250 °C	500 °C	101 °C	No information available	No information available	No information available
GHS[2] safety indication:						
NFPA[3] 704 Hazmat Diamond [80]:						

[1] Source: https://pubchem.ncbi.nlm.nih.gov/ [2] Globally Harmonised System of Classification and Labelling of Chemicals [3] NFPA 704: System for Identification of Hazards of Materials from the National Fire Protection Association of United stated

Table B.11: Safety aspect of different fuels

B.7. Chemical compatibilty

A: Excellent
B: Good
C: Fair to Poor
D: Not recommended
- No Data

Chemicals		Methanol	Ethanol (Ethyl Alcohol)	Ammonia Anhydrous	Dimethyl Ether (DME)	Gas natural	Diesel Oil (Fuel ASTM #2)	Hydrogen Gas	Formic Acid	Debenzyltoluene (LOHC)[59]	Sodium Borohydride ($NaBH_4$)	Metal Hydride (MgH_2)
Metals	Aluminum	B	B	A	B	A	A	A	D	-	-	-
	Carbon Steel	A	B	A	-	A	-	A	D	A	-	-
	Cast/Ductile Iron	A	B	A	B	A	A	A	D	-	-	-
	304 Stainless Steel	A	A	A	B	A	A	A	C	A	-	-
	316 Stainless Steel	A	A	A	-	A	-	A	C	A	-	-
Plastics, Elastomers & Leather	Acetal	A	A	D	-	A	A	C	D	-	-	-
	Buna	A	C	B	A	A	A	A	D	-	-	-
	CSM (Hypalon)	A	A	-	-	-	-	A	A	-	-	-
	EPR, EPDM	A	A	A	-	D	D	B	B	-	-	-
	Fluorocarbon	-	-	D	A	-	A	-	C	-	-	-
	Fluoroelastomer (FKM)	D	A	D	-	A	A	A	C	-	-	-
	Geolast (Buna & Polypropylene)	-	-	-	A	-	-	A	D	-	-	-
	Hastelloy C	A	A	A	B	-	A	A	A	-	-	-
	TPE	B	A	D	-	B	B	A	C	-	-	-
	Leather	-	-	D	-	-	-	-	-	-	-	-
	Nitrile (TS)	A	A	-	-	-	A	A	D	-	-	-
	Nitrile (TPE)	A	A	-	-	-	B	A	A	-	-	-
	Nylon	B	C	B	-	A	-	B	D	-	-	-
	Polychloroprene	A	A	B	B	C	D	A	D	-	-	-
	Polypropylene	A	A	A	-	B	B	A	B	-	-	-
	PTFE	A	A	A	A	A	A	A	A	-	-	-
	PVDF	A	A	A	-	A	A	A	A	-	-	-
	Santoprene (EPDM & Polypropylene)	A	A	A	-	D	D	A	A	-	-	-
	UHMWPE	A	A	A	-	-	A	A	A	-	-	-
	Urethane	D	D	-	-	-	B	B	D	-	-	-

Source: GRACO, Chemicial Compatibility Guide (7-2-2013)

Table B.12: Chemicial Compatibility Guide

C Fuel Cell Decision making

C.1. TRL levels

nr.	Fuel cell	Reformer/ Special type of fuel	Fuel cell and fuel system	TRL	Manufacturer	TRL*manufacturer	Normalized
1	LT-PEMFC		LH2, LT-PEMFC	8	1,00	8	0,89
2	LT-PEMFC		CH2 700 bar small H2 tank, LT-PEMFC	8	1,00	8	0,89
3	LT-PEMFC		CH2 350 bar large H2 tank, LT-PEMFC	8	1,00	8	0,89
4	LT-PEMFC		CH2 250 bar container H2 tank, LT-PEMFC	8	1,00	8	0,89
5	LT-PEMFC		Formic Acid, LT-PEMFC (NO Weight reformer!)	5	0,75	3,75	0,42
6	LT-PEMFC		SodiumBorohydride, LT-PEMFC (30% Fuel)	3	0,00	0	0,00
7	LT-PEMFC		SodiumBorohydride, LT-PEMFC (Powder, fuel exchange tank)	3	0,00	0	0,00
8	LT-PEMFC		LOHC, LT-PEMFC	7	1,00	7	0,78
9	LT-PEMFC		Metal Hydride, LT-PEMFC (MgH2 NO STORAGE SYSTEM!)	3	0,00	0	0,00
10	LT-PEMFC		Metal Hydride, LT-PEMFC (Small tank, Ready to buy)	8	1,00	8	0,89
11	LT-PEMFC		Metal Hydride, LT-PEMFC (Big rack, Ready to buy)	8	1,00	8	0,89
12	LT-PEMFC	Flox reformer	Methanol_R, LT-PEMFC, MS-30	4	0,75	3	0,33
13	LT-PEMFC	Flox reformer	Ethanol_R, LT-PEMFC, MS-30	4	0,75	3	0,33
14	LT-PEMFC	Flox reformer	Ammonia_R, LT-PEMFC, MS-30	4	0,75	3	0,33
15	LT-PEMFC	Flox reformer	Liquid DME_R, LT-PEMFC, MS-30	4	0,75	3	0,33
16	LT-PEMFC	Flox reformer	LNG_R, LT-PEMFC, MS-30	6	0,75	4,5	0,50
17	HT-PEMFC		Methanol, HT-PEMFC	8	1,00	8	0,89
18	HT-PEMFC		Methanol, HT-PEMFC, MFCU	8	1,00	8	0,89
19	SOFC		Diesel, SOFC	5	0,25	1,25	0,14
20	SOFC		LNG, SOFC	5	0,75	3,75	0,42
21	SOFC		Methanol, SOFC	5	0,25	1,25	0,14
22	SOFC		Ammonia, SOFC	4	0,00	0	0,00
23	SOFC		Ethanol, SOFC	4	0,00	0	0,00
24	SOFC		Liquid DME, SOFC	4	0,00	0	0,00
25	DIESEL engine		Diesel engine, Engine (MTU 16V4000M73L)	9	1,00	9	1,00
26	DIESEL engine		Diesel engine, Genset (16V2000M41A)	9	1,00	9	1,00
27	LT-PEMFC_AIP		LH2, LT-PEMFC_AIP	8	1,00	8	0,89
28	LT-PEMFC_AIP		CH2 700 bar small H2 tank, LT-PEMFC_AIP	8	1,00	8	0,89
29	LT-PEMFC_AIP		CH2 350 bar large H2 tank, LT-PEMFC_AIP	8	1,00	8	0,89
30	LT-PEMFC_AIP		CH2 250 bar container H2 tank, LT-PEMFC_AIP	8	1,00	8	0,89
31	LT-PEMFC_AIP		Formic Acid, LT-PEMFC_AIP (NO Weight reformer!)	5	0,75	3,75	0,42
32	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (30% Fuel)	3	0,00	0	0,00
33	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (Powder, fuel exchange tank)	3	0,00	0	0,00
34	LT-PEMFC_AIP		LOHC, LT-PEMFC_AIP	7	1,00	7	0,78
35	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (MgH2 NO STORAGE SYSTEM!)	3	0,00	0	0,00
36	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Small tank, Ready to buy)	8	1,00	8	0,89
37	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Big rack, Ready to buy)	8	1,00	8	0,89
38	SOFC_L		Diesel, SOFC_L	5	0,25	1,25	0,14
39	SOFC_L		LNG, SOFC_L	5	0,75	3,75	0,42
40	SOFC_L		Methanol, SOFC_L	5	0,25	1,25	0,14
41	SOFC_L		Ammonia, SOFC_L	4	0,00	0	0,00
42	SOFC_L		Ethanol, SOFC_L	4	0,00	0	0,00
43	SOFC_L		Liquid DME, SOFC_L	4	0,00	0	0,00
44	LT-PEMFC	RENEWABLE	Formic Acid, LT-PEMFC	5	0,75	3,75	0,42
45	LT-PEMFC	RENEWABLE | Flox reformer	Methanol, LT-PEMFC	4	0,75	3	0,33
46	LT-PEMFC	RENEWABLE | Flox reformer	Liquid DME, LT-PEMFC	4	0,75	3	0,33
47	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC	8	1,00	8	0,89
48	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC, MFCU	8	1,00	8	0,89
49	SOFC	RENEWABLE	Methanol, SOFC	5	0,25	1,25	0,14
50	SOFC	RENEWABLE	Liquid DME, SOFC	4	0,00	0	0,00
51	LT-PEMFC_AIP	RENEWABLE	Formic Acid, LT-PEMFC_AIP	5	0,75	3,75	0,42
52	SOFC_L	RENEWABLE	Methanol, SOFC_L	5	0,25	1,25	0,14
53	SOFC_L	RENEWABLE	Liquid DME, SOFC_L	4	0,00	0	0,00

C.2. Example cases decision making tool

Nr.	Fuel cell:		Type of technology:	Weight	Volume	Storage type	TRL	Fire hazard	Health hazard	Instability	CO2 emission	TOTAL:
				Density			Maturity	Safety			Emission	
								Overall Safety ranking:		3		
				4	1	0	1	3	3	1	3	
1	LT-PEMFC		Metal Hydride, LT-PEMFC (MgH2 *NO STORAGE SYSTEM!*)	1,00	1,00	0,00	0,00	1,00	1,00	1,00	1,00	9,17
2	LT-PEMFC		LH2, LT-PEMFC	0,97	0,74	0,00	0,89	0,00	0,25	1,00	1,00	7,70
3	LT-PEMFC		CH2 350 bar large H2 tank, LT-PEMFC	0,96	0,51	0,00	0,89	0,00	0,25	1,00	1,00	7,48
4	LT-PEMFC		LOHC, LT-PEMFC	0,65	0,03	1,00	0,78	0,75	0,75	1,00	1,00	7,31
5	LT-PEMFC		CH2 700 bar small H2 tank, LT-PEMFC	0,87	0,58	0,00	0,89	0,00	0,25	1,00	1,00	7,23
6	LT-PEMFC		Metal Hydride, LT-PEMFC (Small tank, Ready to buy)	0,21	0,72	0,00	0,89	1,00	1,00	1,00	1,00	7,04
7	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Small tank, Ready to buy)	0,14	0,68	0,00	0,89	1,00	1,00	1,00	1,00	6,79
8	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (MgH2 *NO STORAGE SYSTEM!*)	0,29	0,90	0,00	0,00	1,00	1,00	1,00	1,00	6,71
9	LT-PEMFC		Metal Hydride, LT-PEMFC (Big rack, Ready to buy)	0,19	0,37	0,00	0,89	1,00	1,00	1,00	1,00	6,69
10	LT-PEMFC		CH2 250 bar container H2 tank, LT-PEMFC	0,75	0,32	0,00	0,89	0,00	0,25	1,00	1,00	6,64

Normalized Ranking

Time factor (t, hours): 1,25

Table C.1: Example case 1, Fast passenger ferry

Nr.	Fuel cell:		Type of technology:	Weight	Volume	Storage type	TRL	Fire hazard	Health hazard	Instability	CO2 emission	TOTAL:
				Density			Maturity	Safety			Emission	
								Overall Safety ranking:		2		
				1,5	3	1,5	1	3	2	1	3	
1	DIESEL engine		Diesel engine, Engine (MTU 16V4000M73L)	1,00	1,00	1,00	1,00	0,50	1,00	1,00	0,54	8,44
2	DIESEL engine		Diesel engine, Genset (16V2000M41A)	0,91	0,82	1,00	1,00	0,50	1,00	1,00	0,55	7,88
3	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC	0,47	0,40	1,00	0,89	0,25	0,75	1,00	1,00	6,98
4	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC, MFCU	0,48	0,36	1,00	0,89	0,25	0,75	1,00	1,00	6,88
5	SOFC	RENEWABLE	Methanol, SOFC	0,65	0,50	1,00	0,14	0,25	0,75	1,00	1,00	6,81
6	SOFC		Diesel, SOFC	0,79	0,66	1,00	0,14	0,50	1,00	1,00	0,61	6,79
7	SOFC_L	RENEWABLE	Methanol, SOFC_L	0,58	0,43	1,00	0,14	0,25	0,75	1,00	1,00	6,58
8	LT-PEMFC	RENEWABLE | FR	Methanol, LT-PEMFC	0,43	0,39	1,00	0,33	0,25	0,75	1,00	1,00	6,45
9	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (Powder, fuel exchange tank)	0,35	0,63	1,00	0,00	0,50	0,25	0,50	1,00	6,44
10	SOFC_L		Diesel, SOFC_L	0,67	0,53	1,00	0,14	0,50	1,00	1,00	0,66	6,42

Normalized Ranking

Time factor (t, hours): 357,14

Table C.2: Example case 2, Yacht

Nr.	Fuel cell:		Type of technology:	Weight	Volume	Storage type	TRL	Fire hazard	Health hazard	Instability	CO2 emission	TOTAL:
				Density			Maturity	Safety			Emission	
								Overall Safety ranking:		1		
				1	4	2	1	3	1	1	3	
1	DIESEL engine		Diesel engine, Engine (MTU 16V4000M73L)	1,00	1,00	1,00	1,00	0,50	1,00	1,00	0,54	8,61
2	DIESEL engine		Diesel engine, Genset (16V2000M41A)	0,97	0,93	1,00	1,00	0,50	1,00	1,00	0,55	8,35
3	SOFC		Diesel, SOFC	1,00	0,91	1,00	0,14	0,50	1,00	1,00	0,61	7,77
4	SOFC_L		Diesel, SOFC_L	0,98	0,86	1,00	0,14	0,50	1,00	1,00	0,66	7,68
5	SOFC_L	RENEWABLE	Methanol, SOFC_L	0,70	0,57	1,00	0,14	0,25	0,75	1,00	1,00	7,18
6	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC	0,49	0,43	1,00	0,89	0,25	0,75	1,00	1,00	7,17
7	SOFC	RENEWABLE	Methanol, SOFC	0,67	0,56	1,00	0,14	0,25	0,75	1,00	1,00	7,14
8	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC, MFCU	0,49	0,41	1,00	0,89	0,25	0,75	1,00	1,00	7,10
9	SOFC_L		Ethanol, SOFC_L	0,89	0,71	1,00	0,00	0,25	0,50	1,00	0,74	6,98
10	SOFC		Ethanol, SOFC	0,89	0,72	1,00	0,00	0,25	0,50	1,00	0,70	6,94

Normalized Ranking

Time factor (t, hours): 1025,00

Table C.3: Example case 3, Bulk carrier

C.3. Results reference yacht

C.3.1. Unranked

				Normalized Ranking								
				Density			Maturity	Safety			Emission	
				Weight	Volume	Storage type	TRL	Fire hazard	Health hazard	Instability	CO2 emission	
									Overall Safety ranking:	1		
	Fuel cell:		Type of technology:	1,5	2,5	1	3,5	3	2	1	2,5	TOTAL:
1	LT-PEMFC		LH2, LT-PEMFC	0,30	0,18	0,00	0,89	0,00	0,25	1,00	1,00	5,64
2	LT-PEMFC		CH2 700 bar small H2 tank, LT-PEMFC	0,24	0,11	0,00	0,89	0,00	0,25	1,00	1,00	5,40
3	LT-PEMFC		CH2 350 bar large H2 tank, LT-PEMFC	0,29	0,08	0,00	0,89	0,00	0,25	1,00	1,00	5,43
4	LT-PEMFC		CH2 250 bar container H2 tank, LT-PEMFC	0,18	0,04	0,00	0,89	0,00	0,25	1,00	1,00	5,20
5	LT-PEMFC		Formic Acid, LT-PEMFC *(NO Weight reformer!)*	0,14	0,20	1,00	0,42	0,50	0,25	0,75	0,00	3,03
6	LT-PEMFC		SodiumBorohydride, LT-PEMFC (30% Fuel)	0,13	0,16	1,00	0,00	0,50	0,25	0,50	1,00	3,75
7	LT-PEMFC		SodiumBorohydride, LT-PEMFC (Powder, fuel exchange tank)	0,33	0,58	1,00	0,00	0,50	0,25	0,50	1,00	4,89
8	LT-PEMFC		LOHC, LT-PEMFC	0,15	0,15	1,00	0,78	0,75	0,75	1,00	1,00	6,35
9	LT-PEMFC		Metal Hydride, LT-PEMFC (MgH2 *NO STORAGE SYSTEM!*)	0,32	0,53	0,00	0,00	1,00	1,00	1,00	1,00	4,42
10	LT-PEMFC		Metal Hydride, LT-PEMFC (Small tank, Ready to buy)	0,03	0,17	0,00	0,89	1,00	1,00	1,00	1,00	5,91
11	LT-PEMFC		Metal Hydride, LT-PEMFC (Big rack, Ready to buy)	0,03	0,05	0,00	0,89	1,00	1,00	1,00	1,00	5,66
12	LT-PEMFC	Flox reformer (FR)	Methanol_R, LT-PEMFC, MS-30	0,43	0,39	1,00	0,33	0,25	0,75	1,00	0,53	4,71
13	LT-PEMFC	Flox reformer (FR)	Ethanol_R, LT-PEMFC, MS-30	0,57	0,51	1,00	0,33	0,25	0,50	1,00	0,51	5,02
14	LT-PEMFC	Flox reformer (FR)	Ammonia_R, LT-PEMFC, MS-30	0,33	0,29	0,00	0,33	0,75	0,25	1,00	1,00	4,59
15	LT-PEMFC	Flox reformer (FR)	Liquid DME_R, LT-PEMFC, MS-30	0,48	0,42	0,00	0,33	0,00	0,75	0,75	0,53	3,87
16	LT-PEMFC	Flox reformer (FR)	LNG_R, LT-PEMFC, MS-30	0,55	0,38	0,00	0,50	0,00	0,25	1,00	0,56	4,30
17	HT-PEMFC		Methanol, HT-PEMFC	0,47	0,40	1,00	0,89	0,25	0,75	1,00	0,60	6,56
18	HT-PEMFC		Methanol, HT-PEMFC, MFCU	0,48	0,36	1,00	0,89	0,25	0,75	1,00	0,60	6,47
19	SOFC		Diesel, SOFC	0,79	0,66	1,00	0,14	0,50	1,00	1,00	0,61	5,51
20	SOFC		LNG, SOFC	0,89	0,53	0,00	0,42	0,00	0,25	1,00	0,76	5,23
21	SOFC		Methanol, SOFC	0,65	0,50	1,00	0,14	0,25	0,75	1,00	0,71	5,00
22	SOFC		Ammonia, SOFC	0,56	0,43	0,00	0,00	0,75	0,25	1,00	1,00	4,20
23	SOFC		Ethanol, SOFC	0,83	0,61	1,00	0,00	0,25	0,50	1,00	0,70	4,97
24	SOFC		Liquid DME, SOFC	0,79	0,58	0,00	0,00	0,00	0,75	0,75	0,75	4,06
25	DIESEL engine		Diesel engine, Engine (MTU 16V4000M73L)	1,00	1,00	1,00	1,00	0,50	1,00	1,00	0,54	8,84
26	DIESEL engine		Diesel engine, Genset (16V2000M41A)	0,91	0,82	1,00	1,00	0,50	1,00	1,00	0,55	8,35
27	LT-PEMFC_AIP		LH2, LT-PEMFC_AIP	0,31	0,20	0,00	0,89	0,00	0,25	1,00	1,00	5,69
28	LT-PEMFC_AIP		CH2 700 bar small H2 tank, LT-PEMFC_AIP	0,25	0,12	0,00	0,89	0,00	0,25	1,00	1,00	5,44
29	LT-PEMFC_AIP		CH2 350 bar large H2 tank, LT-PEMFC_AIP	0,31	0,09	0,00	0,89	0,00	0,25	1,00	1,00	5,46
30	LT-PEMFC_AIP		CH2 250 bar container H2 tank, LT-PEMFC_AIP	0,20	0,05	0,00	0,89	0,00	0,25	1,00	1,00	5,23
31	LT-PEMFC_AIP		Formic Acid, LT-PEMFC_AIP *(NO Weight reformer!)*	0,15	0,22	1,00	0,42	0,50	0,25	0,75	0,07	3,23
32	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (30% Fuel)	0,14	0,17	1,00	0,00	0,50	0,25	0,50	1,00	3,79
33	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (Powder, fuel exchange tank)	0,35	0,63	1,00	0,00	0,50	0,25	0,50	1,00	5,00
34	LT-PEMFC_AIP		LOHC, LT-PEMFC_AIP	0,16	0,17	1,00	0,78	0,75	0,75	1,00	1,00	6,38
35	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (MgH2 *NO STORAGE SYSTEM!*)	0,34	0,57	0,00	0,00	1,00	1,00	1,00	1,00	4,52
36	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Small tank, Ready to buy)	0,04	0,19	0,00	0,89	1,00	1,00	1,00	1,00	5,94
37	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Big rack, Ready to buy)	0,03	0,06	0,00	0,89	1,00	1,00	1,00	1,00	5,67
38	SOFC_L		Diesel, SOFC_L	0,67	0,53	1,00	0,14	0,50	1,00	1,00	0,66	5,17
39	SOFC_L		LNG, SOFC_L	0,68	0,43	0,00	0,42	0,00	0,25	1,00	0,76	4,75
40	SOFC_L		Methanol, SOFC_L	0,58	0,43	1,00	0,14	0,25	0,75	1,00	0,74	4,87
41	SOFC_L		Ammonia, SOFC_L	0,47	0,36	0,00	0,00	0,75	0,25	1,00	1,00	3,94
42	SOFC_L		Ethanol, SOFC_L	0,71	0,50	1,00	0,00	0,25	0,50	1,00	0,74	4,68
43	SOFC_L		Liquid DME, SOFC_L	0,63	0,45	0,00	0,00	0,00	0,75	0,75	0,75	3,60
44	LT-PEMFC	RENEWABLE	Formic Acid, LT-PEMFC	0,14	0,20	1,00	0,42	0,50	0,25	0,75	1,00	5,11
45	LT-PEMFC	RENEWABLE | FR	Methanol, LT-PEMFC	0,43	0,39	1,00	0,33	0,25	0,75	1,00	1,00	5,69
46	LT-PEMFC	RENEWABLE | FR	Liquid DME, LT-PEMFC	0,48	0,42	0,00	0,33	0,00	0,75	0,75	1,00	4,84
47	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC	0,47	0,40	1,00	0,89	0,25	0,75	1,00	1,00	7,38
48	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC, MFCU	0,48	0,36	1,00	0,89	0,25	0,75	1,00	1,00	7,30
49	SOFC	RENEWABLE	Methanol, SOFC	0,65	0,50	1,00	0,14	0,25	0,75	1,00	1,00	5,61
50	SOFC	RENEWABLE	Liquid DME, SOFC	0,79	0,58	0,00	0,00	0,00	0,75	0,75	1,00	4,59
51	LT-PEMFC_AIP	RENEWABLE	Formic Acid, LT-PEMFC_AIP	0,15	0,22	1,00	0,42	0,50	0,25	0,75	1,00	5,16
52	SOFC_L	RENEWABLE	Methanol, SOFC_L	0,58	0,43	1,00	0,14	0,25	0,75	1,00	1,00	5,40
53	SOFC_L	RENEWABLE	Liquid DME, SOFC_L	0,63	0,45	0,00	0,00	0,00	0,75	0,75	1,00	4,12

Time factor (t, hours):	357,14

Table C.4: Multi criteria analysis fuel cell systems

C.3.2. Ranked

				Normalized Ranking								
				Density			Maturity	Safety			Emission	
				Weight	Volume	Storage type	TRL	Fire hazard	Health hazard	Instability	CO2 emission	
									Overall Safety ranking:	1		
	Fuel cell:		Type of technology:	1,5	2,5	1	3,5	3	2	1	2,5	TOTAL:
25	DIESEL engine		Diesel engine, Engine (MTU 16V4000M73L)	1,00	1,00	1,00	1,00	0,50	1,00	1,00	0,54	8,84
26	DIESEL engine		Diesel engine, Genset (16V2000M41A)	0,91	0,82	1,00	1,00	0,50	1,00	1,00	0,55	8,35
47	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC	0,47	0,40	1,00	0,89	0,25	0,75	1,00	1,00	7,38
48	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC, MFCU	0,48	0,36	1,00	0,89	0,25	0,75	1,00	1,00	7,30
17	HT-PEMFC		Methanol, HT-PEMFC	0,47	0,40	1,00	0,89	0,25	0,75	1,00	0,60	6,56
18	HT-PEMFC		Methanol, HT-PEMFC, MFCU	0,48	0,36	1,00	0,89	0,25	0,75	1,00	0,60	6,47
34	LT-PEMFC_AIP		LOHC, LT-PEMFC_AIP	0,16	0,17	1,00	0,78	0,75	0,75	1,00	1,00	6,38
8	LT-PEMFC		LOHC, LT-PEMFC	0,15	0,15	1,00	0,78	0,75	0,75	1,00	1,00	6,35
36	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Small tank, Ready to buy)	0,04	0,19	0,00	0,89	1,00	1,00	1,00	1,00	5,94
10	LT-PEMFC		Metal Hydride, LT-PEMFC (Small tank, Ready to buy)	0,03	0,17	0,00	0,89	1,00	1,00	1,00	1,00	5,91
45	LT-PEMFC	RENEWABLE | FR	Methanol, LT-PEMFC	0,43	0,39	1,00	0,33	0,25	0,75	1,00	1,00	5,69
27	LT-PEMFC_AIP		LH2, LT-PEMFC_AIP	0,31	0,20	0,00	0,89	0,00	0,25	1,00	1,00	5,69
37	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Big rack, Ready to buy)	0,03	0,06	0,00	0,89	1,00	1,00	1,00	1,00	5,67
11	LT-PEMFC		Metal Hydride, LT-PEMFC (Big rack, Ready to buy)	0,03	0,05	0,00	0,89	1,00	1,00	1,00	1,00	5,66
1	LT-PEMFC		LH2, LT-PEMFC	0,30	0,18	0,00	0,89	0,00	0,25	1,00	1,00	5,64
49	SOFC	RENEWABLE	Methanol, SOFC	0,65	0,50	1,00	0,14	0,25	0,75	1,00	1,00	5,61
19	SOFC		Diesel, SOFC	0,79	0,66	1,00	0,14	0,50	1,00	1,00	0,61	5,51
29	LT-PEMFC_AIP		CH2 350 bar large H2 tank, LT-PEMFC_AIP	0,31	0,09	0,00	0,89	0,00	0,25	1,00	1,00	5,46
28	LT-PEMFC_AIP		CH2 700 bar small H2 tank, LT-PEMFC_AIP	0,25	0,12	0,00	0,89	0,00	0,25	1,00	1,00	5,44
3	LT-PEMFC		CH2 350 bar large H2 tank, LT-PEMFC	0,29	0,08	0,00	0,89	0,00	0,25	1,00	1,00	5,43
2	LT-PEMFC		CH2 700 bar small H2 tank, LT-PEMFC	0,24	0,11	0,00	0,89	0,00	0,25	1,00	1,00	5,40
52	SOFC_L	RENEWABLE	Methanol, SOFC_L	0,58	0,43	1,00	0,14	0,25	0,75	1,00	1,00	5,40
20	SOFC		LNG, SOFC	0,89	0,53	0,00	0,42	0,00	0,25	1,00	0,76	5,23
30	LT-PEMFC_AIP		CH2 250 bar container H2 tank, LT-PEMFC_AIP	0,20	0,05	0,00	0,89	0,00	0,25	1,00	1,00	5,23
4	LT-PEMFC		CH2 250 bar container H2 tank, LT-PEMFC	0,18	0,04	0,00	0,89	0,00	0,25	1,00	1,00	5,20
38	SOFC_L		Diesel, SOFC_L	0,67	0,53	1,00	0,14	0,50	1,00	1,00	0,66	5,17
51	LT-PEMFC_AIP	RENEWABLE	Formic Acid, LT-PEMFC_AIP	0,15	0,22	1,00	0,42	0,50	0,25	0,75	1,00	5,16
44	LT-PEMFC	RENEWABLE	Formic Acid, LT-PEMFC	0,14	0,20	1,00	0,42	0,50	0,25	0,75	1,00	5,11
13	LT-PEMFC	Flox reformer (FR)	Ethanol_R, LT-PEMFC, MS-30	0,57	0,51	1,00	0,33	0,25	0,50	1,00	0,51	5,02
21	SOFC		Methanol, SOFC	0,65	0,50	1,00	0,14	0,25	0,75	1,00	0,71	5,00
33	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (Powder, fuel exchange tank)	0,35	0,63	1,00	0,00	0,50	0,25	0,50	1,00	5,00
23	SOFC		Ethanol, SOFC	0,83	0,61	1,00	0,00	0,25	0,50	1,00	0,70	4,97
7	LT-PEMFC		SodiumBorohydride, LT-PEMFC (Powder, fuel exchange tank)	0,33	0,58	1,00	0,00	0,50	0,25	0,50	1,00	4,89
40	SOFC_L		Methanol, SOFC_L	0,58	0,43	1,00	0,14	0,25	0,75	1,00	0,74	4,87
46	LT-PEMFC	RENEWABLE | FR	Liquid DME, LT-PEMFC	0,48	0,42	0,00	0,33	0,00	0,75	0,75	1,00	4,84
39	SOFC_L		LNG, SOFC_L	0,68	0,43	0,00	0,42	0,00	0,25	1,00	0,76	4,75
12	LT-PEMFC	Flox reformer (FR)	Methanol_R, LT-PEMFC, MS-30	0,43	0,39	1,00	0,33	0,25	0,75	1,00	0,53	4,71
42	SOFC_L		Ethanol, SOFC_L	0,71	0,50	1,00	0,00	0,25	0,50	1,00	0,74	4,68
14	LT-PEMFC	Flox reformer (FR)	Ammonia_R, LT-PEMFC, MS-30	0,33	0,29	0,00	0,33	0,75	0,25	1,00	1,00	4,59
50	SOFC	RENEWABLE	Liquid DME, SOFC	0,79	0,58	0,00	0,00	0,00	0,75	0,75	1,00	4,59
35	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (MgH2 *NO STORAGE SYSTEM!*)	0,34	0,57	0,00	0,00	1,00	1,00	1,00	1,00	4,52
9	LT-PEMFC		Metal Hydride, LT-PEMFC (MgH2 *NO STORAGE SYSTEM!*)	0,32	0,53	0,00	0,00	1,00	1,00	1,00	1,00	4,42
16	LT-PEMFC	Flox reformer (FR)	LNG_R, LT-PEMFC, MS-30	0,55	0,38	0,00	0,50	0,00	0,25	1,00	0,56	4,30
22	SOFC		Ammonia, SOFC	0,56	0,43	0,00	0,00	0,75	0,25	1,00	1,00	4,20
53	SOFC_L	RENEWABLE	Liquid DME, SOFC_L	0,63	0,45	0,00	0,00	0,00	0,75	0,75	1,00	4,12
24	SOFC		Liquid DME, SOFC	0,79	0,58	0,00	0,00	0,00	0,75	0,75	0,75	4,06
41	SOFC_L		Ammonia, SOFC_L	0,47	0,36	0,00	0,00	0,75	0,25	1,00	1,00	3,94
15	LT-PEMFC	Flox reformer (FR)	Liquid DME_R, LT-PEMFC, MS-30	0,48	0,42	0,00	0,33	0,00	0,75	0,75	0,53	3,87
32	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (30% Fuel)	0,14	0,17	1,00	0,00	0,50	0,25	0,50	1,00	3,79
6	LT-PEMFC		SodiumBorohydride, LT-PEMFC (30% Fuel)	0,13	0,16	1,00	0,00	0,50	0,25	0,50	1,00	3,75
43	SOFC_L		Liquid DME, SOFC_L	0,63	0,45	0,00	0,00	0,00	0,75	0,75	0,75	3,60
31	LT-PEMFC_AIP		Formic Acid, LT-PEMFC_AIP *(NO Weight reformer!)*	0,15	0,22	1,00	0,42	0,50	0,25	0,75	0,07	3,23
5	LT-PEMFC		Formic Acid, LT-PEMFC *(NO Weight reformer!)*	0,14	0,20	1,00	0,42	0,50	0,25	0,75	0,00	3,03

Time factor (t, hours):	357,14

Table C.5: Ranked multi criteria analysis fuel cell systems

C.3.3. Sensitivity analysis

C.3.3.1. Matrix

			Type of technology:	Weight	Volume	Storage type	Maturity	Fire hazard	Health hazai	Instability	CO_2 emission	TOTAL, Based on 700 random values					
Nr.	Fuel cell:		Type of technology:	Random	Random	Random	Random	Random	Random	Random	Random	GeoMean	Rank	Average	Rank	Median	Rank
25	DIESEL engine		Diesel engine, Engine (MTU 16V4000M73L)	1,00	1,00	1,00	1,00	0,50	1,00	1,00	0,54	8,93	1	8,94	1	8,94	1
26	DIESEL engine		Diesel engine, Genset (16V2000M41A)	0,91	0,82	1,00	1,00	0,50	1,00	1,00	0,55	8,48	2	8,49	2	8,49	2
47	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC	0,47	0,40	1,00	0,89	0,25	0,75	1,00	1,00	7,31	3	7,34	3	7,33	3
48	HT-PEMFC	RENEWABLE	Methanol, HT-PEMFC, MFCU	0,48	0,36	1,00	0,89	0,25	0,75	1,00	1,00	7,24	4	7,28	4	7,27	4
19	SOFC		Diesel, SOFC	0,79	0,66	1,00	0,14	0,50	1,00	1,00	0,61	6,68	5	6,72	5	6,68	5
17	HT-PEMFC		Methanol, HT-PEMFC	0,47	0,40	1,00	0,89	0,25	0,75	1,00	0,60	6,65	6	6,67	6	6,68	6
49	SOFC	RENEWABLE	Methanol, SOFC	0,65	0,50	1,00	0,14	0,25	0,75	1,00	1,00	6,52	8	6,57	8	6,62	7
18	HT-PEMFC		Methanol, HT-PEMFC, MFCU	0,48	0,36	1,00	0,89	0,25	0,75	1,00	0,60	6,58	7	6,61	7	6,61	8
34	LT-PEMFC_AIP		LOHC, LT-PEMFC_AIP	0,16	0,17	1,00	0,78	0,75	0,75	1,00	1,00	6,44	9	6,50	9	6,47	9
8	LT-PEMFC		LOHC, LT-PEMFC	0,15	0,15	1,00	0,78	0,75	0,75	1,00	1,00	6,40	10	6,47	10	6,43	10
52	SOFC_L	RENEWABLE	Methanol, SOFC_L	0,58	0,43	1,00	0,14	0,25	0,75	1,00	1,00	6,30	12	6,36	12	6,39	11
45	LT-PEMFC	RENEWABLE | FR	Methanol, LT-PEMFC	0,43	0,39	1,00	0,33	0,25	0,75	1,00	1,00	6,30	13	6,35	13	6,37	12
38	SOFC_L		Diesel, SOFC_L	0,67	0,53	1,00	0,14	0,50	1,00	1,00	0,66	6,32	11	6,36	11	6,35	13
23	SOFC		Ethanol, SOFC	0,83	0,61	1,00	0,00	0,25	0,50	1,00	0,70	6,14	14	6,20	14	6,13	14
21	SOFC		Methanol, SOFC	0,65	0,50	1,00	0,14	0,25	0,75	1,00	0,71	6,04	15	6,08	15	6,07	15
40	SOFC_L		Methanol, SOFC_L	0,58	0,43	1,00	0,14	0,25	0,75	1,00	0,74	5,88	16	5,92	16	5,93	16
42	SOFC_L		Ethanol, SOFC_L	0,71	0,50	1,00	0,00	0,25	0,50	1,00	0,74	5,82	17	5,88	17	5,84	17
13	LT-PEMFC	Flox reformer (FR)	Ethanol_R, LT-PEMFC, MS-30	0,57	0,51	1,00	0,33	0,25	0,50	1,00	0,51	5,79	18	5,82	18	5,79	18
33	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (Powder, fuel exchange tank)	0,35	0,63	1,00	0,00	0,50	0,25	0,50	1,00	5,56	19	5,64	19	5,66	19
7	LT-PEMFC		SodiumBorohydride, LT-PEMFC (Powder, fuel exchange tank)	0,33	0,58	1,00	0,00	0,50	0,25	0,50	1,00	5,46	21	5,54	21	5,57	20
12	LT-PEMFC	Flox reformer (FR)	Methanol_R, LT-PEMFC, MS-30	0,43	0,39	1,00	0,33	0,25	0,75	1,00	0,53	5,51	20	5,54	20	5,52	21
51	LT-PEMFC_AIP	RENEWABLE	Formic Acid, LT-PEMFC_AIP	0,15	0,22	1,00	0,42	0,50	0,25	0,75	1,00	5,37	22	5,45	22	5,47	22
44	LT-PEMFC	RENEWABLE	Formic Acid, LT-PEMFC	0,14	0,20	1,00	0,42	0,50	0,25	0,75	1,00	5,33	23	5,40	23	5,43	23
36	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Small tank)	0,04	0,19	0,00	0,89	1,00	1,00	1,00	1,00	5,03	24	5,17	24	5,20	24
10	LT-PEMFC		Metal Hydride, LT-PEMFC (Small tank)	0,03	0,17	0,00	0,89	1,00	1,00	1,00	1,00	5,00	26	5,15	25	5,18	25
20	SOFC		LNG, SOFC	0,89	0,53	0,00	0,42	0,00	0,25	1,00	0,76	5,01	25	5,08	26	5,11	26
37	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (Big rack, Ready to buy)	0,03	0,06	0,00	0,89	1,00	1,00	1,00	1,00	4,79	27	4,95	27	4,98	27
11	LT-PEMFC		Metal Hydride, LT-PEMFC (Big rack, Ready to buy)	0,03	0,05	0,00	0,89	1,00	1,00	1,00	1,00	4,77	28	4,94	28	4,97	28
35	LT-PEMFC_AIP		Metal Hydride, LT-PEMFC_AIP (MgH2 NO STORAGE SYSTEM!)	0,34	0,57	0,00	0,00	1,00	1,00	1,00	1,00	4,75	29	4,87	29	4,84	29
50	SOFC	RENEWABLE	Liquid DME, SOFC	0,79	0,58	0,00	0,00	0,00	0,75	0,75	1,00	4,73	30	4,84	30	4,82	30
9	LT-PEMFC		Metal Hydride, LT-PEMFC (MgH2 NO STORAGE SYSTEM!)	0,32	0,53	0,00	0,00	1,00	1,00	1,00	1,00	4,65	31	4,77	31	4,73	31
27	LT-PEMFC_AIP		LH2, LT-PEMFC_AIP	0,31	0,20	0,00	0,89	0,00	0,25	1,00	1,00	4,59	32	4,71	32	4,73	32
1	LT-PEMFC		LH2, LT-PEMFC	0,30	0,18	0,00	0,89	0,00	0,25	1,00	1,00	4,53	33	4,65	33	4,68	33
46	LT-PEMFC	RENEWABLE | FR	Liquid DME, LT-PEMFC	0,48	0,42	0,00	0,33	0,00	0,75	0,75	1,00	4,51	34	4,58	34	4,63	34
39	SOFC_L		LNG, SOFC_L	0,68	0,43	0,00	0,42	0,00	0,25	1,00	0,76	4,49	35	4,55	35	4,59	35
32	LT-PEMFC_AIP		SodiumBorohydride, LT-PEMFC_AIP (30% Fuel)	0,14	0,17	1,00	0,00	0,50	0,25	0,50	1,00	4,38	37	4,51	37	4,58	36
29	LT-PEMFC_AIP		CH2 350 bar large H2 tank, LT-PEMFC_AIP	0,31	0,09	0,00	0,89	0,00	0,25	1,00	1,00	4,39	36	4,52	36	4,54	37
6	LT-PEMFC		SodiumBorohydride, LT-PEMFC (30% Fuel)	0,13	0,16	1,00	0,00	0,50	0,25	0,50	1,00	4,34	40	4,48	40	4,54	38
28	LT-PEMFC_AIP		CH2 700 bar small H2 tank, LT-PEMFC_AIP	0,25	0,12	0,00	0,89	0,00	0,25	1,00	1,00	4,33	41	4,46	41	4,51	39
3	LT-PEMFC		CH2 350 bar large H2 tank, LT-PEMFC	0,29	0,08	0,00	0,89	0,00	0,25	1,00	1,00	4,35	39	4,48	38	4,51	40
22	SOFC		Ammonia, SOFC	0,56	0,43	0,00	0,00	0,75	0,25	1,00	1,00	4,38	38	4,48	39	4,48	41
2	LT-PEMFC		CH2 700 bar small H2 tank, LT-PEMFC	0,24	0,11	0,00	0,89	0,00	0,25	1,00	1,00	4,29	44	4,42	42	4,47	42
14	LT-PEMFC	Flox reformer (FR)	Ammonia_R, LT-PEMFC, MS-30	0,33	0,29	0,00	0,33	0,75	0,25	1,00	1,00	4,30	43	4,39	44	4,38	43
24	SOFC		Liquid DME, SOFC	0,79	0,58	0,00	0,00	0,00	0,75	0,75	0,75	4,32	42	4,41	43	4,38	44
53	SOFC_L	RENEWABLE	Liquid DME, SOFC_L	0,63	0,45	0,00	0,00	0,00	0,75	0,75	1,00	4,24	45	4,34	45	4,34	45
30	LT-PEMFC_AIP		CH2 250 bar container H2 tank, LT-PEMFC_AIP	0,20	0,05	0,00	0,89	0,00	0,25	1,00	1,00	4,10	46	4,25	46	4,30	46
4	LT-PEMFC		CH2 250 bar container H2 tank, LT-PEMFC	0,18	0,04	0,00	0,89	0,00	0,25	1,00	1,00	4,07	48	4,22	47	4,27	47
41	SOFC_L		Ammonia, SOFC_L	0,47	0,36	0,00	0,00	0,75	0,25	1,00	1,00	4,10	47	4,20	48	4,20	48
16	LT-PEMFC	Flox reformer (FR)	LNG_R, LT-PEMFC, MS-30	0,55	0,38	0,00	0,50	0,00	0,25	1,00	0,56	3,97	49	4,02	49	4,03	49
43	SOFC_L		Liquid DME, SOFC_L	0,63	0,45	0,00	0,00	0,00	0,75	0,75	0,75	3,84	50	3,92	50	3,90	50
31	LT-PEMFC_AIP		Formic Acid, LT-PEMFC_AIP (NO Weight reformer!)	0,15	0,22	1,00	0,42	0,50	0,25	0,75	0,07	3,80	51	3,88	51	3,86	51
15	LT-PEMFC	Flox reformer (FR)	Liquid DME_R, LT-PEMFC, MS-30	0,48	0,42	0,00	0,33	0,00	0,75	0,75	0,53	3,75	52	3,80	52	3,81	52
5	LT-PEMFC		Formic Acid, LT-PEMFC (NO Weight reformer!)	0,14	0,20	1,00	0,42	0,50	0,25	0,75	0,00	3,61	53	3,71	53	3,68	53

Table C.6: Sensitivity analysis, ranked on median scores

C.3.3.2. Box-plot

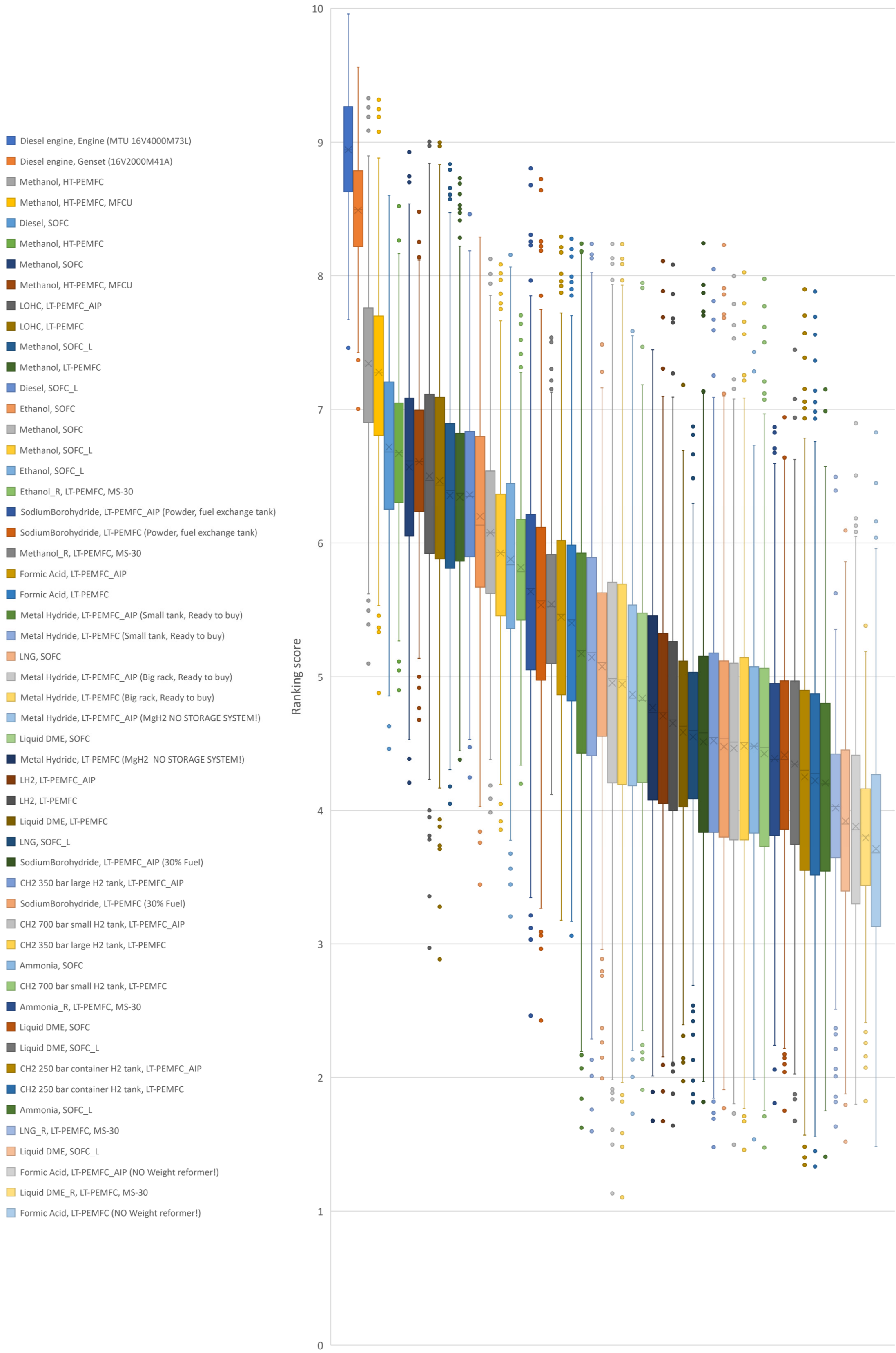


Figure C.1: Sensitivity analysis box-plot, ranked on median scores

D

Regulations

D.1. Methanol

For methanol three different references are used to compare the regulations concerning the storage and handling of methanol. These references are: IMO with the report of the 5th CCC for the revision of the IGF code [20], Lloyd's register[88] and DVN-GL[23]. Only the most important regulations for the initial design of a ship powered by methanol are mentioned, some rules have been omitted since these are not of big relevance now because of the high level of detail, but should be used during any final or more detailed design phase. The rules as mentioned below are directly quoted from the regulational documents as refered to in the right top of each section.

D.1.1. IGF Code

The IGF code is currently being revised, with this revision ethyl/methyl alcohols as well as fuel cells will be added to the code. Since the revision is still in progress and thereby no yet adopted by the IMO, the development report of the 5th CCC working group is used now.

Sub-committee on carriage of cargoes and containers 5th session , Agenda items 3 and 8[20]

IMO, 13 September 2018

General provisions
5.3.1 Tanks containing fuel should not be located within the accommodation spaces or machinery spaces of category A.
5.3.2 Integral fuel tanks should be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methyl/ethyl alcohol, or fuel preparation space.
5.3.3 The fuel containment system should be abaft of the collision bulkhead and forward of the aft peak bulkhead.

Provisions for machinery space
5.6.1 A single failure within the fuel system should not lead to a release of fuel into the machinery space.
5.6.2 All fuel piping within machinery space boundaries should be enclosed in gas and liquid tight enclosures.

Provisions for location and protection of fuel piping
5.7.1 Fuel pipes should not be located less than 800 mm from the ship's side.
5.7.2 Fuel piping should not be led directly through accommodation spaces, service spaces, electrical equipment rooms or control stations as defined in the SOLAS Convention.
5.7.4 Fuel piping should comply with the following:

1. *Fuel piping that passes through enclosed spaces in the ship should be enclosed in a pipe or duct that is gas and liquid tight towards the surrounding spaces with the fuel contained in the inner pipe. Such double walled piping is not required in cofferdams surrounding fuel tanks, fuel preparation spaces, spaces containing independent fuel tanks as the boundaries for these spaces will serve as a second barrier.*

2. *All fuel pipe should be self-draining to suitable fuel or collecting tanks in normal condition of trim and list of the ship. Alternative arrangements for draining the piping may be accepted by the Administration;*

Provisions for fuel preparation spaces design
5.8.1 Fuel preparation spaces should be located outside machinery spaces of category A.

Provisions for arrangement of entrances and other openings in enclosed spaces
5.11.1 Direct access should not be permitted from a non-hazardous area to a hazardous area. Where such openings are necessary for operational reasons, an airlock which complies with the provisions of section 5.12 should be provided..
5.11.2 Fuel preparation spaces should have independent access direct from open deck, where practicable. Where a separate access from open deck is not practicable, an airlock complying with section 5.12 should be provided.
5.11.3 Fuel tanks and surrounding cofferdams should have suitable access from the open deck, where practicable, for gas-freeing, cleaning, maintenance and inspection.
5.11.4 Without direct access to open deck, an entry space to fuel tanks or surrounding cofferdams should be provided and comply with the following:

1. *be fitted with an independent mechanical extraction ventilation system, providing a minimum of 6 air changes per hour. A low oxygen alarm and a gas detection alarm should be fitted;*
2. *All fuel pipe should be self-draining to suitable fuel or collecting tanks in normal condition of trim have sufficient open area around the fuel tank hatch for efficient evacuation and rescue operation;*
3. *not be an accommodation space, service space, control station or machinery space of category A; and*
4. *a cargo space may be accepted as an entry space, depending upon the type of cargo, if the area is cleared of cargo and no cargo operation is undertaken during entry to the space.*

5.11.6 For safe access, horizontal hatches or openings to or within fuel tanks or surrounding cofferdams should have a minimum clear opening of 600 X 600 mm that also facilitates the hoisting of an injured person from the bottom of the tank/cofferdam. For access through vertical openings providing main passage through the length and breadth within fuel tanks and cofferdams, the minimum clear opening should not be less than 600 X 800 mm at a height of not more than 600 mm from bottom plating unless gratings or footholds are provided. Smaller openings may be accepted provided evacuation of an injured person from the bottom of the tank/cofferdam can be demonstrated.

Provisions for airlocks
5.12.1 An airlock is a space enclosed by gas tight bulkheads with two gas tight doors spaced at least 1.5 m and not more than 2.5 m apart. Unless subject to the requirements of the International Convention on Load Line, the door sill should not be less than 300 mm in height. The doors should be self-closing without any hold-back arrangements.
5.12.3 Airlocks should have a simple geometrical form. They should provide for free and easy passage, and should have a deck area not less than 1.5 m2. Airlocks should not be used for other purposes, for instance as store rooms.

Fuel containment system
6.3.1 The fuel tanks should be fitted with a controlled tank venting system.
6.3.2 A fixed piping system should be arranged to enable each fuel tank to be safely gas freed, and to be safely filled with fuel from a gas-free condition.
6.3.4 Pressure and vacuum relief valves should be fitted to each fuel tank to limit the pressure or vacuum in the fuel tank. The tank venting system may consist of individual vents from each fuel tank or the vents from each individual fuel tank may be connected to a common header. Design and arrangement should prevent flame propagation into the fuel containment system. If pressure relief valves (PRVs) of the high velocity type are fitted to the end of the vent pipes, they should be certified for endurance burning in accordance with MSC/Circ.677. If PRVs are fitted in the vent line, the vent outlet should be fitted with a flame arrestor certified for endurance burning in accordance with MSC/Circ.677.
6.3.9 The fuel tank vent system should be connected to the highest point of each tank and vent lines should be self-draining under all normal operating conditions.
6.4.1 All fuel tanks should be inerted at all times during normal operation.
6.4.7 Fuel tank vent outlets should be situated normally not less than 3 m above the deck or gangway if located within 4 m from such gangways. The vent outlets are also to be arranged at a distance of at least 10m from the nearest air intake or opening to accommodation and service spaces and ignition sources. The vapour discharge should be directed upwards in the form of unimpeded jets.
6.4.9 The arrangements for gas-freeing and ventilation of fuel tanks should be such as to minimize the

hazards due to the dispersal of flammable vapours to the atmosphere and to flammable gas mixture in the tanks. The ventilation system for fuel tanks should be exclusively for ventilating and gas freeing purposes. Connection between fuel tank and fuel preparation space ventilation will not be accepted.
6.4.10 Gas-freeing operations should be carried out such that vapour is initially discharged in one of the following ways:

1. *through outlets at least 3 m above the deck level with a vertical efflux velocity of at least 30 m/s maintained during the gas freeing operation;*
2. *through outlets at least 3 m above the deck level with a vertical efflux velocity of at least 20 m/s which are protected by suitable devices to prevent the passage of flame; or*
3. *through outlets underwater.*

6.5.1 Inert gas should be available permanently on board in order to achieve at least one trip from port to port considering maximum consumption of fuel expected and maximum length of trip expected and to keep tanks inerted during two weeks in harbour with minimum port consumption.
6.5.2 A production plant and/or adequate storage capacities might be used to achieve availability target defined in 6.5.1.

Fuel supply to consumers
9.4.1 The outer pipe or duct should be gas and liquid tight.
9.4.2 The annular space between inner and outer pipe should have mechanical ventilation of underpressure type with a capacity of minimum 30 air changes per hour and be ventilated to open air. Appropriate means for detecting leakage into the annular space should be provided. The double wall enclosure should be connected to a suitable draining tank allowing the collection and the detection of any possible leakage.
9.4.3 Inerting of the annular space might be accepted as an alternative to ventilation. Appropriate means of detecting leakage into the annular space should be provided. Suitable alarms should be provided to indicate a loss of inert gas pressure between the pipes.
9.5.1 Propulsion and power generation arrangements, together with fuel supply systems should be arranged, so that a failure in fuel supply does not lead to an unacceptable loss of power.
9.6.1 All fuel piping should be arranged for gas-freeing and inerting.
9.7.1 Any fuel preparation space should not be located within a machinery space of category A, should be gas- and liquid-tight to surrounding enclosed spaces and vented to open air.

Ventilation
13.3.1 Ventilation inlets and outlets for spaces required to be fitted with mechanical ventilation should be so located that according to International Load Line Convention they will not be required to have closing appliances.
13.3.2 Any ducting used for the ventilation of hazardous spaces should be separate from that used for the ventilation of non-hazardous spaces. The ventilation should function at all temperatures and environmental conditions the ship will be operating in.
13.3.6 Air inlets for hazardous enclosed spaces should be taken from areas that, in the absence of the considered inlet, would be non-hazardous. Air inlets for non-hazardous enclosed spaces should be taken from non-hazardous areas at least 1.5 m away from the boundaries of any hazardous area. Where the inlet duct passes through a more hazardous space, the duct should be gas tight and have over-pressure relative to this space.
13.4.1 Fuel preparation spaces should be provided with an effective mechanical forced ventilation system of extraction type. During normal operation the ventilation should be at least 30 air changes per hour.

D.1.2. Lloyds Register, Provisional Rules for the classification of methanol fuelled ships, July 2019

Fuel storage hold space: is an enclosed or semi-enclosed area in which an independent methanol fuel storage tank is located.

Rules for the Classification of Methanol Fuelled Ships

Lloyd's Register
2019

Materials, components and equipment

4.2.2: Materials that are sensitive to methanol and methanol containing water, such as aluminium alloys, galvanised steel, lead alloys, nitrile, buthyl and others shall not be used in systems containing fuel.
4.2.5: Tank coatings and tank access hatch sealing materials shall be resistant to: methanol liquid, methanol where it may contain water, methanol vapour, gases used for inerting.

Location and arrangement of spaces

5.1.2 Escape routes shall not pass through hazardous areas.

5.3.1 Fuel storage tanks can be integral tanks or independent tanks.
5.3.2 Fuel storage tanks shall not be located within the accommodation area or high fire risk spaces such as machinery spaces of category A.
5.3.3 No part of the outer extent of fuel storage tanks shall be less than 800mm inboard from the ship shell side or from the boundary of any adjacent space except as otherwise allowed.
5.3.5 Spaces forward of the collision bulkhead (fore peak) ad/or, aft of the after most bulkhead (aft peak) shall not be arranged as fuel storage tanks.
5.3.6 Integral fuel storage tanks shall be surrounded by a cofferdam where not bounded by bottom shell plating or fuel pump rooms.

5.4.1 All equipment containing fuel that is provided for supply to consumers shall be located in a dedicated space (e.g. a pump room) an these spaces shall be:

- *a) considered hazardous;*
- *b) gas-tight and liquid-tight;*
- *c) provided with approved piping and cabling penetrations;*
- *d) located outside of he machinery spaces.*

5.4.2 The fuel supply system and equipment shall not be adjacent to accommodation spaces, service spaces or control stations, where practicable.

5.6.1 Direct access from a non-hazardous space to a hazardous space is not permitted. Where access from a non-hazardous space to a hazardous space is required for operational reasons, an air-lock shall be provided
5.6.2 Air-locks shall be:

- *a) of simple geometric from;*
- *b) provided with clear passage;*
- *c) comprise of two self-closing gas tight steel doors.*

5.6.3 Air-locks shall be:

- *a) spaced at least 1.5m by no more than 2.5m apart;*
- *b) provided without any hold-back arrangements;*
- *c) capable of maintaining the differential pressure.*

5.6.4 The air-lock space shall be maintained with a differential pressure and shall ensure that no fuel can be released to non-hazardous spaces in the event of a fuel release into the hazardous spaces
5.6.5 The air-lock space shall be mechanically ventilated from non-hazardous area.
5.6.12 Fuel storage tanks and surrounding cofferdams shall have suitable access from open deck for cleaning, maintenance, inspection and purging of fuel.
5.6.13 The pump room shall have an independent access direct from open deck. An airlock shall be provided where this is not practicable.

5.6.14 For fuel storage tanks and cofferdams without direct access from open deck, the arrangements shall be such to ensure that, these spaces are free from flammable and toxic vapour or other gases that represent a hazard to the crew before any access hatch is opened.
5.6.15 For fuel storage tanks or cofferdams without direct access from open deck, the entry space shall comply with the following:

a) *the entry space shall be well ventilated;*
b) *the entry space shall have sufficient open area around the fuel storage tank hatch for efficient evacuation and rescue operation.*

5.6.16 Direct access to fuel storage tanks or cofferdams from accommodation spaces, service spaces, control stations and machinery spaces of category A will not be accepted.
5.6.18 Horizontal hatches or openings to or within fuel storage tanks or cofferdams shall have a minimum clear opening of 600x600mm that also facilitates the hoisting of an injured person from the bottom of the tank/cofferdam.

5.7.3 All enclosed hazardous areas, except for cofferdams, shall be provided with fixed mechanical ventilation of negative pressure that has a capacity of at least 30 air changes per hour under all foreseeable operating conditions, including a single failure in equipment or control system. The arrangements shall be such that there will be no regions of stagnant air within the ventilated space.
5.7.4 Air supplied for ventilation shall be in addition to the air supplied for combustion in consumers.
5.7.5 Ventilation exhaust shall discharge to atmosphere at least 3m from the nearest air intakes or open decks that are accessible to personnel, or openings to accommodation and enclosed working spaces, and from any possible source of ignition, to ensure that any such opening, air intake or source of ignition lies outside the hazardous area associated with the ventilation exhaust.

System Design
6.3.2 All tank connections, fittings, flanges and tank valves shall be enclosed in a cofferdam or a space meeting the requirements of a cofferdam
6.3.3 Arrangement shall be provided to: safely drain and empty fuel from the fuel storage tanks, safely purge and vent the fuel storage tanks.
6.3.4 Arrangements shall be provided to:

a) *safely drain and empty fuel from the fuel storage tanks;*
b) *safely purge (i.e. make liquid and vapour free) and vent the fuel storage tanks.*

6.3.5 For single fuel installations (methanol only), the fuel storage shall be arranged in no fewer than two tanks so that, in the event of any one tank becoming unavailable, the remaining tanks(s) will provide sufficient fuel to enable the ship to operate within its service profile. The tanks shall be located in separate fire-protected compartments.
6.3.10 The maximum degree of filling of fuel tanks shall be 98 per cent. This is the maximum allowable liquid volume relative to the tank volume to which the tank may be loaded.
6.3.11 The fuel storage tank venting system shall be designed with redundancy for the relief of full flow over pressure and/or vacuum.
6.3.13 The outlet from the pressure relief valves shall normally be located at least B/3 or 6m, whichever is greater, above the weather deck an 6m above the working area and gangways, where B is the greatest moulded breadth of the ship in meters. The outlet from pressure relief valves shall be led to the opening at least 10m from the nearest air intake or opening to accommodation spaces, service spaces and control stations, or open decks which are accessible to personnel, or other non-hazardous spaces. It is also to be located at least 10m from the nearest exhaust outlet from machinery installations.

6.5.7. For installations with a single source of propulsion power, arrangements shall be such that, in case of loss of the fuel supply, a secondary separate and independent fuel supply shall be available.
6.5.10 All fuel supply piping within non-hazardous areas shall be enclosed in a gastight enclosure, i.e. double-walled piping or ventilated gastight ducting.

Inert gas system
6.8.1 Provision shall be made for supply of nitrogen inert gas. This shall be either through on board generation or inert gas or through an inert gas storage system with provision for refilling from shore.
6.8.2 The inerting arrangements shall provide for: inerting of all fuel piping during normal operation and emergency shutdown activation, inerting of methanol-fuelled consumers, atmospheric control, fire protection system.

Piping
7.2.13 Fuel piping is not to be located less than 800mm from the ship's side.

7.2.14 Fuel piping shall be entirely separate from other piping systems and is not to pass through accommodation, service spaces and control stations.
7.2.16 All fuel supply piping within enclosed spaces, including machinery spaces, shall be enclosed in a secondary gastight and liquid-tight enclosure of the following type:

a) *double-walled piping or ventilated ducting provided with forced draught ventilation;*
b) *double-walled piping with the annular space between pipes pressurised with inert gas;*
c) *cofferdam*

D.1.3. DNV Fuel, Section 6 Low flashpoint liquid fuelled engines - LFL fuelled

Part 6 Additional class notations Chapter 2 Propulsion, power generation and auxiliary systems [23]

DNV-GL
Edition January 2018

Fuel storage
3.2.1.1 Fuel tanks shall not be located within machinery spaces or within accomodation spaces.
3.2.1.2 Other tanks containing LFL-fuel, e.g. drain tanks, shall not be located within machinery spaces or within accomodation spaces.
3.2.1.3 Minimum distance between the fuel tank and fuel pipes and the ship's side shell shall be at least 800mm.
3.2.1.4 The spaces forward of the collision bulkhead (forepeak) and aft of the aftermost bulkhead (afterpeak) shall not be used as fuel tanks.
3.2.1.5 Each fuel service tank shall have a capacity sufficient for continuous rating of the propulsion plant and normal operating load at sea of the generator plant for a period of not less than 8 hours.
3.2.2.1 In ships other than tankers, integral fuel tanks for LFL shall be surrounded by protective cofferdams, except on those surfaces bound by bottom shell plating or the fuel pump room.
3.2.2.2 The cofferdams shall be arranged with vapour and liquid leakage detection and possibility for water filling upon detection of leakage. The water filling shall be through a system without permanent connections to water systems in non-hazardous areas. Emptying shall be done with a separate system. Bilge ejectors serving hazardous spaces shall not be permanently connected to the drive water system.
3.2.3.1 Fuel tanks shall be provided with an arrangement for inert gas purging and gas freeing.
3.2.3.2 Fuel tanks shall have a sufficient number of ventilation inlets and outlets to ensure complete gas-freeing. Outlets for ventilation and purging shall be fitted with flame screens of approved type, see IMO MSC/Circ.677
3.2.3.4 Vent outlets from p/v valves and outlets for purging shall be led to open air and located so that the hazardous zone associated with the outlets does not conflict with ventilation inlets or outlets for gas safe spaces or equipment representing sources of ignition. The venting system shall be connected to the highest point of each fuel tank and vent lines shall be selfdraining under all normal operating conditions of list and trim.
3.2.3.8 Intake openings of pressure/vacuum relief valves shall be located at least 1.5 m above weather deck, and shall be protected against the sea.
3.2.3.9 Fuel tank vent outlets shall be situated not less than 3 m above the deck or gangway if located within 4 m from such gangways. The fuel tank vent outlets are also to be arranged at a distance of at least 10 m from the nearest air intake or opening to accommodation and service spaces and ignition sources. The vapour discharge shall be directed upwards in the form of unimpeded jets.
3.2.3.12 Gas freeing of fuel tanks shall be carried out in a way that flammable atmosphere in the tank is avoided, i.e. by purging tank with inert gas until gas content is below 2% before ventilation with air is started. Purging and gas freeing operations shall be carried out such that vapour is initially discharged through outlets at least 2 m above the deck level with a vertical efflux velocity of at least 20 m/s.

Fuel transfer and supply
3.3.1.1 The fuel system shall be entirely separate from all other piping systems on board.
3.3.1.2 The piping shall be located no less than 800 mm from the ship side.
3.3.1.3 All piping containing LFL shall be arranged for gas-freeing and inerting.
3.3.2.2 All piping containing LFL that pass through enclosed spaces in the ship shall be enclosed in a pipe that is gas tight and water tight towards the surrounding spaces with the LFL contained in the inner pipe. Such double walled piping is not required in cofferdams surrounding fuel tanks, fuel pump rooms, fuel tank hold spaces or other hazardous fuel treatment spaces as the boundaries for these spaces will serve as a second barrier.
3.3.2.3 Fuel piping shall not be lead through accommodation spaces, service spaces or control stations. In cases where fuel piping shall be led through accommodation spaces, the double walled fuel piping shall be led through a dedicated duct. The duct shall be of substantial construction and be gas tight and water tight.
3.3.2.4 The annular space in the double walled fuel pipe shall have mechanical ventilation of underpressure type with a capacity of minimum 30 air changes per hour. Ventilation inlets and outlets shall be located in open air. The annular space shall be equipped with vapour and liquid leakage detection.
3.3.2.7 There shall be no openings between the annular space in the double walled fuel piping and enclosed spaces in the ship.

3.3.5.1 Any pump room shall be located outside the engine room, be gas tight and water tight to surrounding enclosed spaces and vented to open air.
3.3.5.2 The pump room shall have separate mechanical ventilation of underpressure type with capacity of minimum 30 air changes per hour.
3.4.1.1 For safe access, horizontal hatches or openings to or within fuel tanks or cofferdams shall have a minimum clear opening of 600 × 600 mm that also facilitates the hoisting of an injured person from the bottom of the tank/cofferdam. For access through vertical openings providing main passage through the length and breadth within cargo tanks and cofferdams, the minimum clear opening shall not be less than 600 × 800 mm at a height of not more than 600 mm from bottom plating unless gratings or footholds are provided. Smaller openings may be accepted provided evacuation of an injured person from the bottom of the tank/cofferdam can be demonstrated.
3.4.1.3 Fuel tanks and surrounding cofferdams shall have suitable access from open deck for cleaning and gas-freeing, except as given in [3.4.1.4] and [3.4.1.5] below.
3.4.1.4 For fuel tanks without direct access from open deck, the arrangement shall be such that before opening any tank access located in enclosed spaces, the tanks shall be completely free of flammable gas or other gases that represent a hazard to the crew.
3.4.1.5 For fuel tanks without direct access from open deck, the entry space shall comply with the following:

- *The entry space shall be well ventilated.*
- *The entry space shall have sufficient open area around the fuel tank hatch for efficient evacuation and rescue operations.*
- *Entry from accommodation spaces, service spaces, control stations and machinery spaces will not be accepted.*
- *Entry from cargo areas may be accepted if the area is cleared for cargo and no cargo operations are ongoing during tank entry.*

3.4.2.1 Entrance to the pump room shall be from open deck. Access from an enclosed space through an air lock may be accepted upon special considerations. If accepted, airlocks shall comply with the requirements as given in Sec.5 [3.4].
3.5.1.4 Ventilation inlets and outlets for spaces required to be fitted with mechanical ventilation in this rule section shall be so located that ingress of seawater is avoided. A location of minimum 4.5 m above the freeboard deck is regarded acceptable.
3.5.2.1 Air inlets for hazardous enclosed spaces shall be taken from areas which, in the absence of the considered inlet, would be non-hazardous. Air inlets for non-hazardous enclosed spaces shall be taken from non-hazardous areas at least 1.5 m away from the boundaries of any hazardous area. Where the inlet duct passes through a more hazardous space, the duct shall have over-pressure relative to this space, unless mechanical integrity and gas-tightness of the duct will ensure that gases will not leak into it.
3.7.1.1 All tanks containing LFL shall be inerted regardless of size.
3.7.1.6 Where a nitrogen generator or nitrogen storage facilities are installed in a separate compartment, outside of the engine room, the separate compartment shall be fitted with an independent mechanical extraction ventilation system, providing 6 air changes per hour. A low oxygen alarm shall be fitted. Such separate compartments shall be treated as one of other machinery spaces, with respect to fire protection.
3.8.1.4 All consumers of LFL fuel shall have a separate exhaust system.

D.2. Fuel Cell

For the fuel cell installation the regulation from DNV-GL part 6 chapter 2 section 3 (Fuel cell installations -FC) are used.[23]

Part 6 Additional class notations Chapter 2 Propulsion, power generation and auxiliary systems [23]

DNV-GL
Edition January 2018

General
3.1.1 The design shall ensure that a single failure in the FC power installation shall not lead to an unacceptable loss of power.

Requirements for fuel cell power systems
4.1.1 All primary and reformed fuel piping shall be fitted with secondary enclosure capable of safely containing any leakages. An arrangement where the secondary enclosure is nitrogen filled and monitored for pressure may be an acceptable solution.
4.1.2 Alternatively, the following arrangement may be accepted: All primary and reformed fuel pipes shall be fully welded. The ventilation rate in the fuel cell space shall be sufficient to dilute the gas concentration below the flammable range in all leakage scenarios, including pipe rupture. Possible liquid leakages shall be shielded from ignition sources.
4.2.1 Exhaust air and exhaust gases from the fuel cell power systems shall be led to the open air and shall not be combined with ventilation systems.
4.2.2 If the presence of explosive gases cannot be excluded, the exhaust air and/or exhaust gas shall be arranged as an outlet from a hazardous zone.
4.3.1 Purge piping from the fuel cell power systems shall be led separately to the open air and shall be arranged as an outlet from a hazardous zone.

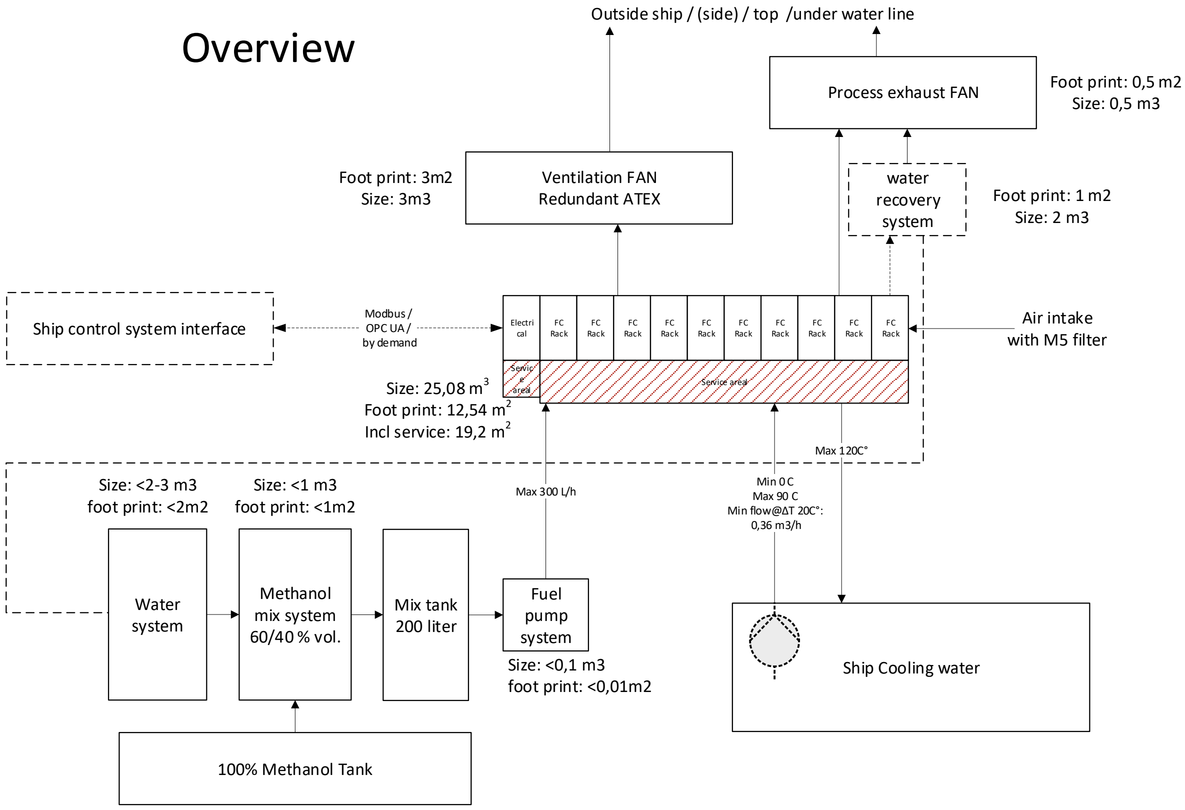
Design principles for fuel cell spaces
5.1.1 Fuel cell space boundaries shall be gas tight towards other enclosed spaces in the ship.
5.1.2 Fuel cell spaces shall be designed to safely contain fuel leakages.
5.1.3 Fuel cell spaces shall be arranged to avoid the accumulation of hydrogen rich gas by having simple geometrical shape and no obstructing structures in the upper part. Large fuel cell spaces shall be arranged with a smooth ceiling sloping up towards the ventilation outlet. Thin plate ceiling to cover support structure under the deck plating is not acceptable.
5.1.4 Fuel cell spaces containing fuel reformers shall also comply with the requirements relevant for the primary fuel.
5.1.5 Tanks for intermediate storage of primary or reformed fuel, if necessary, shall be located outside the fuel cell space containing the fuel cells.
5.2.1 Fuel cell spaces shall be arranged outside of accommodation, service and machinery spaces and control stations.
5.2.2 Where an independent and direct access to the fuel cell spaces from the open deck cannot be arranged, access to fuel cell spaces shall be through an air lock.

5.3.1.1 Fuel cell spaces shall be equipped with a mechanical ventilation system of the extraction type providing effective ventilation of the complete space, also taking into consideration the density of potentially leaking fuel gases.
5.3.1.3 Any ducting used for the ventilation of fuel cell spaces shall not serve any other spaces.
5.3.1.6 Two fans shall be installed for the ventilation of the fuel cell space with 100% capacity each. Both fans shall be supplied from separate circuits.

5.3.2.1 Ventilation air inlets for fuel cell spaces shall be taken from areas, which in the absence of the considered inlet would be non-hazardous.
5.3.2.2 Ventilation air inlets for non-hazardous enclosed spaces shall be taken from non-hazardous areas at least 1.5 m away from the boundaries of any hazardous area.
5.3.3.1 Ventilation air outlets from fuel cell spaces shall be located in an open area which, in the absence of the considered outlet, would be of the same or lesser hazard than the ventilated space.

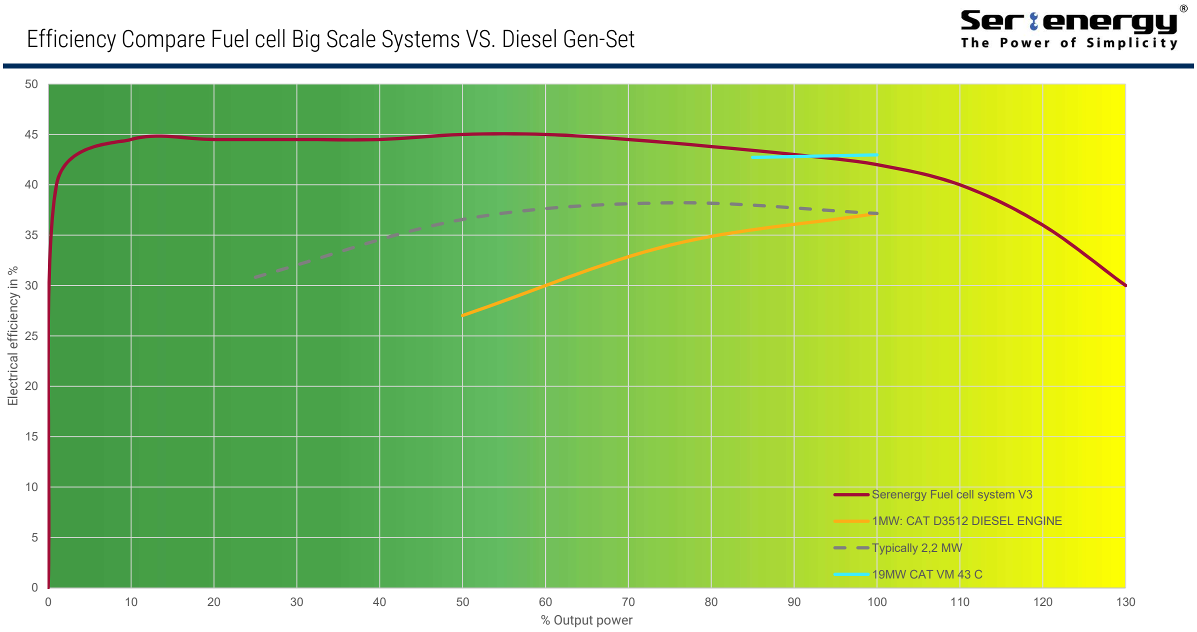
E

Serenergy MFCU



Source: SerEnergy A/S [5]

Figure E.1: Serenergy MFCU system overview



Source: SerEnergy A/S [5]

Figure E.2: Serenergy efficiency diagram

F

Propulsion efficiency calculations

	TU Delft			ABB	
	Shaft	Pod		Shaft	Pod
		1	2		
Pe	1	0,909090909		1	0,909091
η_O	0,69	0,66			
η_H	0,88	0,88	0,93		
η_R	1	1			
η_D	0,6072	0,5808	0,6138	0,686	0,708

Legend

- Diesel
- Diesel electric
- Fuel Cell Electric
- Shaft
- Pod

		MAN		ABB	
		1	2		
η_S_diesel	0,97	0,903	0,923	0,91	|--> Diesel electric, 3% differnce for generator
η_S_full _electric		0,903 0,933	0,943 0,953	0,94	

Options, nS	nS	nD [TU Delft]		nT		Pe	Pd=x*Pe		Pb=x*Pe		%Change	
Twin shaft, diesel only	0,97	0,6072		0,588984		1	1,646904		1,697839			
Twin shaft, diesel-elect . MAN1	0,903	0,6072		0,548302		1	1,646904		1,823814		7,4%	
Twin shaft, diesel-elect. MAN2	0,923	0,6072		0,560446		1	1,646904		1,784294		5,1%	
Pod, diesel-elect. ABB	0,91	0,5808	0,6138	0,528528	0,558558	0,909091	*1,565239*	*1,481087*	1,720043	1,627568	1,3%	-4,1%
Twin shaft, elect . MAN1	0,903	0,6072		0,548302		1	**1,646904**		**1,823814**		7,4%	
Twin shaft, elect. MAN2	0,943	0,6072		0,57259		1	**1,646904**		**1,746452**		2,9%	
POD, elect . MAN1	0,933	0,5808	0,6138	0,541886	0,572675	0,909091	1,565239	1,481087	**1,677641**	1,587445	-1,2%	-6,5%
POD, elect. MAN2	0,953	0,5808	0,6138	0,553502	0,584951	0,909091	1,565239	1,481087	1,642434	**1,554131**	-3,3%	-8,5%
POD, elect. ABB	0,94	0,5808	0,6138	0,545952	0,576972	0,909091	1,565239	1,481087	1,665148	1,575624	-1,9%	-7,2%

Options, nS	nS	nD [ABB]	nT	Pe	Pd=x*Pe	Pb=x*Pe	%Change	
Twin shaft, diesel only ABB	0,965	0,686	0,66199	1	1,457726	1,510597		
Twin shaft, diesel-elect . MAN1	0,903	0,686	0,619458	1	1,457726	1,614314	6,9%	
Twin shaft, diesel-elect. MAN2	0,923	0,686	0,633178	1	1,457726	1,579335	4,6%	
Pod, diesel-elect. ABB	0,91	0,708	0,64428	0,909091	*1,284027*	1,411018	**-6,6%**	|->Value ABB
Twin shaft, elect . MAN1	0,903	0,686	0,619458	1	**1,457726**	**1,614314**	6,9%	
Twin shaft, elect. MAN2	0,943	0,686	0,646898	1	**1,457726**	**1,545839**	2,3%	
POD, elect . MAN1	0,933	0,708	0,660564	0,909091	1,284027	**1,376234**	-8,9%	
POD, elect. MAN2	0,953	0,708	0,674724	0,909091	1,284027	1,347352	-10,8%	
POD, elect. ABB	0,94	0,708	0,66552	0,909091	1,284027	1,365986	-9,6%	

Data sources to calculate these efficiencies and needed propulsion power: [32, 60, 71]

Table F.1: Propulsion efficiency calculations

G

Zero emission auxiliaries

Including TRL

#	Fuel cell:	Type of technology:	Weight	Volume	Storage type	TRL	Fire hazard	Health hazard	Instability	SCORE:
			Density			Maturity	Safety			
							Overall Safety ranking:		1	
			1,5	2,5	1	3,5	3	2	1	
16	LT-PEMFC_AIP	LOHC, LT-PEMFC_AIP	0,16	0,16	1,00	0,78	0,75	0,75	1,00	5,43
7	LT-PEMFC	LOHC, LT-PEMFC	0,15	0,15	1,00	0,78	0,75	0,75	1,00	5,39
17	LT-PEMFC_AIP	Metal Hydride, LT-PEMFC_AIP (Small tank)	0,04	0,19	0,00	0,89	1,00	1,00	1,00	4,88
8	LT-PEMFC	Metal Hydride, LT-PEMFC (Small tank)	0,03	0,17	0,00	0,89	1,00	1,00	1,00	4,84
10	LT-PEMFC_AIP	LH2, LT-PEMFC_AIP	0,32	0,20	0,00	0,89	0,00	0,25	1,00	4,56
18	LT-PEMFC_AIP	Metal Hydride, LT-PEMFC_AIP (Big rack, Ready to buy)	0,03	0,06	0,00	0,89	1,00	1,00	1,00	4,53
9	LT-PEMFC	Metal Hydride, LT-PEMFC (Big rack, Ready to buy)	0,03	0,05	0,00	0,89	1,00	1,00	1,00	4,51
1	LT-PEMFC	LH2, LT-PEMFC	0,30	0,18	0,00	0,89	0,00	0,25	1,00	4,49
12	LT-PEMFC_AIP	CH2 350 bar large H2 tank, LT-PEMFC_AIP	0,31	0,09	0,00	0,89	0,00	0,25	1,00	4,27
11	LT-PEMFC_AIP	CH2 700 bar small H2 tank, LT-PEMFC_AIP	0,25	0,12	0,00	0,89	0,00	0,25	1,00	4,24
3	LT-PEMFC	CH2 350 bar large H2 tank, LT-PEMFC	0,29	0,09	0,00	0,89	0,00	0,25	1,00	4,22
2	LT-PEMFC	CH2 700 bar small H2 tank, LT-PEMFC	0,24	0,11	0,00	0,89	0,00	0,25	1,00	4,20
13	LT-PEMFC_AIP	CH2 250 bar container H2 tank, LT-PEMFC_AIP	0,20	0,05	0,00	0,89	0,00	0,25	1,00	3,97
4	LT-PEMFC	CH2 250 bar container H2 tank, LT-PEMFC	0,19	0,04	0,00	0,89	0,00	0,25	1,00	3,94
15	LT-PEMFC_AIP	SodiumBorohydride, LT-PEMFC_AIP (Powder, fuel exchange tank)	0,35	0,63	1,00	0,00	0,50	0,25	0,50	3,69
6	LT-PEMFC	SodiumBorohydride, LT-PEMFC (Powder, fuel exchange tank)	0,33	0,59	1,00	0,00	0,50	0,25	0,50	3,55
14	LT-PEMFC_AIP	SodiumBorohydride, LT-PEMFC_AIP (30% Fuel)	0,14	0,17	1,00	0,00	0,50	0,25	0,50	2,15
5	LT-PEMFC	SodiumBorohydride, LT-PEMFC (30% Fuel)	0,13	0,16	1,00	0,00	0,50	0,25	0,50	2,11

Normalized Ranking

Time factor (t, hours): 336,00

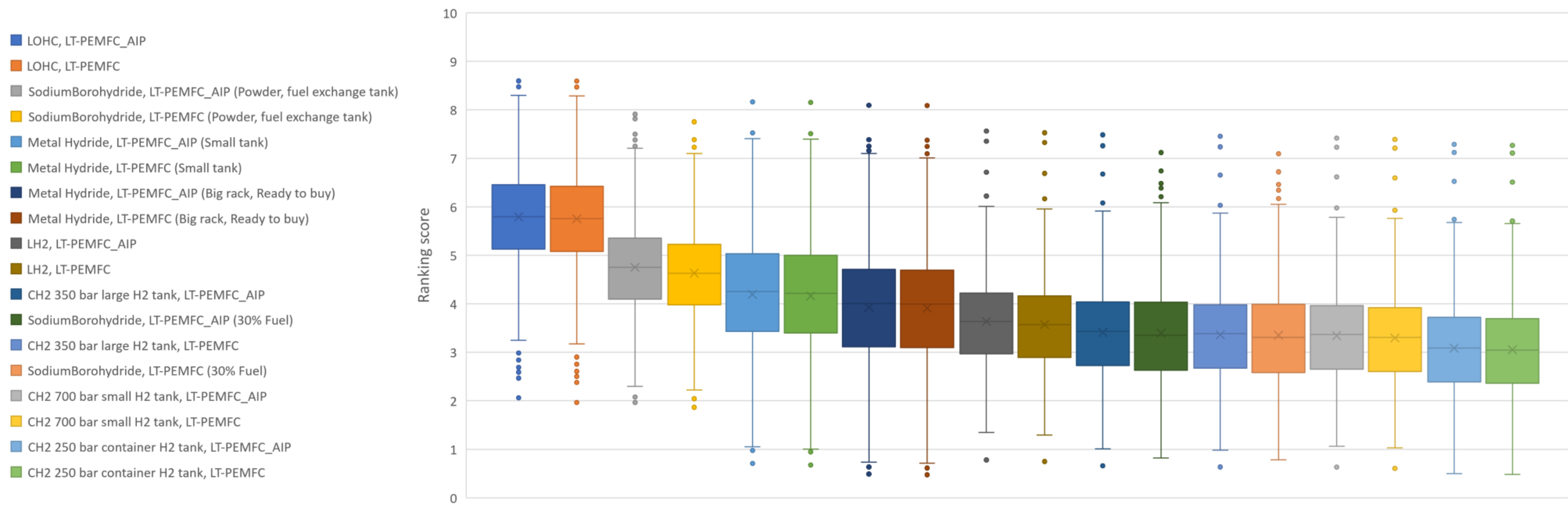


Figure G.1: Zero emission solutions, ranking and sensitivity analysis including TRL levels

Without TRL

	Fuel cell:	Type of technology:	Weight	Volume	Storage type	TRL	Fire hazard	Health hazard	Instability	SCORE:
			Density			Maturity	Safety			
			Normalized Ranking				Overall Safety ranking:		1	
			1,5	2,5	1	0	3	2	1	
15	LT-PEMFC_AIP	SodiumBorohydride, LT-PEMFC_AIP (Powder, fuel exchange tank)	0,35	0,63	1,00	0,00	0,50	0,25	0,50	5,84
6	LT-PEMFC	SodiumBorohydride, LT-PEMFC (Powder, fuel exchange tank)	0,33	0,59	1,00	0,00	0,50	0,25	0,50	5,62
16	LT-PEMFC_AIP	LOHC, LT-PEMFC_AIP	0,16	0,16	1,00	0,78	0,75	0,75	1,00	4,06
7	LT-PEMFC	LOHC, LT-PEMFC	0,15	0,15	1,00	0,78	0,75	0,75	1,00	3,99
14	LT-PEMFC_AIP	SodiumBorohydride, LT-PEMFC_AIP (30% Fuel)	0,14	0,17	1,00	0,00	0,50	0,25	0,50	3,41
5	LT-PEMFC	SodiumBorohydride, LT-PEMFC (30% Fuel)	0,13	0,16	1,00	0,00	0,50	0,25	0,50	3,34
17	LT-PEMFC_AIP	Metal Hydride, LT-PEMFC_AIP (Small tank)	0,04	0,19	0,00	0,89	1,00	1,00	1,00	2,54
8	LT-PEMFC	Metal Hydride, LT-PEMFC (Small tank)	0,03	0,17	0,00	0,89	1,00	1,00	1,00	2,47
10	LT-PEMFC_AIP	LH2, LT-PEMFC_AIP	0,32	0,20	0,00	0,89	0,00	0,25	1,00	2,03
18	LT-PEMFC_AIP	Metal Hydride, LT-PEMFC_AIP (Big rack, Ready to buy)	0,03	0,06	0,00	0,89	1,00	1,00	1,00	1,99
9	LT-PEMFC	Metal Hydride, LT-PEMFC (Big rack, Ready to buy)	0,03	0,05	0,00	0,89	1,00	1,00	1,00	1,96
1	LT-PEMFC	LH2, LT-PEMFC	0,30	0,18	0,00	0,89	0,00	0,25	1,00	1,93
12	LT-PEMFC_AIP	CH2 350 bar large H2 tank, LT-PEMFC_AIP	0,31	0,09	0,00	0,89	0,00	0,25	1,00	1,57
11	LT-PEMFC_AIP	CH2 700 bar small H2 tank, LT-PEMFC_AIP	0,25	0,12	0,00	0,89	0,00	0,25	1,00	1,53
3	LT-PEMFC	CH2 350 bar large H2 tank, LT-PEMFC	0,29	0,09	0,00	0,89	0,00	0,25	1,00	1,50
2	LT-PEMFC	CH2 700 bar small H2 tank, LT-PEMFC	0,24	0,11	0,00	0,89	0,00	0,25	1,00	1,46
13	LT-PEMFC_AIP	CH2 250 bar container H2 tank, LT-PEMFC_AIP	0,20	0,05	0,00	0,89	0,00	0,25	1,00	1,10
4	LT-PEMFC	CH2 250 bar container H2 tank, LT-PEMFC	0,19	0,04	0,00	0,89	0,00	0,25	1,00	1,06

Time factor (t, hours):	336,00

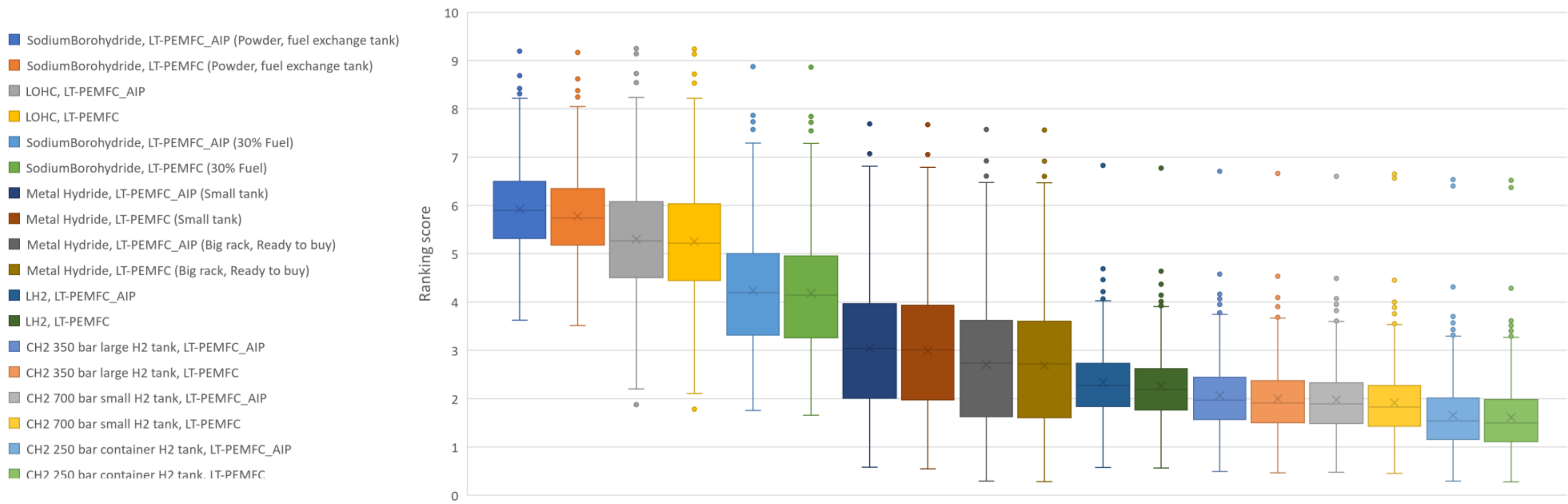
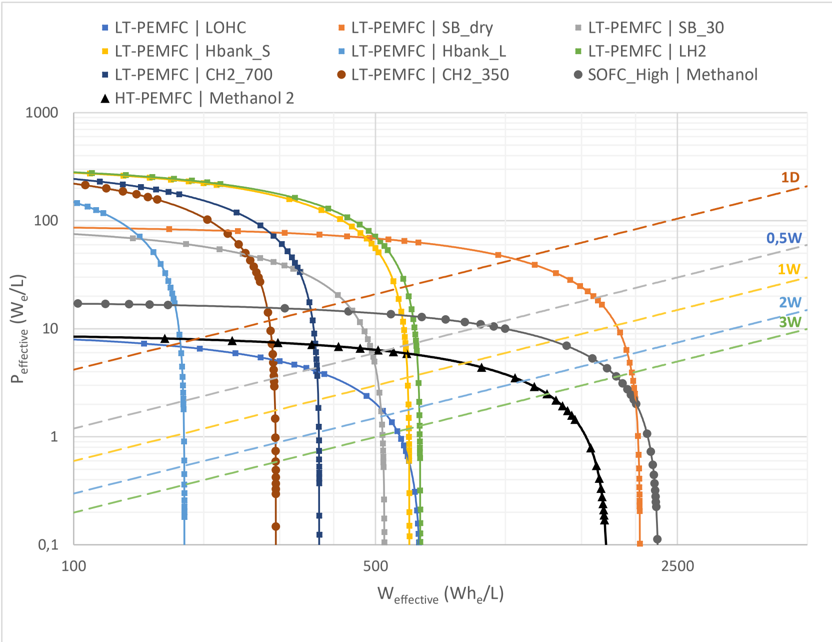


Figure G.2: Zero emission solutions, ranking and sensitivity analysis without TRL levels

Reference	Fuel ton	Fuel m3		Nr.	Energy converter ton	Energy converter m3	Fuel Reformer ton	Fuel Reformer m3		Total ton	Total norm.	Total m3	Total norm.
MGO	47,7	53,6	Genset	1	12,61	25,30	0,00	0,00		60,32	0,5	78,91	0,4
MeOH (Methanol)	**96,0**	**120,9**	**HT-PEMFC**	**3**	**21,90**	**75,24**	**0,00**	**0,00**		**117,93**	**1,0**	**196,17**	**1,0**
Zero emission solutions													
Sodium Borohydride (dry) HighDensityRef.	68,0	63,4	LT-PEMFC, Power Cell MS100	7	1,05	2,36	9,38	9,38	Integral tank	78,42	0,7	75,19	0,4
Sodium Borohydride (dry) LowDensityRef.	68,0	63,4		7	1,05	2,36	32,16	32,16		101,20	0,9	97,97	0,5
Sodium Borohydride Spent-fuel (filtered) min	168,9	84,4		7	1,05	2,36	9,38	9,38		179,33	1,5	96,19	0,5
Sodium Borohydride Spent-fuel (filtered) max	183,8	176,7		7	1,05	2,36	32,16	32,16		217,01	1,8	211,23	1,1
Sodium Borohydride Spent-fuel (unfiltered) min	215,6	165,8		7	1,05	2,36	9,38	9,38		226,03	1,9	177,52	0,9
LOHC	427,9	390,0		7	1,05	2,36	?	69,07		428,92	3,6	461,47	2,4
Compressed 350 bar large H2 tank	*230,1*	*910,7*		*7*	*1,05*	*2,36*	*0,00*	*0,00*	Independent tank	*231,13*	2,0	*913,03*	4,7
Compressed 700 bar small H2 tank	*281,5*	*722,8*		*7*	*1,05*	*2,36*	*0,00*	*0,00*		*282,58*	2,4	*725,13*	3,7
Cryogenic liquid H2	*189,6*	*354,5*		*7*	*1,05*	*2,36*	*0,00*	*0,00*		*190,66*	1,6	*356,87*	1,8
Hbank (AB-5 type alloy), Small tank, HB-SC-0660-N	*1653,3*	*375,5*		*7*	*1,05*	*2,36*	*0,00*	*0,00*		*1654,40*	14,0	*377,87*	1,9
Hbank (AB-5 type alloy), Rack HB-SS 16500	*1814,9*	*1246,2*		*7*	*1,05*	*2,36*	*0,00*	*0,00*		*1815,96*	15,4	*1248,61*	6,4



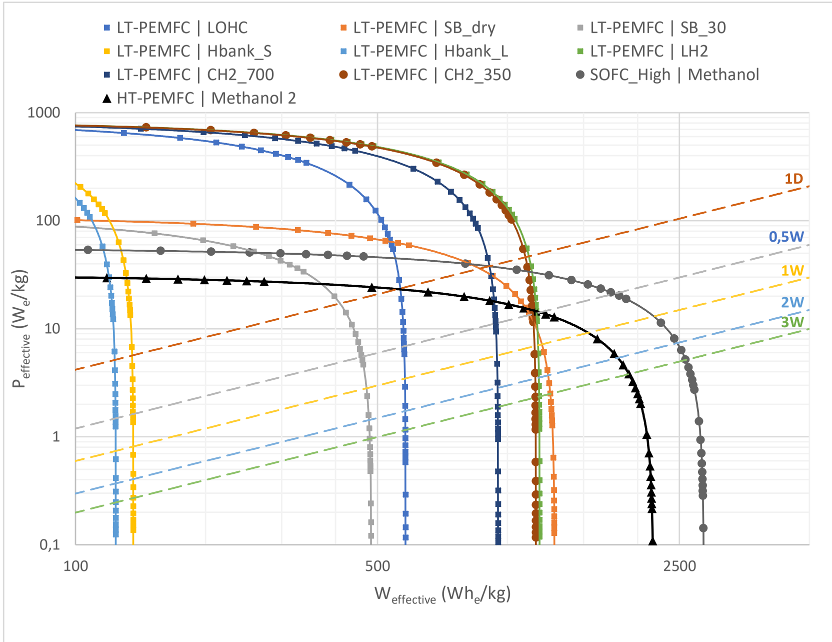


Figure G.3: Zero emission solutions, compared on weight and size