MSc Marine Technology

Feasibility study and concept design on the use of solid oxide fuel cells fuelled by methanol on board of an offshore patrol vessel

Master's thesis

by

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TU Delft Delft University of Technology

Nevesbu
Naval Architects
Since 1935

Thesis for the degree of MSc in Marine Technology in the specializations of Ship Design & Marine Engineering

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Performed at

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Preface

I discovered my passion for technology when I visited with my parents and my brother the Solar Platform of Almeria fifteen years ago. It amazed me how it was possible to obtain energy from a source that came from the sky. I didn't understand it.

After some twists and turns, years later I ended up studying an engineering degree in Delft. Not only was it a technical degree, but it also had a special relation with my biggest hobby: sailing. I liked it so much, that I decided to follow with the Master of Science in Marine Technology. Before you, lies the result of the last year: my master's thesis.

Many have contributed to this report. Nevesbu with its people played a very important role. Not only for the opportunity, but also because of all of those that were open to sit and talk, to me to help me with their expertise. Thank you.

To all the experts that were interviewed during this thesis, especially to Prof. dr. Robert Selman; and to all the manufacturers that provided me with useful information to make my thesis more precise, such as Reintjes Powertrain Solutions. Thank you.

Thanks as well to the external members of my assessment committee Wouter Beelaerts van Blokland and Jurriaan Peeters for taking the time to read my master's thesis. Thanks to Lindert van Biert for being so open for discussion and for adding quality to the content of my thesis, enlightening the uncertain path towards fuel cells. To Professor Hans Hopman, thank you very much for having me as a graduate student. You pushed me to think outside the box and to see the full picture. To Sven Los, daily supervisor and receiver of my many questions. Thank you for teaching me how a ship is designed. I'm very glad I got to learn from you the practical side of the job.

Thanks to my parents and my family for being always there, no matter where we are. Thanks as well to all my friends in Delft, who made me feel at home.

I hope you, the reader, enjoy this report. If it makes you half as passionate as me about the topic, it will be a good sign. Thank you for taking the time.

This thesis sets the end point of my time in Delft. Many experiences and many lessons. It was worth it.

Dedicated to my grandpa, Prof. dr. ir. Gerard Hirs, who sadly passed away during the last phase of this thesis. His love for this university and this city were an inspiration for me to move to Delft to do my studies.

Aldo Hirs Álvarez
Delft, January 2023

Summary

Currently, the energy transition is a topic for discussion and many organizations are taking measures to reduce the effects of climate change. Armed forces are exempt of these new regulations on the grounds of national security, but some have already started taking steps to reduce the amount of harmful emissions.

Due to the high efficiency and advantages that fuel cells present, the aim of this master's thesis is to study their feasibility on board of a naval surface vessel, testing it in a concept design.

The main research question states:

What combination of naval surface vessel, fuel cell, and hydrogen carrier is the most suitable for the medium-term implementation of a fuel-cell-based power plant, and what is the effect of the implementation of such a power plant on the design, operational capabilities, and emissions of the vessel?

This report consists of two main parts. The first part tries to find the most suitable combination of naval surface vessel, type of fuel cell, and type of hydrogen carrier. Due to the nature of the operations that naval surface vessels perform, understanding their requirements is crucial: the vessel must be able to perform specific types of missions, paying close attention to safety. Therefore, the selection of type of naval surface vessel, fuel cell, and hydrogen carrier must match with each other. It is concluded that the types of naval surface vessels that could benefit the most from the use of fuel cells are frigates and mine warfare vessels, in order to reduce their acoustic signatures; and offshore patrol vessels (OPVs), due to their constant base load, because it is a type of ship that is mostly cruising or patrolling.

Solid oxide fuel cells (SOFCs) are here considered to be the most promising type of fuel cells for naval surface vessels. This is not only because of their high efficiency, but also due to their ability to internally reform hydrogen carriers, making them more versatile. Other fuels than pure hydrogen can therefore be selected, which leads to the choice of ethanol and methanol as best candidates. The latter has already shown good performance when combined with SOFCs and is largely available worldwide.

Next, in the second part of this report, the concept design of an OPV using SOFCs fuelled by methanol is tested. On a systems level, the integration of SOFCs adds multiple elements and complexity to the power plant of the concept design. Moreover, since the SOFCs are only used to generate the base load needed to reach cruising speed and its auxiliary power, a peak power source is needed to reach higher speeds. After having considered batteries, diesel engines, and methanol engines, it was concluded that methanol engines provide the highest operational flexibility, on top of being the lightest combination.

The power plant of the concept design is able to fit in the engine room despite its larger volume, due to the lower clearance that fuel cells require, making a more efficient use of the space. Regarding the systems that were already included in the reference design and stay in the concept design, none of them experience significant changes. In terms of weight, both the lightweight and the deadweight of the concept design increase, approximately with a hundred tons each. This is because of the lower power density of fuel cells, the complexity in systems that they entail, and the lower energy density of methanol.

When comparing the concept design to the reference design, they both score similarly in terms of redundancy and they both fulfil the same design requirements. In terms of operational capabilities, the concept design can sprint for less time due to the difference in efficiency of the power source used to cruise (fuel cells) and to sprint (methanol engines), and does not have the ability to extend its range above the design requirement, opposite to what the reference design can.

The use of a SOFC-based power plant shows a reduction in CO_2 emissions between 13-23% depending on the type of mission, a 100% reduction of SOx and PM due to the use of methanol as a fuel, and a reduction of at least 68% in NOx emissions.

Finally, it can be concluded that the integration of fuel cells in a naval surface vessel is considered to be feasible, obtaining a significant reduction of harmful emissions. The recommendations that are done for further research are to study the combination of SOFCs with some kind of heat recovery system to increase their efficiency, to keep in mind ethanol as a possible fuel for this concept design, and to make a power management system that can regulate the energy flow in this more complex power plant.

Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
AFC	Alkaline Fuel Cell
AFR	Air-to-fuel ratio
AIP	Air Independent Propulsion
AoO	Area of Operations
ATR	Autothermal Reforming
BoP	Balance of Plant
BW	Ballast Water
CODAD	Combined Diesel and Diesel
CPOx	Catalytic Partial Oxidation
CPP	Controllable Pitch Propeller
CSA	Compact Solid Oxide Architecture
DC	Direct Current
DE	Diesel Engine
DG	Diesel Generator
DIR	Direct Internal Reforming
DME	Dimethyl Ether
DoD	Depth of Discharge
EEZ	Exclusive Economic Zone
EM	Electric Motor
ER	Engine Room
EU	European Union
FiFi	Fire-fighting
FW	Fresh Water
GA	General Arrangement
GT	Gas Turbine
HT	High Temperature
HV	High Voltage
HVAC	Heat, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
IIR	Indirect Internal Reforming
IMO	International Maritime Organization
IR	Infrared
LCC	Amphibious Command Ship
LCG	Longitudinal Center of Gravity
LDUUV	Large Displacement Underwater Unmanned Vehicle
LHA	Landing Helicopter Assault Ship
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPD	Landing Platform Dock
LT	Low Temperature
MCFC	Molten Carbonate Fuel Cell
ME	Main Engine
Meth.E	Methanol Engine
MGO	Marine Gas Oil

Abbreviation	Definition
NATO	North Atlantic Treaty Organization
NMC	Nickel Manganese Cobalt
NOx	Nitrogen Oxides
OPV	Offshore Patrol Vessel
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Polymer Exchange Membrane Fuel Cell
PHE	Plate Heat Exchanger
PM	Particulate Matter
PrOx	Preferential Oxidation
PSA	Pressure Swing Adsorption
PTI	Power take-in
RAS	Replenishment at Sea
RCS	Radar Cross-Section
RHIB	Rigid-Hulled Inflatable Boat
SBR	Switchboard Room
SFC	Specific Fuel Consumption
SMET	Selective Methanation
SOFC	Solid Oxide Fuel Cell
SOx	Sulphur Oxides
SR	Steam Reforming
ST	Steam Turbine
SW	Sea Water
TCG	Transverse Center of Gravity
TEU	Twenty-Foot Equivalent
TRL	Technology Readiness Level
US	United States
UUV	Underwater Unmanned Vehicle
VCG	Vertical Center of Gravity
VFD	Variable-Frequency Drive
WGS	Water Gas Shift

Symbols

n	Revolutions per minute	rpm
Pb	Brake power	kW
λ	Equivalent air-to-fuel ratio	-

Contents

1

Introduction

This report presents to you the master's thesis for the Master of Science in Marine Technology at TU Delft. In this chapter, the problem definition, the objective and research questions, and the methodology and structure of such are presented.

1.1. Problem definition

The energy transition is a current topic for discussion. Multiple organizations, like the International Maritime Organization (IMO), have taken measures to mitigate the effects of global warming by regulating the emission of greenhouse gasses. Although armies are exempt of these compromises on the grounds of national security, it is estimated that the world's armed forces are responsible for between 1% and 5% of global emissions (Rajaeifar et al., 2022). Some armies, like the US military, produce more harmful emissions than many countries (their army would be the 55th largest CO_2 emitter if it were a country) (McCarthy, 2019).

Therefore, some have agreed to reduce their harmful emissions. NATO, for example, aims to cut its civilian and military greenhouse gas emissions by at least 45% by 2030 and to be carbon neutral by 2050 (Siebold, 2022). In this process, naval vessels play a crucial role.

If the capabilities of a vessel want to be kept the same, the reduction of emissions can come either from an improvement in the fuel or from the technology that is used on board of a vessel. Nowadays, vessels are mostly driven by fossil fuels. Methods such as increasing the quality of the fuel can have an impact on the emissions; for example, by reducing the amount of sulphur, the formation of sulphur oxides (SOx) can be reduced. However, other emissions like carbon dioxide are not tackled and will continue to be an issue. As van de Ketterij, 2018 explains, according to the plans of the Dutch Operational Energy Strategy, the measures taken to meet the objectives of the Treaty of Paris by 2030 are insufficient. Another option to reduce the emissions is to make use of a technology that is more efficient with the fuel it consumes. Multiple alternatives are possible and fuel cells can be especially beneficial since they have advantages that can be favorable for naval surface vessels.

Fuel cells are able to generate electricity having hydrogen as fuel. The only product after the chemical reaction in the fuel cell when working on pure hydrogen is water, which is not harmful. This technology has been pointed out by some in research as one with a lot of potential (van Biert, 2020, van der Schueren, 2022). Currently, fuel cells are mostly used in the automotive industry in hydrogen cars, and in submarines as part of the air independent propulsion system (AIP). From the literature it is proven that fuel cells can even have higher efficiencies than the traditional internal combustion engines (ICEs) (van Biert et al., 2016). However, despite the good results that the literature presents, no implementation of this technology has been done at a large scale.

Twenty three years ago, Gunter Sattler was already writing about the potential that fuel cells could have in the future of the shipping sector (Sattler, 2000). Not only did he mention the application to commercial vessels, but also to naval surface vessels. A lot of options were discussed in his paper, from the different kinds of fuel cells, to the different hydrogen carriers and the possibility to generate hydrogen from them on board. Since then, a lot of research has been done and many authors have contributed to the development and studies on fuel cells. When one looks at naval surface vessels, these have stricter requirements than commercial vessels. Fuel cells have many advantages that can be very useful for naval surface vessels. Some of these are the fact that they reduce noise and vibration, infrared signatures and maintenance, and have a flexible and modular design (van Biert et al., 2016). Moreover, the use of hydrogen carriers instead of pure hydrogen can increase the volumetric energy density of the fuel, making fuel cells more attractive.

Apart from being more efficient and, thus, generate less harmful emissions, fuel cells are already being used in submarines, so why not in naval surface vessels as well? The research presented hereby aims to investigate the feasibility of the application of fuel cells in naval surface vessels.

Nevesbu, an engineering company specialized in the design of naval vessels located in Alblasserdam (the Netherlands), is interested in investigating the application of fuel cells on board of naval surface vessels in the medium term. Therefore, this investigation is commissioned by them.

1.2. Objective and main research question

The goal of this master's thesis is to study the feasibility of the use of fuel cells on board of naval surface vessels in the medium term.

Thus, the main research question of the literature review of this master thesis is:

What combination of naval surface vessel, fuel cell, and hydrogen carrier is the most suitable for the medium-term implementation of a fuel-cell-based power plant, and what is the effect of the implementation of such a power plant on the design, operational capabilities, and emissions of the vessel?

In the first part, the objective is to find a suitable combination of naval surface vessel, fuel cell, and hydrogen carrier and to gather as much information as possible in order to gain enough insight to define clearly how the research needs to be done in the second phase. In the second part, starting from the conclusions of the literature review, the concept design is carried out and it is studied whether fuel cells on board of a naval surface vessel are a feasible option.

1.3. Structure of the report

This research consists of two main parts. The firs one: the literature review. The second one: the concept design.

From the literature review a conclusion is drawn, stating for which kind of naval surface vessel, fuel cell, and hydrogen carrier it is considered that the use of fuel cells could have an added value. In the concept design phase this is put into practice and designed. Finally, the feasibility of the new design can be tested by comparing the new concept design to the reference design.

In chapter 2 the sub-questions and structure of the literature review are presented. In chapter 8 the concept design starts with new sub-questions originating from the conclusions of the literature review. In this case, the concept design is done for an OPV fuelled by methanol that makes use of solid oxide fuel cells (SOFCs).

Finally, in chapter 12 the new concept design is compared with the reference design, to analyse the differences in terms of redundancy, operational capabilities, and emissions. In chapter 13 a sensitivity analysis is performed, and in chapter 14 the conclusions of this master's thesis are presented.

Part I

Literature Review

2

Literature Review Approach

In this first part of the master's thesis the literature review is carried out.

2.1. Objective and research questions

The objective of the literature review is to gather as much information as possible, to conclude for which type of naval surface vessel, fuel cell, and hydrogen carrier the use of fuel cells could have an added value.

Thus, the main research question of the literature review of this master thesis is:

What combination of naval surface vessel, fuel cell, and hydrogen carrier is the most suitable for the implementation of a fuel-cell-based power plant in the medium term?

In order to make this question manageable, some sub-questions are presented that will be answered in the following chapters:

- What are the different types of naval surface vessels and what are their requirements?
- What is a fuel cell and what are the different kinds?
- How can fuel cells be advantageous in a naval surface vessel?
- What are the different hydrogen carriers and how can they be stored in a naval surface vessel to be used by fuel cells?
- How have fuel cells been used so far for maritime applications and why?
- What is the state of the development of fuel cells and what options are there on the market?
- What type of naval surface vessel is the most suitable for the use of fuel cells?
- What is the most suitable combination of fuel cell and fuel to be used on board of a naval surface vessel?

2.2. Structure of the literature review

In order to gather as much information as possible, this research does not only consist of papers published in multiple journals, but also from other sources. These sources include manufacturers and their product specifications, and interviews with experts.

The method that is used in the literature review is to first analyse each of the topics separately, to finally combine them. This research consists of three more theoretical topics: naval surface vessels, fuel cells, and hydrogen carriers.

In chapter 3 this literature review starts by presenting the different kinds of naval surface vessels and their requirements. Naval vessels have stricter requirements than commercial vessels, thus in this chapter the bar is set for fuel cells and hydrogen carriers.

Next, in chapter 4 a theoretical explanation is done about fuel cells. Their working principle, and the different types and the components required are presented. Also, a comparison with ICEs is done.

In chapter 5 the different hydrogen carriers are discussed, where the focus lies on aspects like energy density, storage, and emissions; but also on the safety, since they need to be used on board of a naval surface vessel.

Chapter 6 presents the projects done on fuel cells so far when applied in a maritime environment. Also, the state of the development of the different fuel cells and the different options on the market are analysed.

Finally, in chapter 7 the selection is done. Here, a naval surface vessel and a specific power plant (consisting of a type of fuel cell and a hydrogen carrier) is chosen. The choice made in this chapter is the one that to be designed in the second part of this master's thesis.

3

Naval surface vessels

In order to be able to use fuel cells on board of naval vessels it is crucial to understand what are the different kinds of naval surface vessels and the requirements they have. As mentioned in chapter 1, apart from being more efficient than ICEs, fuel cells have some advantages that can be interesting for their use on board of naval surface vessels. In order to understand the characteristics of naval surface vessels in section 3.1 the different types are described, followed by their requirements in section 3.2.

3.1. Types of naval vessels

The classification of the different types of naval surface vessels is dependent per country. In Figure 3.1 some naval vessels in their categories are plotted by displacement and top speed. One can notice that there is some overlap between the categories. Despite this overlap, a trend within the groups can be observed, be it either by displacement or top speed. Due to their large displacements and few examples of this type, aircraft carriers have been left out the graph.

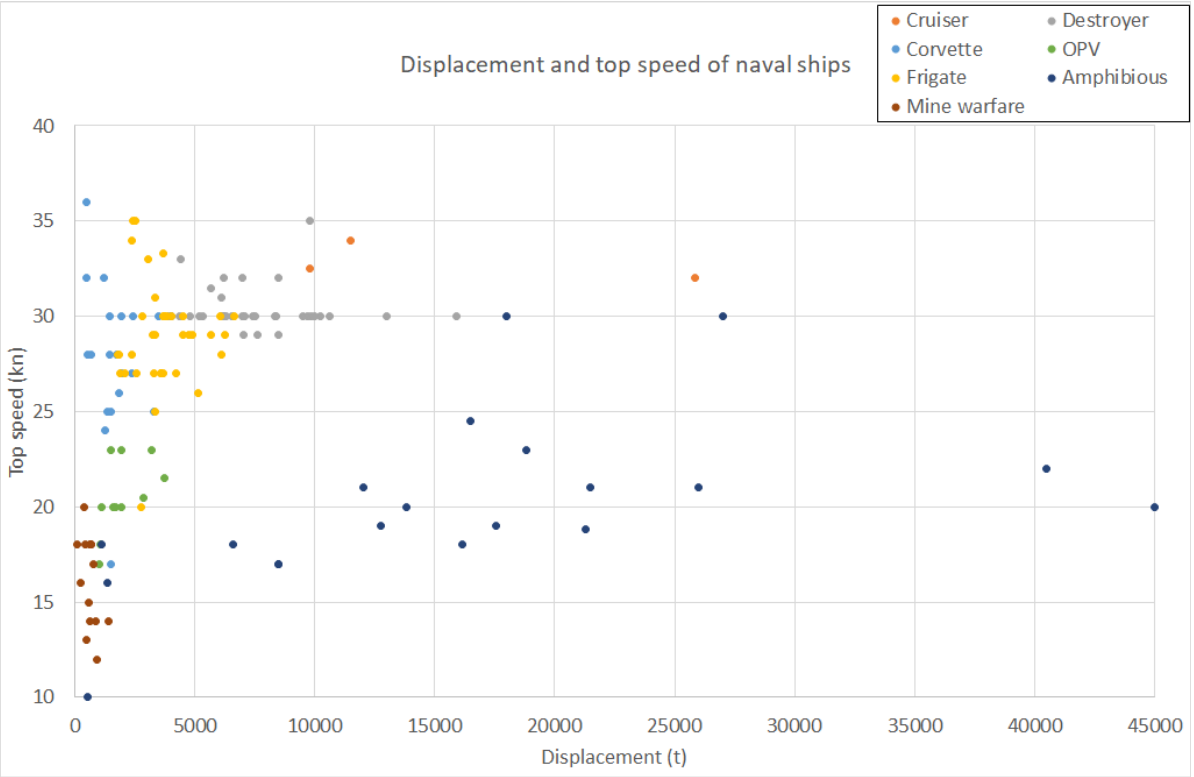

Figure 3.1: Naval surface vessels sorted by displacement and top speed (Wikipedia, 2022).

Another way to categorize naval ships is their operational cluster. According to NATO Naval Group 6, 2004, there are four operational clusters: *Military Aid*, *Military Patrol*, *Military Control*, and *Military Power*. *Military Aid* is related to benign operations like disaster relief operations, humanitarian assistance, non combatant evacuation operations, and search and rescue. *Military Patrol* refers to law enforcement or constabulary operations. These include maritime security, safety of navigation at sea, border control, and environmental protection. *Military Control* stands for all naval sea control operations. Think of gathering information, protection of sea lines of communications and high value units, embargoes and sanctions. Finally, *Military Power* has to do with all power projection operations. These can be amphibious operations, neutralise naval forces or support air and land campaigns. In Figure 3.2, an overview of different naval vessels and their functional spectrum and operational cluster is shown.

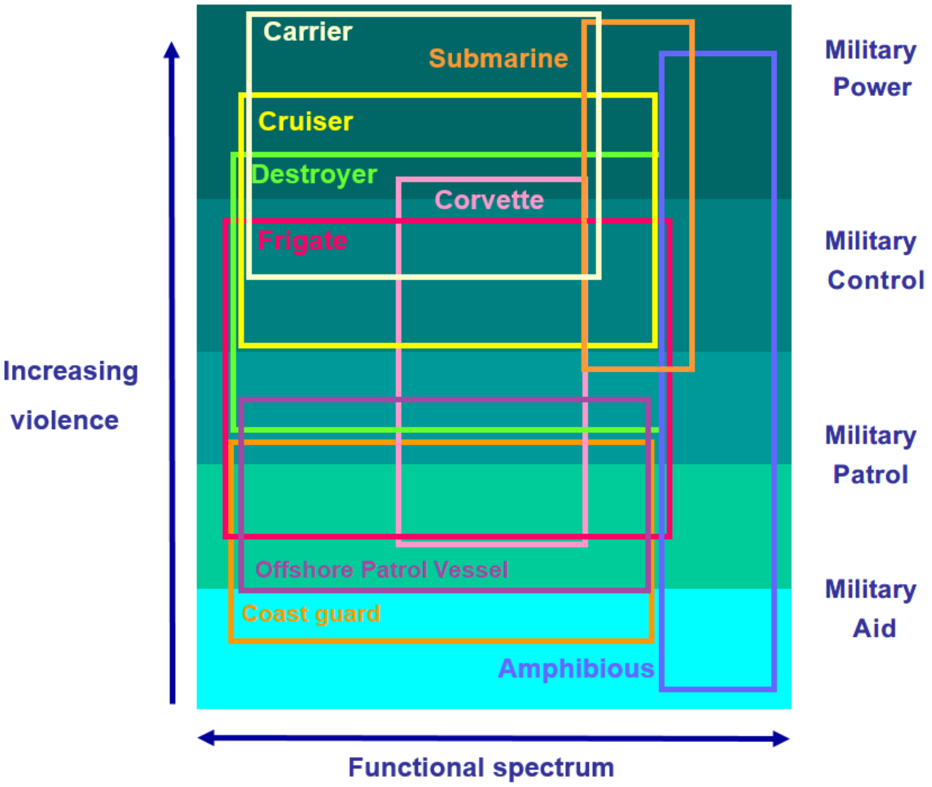

Figure 3.2: Operational cluster and functional spectrum of multiple naval vessels (NATO Naval Group 6, 2004, Hopman, 2007).

The different types of naval surface vessels that can be found are the following:

3.1.1. Aircraft Carriers

The biggest naval surface vessels are the aircraft carriers. These are left out of the graph in Figure 3.1 due to their high displacements. They can go from 12,000 t of displacement up to 100,000 t, like the aircraft carriers of the US Navy. Their top speeds oscillate between the 26 kn and 30 kn. They are meant to operate in high intensity conflicts, by defending themselves directly and with the aircraft they carry onboard. The greatest advantage of an aircraft carrier is that it allows a naval force to project air power worldwide without depending on bases on land. Since there are very few examples of this vessel, this kind is left out of this research.

3.1.2. Cruisers, Destroyers, and Frigates

There is not a clear distinction between cruisers, destroyers, and frigates. According to Figure 3.2, they are listed in a descending order of violence. However, the nomenclature and categorisation of these three types depends on each navy.

The term “cruiser” has changed its meaning over time. At the moment there are few ships of this type. Their displacement is usually comprised between 9,800 t and 25,900 t. They are fast ships, with top speeds between 32 kn and 34 kn. They are meant to operate in high violence situations.

Destroyers have a smaller displacement. Most of them are between 5,000 t and 11,000 t and their top speed is normally around 30 kn, but can go up to 35 kn in some cases. Some countries like Canada, Spain, France, and the Netherlands name their destroyers frigates, which can lead to some confusion. They are heavily weaponed and are meant to be used in *Military Power* and *Military Control* operations.

Frigates are a very popular type of naval vessel. In general, their displacement is between 1,800 t and 5,000 t. Some countries have so-called multipurpose frigates that have the capabilities of a destroyer and are around the 6,000 t. Others, like the German Navy, go a step further and name their 9,900 t newly ordered vessel, the F126, a frigate. The top speeds of the frigates plotted in Figure 3.1 are between 25 kn and 35 kn, having a great number of them top speeds of 30 kn. A frigate is meant to be used mainly for *Military Control*, being also to perform tasks of *Military Patrol*.

3.1.3. Corvettes

A corvette is the smaller sister of a frigate. Its operating speed is very similar, but its displacement is smaller; generally, between 500 t and 2500 t. It is lighter weaponed than a frigate and has a smaller functional spectrum. This does however not mean that it can operate in less violent situations. According to NATO Naval Group 6, 2004 in Figure 3.2, a corvette can even have a slightly higher violence spectrum than a frigate. A corvette has *Military Control* as its main function, but is also able to operate in *Military Power* and *Military Patrol* environments.

3.1.4. Offshore Patrol Vessels (OPV)

An OPV sails at lower speeds than the other naval ships presented hitherto, because it is mainly performing patrol tasks and does not participate in higher violence operational clusters. The size of an OPV is between that of a corvette and a frigate, between 1,100 t and 3,750 t. Its top speeds are between 17 kn and 23 kn. Its primary function is to perform *Military Patrol* and *Military Aid*, but can also be used for sea control operations within the *Military Control* cluster (NATO Naval Group 6, 2004). An OPV is supported in its patrol and control operations by RHIBs and helicopters carried on board, that are able to travel at higher speeds in case they have to chase a target.

In Figure 3.2, a coast guard vessel is also plotted. It has a very similar spectrum to that of the OPV, and their differences are a grey area. In general one could say that since its armament is lighter than that of an OPV, its main role is to provide *Military Aid* and *Military Patrol* only.

3.1.5. Amphibious Vessels

Amphibious vessels can be very varied in size and in operational cluster, as can be see from Figure 3.1 and 3.2. There are many kinds of amphibious vessels. They are meant to support operations in the air or on land by carrying the necessary materials and troops. Some examples of the biggest are: landing helicopter assault ship (LHA), landing helicopter dock ship (LHD), or landing platform dock (LPD). They can also be used as command center for amphibious operations, like an amphibious command ship (LCC). In general these vessels are designed to operate in medium intensity conflict under the protection of other naval vessels, but also have self-defense capabilities (Streng, 2021). Some navies, like the Spanish, use their amphibious vessels as an aircraft carrier as well.

3.1.6. Mine Warfare Vessels

Mine warfare vessels do not participate directly in combat. Instead, they are responsible for cleaning the waters of mines in order to make an area safe. Mines react to acoustic signatures, pressure, magnetism or direct contact. There are mainly two types of mine warfare vessels: minesweepers and minehunters. Minesweepers are designed to clear areas by detonating or removing naval mines, and minehunters are able to seek, detect and destroy individual naval mines. When a ship combines these two capabilities, we talk about a mine countermeasures vessel. They do not have self-defence capabilities, so a combatant needs to protect them (National Research Council (US), 2001).

Due to the sensitivity of mines, the National Research Council (US), 2001 advises to reduce the sailing speed to between 5 kn and 10 kn. For this reason, mine warfare vessels need to sail slowly to keep the amount of acoustic signatures limited. To avoid magnetic signatures, mine warfare vessels are made of non-magnetic materials. In order to reduce the pressure signatures, mine warfare vessels are very light, between 100 t and 1,400 t as seen in Figure 3.1, allowing them as well to sail in shallow waters where mines can be located. Their top speeds are between 12 kn and 20 kn but, as explained before, when looking for mines the speed is significantly lowered to reduce the acoustic signatures.

3.1.7. Auxiliaries

Apart from the naval vessels described above, navies have many auxiliary vessels that support them during their operations. These vessels include among others command ships, support ships, medical ships, ammunition ships, tugs, replenishment ships, and logistical support ships. Their sizes are very varied and they do not participate in military operations directly, only by providing support.

Auxiliary vessels are left out of this research. This is because they are very similar to civil vessels, which is not the purpose of this investigation. It is known that the application of fuel cells to civil vessels is a current topic of research. Therefore, auxiliary naval vessels are considered to be out of scope and are not further discussed.

3.2. Requirements

Depending on the operational cluster, each type of naval vessel has different requirements. In this section, they are grouped first by operational profile and survivability. These two lead to other subcategories, that explain in detail the requirements that have to be met by each type of naval surface vessel.

3.2.1. Operational profile

The operational profile of a vessel presents an overview of the distribution over time of its speed. Different aspects of the vessel's operational profile are important in order to make a categorization.

Vessel speed

Speed is directly related to power, because as it is known, power scales with speed to the third power. Therefore, it is an important parameter to take into account during the design of a vessel. From Figure 3.1, it can be seen that depending on the type of naval vessel, a trend in speed is observed. It is common that the vessels of the same navy are able to sail at the same speed, since they are meant to complement each other and sail as one fleet. This refers mainly to carriers, cruisers, destroyers, frigates, and corvettes. Other naval surface vessels like OPVs and amphibious vessels do not need to reach such high speeds and have therefore lower power requirements. Mine warfare vessels have the lowest speed of them all, because it is crucial for their task to keep the acoustic signatures as low as possible.

Manoeuvrability

Manoeuvrability refers to “the quality of being easy to move and direct” (Cambridge Dictionary, 2022). Applied to a ship this translates in its ability to react rapidly to an increase in speed. This can be seen partially looking at the top speed (because vessels are not constantly sailing at top speed), but also at the operational cluster of each vessel.

Here again, vessels that have higher operational clusters in Figure 3.2 must be able to react rapidly. A high manoeuvrability (also named mobility by some), can help avoid being hit by projectiles or torpedoes, by moving beyond the weapon range or outmanoeuvring the projectile (Streng, 2021).

Endurance/range

The time and distance that a naval vessel can stay in operation is crucial. It is important to define clearly the difference between range and endurance. While the former refers to the distance in nautical miles that a ship can sail, the latter refers to the time that the vessel can spend in the area of operations (AoO) independently (Streng, 2021).

Range is therefore determined by the cruising speed and the fuel capacity, and endurance by the amount of the different consumables. These can be varied; from food, to ammunition, or spare parts. Thus the range determines the maximum distance to the AoO, while the endurance determines the time that a vessel can stay independently in that AoO.

Depending on the operational profile of the vessel and the operational cluster, range and endurance vary. Higher-violence-spectrum vessels must have high endurance and range, because they have to be able to sail to far AoO and stay there for long periods. This affects directly the amount of fuel that must be taken on board (range), and the amount of consumables (endurance). The size of the crew and the mission profile are therefore other factors that influence the amount of consumables that need to be taken on board. Other vessels like OPVs and Coast Guard vessels do not need such high endurance and ranges, since they sail mostly in territorial waters and can go quite often back to port. In the case of an aircraft carrier, it not only needs to take enough fuel to sail to the AoO, but also needs to carry all the aviation oil required for all the aircraft.

3.2.2. Survivability

Survivability is crucial in naval ships. The nature of a naval vessel requires that it is stays operative for as long as possible, no matter what the attacks from the outside are. Evacuating the vessel is the last option. Survivability is a complex topic, that consists of multiple steps, as shown in Figure 3.3.

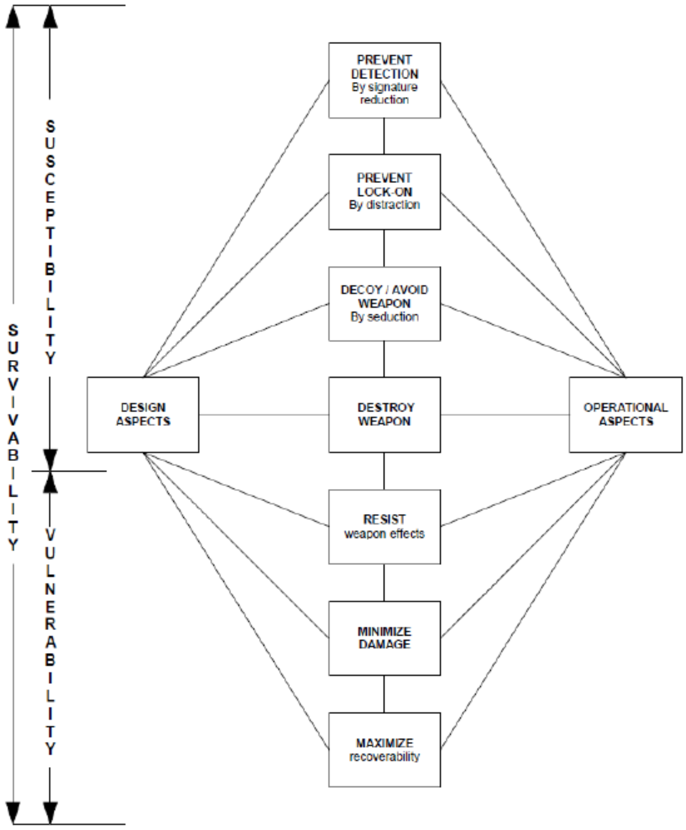

Figure 3.3: Survivability diagram (Piperakis, 2013).

Susceptibility

The first step is to try to not be spotted by the enemy, and if so, try to avoid being hit. In Figure 3.3, susceptibility consists of three steps. The first one is to avoid being seen, where signatures play a crucial role. The second and third steps are to prevent a lock-on, and to decoy or avoid a weapon. In these last two aspects, the military systems on board are of relevance. Since these are not part of the power plant of the vessel, they are considered to be out of the scope of this research.

So, let us focus on remaining being unseen: **signatures**. Signatures are what makes naval vessels susceptible to be recognised by the enemy. There are different kinds and they can be reduced as follows (Nain et al., 2013, Piperakis, 2013, Streng, 2021):

- Infrared (IR) signatures

  Infrared signatures are created by the heat that the vessel generates. Think of the engine room, where the heat is produced, but also of all exhaust pipes and the communications mast. In Figure 3.4, one can see what a vessel looks like through an infrared camera when no measures are taken to reduce the IR signatures.

Figure 3.4: IR image of a typical unsuppressed ship (Thompson et al., 1998).

  IR signatures can be reduced by cooling the exhaust gas, and by spraying water on the hull of the vessel and the communications mast to cool it down.

- Acoustic signatures

  Acoustic signatures have three main sources: the propulsion systems (engines and propellers), other machinery (like pumps or generators), and the flow around the hull (turbulence, wave breaking) (Basten et al., 2015). While the last can only be reduced by sailing slower, the other two can be reduced by placing noise-making equipment on noise dampers, that avoid that the vibrations are transmitted to the hull and, therefore, to the water.

  Not all naval vessels make use of noise dampers. Only high violence spectrum vessels do. Vessels like OPVs and Coast Guard vessels are not that susceptible to signatures because the missions they deal with do not require this level of complexity due to lack of means by the target. Once one goes up in the violence scale, more equipment is placed on noise dampers. Other vessels like mine warfare vessels, despite not being ranked high in the violence spectrum, make extensive use of noise dampers since low signatures are of the utmost importance for their tasks.

- Pressure signatures

  Pressure signatures are due to the hydrodynamic pressure that the vessel generates for the simple fact of displacing water. Their reduction can only be achieved by making the ship lighter, which is not an option for many vessels. This is one of the reasons why mine warfare vessels are one of the lightest in Figure 3.1, because mines are sensitive to pressure differences too.

- (Electro)magnetic signatures

  Electromagnetic signatures have three different sources: permanent field, induced magnetic field, and magnetic field produced by large currents of DC type. Permanent field is generated during the construction and assembly of the vessel. It is the result of the magnetisation due to the earth's magnetic field. Some ways to reduce this type of magnetism is to wipe and deperm the vessel once the construction is finished. When treated correctly, permanent field magnetism is relatively small compared to the induced magnetic field. Induced magnetic field results of the distortion of the earth's magnetic field due to the presence of large steel objects. The only way to reduce this kind of magnetism is to select low magnetic materials when the mechanical requirements allow. Finally, there is magnetic field produced by large currents of DC type, like the ones between the batteries and the main electric motor.

  Naval vessels make use of degaussing systems to reduce the magnetic signatures. Other vessels like mine warfare vessels, that must have very low magnetism, are built with non-magnetic materials.

- Radar cross-section signatures (RCS)

  Radar cross-section signatures are due to the reflection of radar waves on the geometry of a vessel. Some ways to reduce this kind of signatures are to make use of a radar absorbing material, and to reduce the microgeometry.

Vulnerability

Once a naval vessel has been hit, it must be able to try to control the damage and keep operating in the area in the best conditions as possible. In Figure 3.3, vulnerability consists of three steps: resist, minimize damage, and maximize recoverability. The philosophy of a naval ship states the importance of trying to stay operative to continue with the mission. This is why in a military environment these three steps are taken a step further than in commercial vessels.

The first two steps of vulnerability in Figure 3.3 are to resist and to minimize the damage. In the design of a vessel these requirements are already taken into account. Think of shock requirements, by placing sensitive equipment on shock mounts; locating critical equipment and spaces inboard and shielded; water-tight bulkheads in specific parts of the vessel, to keep a leakage controlled; and a trained crew to act rapidly when needed (Piperakis, 2013). Here again it applies that the higher the violence spectrum, the higher the requirements are. Using in-house knowledge at Nevesbu, it is known that Coast Guard vessels, OPVs, and even some corvettes (depending on the specific requirements of a navy) do not have vital systems on shock absorbers due to the low violence spectrum at which they operate. When one goes to higher violence spectra, shock requirements become more relevant. According to Verma and Jain, 2019, shock results in accelerations inside the vessel that can damage or destroy the equipment. The highest shocks come from underwater explosions, and therefore the equipment needs to be shock resistant, especially closer to the bottom where the impact of the explosion is bigger. Mounting the equipment on shock absorbing mounts on top of their foundation, or hardening the equipment that needs to be rigidly mounted are the two approaches to deal with shock absorption (Hwee and Jeremy, 2013).

Once the damage has taken place, it is of the utmost importance for a naval vessel to try to keep operating, as is seen in the last step of vulnerability in Figure 3.3. Some like de Vos, 2018 have studied the effect of a disruption, and how it should be reacted. The general system response curve to a disruption is shown in Figure 3.5. This image indicates the different phases of a disruption and how it affects the system's capability.

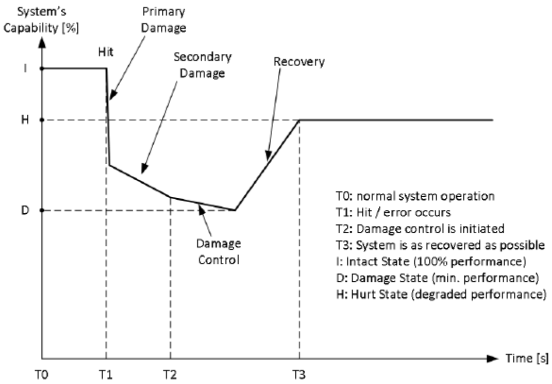

Figure 3.5: General system response curve to a disruption (de Vos, 2018).

In Figure 3.5 it can be seen how the recoverability brings the vessel back to a level where it is able to keep operating, which is in line with the philosophy of naval vessels of continuing the operation no matter what. Aspects like robustness and redundancy are crucial for the recoverability of the vessel. In the design of a naval vessel, it is already stated which elements can fail depending on the type of calamity, and how long it can take until they are working again. Robustness is achieved by how the systems are connected with each other, allowing for new paths to keep operating. The redundancy of the systems is crucial in this aspect, where the separation and duplication of systems can be very helpful.

3.2.3. Overview of the requirements

In the previous sections, the different requirements of naval vessels were presented. In this section the aim is to give an overview of the link between the requirements and the different kinds of naval surface vessels. In Table 3.1, a classification is done based on minus and plus signs, where the scale from less to more important follows the next order:"- -", "-", "- +", "+", and "+ +".

Table 3.1: Importance of the requirements for the different types of naval surface vessels.

Requirements	Mine warfare vessel	OPV	Corvette	Frigate, destroyer, and cruiser
Operational profile				
Vessel speed	- -	- +	+	+ +
Maneouvrability	- -	- +	+ +	+ +
Range/endurance	- +	-	- +	+ +
Survivability				
Susceptibility (signatures)	+ +	-	- +	+ +
Vulnerability (resist, damage control, and recoverability)	-	-	+	+ +

The classification shown in Table 3.1 is not entirely objective, and may differ per country due to the exact requirements or use that that specific country gives to its naval vessels. Nonetheless, it shows a clear relation between the requirements and the violence spectrum in which naval vessels operate. The higher the violence spectrum, the higher the requirements are. The exception are mine warfare vessels that, despite not participating actively in combat, need very low signatures due to the nature of their tasks.

3.3. Conclusion

In this chapter, the different kinds of naval surface vessels were presented. They were grouped by displacement and top speed, and by operational cluster. When plotting them sorted by top speed and displacement, one can observe some general trends, although the classification of the different kinds is very dependent on the country. The classification in operational clusters consists of four clusters of increasing level of violence: *Military Aid*, *Military Patrol*, *Military Control*, and *Military Power*. Aircraft carriers, cruisers, destroyers, frigates, corvettes, OPVs, Coast Guard vessels, and amphibious vessels were plotted by operational cluster. Mine warfare vessels do not belong to any of these clusters, because they do not participate directly in combat.

Depending on the situations in which a naval vessel is meant to operate, the requirements are different. The main requirements of a naval vessel are dependent on the operational profile and the survivability. The operational profile consists of aspects such as the speed of the vessel, which has a direct impact on the amount of power required; the manoeuvrability, related to the rapid increase of speed; and the endurance and range, which affect how far and for how long a vessel can operate independently and therefore the amount of space required for fuel and consumables. Another requirement for naval vessels is their survivability. Survivability consists of two steps. First, susceptibility, when a vessel tries to remain undetected by lowering its signatures. There are multiple types of signatures and all of them have measures that can be taken to reduce them. The most relevant are: infrared signatures (IR), acoustic signatures, pressure signatures, (electro)magnetic signatures, and radar cross-section signatures (RCS). The second aspect of survivability is vulnerability, where a vessel tries to resist, minimize the damage, and use its recoverability to keep operating once it has been hit. Here, aspects like shock requirements, or water-tight bulkheads can help to keep the damage reduced and controlled. The recoverability after a calamity can be achieved when the systems are robust and redundant.

It can be concluded that there is a clear link between the requirements of a naval vessel and the operational cluster in which it is meant to operate. Although the specific requirements can be very case dependent, one can say that the higher the violence spectrum, the higher the requirements. Mine warfare vessels form an exception since they do not belong to any of the operational clusters, but due to their specific tasks they have very high requirements.

4

Fuel cells

In chapter 3 the different types of naval vessels and their requirements were analysed. In this chapter the aim is to make a presentation of fuel cells. In section 4.1 the working principle of fuel cells is explained and in section 4.2 the different types are presented. Section 4.3 describes the additional components that fuel cells require and section 4.4 makes a comparison between ICEs and fuel cells, to see where fuel cells score better than ICEs and how they can be advantageous for their use on board of naval surface vessels.

4.1. Working principle

Fuel cells are able to generate electricity and water from hydrogen and oxygen. Oxygen can be obtained from the air, and hydrogen needs to be supplied to the fuel cells. When they are working on pure hydrogen, the chemical reaction that takes place inside is described by Equation 4.1 (Kaur, 2016):

$$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O \tag{4.1}$$

When mixing H_2 and O_2, these have a natural tendency to form H_2O because the sum of the Gibbs energy of the H_2 and $\frac{1}{2}O_2$ molecules is lower than the Gibbs energy of the H_2O molecule (Kaur, 2016).

Therefore, the only product that fuel cells produce when working on pure hydrogen is water. The electrons that are released during the chemical reaction are the ones responsible for the creation of electricity.

A fuel cell consists of an anode, a cathode and an electrolyte, as shown in Figure 4.1. In the simplest case, the fuel (H_2) enters through the anode, while the oxygen enters through the cathode. Direct chemical combustion of the hydrogen is prevented by the electrolyte, that serves as a barrier to gas diffusion, but allows ions to travel through it (Sossina, 2003). The charge of the ions travelling through the electrolyte must be balanced by charges travelling through an external circuit, which causes the creation of electricity.

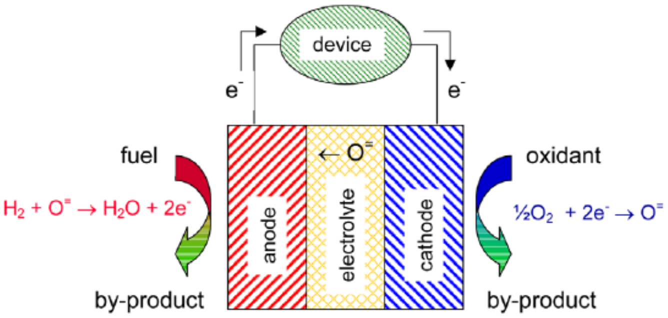

Figure 4.1: Schematic representation of a single fuel cell (Sossina, 2003). $O^=$ in the figure stands for the ion O^{2-}.

4.2. Types of fuel cells

Different categorisations are possible to group the types of fuel cells. Operating temperature can be one of them, where three different categories are found: low temperature fuel cells at around 80°C, intermediate temperature fuel cells working around 200 °C, and high temperature fuel cells between 650 °C and 1000 °C. Depending on the operating temperature, there are three kinds (de Troya et al., 2016, Hortal and Barrera, 2012):

- Low temperature fuel cells: working at around 80°C, such as the AFC and PEMFC.
- Intermediate temperature fuel cells: working around 200°C, like the PAFC.
- High temperature fuel cells: operating between 650°C and 1000°C, such as the MCFC or the SOFC.

As explained before, apart from a cathode and an anode, fuel cells have an electrolyte, which allows the transfer of electrons. This electrolyte can be made of different materials, which leads to another way to categorize fuel cells.

In this report the most relevant types of fuel cells are presented, following the two categorizations mentioned before.

4.2.1. Low temperature fuel cells

Alkaline Fuel Cells (AFC)

Alkaline fuel cells have an alkali as electrolyte, mostly potassium hydroxide (KOH) (de Troya et al., 2016). The chemical reactions taking place are:

At the anode

$$2\mathrm{H_2} + 4\mathrm{OH}^- \longrightarrow 4\mathrm{H_2O} + 4\mathrm{e}^- \tag{4.2}$$

At the cathode

$$\mathrm{O_2} + 4\mathrm{e}^- + 2\mathrm{H_2O} \longrightarrow 4\mathrm{OH}^- \tag{4.3}$$

These fuel cells operate at temperatures between 60°C and 100°C, and their major drawback is their sensitivity to CO_2. This means that both the hydrogen as the oxygen need to be very pure, otherwise their lifetime is reduced drastically (Kaur, 2016). Therefore, their application was limited to some space programs, where pure O_2 instead of air was used, but they were rapidly replaced by polymer exchange fuel cells, that are discussed next.

Polymer Exchange Membrane Fuel Cell (PEMFC)

PEMFCs have a high power density and a quick start-up time. Their major drawback is the amount of platinum required to accelerate the chemical reaction and their sensitivity to fuel impurities, in particular CO because it deactivates the catalyst (van Biert et al., 2016). Therefore, hydrogen with high purity is needed (de Troya et al., 2016). The chemical reactions taking place are:

At anode:

$$\mathrm{H_2} \longrightarrow 2\mathrm{H}^+ + 2\mathrm{e}^- \tag{4.4}$$

At cathode:

$$\frac{1}{2}\mathrm{O_2} + 2\mathrm{H}^+ + 2\mathrm{e}^- \longrightarrow \mathrm{H_2O} \tag{4.5}$$

Overall reaction:

$$\frac{1}{2}\mathrm{O_2} + \mathrm{H_2} \longrightarrow \mathrm{H_2O} \tag{4.6}$$

There are two kinds of PEMFCs: low temperature, and high temperature. Low temperature PEMFCs (LT-PEMFC) have operating temperatures of 65-85°C. High temperature PEMFCs (HT-PEMFCs) can go up to 200°C in operating temperature, increasing their tolerance to CO and reducing the required platinum loading (van Biert et al., 2016). PEMFCs are usually used in the automotive industry and in submarines in small units of a couple hundred kilowatts (de Troya et al., 2016). These examples are discussed later in chapter 6.

4.2.2. Intermediate temperature fuel cells

Phosphoric Acid Fuel Cells (PAFC)

PAFCs are used extensively for stationary applications (Dicks and Rand, 2018). Their operating temperature is around 200°C and their chemical reactions are:

At anode:

$$H_2 \longrightarrow 2H^+ + 2e^- \tag{4.7}$$

At cathode:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O \tag{4.8}$$

Overall reaction:

$$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O \tag{4.9}$$

Phosphoric acid is tolerant to carbon monoxide and dioxide (Kaur, 2016). Therefore, the cost of hydrogen and air purification is diminished (de Troya et al., 2016). According to Han et al., 2012, for these fuel cells, it is also possible to use waste heat in cogeneration, showing efficiencies around 40% (Han et al., 2012). However, according to van Biert et al., 2016, their low power density and their durability issues have so far limited the use of PAFCs in maritime applications.

4.2.3. High temperature fuel cells

For this kind of fuel cells, apart from the existing literature, an interview was done with an expert in the field. The expert is Prof. dr. Robert Selman, Distinguished Professor Emeritus at Illinois Institute of Technology (Chicago, US) and with a chemical technology background. He is considered to be an expert in the field of high temperature fuel cells. According to him, the advantages and disadvantages of high temperature fuel cells are very similar, regardless of what kind of electrolyte is used. Therefore, first a short description of the two kinds of high temperature fuel cells is done, to finish with a recapitulation.

Molten Carbonate Fuel Cells (MCFC)

A MCFC makes use of carbonate salts that melt at high temperatures and conduct carbonate ions from cathode to anode (Kaur, 2016). The operating temperatures of this kind of fuel cell are between 600°C and 700°C (Han et al., 2012). The chemical reactions in MCFCs are:

At anode:

$$2H_2 + 2{CO_3}^{2-} \longrightarrow 2H_2O + 2CO_2 + 4e^- \tag{4.10}$$

At cathode:

$$O_2 + 2CO_2 + 4e^- \longrightarrow 2{CO_3}^{2-} \tag{4.11}$$

Overall reaction:

$$2CO_2(cathode) + 2H_2 + O_2 \longrightarrow 2H_2O + 2CO_2(anode) \tag{4.12}$$

As can be seen, in Equation 4.12 the CO_2 generated at the anode needs to be recycled to the cathode (Kaur, 2016). The amount of CO_2 going in and out the chemical reaction is the same, meaning that once the MCFC is functioning, recirculation can be used. However, when the MCFC wants to be started, the CO_2 must come from another source. Due to the high temperatures at which MCFCs work, hydrocarbons reacting to CO can be converted to hydrogen in the stack (Han et al., 2012, Sossina, 2003).

According to de Troya et al., 2016, MCFCs are suitable for marine applications, where the relatively large size and weight of the MCFC and its slow start-up time are not a real issue. Authors like van Biert et al., 2016 argue, however, that MCFCs still struggle with high cost, and that they have a limited life time and low power density.

Solid Oxide Fuel Cell (SOFC)

This kind of fuel cells needs to operate between 500°C and 1000°C. This is necessary to allow the conductivity of oxide ions (Kaur, 2016). They are able to operate at a high efficiency, between 40 and 60%, which can be increased to 70-80% if a gas turbine is used to recover the heat (Han et al., 2012). The chemical reactions when working on pure hydrogen are:

At anode:

$$2H_2 + 2O^{2-} \longrightarrow 2H_2O + 4e^- \tag{4.13}$$

At cathode:

$$O_2 + 4e^- \longrightarrow 2O^{2-} \tag{4.14}$$

Overall reaction:

$$2H_2 + O_2 \longrightarrow 2H_2O \tag{4.15}$$

Here again, hydrocarbons can be used as a fuel. Some of the drawbacks are the long start-up time and the corrosion of the metal stack components, which limit their power density and their stack life (Han et al., 2012). Others like van Biert et al., 2016 consider it as a promising type of fuel cell, but mention the limited development state and the high cost as a drawback for SOFCs.

Overview of high temperature fuel cells

From the literature one can see that multiple authors mention high temperature fuel cells as a very promising type for shipping. This is mainly because of their high efficiencies and because they allow the use of hydrocarbons, instead of very pure forms of hydrogen. This is very convenient for maritime purposes, where volume is a limiting factor, because hydrocarbons have higher volumetric energy densities than pure hydrogen as is shown in chapter 5.

According to Prof. dr. Robert Selman, the advantages and disadvantages of MCFCs and SOFCs are very similar. They both have high efficiencies and allow internal reforming. However, they have a very limited lifetime. The lifetime varies of course on the use they have, but with the current technology it stays normally around the two to three years, maybe four in some cases. This is because of the high temperatures at which they have to operate to become efficient. While these high temperatures are the ones that allow internal reforming, they also cause corrosion in the fuel cells, which limits their lifetime. This all translates in a decay of the performance of the fuel cells.

Some studies like Sossina, 2003, have proven that the performance stayed constant for a 100kW SOFC system running for 20,000 h. The question is whether this performance would stay constant for longer periods (20,000 h is equivalent to 2.3 years running 24h/day) and in operations where the use of the fuel cells follows a dynamic profile instead a constant power output. Others like Shawuti et al., 2018 are more optimistic and state that the lifetime of SOFCs lays between 40,000-60,000 hours, which is equivalent to 4.5-6.8 years. In this last example, however, the results do not come from performed tests so their validity is questioned. These values give an indication of what is written in the literature but, at the end, comparing them is complex. Due to the high temperatures in the fuel cells, there is a decay in performance, so depending on which decay in performance is considered acceptable, the lifetime may vary.

Even though the literature mentions the long start-up times as an issue of high temperature fuel cells, Prof. dr. Robert Selman holds that it is very case dependent. High temperature fuel cells have of course longer start-up times than lower temperature fuel cells, because a certain temperature needs to be reached to become efficient. However, the characteristics of the fuel cell stack, the distribution of the single fuel cells and the control technology used have a great impact on the start-up time. While some manufacturers offer stacks that reach their highest efficiency in a matter of hours, others need days. Also, this long start-up only takes place when the fuel cell stacks start from room temperature. Therefore, Prof. dr. Robert Selman maintains that the dynamic behaviour of high temperature fuel cells is significantly better when their waste heat is also used to keep them at high temperatures. Nonetheless, he argues that a combination with batteries would be needed to compensate the first long start-up time.

According to Prof. dr. Robert Selman and Shawuti et al., 2018, some investigations are trying to study the effect of running SOFCs at 500°C, which is significantly lower than the 800-1000°C at which they normally operate. This would have a great effect on the lifetime, which would be extended due to less corrosion, and on the start-up times, which would be reduced. This has however not been proven yet with satisfactory results.

High temperature fuel cells have been investigated for more than fifty years and are now gaining a lot of interest. Research keeps going on, which will improve their performance, lifetime, and response. In order to know what the effect of using high temperature fuel cells in a vessel would be, a specific manufacturer is needed. Only then one is able to calculate values like the start-up time or the lifetime.

4.3. Other components

When one wants to make use of fuel cells on board of a vessel, a fuel cell module needs to be placed. This module consists of multiple support systems and the fuel cell stacks. The fuel cell stacks are the ones that consist of multiple fuel cells. Depending on the type of fuel cell, among the support systems different components may be needed. In this section these are presented. A simplified overview of the components is shown in Figure 4.2.

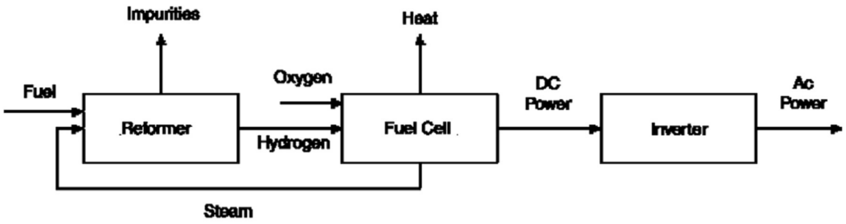

Figure 4.2: Simplified block diagram of a fuel cell module (de Troya et al., 2016).

4.3.1. Fuel reforming

All the fuel cells presented before are able to work on pure hydrogen. However, when another type of hydrogen-rich fuel wants to be used, fuel reforming is required (US Department of Energy, 2022). In this process, a hydrocarbon is converted into a mixture of hydrogen and CO (van Biert et al., 2016).

High temperature fuel cells like SOFCs and MCFCs, allow to reform partly the fuel inside the fuel cell itself due to he high temperatures at which they operate (US Department of Energy, 2022).

According to van Biert et al., 2016, there are three ways of reforming. The first of them is steam reforming (SR), where the hydrocarbon reacts with steam, forming hydrogen and carbon monoxide. In this case, both heat and steam need to be supplied to the system, which reduces its efficiency and releases carbon dioxide. But, according to US Department of Energy, 2022, this carbon dioxide is still less than the traditional ICE due to the higher efficiencies of fuel cells.

Another way to reform fuels is the catalytic partial oxidation (CPOX). This method relies on the oxidation of carbon. In this case air is usually used as oxidant (van Biert et al., 2016). The efficiency of this method is lower than SR, but it is mostly used due to its simplicity and compactness. This simplicity also results in shorter start-up times (van Biert et al., 2016).

The third method for fuel reforming is autothermal reforming (ATR). This method is a combination of SR and CPOX, where the carbon is oxidised by air and the heat that is released from the oxidation is used for SR. This method yields more hydrogen than the previous ones, has a wider temperature window (between 600-1000°C) and is compact and has a fast transient behaviour.

High temperature fuel cells have the advantage that they are capable of performing internal reforming. According to Muñoz de Escalona et al., 2011 there are two types of internal reforming: direct internal reforming (DIR), and indirect internal reforming (IIR). In DIR the unreformed fuel enters the anode and there the reforming process takes place using the heat produced by the fuel cell. In IIR, a reactor is used previous to the anode to convert a big fraction of the fuel into a hydrogen-rich mixture. The rest of the fuel is then reformed in the anode. The heat in IIR also comes from the heat produced in the fuel cell, but in this case the water steam used for reforming must come from a different source.

4.3.2. CO clean-up

As mentioned before, some fuel cells like PEMFC are very susceptible to CO. Therefore, the amount of CO formed during the reforming process needs to be lowered.

Here again, according to van Biert et al., 2016, there are three methods that can be used. The first of them is water gas shift (WGS). In this method the CO reacts with steam in order to form carbon dioxide and hydrogen, yielding more hydrogen.

The second method of carbon monoxide clean-up is preferential oxidation (PrOX), where carbon monoxide is oxidised to form carbon dioxide. Here, because no steam is used, there is no hydrogen formed. The advantage of this method is its simplicity and its low pressure of the reaction (van Biert et al., 2016).

Finally, the third method is the selective methanation (SMET). Here the reaction that takes places is the inverse of the reaction in SR. Carbon monoxide and hydrogen react to form methane and water. This means that the amount of hydrogen is reduced. This method is especially beneficial if the tail gas of the fuel cell is further used for burners or heat engines (van Biert et al., 2016).

4.3.3. Purification

Purification of the fuel is needed for certain types of fuel cells, like PEMFC, where very pure hydrogen is needed.

According to van Biert et al., 2016, membrane separation and pressure swing adsorption (PSA) are the most used methods to purify the fuel. The first makes use of a membrane to remove the impurities and can be integrated in the reforming reactor. The second makes use of a solid adsorbent, which adsorbs the heavier molecules, resulting in higher purity of hydrogen. Around 15-30% of the hydrogen is lost in this process if the tail gas cannot be used for other purposes (van Biert et al., 2016).

4.3.4. Heat recovery

In a high temperature fuel cell, a lot of heat is produced due to the chemical reactions that take place inside of it. This heat can be used in multiple ways. The first way to reuse the heat is to make use of this energy for the reforming process of the fuel as was explained in subsection 4.3.1. The remaining heat can be used to increase the total efficiency of the system by making use of a gas turbine (GT) or a steam turbine (ST) (Sapra, 2020).

Some like Shawuti et al., 2018 even studied the combination of SOFCs with a GT and a ST. Depending on the fuel that has to be reformed, more or less heat is available after the reforming process. In van Veldhuizen et al., 2022 this is shown clearly, where is it seen that not for all fuels the remaining heat is enough to generate saturated steam. This has to do, among other things, with the autothermal reforming temperature that each fuel requires as is explained later in chapter 5.

Another way to use the remaining heat is to keep the fuel cells always at high temperature which, according to Prof. dr. Robert Selman, improves their dynamic response.

4.3.5. Other

There are other components that may be required when installing a fuel cell stack. These are very dependent on the kind of fuel cell to be used.

They are varied and very extended, and therefore are just mentioned in this research. They include air compressors, humidifiers, converters, and desulphurizers.

4.4. Comparison between internal combustion engines (ICEs) and fuel cells

In chapter 1 the benefits of fuel cells were mentioned. They are efficient, and therefore produce less emissions, and they have advantages that can be very useful for naval surface vessels such as the lower acoustic and infrared signatures. Moreover, they require less maintenance, and have a flexible and modular design, which can be advantageous for the redundancy of the vessel.

In Figure 4.3, the total efficiencies of different systems are presented. As can be seen, compared to the traditional ICEs, fuel cells rate high in efficiency, especially high temperature fuel cells. While the efficiency of a diesel engine lies between 30-40%, that of high temperature fuel cells is between 50-60%, which can be increased around 10-15% if it is combined with some gas turbine or steam turbine. In the case of a low temperature fuel cell, the difference in efficiency is not that big compared to a diesel engine.

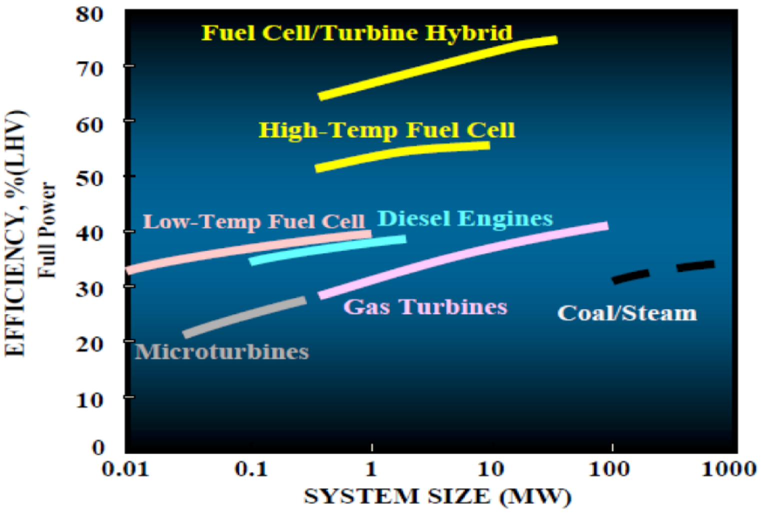

Figure 4.3: Comparison of efficiencies of different fuel cells for electric powerplants from Han et al., 2012.

Apart from the higher efficiencies, fuel cells have lower acoustic signatures than an ICE. The reason for this is that in a fuel cell there are no moving elements, contrary to an ICE. Moreover, even though fuel cells would need to be combined with an electric motor, the fact that there are no explosions taking place inside that motor reduces the sound and vibrations. When a fuel cell is combined with a gas turbine, the reduction in acoustic signatures might not be that favorable. Therefore, depending on the application on which naval vessel, this may be something to take into account.

Lower infrared signatures are also an advantage of fuel cells with respect to ICEs, especially for low temperature fuel cells. Quantifying the exhaust gas temperature for high temperature fuel cells was deemed difficult from the existing literature. SOFCs for example, can operate between 500-1000°C. These temperatures are lower than those inside the cylinders of an ICE, which can be higher than a thousand degrees Celsius. Especially when heat recovery is used after the high temperature fuel cell, the temperature of the exhaust gas can be reduced.

Finally, the last advantage of fuel cells with respect to ICEs is that fuel cells produce less emissions due to their higher efficiencies and the fuels they work with. In section 5.5 a more detailed explanation is given.

ICEs also perform better than fuel cells in some aspects. For example, their energy density. It is known that fuel cells are bulkier than ICEs (in chapter 6 some concrete examples of applications and products on the market are described). Within the fuel cells, PEMFCs are more compact than high temperature fuel cells like SOFCs or MCFCs. It is true than in order to use PEMFCs, either pure hydrogen or an external fuel reformer is needed, which adds up to the size of the total system. According to Sapra, 2020, a spark-ignited natural gas engine has four times the power density by weight and volume compared to SOFCs for a similar power output. This denotes the challenge of replacing the traditional ICE by fuel cells.

Another disadvantage of fuel cells is their limited lifetime. Fuel cells do not need much maintenance, contrary to ICEs. When a fuel cell ends its lifetime it needs to be replaced, while an ICE needs maintenance during its lifetime, but when maintained properly it can last long. PEMFCs have a shorter lifetime than SOFCs, for example; but SOFCs experience a decay in performance during their lifetime. Exact values for the lifetime of the fuel cells are given in chapter 6 for the different manufacturers. Finally, the last disadvantage of fuel cells is their long start-up time and bad dynamic behaviour, especially high temperature fuel cells. Because they have to reach high temperatures to become efficient, their start-up time takes long. In the case of PEMFCs, especially LT-PEMFC, their start-up time and reaction time to load transients is much shorter.

4.5. Conclusion

In this chapter, the working principle and the different kinds of fuel cells were presented. This was followed by a description of the components needed when using fuel cells, and a comparison between internal combustion engines (ICEs) and fuel cells.

It can be said that the literature presents fuel cells as a technology with a lot of potential in order to reduce harmful emissions. Also, they have many advantages with respect to the traditional ICE that can be useful for their use on board of naval surface vessels, such as noise and vibration reduction, reduced infrared signatures, reduced maintenance, and a modular and flexible design (van Biert et al., 2016).

High temperature fuel cells have the highest efficiency. Low temperature fuel cells perform equal or slightly higher than the traditional systems. The most promising type of low temperature fuel cell seems to be PEMFCs, which is already being used on board of submarines, as is explained later in chapter 6. Out of the high temperature fuel cells, SOFCs and MCFCs have great potential. MCFCs have, however, slightly lower efficiencies than SOFCs and they require recirculation of CO_2 from the anode to the cathode, making the system slightly more complex.

High temperature fuel cells have the advantage that they are much more versatile regarding the fuel to use since they allow internal reforming due to the high temperatures at which they work, and that they allow heat recovery. PEMFCs on the other hand require very pure hydrogen because they are very sensitive to impurities, meaning that either hydrogen directly is used as a fuel, or an external fuel reformer is needed that is able to produce hydrogen with a high purity. Regarding the lifetime, PEMFCs seem to have shorter lifetimes than SOFCs, although the latter experience a decay in performance due to the corrosion that takes place inside the fuel cell.

Both PEMFCs and SOFCs are larger than ICEs, where PEMFCs have a higher energy density than SOFCs. PEMFCs do however need either pure hydrogen (with its low energy density as is shown later in chapter 5), or an external fuel reformer, which adds up to the total size. In chapter 6 concrete fuel cells on the market by different manufacturers are presented. The biggest disadvantage of high temperature fuel cells is their long start-up times and their slow dynamic response, due to the high temperatures they need to reach to become efficient. According to sources like Prof. dr. Robert Selman and de Troya et al., 2016, the first can be compensated by making use of other power sources such as batteries. The second, the worse dynamic behaviour, can be improved by keeping the fuel cells at high temperatures making use of the waste heat. This last one comes however at the cost of a shorter lifetime.

In conclusion, the choice of the fuel cell to be used will be between SOFC, and PEMFC. While SOFCs are still being developed, PEMFCs have been used for a longer time and proven to be feasible for maritime applications. Which one specifically and why, will lead from the following chapters. When one kind is chosen, specific characteristics from the manufacturer are required in order to simulate their performance and effect on the design properly.

5

Hydrogen carriers

After having looked at naval surface vessels (chapter 3), and fuel cells (chapter 4), in this chapter the most relevant types of fuels are presented. All of them contain hydrogen, hence the name of hydrogen carriers, which allows them to be used by fuel cells. As explained previously, a low temperature fuel cell like a PEMFC requires very pure hydrogen; which means that either hydrogen is used as a fuel, or another hydrogen carrier needs to be reformed to a very pure form of hydrogen. High temperature fuel cells allow for some internal reforming, thus they are more versatile regarding the choice of a hydrogen carrier.

Since the purpose of this research is to look at the use of fuel cells on board of naval surface vessels, aspects like size and safety are crucial and must be taken into account. In section 5.2, the energy densities of the different fuels are presented. Next, in section 5.3, the safety of the different hydrogen carriers is discussed, after which the general properties and the storage required is introduced in section 5.4. Finally, in section 5.5 the different emissions for each kind of fuel are presented.

5.1. Types

For this chapter, the following hydrogen carriers are discussed:

- Diesel.
- Hydrogen.
- Liquid natural gas (LNG).
- Dimethyl ether (DME).
- Ethanol.
- Methanol.
- Ammonia.
- Sodium borohydride.
- VOYEX's liquid organic hydrogen carrier (LOHC).

5.2. Energy densities

It is known that fossil fuels have the advantage of having high energy densities. Alternative fuels are generally less dense from an energetic point of view, and require more equipment to be used. In Figure 5.1, the challenge is illustrated clearly. This figure presents the volumetric and gravimetric energy densities of alternative fuels with respect to the commonly used diesel fuel.

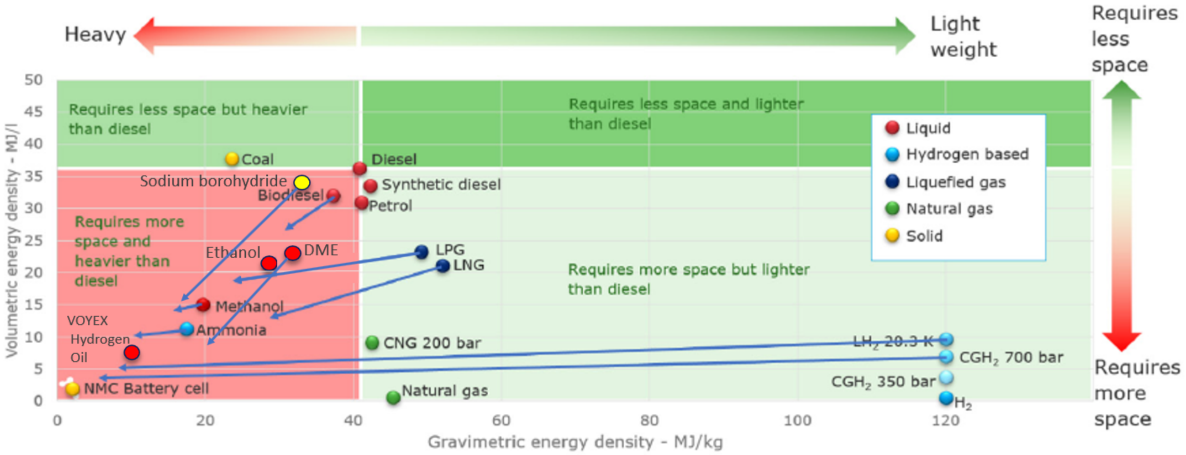

Figure 5.1: Volumetric and gravimetric energy densities of different fuels. The arrows represent the impact on energy density when taking storage systems into account (image from DNV-GL, 2019 with added information from Bell et al., 2011, Mestemaker et al., 2019, Mogensen et al., 2019, van Kranenburg-Bruinsma et al., 2020, van Nievelt, 2019, VOYEX, 2022).

It can be seen how all fuels are either heavier or bulkier than diesel. Some, like hydrogen (both liquid as at high pressure), and LNG, are in the area of more volume but less weight. However, as will be explained later, the arrows in Figure 5.1 indicate the total density once the storage systems are taken into account. In that case, they fall again in the lower left quadrant, showing a total increase in weight as well.

5.3. Safety

Since this research looks for a good combination of fuel and fuel cell to be used on board of naval vessels, safety is a key aspect to take into account. In Table 5.1, the different fuels are presented showing three different parameters: flash point, autoignition temperature, and toxicity.

According to DNV-GL, 2019, the flash point is ”the lowest temperature at which a liquid can form an ignitable mixture in air near the surface of the liquid”. Therefore, the higher the flash point, the lower the flammability and thus the safer it is.

Autoignition temperature is slightly different because it is ”the minimum temperature required to ignite a gas or vapor in air without a spark or flame being present” (DNV-GL, 2019). This means that at the autoignition temperature, no spark is required to burn the fuel. For this reason, the higher the autoignition temperature, the safer the fuel is.

Toxicity refers to how harmful a certain fuel can be to humans when exposed to it. The more toxic a fuel is, the more measures need to be taken to reduce the risk of poisoning.

In section 5.4, when describing each fuel, a reference to the safety of each fuel is done. Mind that in Table 5.1 hydrogen does not have a flash point because it is gaseous at ambient temperature, but it is always a flammable and highly explosive gas.

Table 5.1: Flammability and toxicity of different fuels (Alvarez et al., 2019, Chen et al., 2010, DNV-GL, 2019, Huang et al., 2021, Sürer and Arat, 2018, US National Library of Medicine, 2022, VOYEX, 2022.)

Fuel	Flash point (°C)	Autoignition temperature (°C)	Toxicity
LNG	-188	537	not toxic
Methanol	11 - 12	470	toxic
Hydrogen	not defined, but flammable	500	not toxic
Ammonia	132	630	highly toxic
Diesel	63	350 - 380	not toxic
Dimethyl ether	-41	350	not toxic
Ethanol	14	368	not toxic
Sodium borohydride	70	220	highly toxic
VOYEX Hydrogen Oil	120	436	not toxic

5.4. Properties and storage

In this section a short description of each fuel is done, paying attention to its safety and storage. Mind that the technology readiness level (TRL) of each fuel is different. This means that the information available for each fuel and the accuracy of the values shown before, especially referring to the size of the storage systems, might not be fully correct due to the lack of tests at large scales and experience in the use of that certain fuel.

It is also important to state the difference between the components required depending on the fuel cell that is used. None of these are included in the values shown hitherto in this chapter. Mind that a low temperature fuel cell requires a much higher level of hydrogen purity than a high temperature fuel cell, which affects the size of the reformer when other fuels than pure hydrogen are used.

5.4.1. Diesel

Diesel is the starting point of Figure 5.1. It is a dense fossil fuel with high energy density, both volumetric as gravimetric. As van Biert et al., 2016 states, it is difficult to convert it into a hydrogen-rich gas. Moreover, its sulphur content can be a problem due to the sensitivity of fuel cells to this element. According to Malik et al., 2020 the autothermal reforming temperature (ATR) of diesel is 900°C.

Despite these disadvantages, because of its high energy density, it is one of the most investigated types of hydrogen carrier, also due to the simplicity of adapting the current ships when the same fuel can be used. Some projects, like the current NAUTILUS, 2021 are investigating the use of, among others, bio-diesel (very similar to diesel, but with slightly lower energy density as can be seen in Figure 5.1) in combination with SOFCs in cruise ships.

From Table 5.1 it can be seen that diesel is a safe fuel, having a medium/low flammability and low toxicity. Using diesel does however not have such a positive impact on the reduction of emissions, as is explained later in section 5.5 .

5.4.2. Hydrogen, H_2

Hydrogen can be stored in multiple ways to increase its energy density. In Figure 5.1 two types are shown: hydrogen at high pressure (it can be either at 350 bar or 700 bar), and liquid hydrogen (at -252 °C). As can be observed, despite having very high gravimetric energy densities, once the storage systems are included their energy density becomes very low.

When using compressed hydrogen not all hydrogen taken on board can be used. According to Hua et al., 2017, some residual amount is required in order to keep a certain pressure in the tank. In the case of liquid hydrogen, the tanks storing it are open systems to prevent strong overpressure. These tanks can have a low pressure (10 bar) if they have a robust insulation (Reuß et al., 2017). Due to the heat transfer through the tanks some hydrogen is lost, which is known as boil-off gas (Schlapbach and Züttel, 2001).

Another form of storing hydrogen that is not shown in Figure 5.1 is the use of metal hydrides. These are often used on board of submarines. In Figure 5.2 the energy densities of the different forms to store hydrogen are shown including the storage systems. As can be seen, metal hydrides have a higher volumetric density, but a lower gravimetric energy density. For this reason, metal hydrides are very often used on board of submarines, where volume is very critical. Also, metal hydrides can be kept at room temperature (Von Colbe et al., 2019. Despite all, metal hydrides are still a current topic of investigation with the goal of increasing the gravimetric energy density (van Biert et al., 2016, Schlapbach and Züttel, 2001).

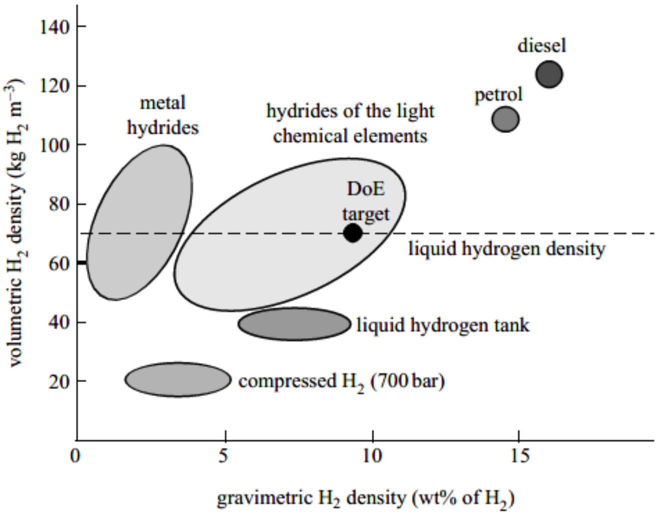

Figure 5.2: Energy density of different forms of hydrogen storage, including storage systems (Edwards et al., 2007).

In Figure 5.2, where the storage systems are included, one can see a significant difference in volume compared to diesel. However, when one takes into account the space requirement, instead of just volume, the difference is bigger. Some like van Kranenburg-Bruinsma et al., 2020 state that an installation of liquid hydrogen and hydrogen at 700 bar require respectively 7.7 times and 15.7 times more space than diesel.

From Table 5.1 it can be said that hydrogen is unsafe since it is always explosive, but has a relatively high autoignition temperature. Hydrogen is considered to be not toxic.

5.4.3. Liquid Natural Gas (LNG)

When natural gas is stored at cryogenic conditions (-162 °C) we talk about LNG. Its composition varies for different sources, but it is mostly composed of methane (CH_4) (van Biert et al., 2016). Despite being a fossil fuel, it is estimated that the emissions on LNG are lower than other fossil fuels (DNV-GL, 2019, Eide et al., 2013). The ATR of LNG is around 827°C (Semelsberger et al., 2006).

The shipping sector has already experience with LNG in LNG carriers. Like all cryogenic liquids, there is some presence of boil-off gas. van Kranenburg-Bruinsma et al., 2020 states that LNG has a packaging factor of 2 compared to diesel, and a space requirement of 3.2.

According to Table 5.1, LNG has a very low flash point, which makes it highly ignitable, but at the same time it has a high autoignition temperature. It is regarded as a not toxic fuel.

5.4.4. Dimethyl ether (DME), C_2H_6O

DME is obtained either by dehydration from methanol or from synthesis of gas directly. It can be stored in liquid form at pressures of 5 bar (Sapra, 2020). Based on thermodynamic equilibrium data it can be said that the ATR of DME is 427°C, although from experiments it appears that this temperature can be lower at about 270°C (Semelsberger et al., 2006).

From Figure 5.1 it can be seen that the pure DME has a relatively high energy density compared to other alternative fuels. However, when the size of the storage systems are taken into account its energy density drops dramatically.

In Table 5.1 DME is regarded as a not toxic fuel, with a low flash point and medium autoignition temperature.

5.4.5. Ethanol, C_2H_5OH; and methanol, CH_3OH

Ethanol and methanol are two hydrogen carriers that are liquid at ambient pressure, which facilitates their storage because they can be used in the conventional liquid infrastructure with minor adjustments (van Biert et al., 2016). Their energy density is lower than that of fossil fuels, and they can be corrosive to some metals (Ellis and Tanneberger, 2015). The ATR of methanol is tested to be within the range of 230-260°C (Chein et al., 2012), while the ATR of ethanol is 727°C (Semelsberger et al., 2006). The lower the ATR, the less energy is required to reform the fuel.

They have many environmental advantages, such as that they do not contain sulphurs. Methanol is regarded as toxic for humans; therefore measures need to be taken when being exposed to it. Ethanol is not classified as toxic for humans (Ellis and Tanneberger, 2015). The infrastructure for methanol is already available around the globe since it is one of the top five chemical commodities shipped around the world each year (DNV, 2022).

According to van Kranenburg-Bruinsma et al., 2020 it is estimated that 2.3 times more space is required to use methanol compared to the space required by diesel. Since ethanol has a higher energy density (see Figure 5.1) and the storage systems are assumed to be similar, ethanol will require even less space, approximately around 1.7 times more space than diesel. Both of them are considered to be slightly unsafe due to their low flash points.

5.4.6. Ammonia, NH_3

Ammonia is a hydrogen carrier that does not contain carbon in its chemical formula, which makes it an interesting candidate due to the low emissions of using it as a fuel. It requires an ATR between 300-400°C to achieve reforming rates above 98% (Lipman and Shah, 2007).

Like hydrogen, ammonia can be either cooled (-30 °C), or compressed (10 bar). Cooled ammonia has a higher volumetric energy density, which translates in a space requirement of times 3.4 compared to diesel, instead of the factor 6.4 for compressed ammonia (van Kranenburg-Bruinsma et al., 2020).

Ammonia has high safety in terms of flammability, since it has a high flash point and autoignition temperature (Table 5.1). Its main disadvantage is its high toxicity.

5.4.7. Sodium borohydride, $NaBH_4$

Sodium borohydride is an inorganic compound with chemical formula $NaBH_4$. It is normally found as a powder and it is stable until 673 K, thus it is not able to provide hydrogen through a thermal activation process (Santos and Sequeira, 2011). In order to release the hydrogen, it is required that it is mixed with water, with the following chemical reaction:

$$\mathrm{NaBH_4} + 2\mathrm{H_2O} \longrightarrow \mathrm{NaBO_2} + 4\mathrm{H_2} \tag{5.1}$$

It could be said that sodium borohydride acts as a water-splitting agent. However, the fact that it has to be mixed with water in order to release the hydrogen reduces the energy density of the entire system. In Figure 5.1 one can see the high energy density that pure sodium borohydride has, and the effect of taking storage systems into account. This last value may not be fully certain, since it is a fuel that is still being researched. The values shown in Figure 5.1 come from van Nievelt, 2019, but others like Mestemaker et al., 2019 argue that the energy density including storage systems is even lower than that of high pressure hydrogen. According to ir. Klaas Visser, an expert in the field of sodium borohydride, the complexity of using it as a fuel is the storage of the spent fuel. $NaBH_4$ generates hydrogen, but also $NaBO_2$ that needs to be kept on board to be exchanged by sodium borohydride when refuelling. This spent fuel can be stored in empty fuel tanks, or in special tanks for spent fuel, which has a significant impact on the size of the system.

According to Table 5.1, sodium borohydride is not highly flammable, but is considered as highly toxic.

5.4.8. VOYEX Hydrogen Oil

Liquid organic hydrogen carriers (LOHC) are a current topic of research. They are regenerative fuels that can be stored under ambient conditions, eliminating any kind of high-pressure or super insulated tank (Reuß et al., 2017).

For this research an interview was conducted with a Dutch company, VOYEX. The properties of their product are shown in Figure 5.1 and Table 5.1. As can be seen, its energy density is low compared to other hydrogen carriers. Regarding safety, it can be even considered as safer than diesel due to its higher flash point and low toxicity. The main advantage of LOHCs is the fact that they are regenerative. This means that once the fuel has been used and has released the hydrogen, the rest of the fuel is stored and brought back to port where it can be exchanged for new hydrogen oil. This can have positive effects on the design of a vessel since it would eliminate most of the ballast tanks due to an almost constant weight. Apart from its low energy density, VOYEX Hydrogen Oil requires a process unit to release the hydrogen. Even for high temperature fuel cells, internal reforming is not an option. For this reason and due to its low energy density, LOHCs are not considered to be suitable for the application with fuel cells. It is still an ongoing topic of research, so it may become an interesting option for the future, especially for smaller applications where volume and weight are not that critical.

5.5. Emissions

As stated in chapter 1, the main reason to perform this research is the emission reduction that can be achieved by using fuel cells instead of internal combustion engines. Apart from the fuels cells, that only by the fact of being more efficient than other prime movers lead to a reduction in emissions, the type of fuel also plays a very important role.

In this section a general presentation of the different kinds of emissions is done for the fuels mentioned before. The fact that fuel cells are not used extensively, and have not been tested with every fuel complicates quantifying these emissions. Therefore, combining logical reasoning and some literature, an overview of the different hydrogen carriers and their emissions is made.

The emissions discussed here are only the ones generated on board of the vessel, the so-called tank-to-wake emissions. Well-to-tank emissions are considered to be out of the scope of this research. This is because the extraction or generation process of a fuel can be sometimes done in multiple ways, which has an impact on the total emissions depending on which source of energy is used. It is also important to mention that bio-fuels, which are produced from biomass, are considered to be ”carbon neutral” in lifecycle assessments regarding tank-to-wake emissions because the amount of carbon dioxide released during combustion is the same as that captured by the plant during growth (Ellis and Tanneberger, 2015).

5.5.1. Carbon dioxide (CO_2)

In Figure 5.3 the tank-to-wake CO_2 emissions of the different hydrogen carriers is shown.

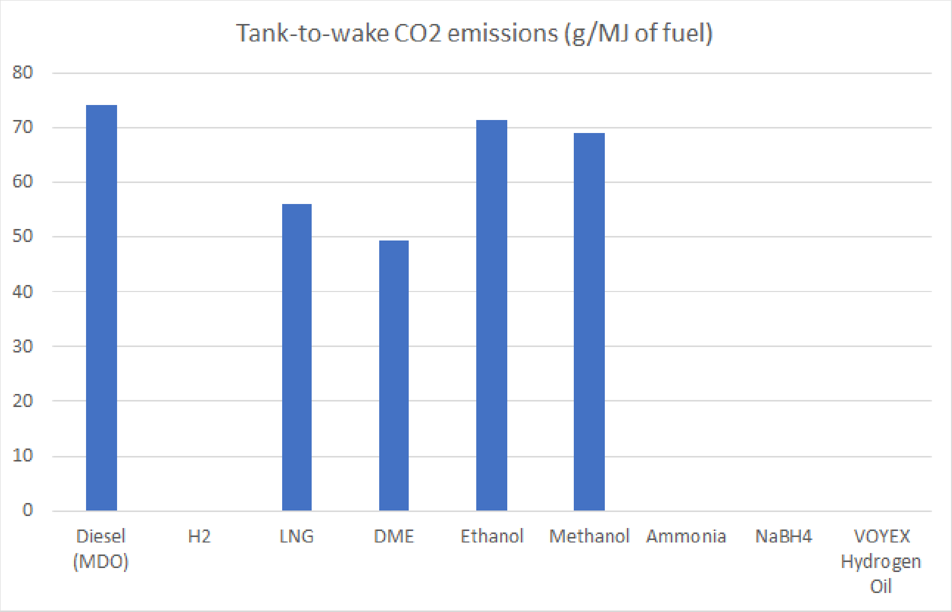

Figure 5.3: Tank-to-wake CO_2 emissions of different hydrogen carriers (Brynolf et al., 2014, DNV-GL, 2018, Ellis and Tanneberger, 2015, Semelsberger et al., 2006).

As can be seen, carbon dioxide emissions are present in those fuels containing carbon in their chemical formula. Diesel has the highest carbon dioxide emissions, followed by ethanol, methanol, LNG, and finally DME. It is important to mention that these values only show the amount of carbon dioxide generated for one megajoule of fuel, and do not take into account other aspects like the efficiency of the fuel cell for each fuel, which has to do with the amount of energy required for reforming.

5.5.2. Nitrogen oxides (NOx)

NOx is formed at high temperatures in contact with air. According to Lewis, 2021 the formation of NOx starts at temperatures above 750°C.

Quantifying the amount of NOx is complex and case dependent. In low temperature fuel cells there are barely no NOx emissions and in high temperature fuel cells these can be higher, but still insignificant compared to those of ICE. In van Veldhuizen et al., 2020, a comparison of the emissions of different types of fuel cells with different fuels is made with respect a diesel generator running on marine gas oil (MGO). It is concluded that regarding NOx emissions, in the worst case scenario which is a SOFC running on NH_3, the NOx emissions are more than 3,800 times lower than in the case of the diesel generator. Therefore, authors like Rathore et al., 2021 consider that fuel cells do not have NOx emissions.

5.5.3. Sulphur oxides (SOx)

SOx emissions occur when sulphur is present in the fuel. In the fuels presented in this chapter, only diesel contains sulphur in it. Therefore, diesel is the only fuel that can result in the emission of sulphur oxides. Different kinds of diesel fuels exist, with different levels of sulphur in them. The lower the sulphur content in the diesel, the lower the SOx emissions are. Another fossil fuel, like LNG, which is formed mostly by methane, is said to achieve a 100% reduction in SOx emissions (Herdzik, 2011). The rest of the hydrogen carriers discussed in this chapter do not have SOx emissions either.

5.5.4. Particulate matter (PM)

Particulate matter, which consists of microscopic solid particles, is also considered to be polluting. Of the fuels presented in this chapter, only diesel generates PM (Winnes and Fridell, 2009). The rest of the fuels mentioned here do not generate significant amount of PM. In the case of LNG and methanol, van Veldhuizen et al., 2020 found that the PM generated when combined with a SOFC is 16,000 times lower than the amount of PM generated by a diesel generator running on MGO. According to Di Natale and Carotenuto, 2015, the PM emission of a diesel engine fuelled with MDO ranges from 0.14 to 0.48g/kW h.

5.6. Conclusion

In this chapter an overview of the different kinds of hydrogen carriers was done. Aspects like energy density, safety, storage, and emissions were considered.

The energy density plot in Figure 5.1 illustrates the challenge of replacing diesel by an alternative hydrogen carrier. While diesel is theoretically a hydrogen carrier, converting it to a hydrogen-rich mixture is complicated. Moreover, since it contains sulphur, the fuel cells can be damaged due to their sensitivity to this component. Furthermore, diesel is out of all the fuels that were analysed, the one with the highest CO_2 emissions; apart from being the only one generating significant amounts of SOx, and PM. All other fuels can be considered cleaner.

Pure hydrogen, both compressed as liquefied, is considered to have too low energy densities when storage systems are taken into account. Therefore, an alternative has to be found that lies between the energy densities of hydrogen and diesel.

If one looks at the energy densities including storage systems in Figure 5.1, ethanol, methanol, LNG, and ammonia rank the highest in this order. Since this research looks at the application of fuel cells on board of naval vessels, safety is a crucial aspect. LNG is highly flammable, having a flash point of -188°C as shown in Table 5.1 and is therefore discarded. Ethanol and methanol have high energy densities and can be stored in liquid form in a very similar infrastructure than the conventional liquid fuels, which makes them an attractive choice. They are considered to be slightly unsafer than diesel with flash points of 50°C lower. Methanol is considered as toxic and ethanol as non toxic. With these characteristics, ethanol seems a better choice than methanol. However, methanol has the advantage of having been researched more extensively than ethanol due to its large availability worldwide, which leads to conclusions such as that methanol requires 2.3 times more space than diesel (van Kranenburg-Bruinsma et al., 2020). Apart from the fact that methanol has been more investigated than ethanol, it has the advantage that it requires a lower autothermal reforming temperature (ATR) than ethanol, which means that it requires less energy to be reformed. Ethanol should be kept in mind as a possibility to replace methanol in the future, having the advantage of having higher energy densities and being non-toxic.

Both ethanol and methanol do however lead to CO_2 emissions. If one wants to reduce the harmful emissions fully, ammonia is a good solution. Out of all ”clean” fuels, it is the one with the highest energy density. Others like sodium borohydride, or liquid organic hydrogen carriers are still being investigated and have not proven yet their performance at large scales. Ammonia is a safe fuel in the sense that it has a higher flash point than diesel, but is regarded as highly toxic for humans, which can complicate its application to any kind of vessel, but especially to a naval vessel due to the nature of their missions in case of a leakage. Moreover, it has a lower energy density than ethanol and methanol, because it requires 3.4 times more space than diesel (van Kranenburg-Bruinsma et al., 2020) and needs to be cooled at -30°C.

It can be concluded that both methanol and ammonia seem good choices to be used with fuel cells on board of naval surface vessels. Methanol has a higher energy density than ammonia and has the advantage that it can be stored in liquid form, requiring minor changes to the current liquid fuels installations. It is considered however as slightly unsafer due to its lower flash point and is toxic. Ethanol can be even a better option due to its higher energy density and non-toxicity. It has however not been investigated as much as methanol in combination with fuel cells. Ammonia is a cleaner fuel that does not generate CO_2 as an emission. It requires however more space to be stored and needs to be cooled, and it is considered as highly toxic.

6

Fuel cells for maritime applications

Now that both fuel cells and fuels have been introduced, examples of the use of fuel cells in maritime applications are presented. First, in section 6.1 the theoretical studies done on this matter are presented, followed by section 6.2 where examples of projects of vessels using fuel cells are introduced, next in section 6.3 the existing fuel cell modules on the market are shown.

6.1. Previous studies

In this section, different researches on the use of fuel cells are discussed. In the literature, investigations on PEMFCs, SOFCs, and MCFCs were found.

To start with the PEMFC. Minnehan and Pratt, 2017 did a feasibility study on the use of batteries or PEMFCs for fourteen different vessels, from small passenger vessels to large cargo ships. They took into account their routes to ensure that the new configuration would be at least able to sail one full trip. The weight and volume available were also studied, since the weight should not exceed the weight of the current prime mover and the whole system should still fit given the available volume. According to Minnehan and Pratt, 2017, an engine normally takes up to 20% of the volume available in an engine room. This number can be increased to 50% when talking about fuel cells or batteries, since less clearance is required for these components. This means that in the same engine room, up to 2.5 times more volume can be used. Regarding the fuels considered, Minnehan and Pratt, 2017 contemplated liquid hydrogen (at -252°C), and high pressure hydrogen (350 bar). The report concludes that volume appears to be a limiting factor, and not weight, mainly due to the lower gravimetric energy density of hydrogen compared to the traditional fossil fuels. Out of the fourteen vessels that were considered in this research, thirteen were feasible to use either batteries or PEMFCs. When looking at the configurations using PEMFCs only, twelve out of the fourteen vessels were considered feasible when using liquid hydrogen, which proved to be more versatile than high pressure hydrogen. The only two cases where PEMFCs were not feasible were the *Trondheimsfjord II*, a ferry of 24.5 m length with very little volume available, and *Trearddur Bay*, a high speed catamaran of 20.6 m length, where the available volume under deck was the limiting factor. In all other cases the configuration using PEMFCs fulfilled the mass and volume requirements and ensured an endurance for at least one trip. The report by Minnehan and Pratt, 2017 does, however, not take into account the effects of the arrangement of the different components in the vessels, such as the shape of the hydrogen tanks, because it looks merely at the total volume available. Also, it does not show the difference in range compared to the previous configuration, since it assumes that being able to sail one trip is enough.

Kim et al., 2020 looked at the use of PEMFCs and SOFCs using ammonia as a fuel. This paper takes a 2500 Twenty-Foot Equivalent Unit (TEU) container feeder ship as a target ship, of 195.0 m length and with a main engine with a power output 13.5 MW and three gensets with power outputs of 1.5 MW each. Ammonia is considered in this case, also for the configuration using PEMFCs, since it has a higher volumetric energy density than liquid and compressed hydrogen. Therefore, for the configuration with PEMFCs, a cracker is required to convert the ammonia into hydrogen. Also, both PEMFC and SOFC configurations make use of batteries. In the case of the PEMFCs, the batteries are used to compensate the lack of power during the cold-start up in order to start the cracker. For the SOFCs, due to their poorer slow dynamics, the batteries are bigger and used to compensate the peaks in power demand, that could be even used for operations in port (Kim et al., 2020). In Table 6.1, an overview of the results of Kim et al., 2020 is presented, where the weight and volume include all necessary components and fuel, and the cost is calculated for a lifespan of twenty-five years. For the cost, a lifetime of six years is assumed for the PEMFCs, five years for SOFCs, and between ten and twelve years for the batteries.

Table 6.1: Comparison in volume, mass, and cost for different configurations with respect to the traditional heavy fuel oil main engine configuration including ammonia as fuel (Kim et al., 2020)

System	Volume	Mass	Cost
HFO ME and gensets	1.0	1.0	1.0
SOFC + batteries	2.3	1.5	5.2
PEMFC + batteries	2.0	1.4	5.0

Considering everything, Kim et al., 2020 presents a good overview of the impact of replacing a power plant running on fossil fuels by an alternative fuel and different types of fuel cells. The differences in cost could be reduced, since they are dependent on the price of ammonia and this is expected to reduce significantly in the future (Kim et al., 2020). Despite being the most expensive configuration, the combination of SOFCs and batteries is the most eco-friendly and has the lowest fuel consumption due to the high efficiency of the fuel cells.

Others like Ghezel-Ayagh et al., 2013, studied and tested the use of SOFCs and batteries for a large displacement unmanned underwater vehicle (LDUUV). This UUV of 3.03 m long has liquid oxygen inside since air inlet is not possible underwater and runs on JP-10 fuel, which is a hydrocarbon with chemical formula $C_{10}H_{16}$ that needs a fuel reformer. The SOFC showed great performance and was validated through long term steady tests of more than 28,000 hours (equivalent to 3.2 years when running 24 h/day). It showed a degradation rate of 0.28%/1,000 hours after the first 16,000 hours at 750°C. This is equivalent to a decay in performance of 3.36% after 3.2 years of operation. This design was considered to be feasible.

A relatively new paper that also studied the impact of using SOFCs in a design is Haseltalab et al., 2021. In this paper, the authors study the application of 8.3 MW of SOFCs fuelled by LNG to a dredger that also makes use of batteries to shave peak powers and keep up with the fast load transients (Haseltalab et al., 2021). Here, the batteries must be able to provide the same power than the SOFCs when the system faces fast transient loads. Looking at the size of the fuel cell stacks required, the paper considers that an increase of 70% in engine room volume is needed. From an environmental point of view, a CO_2 emission reduction of 53% is achieved for the configuration using SOFCs and batteries, with respect to the original configuration with diesel engines.

An example of the application of MCFCs to a marine environment was the conceptual study done for the USCGC VINDICATOR, a ship that served in the United States Coast Guard from 1994 to 2001. In Karni and Fontneau, 1999 a feasibility study for the replacement of four Caterpillar diesel generators of 600 kW each is performed. The USCGC VINDICATOR also had two 800 hp direct current propulsion motors driving the two fixed pitch propellers. It was considered to be feasible to replace the diesel generators by four MCFC stacks, that were fueled by F-76, a NATO distilled marine fuel with a very low sulphur oxides concentration (de Troya et al., 2016). The volume of the fuel cell system was more than two-and-a-half times the volume of the generators it replaced. It was possible to fit these in the engine room, but the removal of two void bulkheads was needed in order to make some space free, due to the larger size of the stacks. Karni and Fontneau, 1999 also pointed out that the stability and sea keeping were expected to remain unchanged, but that steps to enhance the instantaneous transient response were needed.

6.2. Use of fuel cells

Apart from research done on a conceptual phase, some have gone a step further and have tested fuel cells physically in ships. In this section, different examples of vessels using fuel cells are introduced. First, some projects on the use of fuel cells in surface vessels are presented, followed by the use of fuel cells in submarines.

6.2.1. Surface vessels

Zero Emission Ships(ZEMSHIP)

In 2006, the European Union (EU) and a group of companies financed a project where two 48 kW PEMFC stacks were built into a small passenger ship, the *FCS Alsterwasser* of 25 m length able to carry 100 passengers, which started to sail in 2008 (Wagner, 2008). This ship was fueled by hydrogen stored at 350 bar, reducing the local emissions to zero. It also made used of batteries for energy storage and peak load shaving. Despite the high costs due to being a prototype, the design was considered to be feasible (European Commission, 2010).

DESIRE

The diesel fuel processing for fuel cells (DESIRE) was a project performed between 2001 and 2004. It was done by some European NATO countries that wanted to study the possibility of using F76 diesel reforming in naval surface vessels in order to be used by PEMFCs . The setup was made with a 25 kW PEMFC stack and it showed promising results. However, steps like desulphurization seemed to be crucial due to the sensitivity of the pre-reformer to sulphur (Krummrich et al., 2006).

Nemo H_2

The *Nemo* H_2 is a canal cruise in Amsterdam able to carry 82 passengers that was delivered in 2011. It was powered by two 65 kW PEMFCs in combination with a 55kW lead acid battery pack (McConnell, 2010). The fuel was hydrogen stored at 350 bar (Shakeri et al., 2020). Due to the absence of a proper permanent hydrogen station it was unable to sail actively (van Biert et al., 2016).

e4ships

This project consists of two subprojects, the SchIBZ and the Pa-X-ell.

In the SchIBZ the aim was to use a SOFC stack of 500 kW to generate auxiliary power running on diesel with low sulphur content onboard of the *MS Forester* (Leites et al., 2012). An electrical efficiency of 50% was achieved with a 27 kW stack (van Biert et al., 2016). This project continued with the MultiSchIBZ, where company Sunfire GmbH provided the 50 kW SOFC stack. However, according to Sunfire GmbH, this product is no longer produced due to the lack of interest from an industry partner and therefore no mass market and competitiveness.

In Pa-X-ell the goal was to look at the reduction of emissions of cruise ships, yachts, and RoPax-ferries. Here, the first step was to install a 30 KW high-temperature PEMFC (HT-PEMFC) running on hydrogen that was reformed from methanol. In the second phase, a 120 kW stack was tested but this time running on LNG. The results showed that it was successful to integrate a HT-PEMFC as an auxiliary power source onboard of a vessel, with significant lower emissions and noise levels (Tronstad et al., 2017).

METHAPU

The methanol auxiliary power unit (METHAPU) project looked at the use of SOFCs running on methanol as an electricity supply in the merchant navy. Here, a 20 kW fuel cell stack was placed on board the car carrier *Undine* (Fuel Cells Bulletin, 2010). It also made use of a heat recovery system to increase the efficiency. It concluded that using SOFCs reduced significantly the environmental impact (Strazza et al., 2010).

FELICITAS

The FELICITAS project investigated the use of fuel cells in heavy duty transport. Among these, the use of SOFCs fueled with LNG on board a super yacht as an auxiliary power generator was studied in combination with the use of flywheels (European Commission, 2008). Later, in Tse et al., 2011 the integration of SOFCs with gas turbines and heat, ventilation, and air conditioning systems (HVAC) was examined.

FellowSHIP - Viking Lady

In this project an offshore supply vessel, the *Viking Lady*, was used to test a MCFC stack of 330 kW fueled by LNG (Fuel Cells Bulletin, 2012). Efficiencies of the fuel stack of 52.1% were measured at 100% load and operational times of more than 18,500 hours successfully demonstrated (Tronstad et al., 2017). The *Viking Lady* was the first vessel to use high-temperature fuel cell technology and to obtain FC-Safety class notation (de Troya et al., 2016).

Ship Service Fuel Cell (SSFC)

The US Navy also did some research on the use of fuel cells in naval vessels. The SSFC project consisted of the design of 625 kW MCFC stacks and 500 kW PEMFC stacks. Four of the MCFC stacks fuelled by diesel would be able generate 2.5 MW and five of the PEMFC stacks would be able to generate the same amount of power, but with the need of a fuel reformer in order to allow the use of diesel with PEMFC (Abens et al., 2000, Tronstad et al., 2017). This project also included shock and vibration tests, and the analysis to prove that the fuel cells were able to operate in a salt air environment (Allen et al., 1998).

Molten Carbonate Fuel Cells for Waterborne Application (MC-WAP)

In this project, a 150 kW MCFC stack was tested and a concept design of a 500 KW MCFC stack was made. The fuel used was diesel, which went through a fuel processing module first to be converted into syngas, to then enter the fuel cell module. The fuel cell stack of 150 kW was tested on shore and on board (Tronstad et al., 2017). In further studies such as Specchia et al., 2008 and Bensaid et al., 2009, the concept study of the 500 kW fuel cell module was studied to be used on large vessels such as commercial cruising ships as an auxiliary power source.

6.2.2. Submarines

Submarines make use of fuel cells as part of their air independent propulsion system (AIP). In the 1980s the German Navy decided to incorporate fuel cells in their submarines after a decade of research (Sattler, 2000). Since then, many submarines use this system in order to sail silently and submerged for longer periods when being in theatre. Fuel cells have the advantage that when oxygen and hydrogen are taken on board, no air inlet is required, which means that the submarine can power itself without having to surface. Mostly, PEMFC are used in combination with liquid oxygen and hydrogen stored in metal hydride cylinders (Han et al., 2012).

As Han et al., 2012 explains, the differences in power requirements when being surfaced or when being submerged and using AIP are large. While the former may need some megawatts, the latter suffices with a couple hundred kilowatts. This allows the use of a technology that requires more volume than the traditional fossil fuels and combustion engines/generators. However, especially the storage tanks of hydrogen are heavy and limit the endurance of the submarine (Han et al., 2012, Krummrich and Llabrés, 2015). The bigger size and weight can be critical when going to bigger-sized submarines, which leads to think of the use of hydrocarbons in combination with a fuel reformer to generate very pure hydrogen to be used by the PEMFC. This is something that Krummrich and Llabrés, 2015 already studied to conclude that methanol was a good candidate for such reforming on board of a submarine. Navies like the Spanish have already incorporated fuel reforming from bioethanol to be later converted into hydrogen to be used by the 300 kW PEMFC in the S-80 Plus class. The CO_2 generated during the reforming process is discharged underwater (de Troya et al., 2016).

6.3. Manufacturers

In this section, an overview of the current fuel cells on the market is presented. Keeping the eye on the application to a marine environment as part of the main propulsion of a vessel, only the promising types of fuel cells are presented and the manufacturers providing higher power ranges, since the propulsion of a ship requires in the order of megawatts. Other manufacturers offer smaller fuel cell modules, that can for example be used for households. These are left out of this research, due to the difficulty to scale them for higher power demands and the lack of experience of the manufacturer.

6.3.1. PEMFC

As explained previously, PEMFCs are in a further development stage and are already being used, also in a marine environment in the case of submarines. In this section, four different manufacturers of fuel cell modules are presented[1].

Mind that when one thinks of the use of fuel cells at a larger scale, and not in the range of a couple hundred of kilowatts for auxiliary power or AIP, the support systems can be optimized by combining them for the different fuel cell stacks instead of having a separate support system module per stack.

Nedstack

Nedstack is a Dutch company specialized in PEM fuel cell solutions.

Nedstack offers two different sets of Maritime PEMFC modules. The first one is able to generate 100 kWe nominal power and the second one 500 kWe. The dimensions and weight are shown in Table 6.2. Mind that the dimensions and weight shown here are the ones of the entire module, and not only the stacks.

Table 6.2: Specifications of the PEMFC modules of Nedstack (Nedstack Fuel Cell Technology, 2022a, Nedstack Fuel Cell Technology, 2022b).

	MT-FCPI-100	MT-FCPI-500
Nominal power (kWe)	100	500
Weight (kg)	2,500	15,000
Length (m)	2.01	6.06
Width (m)	1.10	2.44
Height (m)	2.09	2.90

Figure 6.1: MT-FCPI-500 Nedstack Fuel Cell Technology, 2022b.

According to Nedstack the stacks need to be refurbished after 24,000-30,000 hours, which is equivalent to 2.7-3.4 years running 24 h/day. Nedstack offers these modules to be placed directly on top of the deck of a vessel, which means that they include all the necessary components inside, together with the fuel cell stack.

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[1] A fuel cell module consists of a fuel cell stack and its support systems. A fuel cell stack consists of multiple fuel cells.

PowerCellution

PowerCellution is a Swedish company owned by PowerCell. They offer a module, consisting of PEMFC and all the other support systems. The dimensions of such a module are shown in Table 6.3. In Figure 6.2, only the top part is the fuel cell stack, while the rest are all other support systems.

Table 6.3: Specifications of the PEMFC module of PowerCellution (PowerCellution, 2022).

	Marine System 200
Nominal power (kWe)	200
Weight (kg)	1,070
Length (m)	0.73
Width (m)	0.90
Height (m)	2.20

Figure 6.2: Marine System 200 PowerCellution, 2022.

PowerCell has so far not applied this module to shipping, but it is currently busy with a project consisting of multiple of such modules for a ”leading European shipyard” with a total power of 3 MW that will be delivered and developed by 2023 (Randall, 2021). After an interview with PowerCell some other information was shared, such as that the lifetime of the aforementioned fuel cells is very dependent on their use, but it is generally between the 15,000-35,000 hours, which is equivalent to 1.7-4.0 years running 24 h/day. The efficiency varies between 44-58% depending on the load applied (PowerCellution, 2022).

Ballard

A very similar product to the one of PowerCellution is provided by the Danish company Ballard Power Systems. The specifications of the PEMFC module meant for maritime applications are found in Table 6.4. Like in the previous examples, the fuel cell module shown in Figure 6.3 includes the fuel cell stacks and the support systems.

Table 6.4: Specifications of the PEMFC module of Ballard (Ballard Power Systems, 2022).

	FC wave
Nominal power (kWe)	200
Weight (kg)	1,050
Length (m)	1.21
Width (m)	0.74
Height (m)	2.20

Figure 6.3: FC wave (Ballard Power Systems, 2022).

The peak fuel efficiency is 53.5%. Also, Ballard claims that this fuel cell module has a durability greater than 30,000 hours, which is equivalent to 3.4 years running 24 h/day (Ballard Power Systems Inc., 2020).

Siemens SINAVY
The German company Siemens has wide experience in the use of PEMFCs for AIP in submarines. They offer different fuel cell modules that are presented in Table 6.5. Because these modules are meant to be used in submarines, where space is very limited, they are already very optimised in terms of volume including all other components in the module (Siemens, 2013).

Table 6.5: Specifications of the PEMFC module of Siemens (Siemens, 2013).

	FCM 34	FCM 120
Nominal power (kWe)	34	120
Weight without module electronics (kg)	650	900
Length (m)	1.45	1.76
Width (m)	0.48	0.53
Height (m)	0.48	0.50

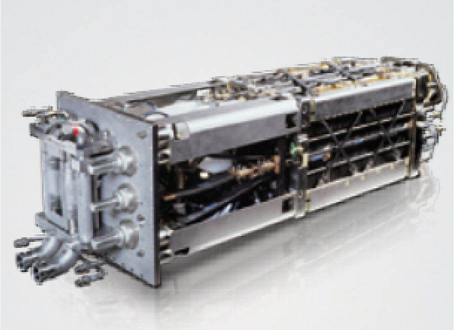

Figure 6.4: FCM 34 (Siemens, 2013).

The efficiencies vary between 54-69% depending on the load (Siemens, 2013). The weights presented in Table 6.5 do not include the module for electronics. These modules are made to work on pure oxygen, since this is carried inside of the submarine for its use for the AIP.

6.3.2. MCFC

Some of the projects described in section 6.2 used MCFCs. However, in recent years research has focused more on SOFCs due to their higher efficiencies and because both types have very similar advantages and disadvantages. Companies like the American Fuel Cell Energy still sell MCFC modules, like the ones that were taken into account in the concept design of the USCGC VINDICATOR explained in section 6.1.

Fuel Cell Energy
For this research, the American company Fuel Cell Energy is the one that appears to offer the biggest fuel cell modules. They offer on-site power generation for large installations, with fuel cell plants from 1.4 MW up to 3.7 MW. Because they are meant to be kept outside, where large spaces are available, they are not contained inside a module in contrast to the previous examples. The picture on the left in Figure 6.5 shows a 1.4 MW MCFC plant, and the picture on the right in Figure 6.5 is the fuel cell stacks in an isolation case.

Figure 6.5: SureSource1500 by Fuel Cell Energy (Fuel Cell Energy, 2022).

The SureSource1500 for example, shown in Figure 6.5 is able to generate 1.4 MW running on natural gas and reaching a LHV efficiency of 47% (Fuel Cell Energy, 2022).

6.3.3. SOFC

SOFCs are not as far in a development stage as PEMFC. Therefore, the products that are currently on the market are undergoing rapid changes, increasing the efficiencies and lifetimes of the fuel cell stacks. This subsection presents the current products on the market for three different manufacturers.

Mitsubishi

The Japanese Mitsubishi Heavy Industries offers a SOFC module, which includes, apart from the stack, a gas turbine for heat recovery. The specifications of the SOFC module are presented in Table 6.6.

Table 6.6: Specifications of the SOFC module of Mitsubishi (Mitsubishi Power, 2019).

	MEGAMIE
Nominal power (kWe)	250
Weight (kg)	33,000
Length (m)	11.40
Width (m)	3.30
Height (m)	3.20

One may notice that the table above presents a big module for the amount of power that is generated. Here again, it is important to mention that the module contains all necessary components and support systems and that the fuel cell stack is only one of them. A diagram of the composition of such module is shown in Figure 6.6.

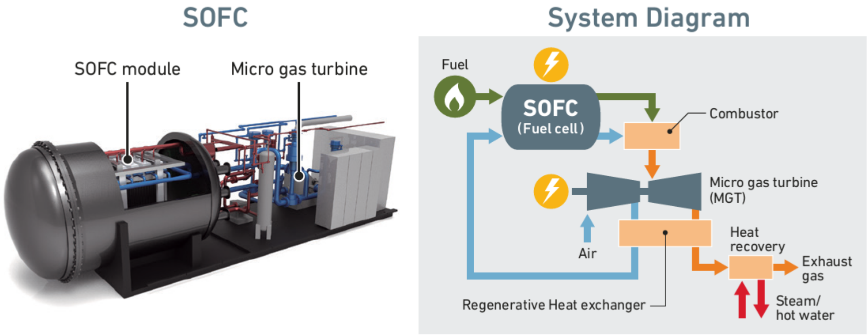

Figure 6.6: MEGAMIE SOFC module (Mitsubishi Power, 2019).

This module achieved an electrical efficiency of 53%, and a total efficiency of 73% when using hot-water recovery and 65% when using steam recovery (Mitsubishi Power, 2019). It proved a good performance for more than 25,000 hours (2.8 years at 24 h/day) (Mitsubishi Power, 2020).

Mitsubishi designed this module to work on LNG. Its starting time when starting cold is of 24 h and 2 h when it is already hot (Mitsubishi Power, 2019).

Mitsubishi is contemplating to expand the MEGAMIE to a 1 MW version, but this product is not yet on the market.

Bloomenergy

Another manufacturer that produces SOFC modules is the American company Bloomenergy. They offer a 325 kW module with the specifications as shown in Table 6.7. A picture of such module can be seen in Figure 6.7.

Table 6.7: Specifications of the SOFC module of Bloomenergy (Bloomenergy, 2022).

	Bloom Energy Server 5.5
Nominal power (kWe)	325
Weight (kg)	15,800
Length (m)	5.46
Width (m)	2.64
Height (m)	2.18

Figure 6.7: Bloom Energy Server 5.5 (Bloomenergy, 2022).

Bloomenergy, 2022 reports that the electrical efficiencies of such a module lie between 53% and 65% when working on natural gas.

Fuel Cell Energy

Apart from selling MCFCs, Fuel Cell Energy is also considering some other kinds of stacks, like the SOFCs shown in Figure 6.8. The one on the left, consisting of 16 stacks is able to generate 107 kW, while the one on the right containing 48 stacks is able to generate 322 kW.

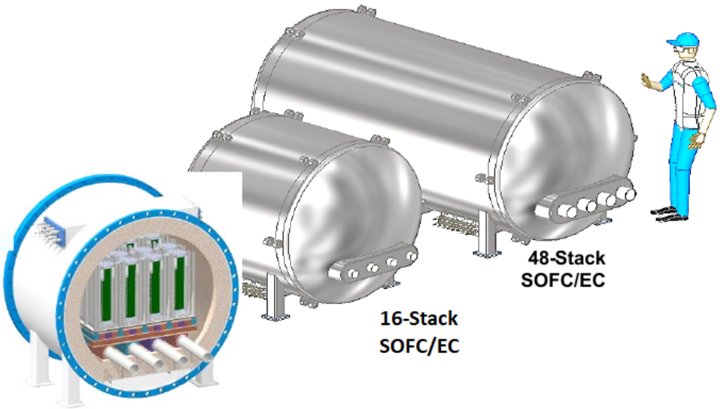

Figure 6.8: SOFC stacks by Fuel Cell Energy (Ghezel-Ayagh, 2021).

Combining the fuel cell stacks in Figure 6.8, Fuel Cell Energy aims to be able to offer in the future the fuel cell plant shown in Figure 6.9. This plant would be able to produce 1.2 MW achieving a LHV efficiency on natural gas of 62% (Ghezel-Ayagh, 2021).

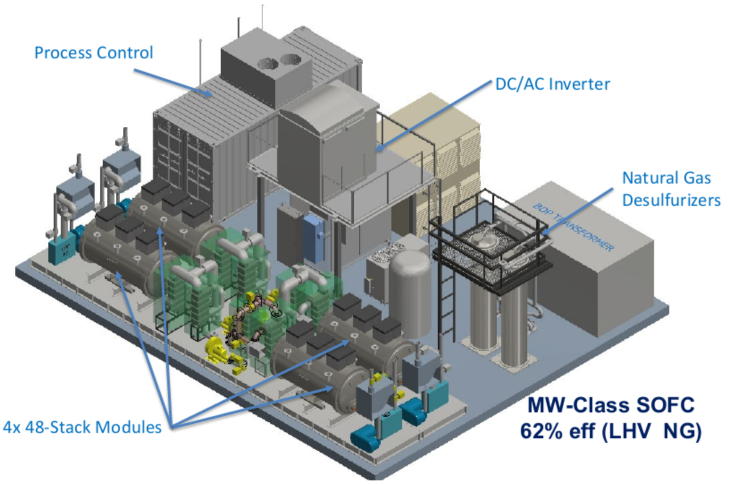

Figure 6.9: Future MW-Class SOFC system of Fuel Cell Energy (Ghezel-Ayagh, 2021).

In 2021, Fuel Cell Energy claimed to have obtained SOFC stacks with an endurance of more than 1.5 years, after which the decay rate was 0.26%/1,000 h (Ghezel-Ayagh, 2021). However, it is known that it is an industry target to keep the decay in performance limited to 0.10%/1,000 hours.

Elcogen

The last company that is discussed is the Estonian-Finish Elcogen. This company only makes fuel cells and fuel cell stacks, but not fuel cell modules. They are able to produce currently 1 MW/year of stacks and they are going to start this year the construction of a new factory that will allow them to produce up to 50 MW/year of SOFCs.

In order to gather more information, an interview with Elcogen was held.

At the moment Elcogen only produces two SOFC stacks, of 1 kW and 3 kW. The 3 kW stack is shown in Figure 6.10. Its specifications are presented in Table 6.8.

Table 6.8: Specifications of the SOFC stack by Elcogen (Elcogen, 2021).

	E3000
Nominal power (kWe)	3
Weight (kg)	33
Length (m)	0.23
Width (m)	0.19
Height (m)	0.28

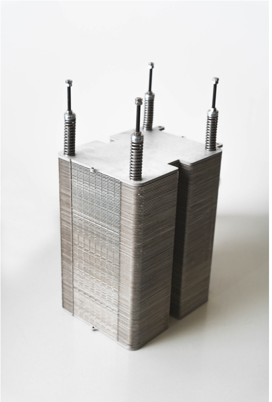

Figure 6.10: E3000 SOFC stack by Elcogen (Elcogen, 2021).

Elcogen does not supply all other support systems that are required for the complete operation of a SOFC. They do, however, have the knowledge in-house and advise clients like Convion, a Finish company that built a 60 kW SOFC module consisting of Elcogen SOFC stacks.

Elcogen claims to have obtained an efficiency of 75% for the 3 kW SOFC stack when running on natural gas. When combining multiple stacks like in the Convion 60 kW stack the efficiency became 60% without heat recovery (Convion FC systems, 2021). With heat recovery the efficiency is expected to increase around 10%. They recommend some kind of pre-reforming, since the maximum degree of internal reforming of the stacks is 0.65 (Elcogen, 2021).

The fuel cells stack by Elcogen work at around 650°C, which is, for a SOFC, on the lower side of the temperature range. As was explained in subsection 4.2.3, temperature and lifetime are inversely related. Keeping the temperature “low” allows to obtain longer lifetimes. At the moment Elcogen has tested its SOFCs stacks for 25,000 hours with a linear decay in performance. These tests are expected to be conducted successfully until the 40,000 hours (4.6 years at 24 h/day), with a total decay in performance of around 20%.

Elcogen emphasized the importance to make a controlled warm-up and cool-down of the SOFCs stacks, due to their sensitivity to high temperature differences. Therefore, the warm-up needs to happen at a rate of 120°C/hour, which means that the start up time of such a SOFC stack from room temperature is around 5 hours. The cool-down needs to happen in a controlled way, making use of a safety gas, which is a pre-heated mixture of hydrogen and nitrogen that reduces its temperature in a gradual and controlled manner to ensure a safe cool-down of the fuel cells. However, from Elcogen it was stressed out that the best way to increase the lifetime of their stacks is to never turn them off completely. Keeping them on, at a very low load, but at a high temperature, is the best way to avoid any malfunction and to increase the dynamic response.

6.4. Conclusion

In this chapter, an overview of the use of fuel cells in maritime applications was presented.

From the literature study that was performed, it can be concluded that volume seemed to be the critical factor when looking at the implementation of fuel cells on board of ships. Also, compared to the traditional engine rooms including internal combustion engines and diesel generators, it can be said that when one wants to use fuel cells and batteries the space can be utilized more efficiently. The exact volume difference of the traditional internal combustion engines and fuel cells is complex to determine. PEMFC stacks have a higher volumetric energy density than SOFC stacks, but at the same time PEMFCs require very pure hydrogen, that can be obtained if pure hydrogen is taken on board, or another hydrocarbon is reformed, which also takes space in the engine room. Looking at the fuel cell stacks only, it can be approximated that PEMFCs will require twice the volume of a diesel engine, which in the case of a SOFCs can go up to two-and-a-half times. Even in the literature the results presented by different studies do not converge, which means that this needs to be studied thoroughly in a later phase. Due to the longer start-up times of SOFCs, it can be said that another power source must be able to compensate for the same amount of power until a high efficiency is reached, which in the case of PEMFC is only the case for a couple of minutes. The biggest advantage of the SOFCs, apart from their higher performance, is their versatility to be used with different fuels, while the PEMFCs require very pure hydrogen.

Regarding the tests performed on board of ships, it is quite remarkable how all the projects presented are for very low amounts of power. None of them was tested for more than a couple hundred kilowatts, which shows how this technology is so far not used for propulsion of bigger ships, but for auxiliary power generation instead. It can be said that all the projects that were discussed were in some way successful, and that applying fuel cells to a marine environment was never seen as a problem.

Finally, the options for fuel cells on the market were presented. It is evident that PEMFCs are in a further development stage, offering already fuel cell modules approved by class for their use on board of ships. The fuel cell modules that were presented are able to produce a couple hundred of kilowatts. The lifetimes of PEMFCs do not seem to exceed the 3.5-4.0 years, and their efficiencies are around 40-60%, but always running on pure hydrogen. In the case of SOFCs, which are still being developed, these values increase. While one would think that SOFCs have a very limited lifetime, current tests like the ones at Elcogen show promising results, even being able to surpass PEMFCs if the 40,000 hours (4.6 years) are reached at a very reasonable decay in performance. Regarding the efficiency of SOFCs, it is normally between the 50-65%, that can be increased at least up to around 75% when using heat recovery.

7

Selection of naval surface vessel and power plant

Naval vessels, fuel cells, and hydrogen carriers have been presented hitherto in chapters 3, 4, 5, and 6. Now it is time to make a choice for the concept design phase of this research, where the feasibility of fuel cells applied to an existing design will be tested.

7.1. Selection of naval surface vessel

In chapter 3 the different naval surface vessels were explained. The categorization can be done by means of size or operational cluster. The requirements that naval vessels have are dependent on aspects like the operational profile and the level of survivability of a certain vessel. The higher one goes in the violence spectrum, the higher the requirements are.

Fuels cells are considered to be feasible to be used in naval surface vessels. In section 6.2 none of the investigations pointed out that using fuel cells in a marine environment was an issue. Moreover, in the specific case of naval vessels, in order to fulfill to shock requirements, like any other crucial equipment, shock absorbers can be used in case they are applied in high violence spectrum vessels. Fuel cells also have the advantage of having low signatures, especially acoustic and infrared. They are more efficient than the traditional ICEs, and produce less harmful emissions. These aspects lead to the next suggested types of applications on board of naval vessels:

- Mine warfare vessels: since this kind of vessels is very susceptible to signatures due to the nature of their operations, fuel cells could have an added value. Mine warfare vessels need to sail slowly and silently when trying to locate mines. For this application, fuel cells could be used to reduce the acoustic signatures of the vessel. The combination with batteries as an extra power source is discouraged, since these generate a magnetic field that could increase the magnetic signatures of the mine warfare vessel. The lower gravimetric energy density of fuel cells with respect to an ICE should be taken into account, because the extra weight of the fuel cells would increase the pressure signatures of the mine warfare vessel.
- Frigates: in the case of a frigate, fuel cells can have an interesting application when acoustic signatures are of high importance. This is the case when submarines are trying to be tracked, because the lower the acoustic signatures of the frigate are, the easier it is to “hear” the submarine and to not be “heard” by the submarine. Since this kind of vessel requires a high manoeuvrability it needs to maintain its capabilities, also to be able to sail at the same speed as the rest of the fleet. Therefore, the existing power plant would have to be maintained, and the fuel cells would be an add-on, with the impact that that would have on the size of the total power plant, including the fuel cells for the “silent mode”.
- OPV: an OPV is considered to be suitable to be integrated with fuel cells. OPVs are sailing at a constant speed while patrolling and in transit, and only need to increase their speed once a target has been detected. Moreover, as was shown in Figure 3.1, their top speed is not as high as that of other naval vessels since they carry RHIBs and helicopters that can be used when a

rapid intervention is needed. The fact that the manoeuvrability of this kind of vessel is not as high as others means that fuel cells could be used to generate power for the base load, while a combination with other power sources would be required when the speed needs to be increased.

7.1.1. Availability at Nevesbu

The next step after this literature review is to perform a concept design of the chosen configuration. In order to do so, a reference design is needed. Since Nevesbu is specialized in the design of naval vessels, an existing design can be used as a starting point. The availability at Nevesbu is therefore a limiting factor, because only with an existing design the research can be continued.

After consulting the possibilities, it has been decided to use an existing OPV design made for a foreign navy. That means that the fuel cells will be used as a base load, combined with additional power sources for extra propulsion when higher speeds are required. The fact that the OPV can run on fuel cells while patrolling and in transit is expected to give positive results in terms of emissions and signatures.

7.2. Selection of fuel cell type

Now that a naval surface vessel has been chosen, the type of fuel cell can be selected. From the information described in chapter 4 and chapter 6 it was concluded that fuel cells have many advantages compared to the traditional ICEs. Fuel cells allow for modularity in a vessel, are silent, more efficient, require less maintenance, and produce less harmful emissions. PEMFCs and SOFCs have the highest potential to be used in the shipping sector. Both of them have already been tested on board of vessels, proving that they are suitable for a marine environment. However, the technology readiness level (TRL) is different. PEMFCs have been used for much longer, like in submarines, which explains that they are in a further stage of development. SOFCs, on the other hand, are still a topic of research, showing promising results. Since this research is focused on the medium term, the stage of development should not be a determining factor in order to choose a technology, as long as its effectiveness is proven, which is the case for the two types of fuel cells mentioned before.

PEMFCs are already being sold on the market and will be used in short term on board of vessels, especially ferries with small ranges running on pure hydrogen. There are many options of PEMFC modules on the market and some of them have been already approved by class. PEMFCs have the advantage that they can react relatively rapidly to load transients. Their biggest disadvantage is their sensitivity to fuel impurities, which limits the fuel choice or requires a fine reforming of the fuel to be used, with the complexity in systems that this entails.

SOFCs are being researched and show promising results. They have higher efficiencies and have the advantage that their sensitivity to fuel impurities is lower, allowing some internal reforming which is translated in a higher versatility regarding the fuel to be used. Moreover, since they work at high temperatures, heat recovery is allowed, which can be used to pre-reform the fuel or can be combined with a gas turbine or steam turbine to increase the total efficiency. Their lifetimes are longer than those of PEMFCs. The biggest disadvantage of SOFCs is their low transient capabilities; therefore, they need to be combined with other power sources in case a rapid response is required.

For this research SOFCs are considered to be more promising. Their high efficiencies and versatility to be used with different hydrogen carriers are a determining factor. Their lifetime is longer than that of PEMFCs and it is improving in current investigations. Their disadvantages are their slow dynamic response and long start-up time. These are issues that are considered to be solvable when combined with other power sources such as batteries or diesel generators.

7.3. Selection of hydrogen carrier

An OPV using SOFCs to generate the base load needed for patrolling and being in transit and its corresponding auxiliary power is the combination that has been chosen in the previous two sections. Here, in order to choose a hydrogen carrier for the SOFCs, a multi-criteria analysis is performed with the candidates from the conclusion of chapter 5. In chapter 5 the different hydrogen carriers were presented, taking into account their energy densities, storage, safety, and emissions. It was concluded that ethanol, methanol, and ammonia have the highest potential to be used in combination with fuel cells, with higher energy densities than pure hydrogen. In Table 7.1 a multi-criteria analysis for an OPV is shown for ammonia, methanol, and ethanol. The weights for each of the aspects go from 1 to 5, where 1 is bad and 5 is good.

Table 7.1: Multi-criteria analysis for the choice of a fuel for an OPV.

	Weight factor	**Ammonia**	**Methanol**	**Ethanol**
Safety				
Flammability	x 3	5	3	3
Toxicity	x 4	1	4	5
Emissions				
CO_2	x 5	5	3	2
SOx	x 5	5	5	5
Space requirement	x 4	2	3	4
Complexity of storage systems	x 2	2	4	4
TRL	x 3	2	4	2
Total		**87**	**97**	**94**

The weights in Table 7.1 indicate the importance of each aspect, specifically for an OPV. As can be seen, since it is the main goal of this research when looking at fuel cells, emissions have the highest importance. Other aspects that need to be taken into account when looking at the application of fuel cells on board of a naval surface vessel are flammability and toxicity. Finally, some more general aspects like the space requirement, the complexity of the storage systems, and the technology readiness level (TRL) of each fuel to be used with fuel cells are considered.

Ammonia is considered to be suitable for its use with fuel cells. In section 6.2 none of the projects used this hydrogen carrier in combination with fuel cells. It is considered however as a feasible option because the use of a cracker converts ammonia to hydrogen that can be used by the fuel cells. The major drawback of ammonia is its high toxicity. Also, in order to achieve a reasonable energy density it needs to be cooled at -30°C, with the complexity in systems that entails and the presence of boil-off gas. For the reasons named before, despite being the only hydrogen carrier out of the three chosen that does not generate harmful emissions, it is considered that ammonia is not suitable for its use with fuel cells on board of a naval vessel.

Methanol and ethanol are liquid at ambient temperature and can be stored in the current storage systems with minor modifications, which facilitates their implementation to the design of the current naval vessels. Theoretically, ethanol seems a better choice than methanol due to its higher energy density and non-toxicity. However, the TRL in Table 7.1 of ethanol as a hydrogen carrier for fuel cells is far away from that of methanol. In section 6.2 different examples of projects were presented where fuel cells were tested on board of different vessels. Methanol was tested in combination with SOFCs in the METHAPU project, showing promising results. Ethanol, however, has not been a topic of investigation so far. It is known that the new S-80 Plus Spanish submarines are designed to run their AIP system with PEMFCs on hydrogen that is reformed from bio-ethanol. This system has however not been proven yet, since the first submarine including this system is expected to be delivered in 2026 (Ministerio de Defensa de España, 2022). Both ethanol and methanol have lower flash points than diesel, meaning that the risk of a fire in presence of a spark is higher. This aspect might limit their use in high violence spectrum vessels. It is considered that methanol is sufficiently safe to be used on board of an OPV.

7.4. Conclusion

After having looked at the different kinds of fuel cells, hydrogen carriers, and types of naval surface vessels separately, it can be concluded that three types of ships are suitable to be integrated with fuel cells. The first of them is a mine warfare vessel, where the fuel cells are used when it is sailing slowly looking for mines to reduce the acoustic signatures. The second possibility is to add a “silent mode” to a frigate, to be used when it does not want to be spotted that quickly by reducing its acoustic signatures (for example, when it is tracking submarines). The third and last suggested option is to integrate the fuel cells on board of an OPV, so that they can be used to provide the base load when patrolling and in transit at constant speeds.

Taking the availability at Nevesbu into account, it is concluded that the chosen configuration is an OPV with SOFCs running on methanol. The fuel cells could be used to provide the base load used to reach cruising speed and its auxiliary power. When more speed is required, other power sources can be used to provided the required propulsive power. As mentioned in chapter 5, methanol is unsafer than diesel because it has a lower flash point. Since an OPV is in the lowest violence spectrum, this is not considered an issue as an OPV does not take part in high violence combats where the chance of a fire is higher. It is expected that the implementation of fuel cells in an OPV will lead to a reduction in emissions and signatures.

Part II

Concept Design

8

Design Approach

In chapter 7 the selection of the naval vessel and the power plant was made. It was concluded that an OPV making use of SOFCs fuelled by methanol is the combination to be tested in the concept design phase of this master thesis.

In this chapter, the design approach of this master thesis is explained. The whole research starts from the reference design that is used as a benchmark. This design, that is later explained in more detail in chapter 9, was ordered by a foreign navy to fulfil certain requirements. The goal of this part of the master's thesis is to perform a concept design of an OPV making use of fuel cells fuelled by methanol. The impact of the SOFC-based power plant is at this point unknown, but the intention is to keep the capabilities of the vessel unaltered, so that it can perform the same kind of missions.

When talking about requirements one must think of the capabilities that the vessel needs to perform the types of missions that it is made for. These mission requirements are based on speed, range, endurance, redundancy, signatures, and capabilities of the vessel. Speed has a direct effect on the size of the engines, while range and endurance affect the capacity of the tanks and the storage compartments. Signatures must be kept at least equal to not increase the detectability of the vessel. The redundancy of the vessel must remain at the same level to ensure the same degree of recoverability. When talking about capabilities one must think of the ability to take the same items on board, such as weapon systems, surveillance equipment, and other support systems such as RHIBs or helicopters to be able to perform the same kind of missions. Apart from the mission requirements, there are other design requirements that are inherent to the design of every ship that always must be fulfilled, such as the stability of the vessel.

Since the motive of this research is to look for a power plant configuration that reduces the emissions of a vessel, once a feasible design is achieved, the emissions of the new concept design can be compared with the reference design to quantify the improvement in this matter. Other aspects like the cost of the new power plant and the cost of the fuel are left out of the scope. These do not add to the technical feasibility, but are part of the economical feasibility of the new design.

In section 8.1 the objective of this part of the master's thesis and the research questions are presented. To clarify the different steps of this research, in section 8.2, the structure of the research is presented.

8.1. Objective and research questions

The objective of the concept design phase of this master's thesis is to study the feasibility of the use of SOFCs fuelled by methanol on board of an offshore patrol vessel (OPV), the impact on the operational performance of the vessel, and to test this in a concept design phase.

With the main research question being:

What is the effect of a SOFC-based power plant fuelled by methanol on the design, operational capabilities, and emissions of an OPV, and what is the technical feasibility of such design in the medium term?

The sub-questions are:

- What are the characteristics of the OPV used as reference design?
- What is the impact on a systems level of the implementation of SOFC-based power plants in an OPV?
- What is the optimal configuration of SOFCs and peak power source to be used on board of an OPV?
- What is the effect on the design of an OPV of the use of a SOFC-based power plant fuelled by methanol and what would that design look like?
- How are the operational capabilities of the OPV affected by the use of a SOFC-based power plant?
- How are the emissions of the OPV affected by the use of a SOFC-based power plant?

8.2. Structure of the research

Reflecting back on the research questions, the main steps that need to be made from now on are:

1. As explained previously, the first step is to analyse the reference design, which is done in chapter 9. In this step the current design is explained and the requirements regarding the aspects aforementioned are presented. The requirements include the operational capabilities that the OPV must have to perform the different types of missions.

2. Second of all, a system design (chapter 10). Here all the components of the different configurations are explained and designed. Think of the SOFC modules with their support systems and the additional power sources. This step finishes with a comparison of the different configurations of SOFCs and the peak power sources, that leads to the choice of the optimal configuration reflecting back on the mission requirements of the OPV.

3. Third of all, the concept design must be done for the chosen configuration of SOFCs and the peak power source (chapter 11). Here, the design spiral is run through with the aim of obtaining a convergent design that fulfills all the requirements.

   The design spiral starts with a reconfiguration of the general arrangement (GA) of the OPV, to study if the new power plant fits in the current vessel. If it does not fit, or exceeds in weight significantly compared to the previous configuration, an iterative process must be started to scale the vessel until a convergent design is found that fulfils all requirements. If necessary, the scaling is planned to be done at first in length, to benefit from a higher length/beam ratio and thus lower water resistance. This, however, cannot compromise the intact stability of the vessel, which should be checked to ensure that it is still a safe design. Another aspect that is crucial for any naval vessel that must be kept in mind during this step is the redundancy level of the OPV.

   The design spiral is run through as many times as necessary until an optimum design is obtained.

4. Fourth all, a reflection on the new concept design is made in the comparison study in chapter 12. This reflection analyses how the new design scores in terms of emissions and operational capabilities. For the typical operational profiles that have been described for an OPV, the performance of the previous and the new configuration can be compared. Also, a redundancy analysis is made.
5. Fifth of all, in chapter 13 a sensitivity analysis is performed. This is done in order to quantify the impact of possible deviations in the most relevant parameters of the assumptions made in this research.

9

Reference Design

In order to perform this research, a reference design is required to test whether fuel cells are a feasible solution to replace the existing ICE-based power plant. As explained in chapter 7, an OPV was the final choice due to its suitability and its availability at Nevesbu.

The design that is used in this master's thesis as a reference design is provided by Nevesbu. It consists of an OPV designed for a foreign navy. The choice of this design is in line with the conclusions of the previous literature review, where it was concluded that fuel cells could be feasible for their use on board of three types of naval surface vessels: mine warfare vessels, frigates, and OPVs. An OPV has the characteristic that it has a constant load profile, because it sails at very constant speeds most of the time while patrolling and in transit, and is supported by RHIBs and helicopters that can travel at higher speeds in case a target needs to be chased. The fuel cells should be able to provide this base load, while a combination with another, more dynamic, power source would be required to reach the higher speeds and compensate the long start-up times of SOFCs.

By analysing the existing design, a benchmark is set for this research. The new configuration should be as close as possible to the original one in terms of performance and maintain its capabilities.

9.1. Technical specifications

The first step is to understand the reference design. In Figure C.1 of the confidential appendix a side view of the reference design is shown. It can be seen how this OPV includes a slipway at the stern for a RHIB, and a helideck. It also has another RHIB that can be used for operations that can be lowered with a davit crane.

In Table 9.1 the technical specifications of the chosen OPV are presented. As can be observed, the chosen OPV has a cruising speed of 12.0 kn, but a maximum speed of 22.0 kn. Moreover, it should be able to sail 4,500 nm at cruising speed, and it should be able to stay for 30 days in the area of operations autonomously. Because it carries a helicopter, aviation fuel must be taken on board. For all auxiliary power, a total of 1,200 kW are installed, apart from an emergency diesel generator able to produce 300 kW. The entire ship is designed to follow IMO Tier II emissions, which indicates that it does not fulfil the strictest IMO requirements regarding harmful emissions.

Table 9.1: Specifications of the reference design OPV.

Technical Specification	Unit	
Lwl	m	**89.0**
Boa	m	**14.6**
T	m	**3.75**
Lightship	t	**2,154**
Cruising speed	kn	**12.0**
Maximum speed	kn	**22.0**
Endurance	days	**30**
Range	nm	**4,500**
Emissions	-	**IMO Tier II**

The ship is designed in accordance with NR467 Bureau Veritas Rules for the Classification of Steel Ships. On top of that it complies with Comf-Vib-3/Comf-Noise-3 regulations for noise and vibrations for commercial vessels, and it has replenishment at sea (RAS) capabilities.

9.2. Power plant

The power plant of the reference design (shown in Figure C.2) consists of two engine rooms. Each of them contains two diesel engines, with a break power of 2,525 kW each. The four main diesel engines are installed in Combined Diesel and Diesel (CODAD) configuration, with two gearboxes and two controllable pitch propellers (CPPs).

Figure 9.1 shows a schematic representation of such power plant.

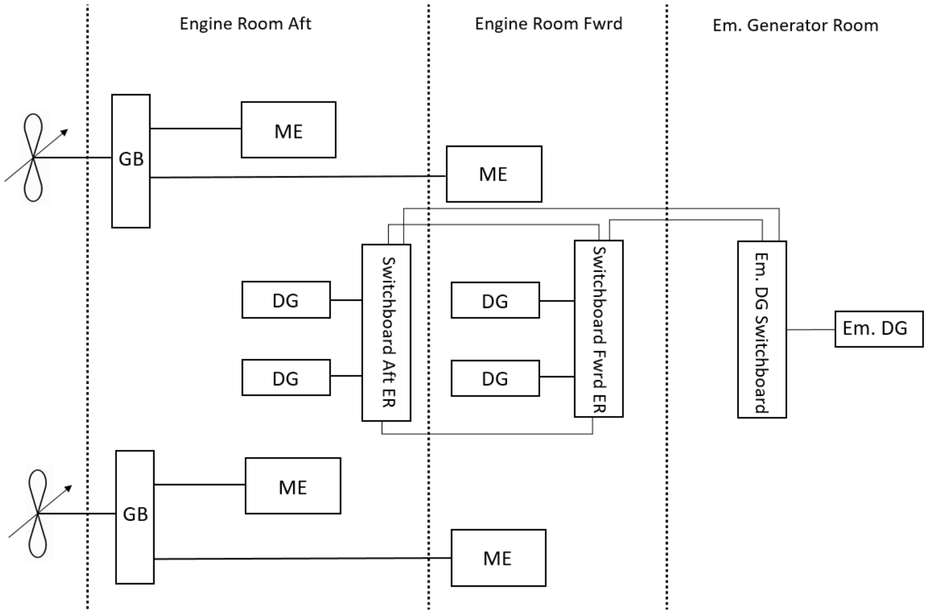

Figure 9.1: Block diagram of power plant of the reference design.

Apart from the main engines, the power plant includes four diesel auxiliary generating sets able to produce 325 kW each, and one emergency generator of the same characteristics located on the B-Deck, at the same level as the Command Control Room.

As can be seen in Figure 9.1, there are different switchboards. Each of them is located in a different engine room. This, together with the fact that the switchboards are connected with each other, allows for redundancy in case of a failure. The switchboards located in the fore and aft engine room are connected by two lines, where one goes along the port side of the vessel and the other along starboard.

9.2.1. Cooling system

The cooling system on board of the reference design is designed as such that it has two independent loops, one for the aft engine room and another one for the forward engine room. Both plate heat exchangers (PHEs) are cross-connected, meaning that they can work as the backup of the other. The cooling medium is fresh water (FW) that is cooled with sea water (SW) in the heat exchangers. Each of the loops is served by a central PHE that is cooled by an independent open SW circuit served by three pumps per loop. This can be observed in Figure 9.2, where the diagram from the sea water inlet to one of the heat exchangers is shown. Moreover, in the aft engine room there is a spare PHE.

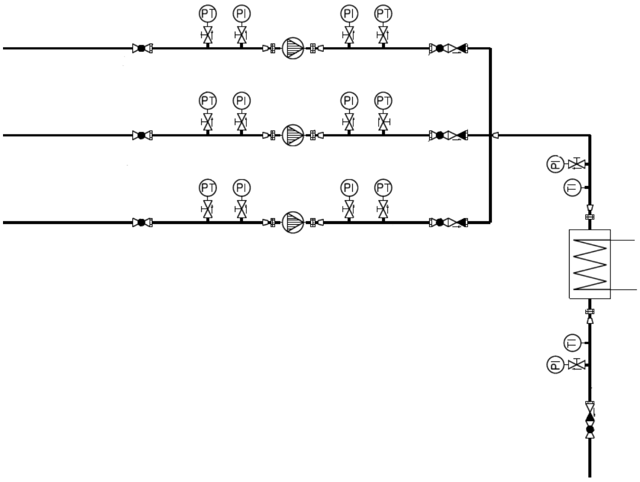

Figure 9.2: Sea water cooling system diagram for one engine room of the reference design.

After the heat exchanger, the cooled FW goes through those components that require cooling. The main consumers are the main engines, the gearboxes, and the diesel generators respectively. Here the gearboxes are cross-connected again, allowing that any of the FW loops can cool them.

The main engines have their own heat exchanger for the fuel. The remaining fuel leaving the main engines is cooled and stored again in the day tanks.

9.3. Tank arrangement

As any other ship, the reference design carries on board different types of liquids for its functioning. As a special characteristic, these vessel needs to have aviation fuel for the helicopter. In Table 9.2 the total volumes, weight, and gravimetric location within the vessel are presented.

Table 9.2: Overview of the contents of the tanks of the reference design.

Type of fluid	Vol. net (m^3)	Weight (t)	VCG (m)	LCG (m)	TCG (m)
Ballast	382	391	2.60	47.2	0
Fresh water	73.1	73.1	2.70	59.1	0
Fuel Oil	314	267	2.50	38.4	0
Miscellaneous	68.8	67.0	0.90	37.8	0
Aviation fuel	17.9	14.0	2.70	14.7	0
VOID spaces	350	0	3.20	25.9	0

The vessel carries on board two water makers that provide fresh water. Within miscellaneous other types of fluid such as lubrication oil, dirty oil, and sewage are included.

9.4. Resistance and power

The brake power required to reach each speed is shown in Figure 9.3. The blue line shows the power-speed curve for the reference design at design draft. As can be seen, with the available brake power of 10,100 kW the vessel can reach 22.6 kn instead of the 22.0 kn that were required. This higher speed gives some margin to the design, allowing it to be slightly deeper and still being able to reach the 22.0 kn imposed as a requirement by the client.

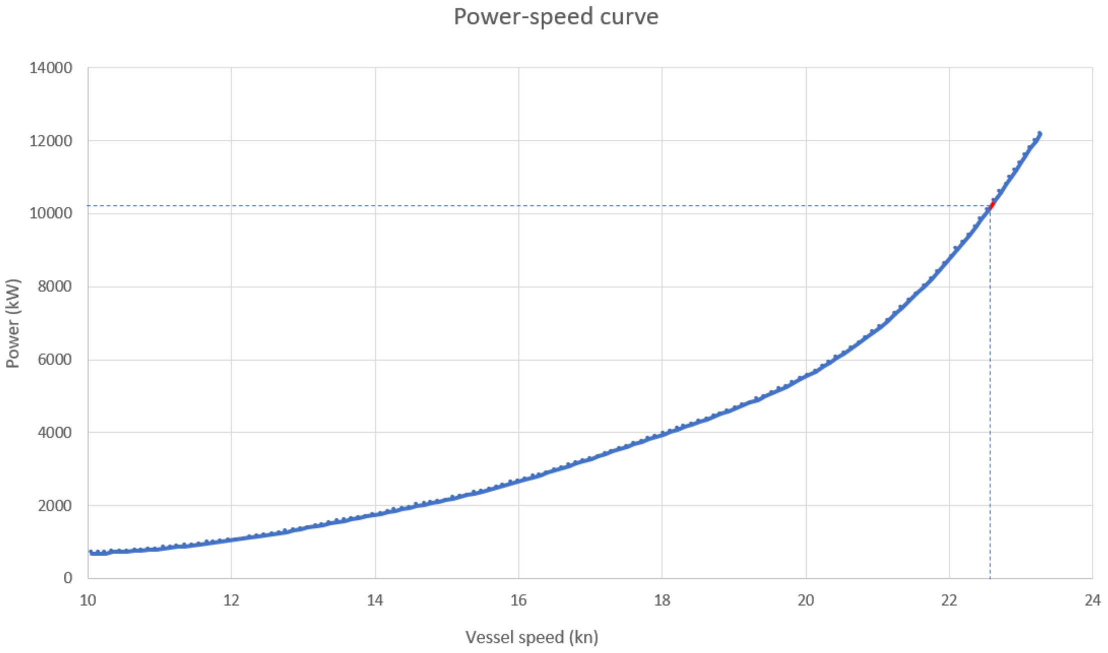

Figure 9.3: Brake power-speed curve of the OPV.

Analysing Figure 9.3, exact values for the brake power required for each speed are obtained. The results are presented in Table 9.3. As explained before, with the optimised bulbous bow for the reference design the amount of brake power required to reach the 22.0 kn is 8,641 kW, instead of the 10,100 kW that are installed and that allow the ship to reach 22.6 kn at design draft.

Table 9.3: Brake power required for each speed from Figure 9.3.

v_s(kn)	P_b (kW)
10.0	737
11.0	815
12.0	1,075
13.0	1,334
14.0	1,728
15.0	2,207
16.0	2,726
17.0	3,344
18.0	3,955
19.0	4,614
20.0	5,493
21.0	6,873
22.0	8,641
22.6	10,100

In Table 9.4, the exact requirements for each speed are shown. Knowing the total available brake power produced by the four main engines, the configurations are chosen to reach each speed. As it can be seen, the cruising speed, which is the one that determines the range, can be also reached with only one propeller.

Table 9.4: Performance of the speeds of the reference design.

	Speed (kn)	Propellers running	Engines per shaft	Engines total
Maximum speed	22.0	2	2	4
Cruising speed	12.0	1	1	1
		2	1	2

9.4.1. Electrical load balance

The reference design has four main diesel generators, with a break power each of 325 kW. On top of that, it also has an emergency diesel generator of the same characteristics.

In Table 9.5, the electrical load balance for the different modes is presented. That is, the amount of auxiliary power required for each mode. Some of them are for when the ship is in port, like the hotel load or the shore mode. Others show the amount of power required for the auxiliary systems of the propulsion and other consumers. Depending on the consumer, the voltage at which it operates is different. Therefore, in Table 9.5 the amount of power required for each voltage and the total power are showed.

Table 9.5: Electrical load balance of the reference design for different modes.

	Load per network (kW)			**Total (kW)**
	440 V	**230 V**	**24 V**	
Sailing (twin shafts)	543	44.5	0.04	**587**
Hotel load	266	24.5	0.35	**291**
Single shaft	500	34.7	0.04	**535**
Max speed	513	22.8	0.04	**536**
Combat mode	777	78.5	0.04	**855**
Emergency mode	130	15.7	0.00	**146**
Shore	181	25.2	0.35	**206**

The total power showed in Table 9.5 must be provided for all modes by the diesel generators. Assuming that the efficiency of the generator is at least 92.3%, the minimum total available power per generator is:

$$P_{installed} = \eta_{generator} \cdot P_b = 0.923 \cdot 325 = 300kW \tag{9.1}$$

Meaning that 300 kW are available per generator. As can be seen from Table 9.5, it would be possible to provide power for all modes with only three diesel generators, since all values are lower than 900 kW (3 x 300 kW). This is a choice from the client, since it wanted that enough power could be generated in case an engine room would be flooded. In that case, the two diesel generators in the remaining engine room and the emergency generator would have to be used together to be able to generate enough power. This is possible thanks to the connection between the emergency switchboard and the aft and forward switchboards as was shown in Figure 9.1.

9.5. Design philosophy: redundancy

In chapter 3, redundancy was mentioned as a crucial aspect for the recoverability of a vessel after a disruption. The separation and duplication of systems can be very helpful for this matter.

When designing a naval vessel, the philosophy is different than in commercial vessels. In naval vessels, it is of the utmost importance to keep the vessel operative to continue with the assigned mission no matter what. This implies that a lot of the systems have to be redundant. The reference design is of course no exception. In this vessel multiple measures have been taken to increase its redundancy and therefore its level of recoverability. In this section, the most relevant measures are presented.

The redundancy starts with the arrangement of the different components. In Figure C.2 of the confidential appendix it can be seen how the power plant consists of two engine rooms that are separated by a watertight door. The amount of power installed in each of the engine rooms is the same, consisting of two main engines and two diesel generators. Moreover, the power plant is arranged in a CODAD configuration that makes use of two shaft lines and therefore two propellers. Thus, the duplicity is in itself redundant: two shaft lines, with two main engines each, distributed in two different engine rooms. This redundancy allows the vessel to be able to reach cruising speed with only one propeller and one main engine functioning as is shown in Table 9.4.

With the diesel generators something similar happens. They are also distributed in two different engine rooms, with a different switchboard in each of the compartments. Apart from that, there is a separate room with an emergency diesel generator with its own switchboard located higher in the vessel, to ensure that it can stay operative in case of flooding in the engine room. The switchboards are all connected with each other, making possible the simultaneous operation of diesel generators in different rooms. In the case of the fore and aft switchboard, the connection between them is double. To ensure that the switchboards remain operative in case of flooding, they are placed on a higher floor inside the engine room. As explained previously, the diesel generators are chosen and placed in such a manner that in the case of failure of an entire engine room, the three remaining diesel generators could be used to provide enough power for all the modes presented in Table 9.5.

In order to keep the engines, the diesel generators, and the gearboxes running they have to be cooled. Therefore, the cooling system is also designed following the philosophy of redundancy. As explained previously, the cooling system consists of two independent loops, one for each engine room. The PHEs on the FW side are cross-connected, allowing that one can work as the backup of the other. In each of the loops there are three SW pumps connected in parallel, adding redundancy to the system. The gearboxes are also cross-connected, meaning that they can be cooled by either of the cooling system loops. On top of that, in the aft engine room, there is a spare PHE.

To make sure that the power plant remains as operative as possible, apart from the measures mentioned hitherto, special attention has been paid to the watertightness of certain components. The gearboxes are designed in such a way that they are sealed until the centerline of the gearbox output shaft. Thus, if the water reached that level, the gearboxes and the main engines would remain operative. The diesel generators, however, would be considered lost at that level of flooding since their alternator would be immersed in water. As explained previously, this is compensated by the fact that the other three diesel generators in the other rooms would stay operative. Other components like the pumps of the cooling system, the junction boxes, or the hydraulic control unit of the CPP are also placed above the considered flooding level.

9.6. Signatures

In chapter 3 the requirements of each of the different naval surface vessels were presented. Signatures appeared to be a very crucial requirement, since the higher one goes in the violence spectrum, the more important these become. The advantage of having chosen an OPV is that, as was illustrated in Table 3.1, signatures are not that important because this kind of vessel operates in the low violence spectrum.

In the case of the reference design, this can also be observed. As any other military vessel, attention has been paid to the design of the propellers to reduce cavitation as much as possible, and thus the acoustic signatures. On top of that it is designed in accordance with Comf-Vib-3 and Comf-Noise-3 Bureau Veritas regulations, which are meant to reduce the amount of noise and vibrations of the vessel. However, these regulations are meant for commercial vessels, so it cannot be said that the engine room of the reference design has lower acoustic signatures than some commercial vessels. On top of that, RCS signatures are reduced by placing all external panels under an angle, which is common practice when designing naval vessels. Apart from these requirements, the reference design does not have any special military requirements for the reduction of signatures, like IR signatures which are not reduced.

9.7. Operational capabilities

According to NATO Naval Group 6, 2004: ”OPVs enforce maritime law and perform search and rescue and humanitarian tasks”. As was shown in Figure 3.2, the primary operations of an OPV are within the *Military Patrol* and *Military Aid* operational clusters, while it can also perform secondary operations within the *Military Control* cluster.

Therefore, in order to define the operational capabilities of an OPV, three types of missions are defined.

- Search and rescue missions.
- Patrolling and intercepting operations.
- Humanitarian and disaster relief missions.

The new design must be able to perform at the same level in all three type of missions. It is important to mention that an OPV is meant to operate within the Exclusive Economic Zone (EEZ). The extension of this area is dependent per country, but it is limited to up to 200 nm from the coast of the country. The exact requirements will obviously depend on the specific wishes of the client and on the coastline of such country, but the requirements undermentioned are considered a minimum that every OPV must fulfil.

9.7.1. Search and rescue missions

Search and rescue missions are characterized by a rapid response of the OPV. Here, the helicopter is the first to be activated, but the OPV must follow after it. This means that the OPV must be able to start rapidly immediately after leaving port and hence a lot of power needs to be available from the beginning when someone needs to be rescued. The range that the OPV must sail at a high speed is of course dependent on the place where the rescue mission has to take place. Since an OPV operates normally within the EEZ, it is assumed that the length of the sprint (the time the vessel is sailing at maximum speed) must be enough to reach the 200 nm when leaving from port. Once the rescue mission has taken place, the vessel can cruise back to port.

Requirements for a search and rescue mission:

- Rapid response after leaving port.
- Long sprints (at least 200 nm).

9.7.2. Patrolling and intercepting operations

When patrolling, an OPV spends most of its time either cruising or standing still. Once a target is detected, the helicopter and the RHIB are activated and the vessel must sprint to follow them. The RHIB and/or the helicopter intercept the target and wait until the OPV arrives. Once the OPV arrives it waits for some time until the operation is finished. After that, it cruises back to port.

Requirements for patrolling and intercepting operations:

- Most of time patrolling, at cruise speed, or standing still.
- When a target is detected, the OPV sprints to follow the RHIB and/or helicopter. The length of the sprint must be at least 175 nm, assuming that the vessel was already in coastal waters patrolling.

9.7.3. Humanitarian and disaster relief missions

In this kind of missions the OPV is used to assist a certain country/area after a natural or man-made disaster. It can be used to transport humanitarian aid or to evacuate civilians. Here range is of a higher importance because the vessel must be able to get beyond the EEZ. Therefore, the vessel travels mostly at cruising speed.

Requirements for humanitarian and disaster relief missions:

- Constant speed to get to the affected area. Most of the time at cruising speed to increase range.

9.7.4. Typical operational profiles

In this subsection three examples of operational profiles are shown for the three types of mission described before. These are the examples that will be used later in chapter 12 to compare the performance and the emissions of the reference and concept design.

Search and rescue operations

In Figure 9.4 an example of the operational profile for a search and rescue mission is shown. In this scenario, the OPV sprints at 22 kn for 16.4 hours (360 nm) to get to the area where the casualty occurred, to then reduce its speed to 8 kn to start searching for a couple of persons that are missing and need help. When some of the people are found, the vessel lays still for a couple of hours, after which it continues searching for the rest of the missing persons. Once they are found, the same action is repeated, and the vessel cruises back to port.

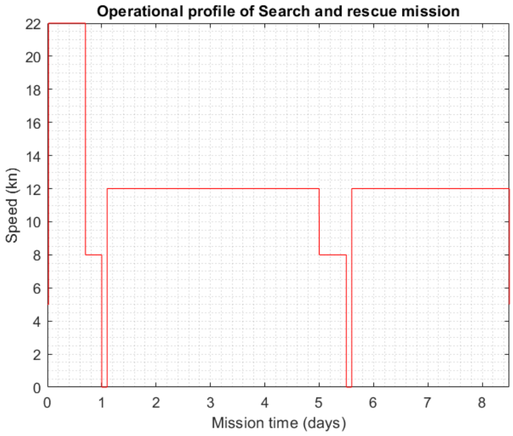

Figure 9.4: Example of operational profile for a search and rescue mission of an OPV.

Patrolling and intercepting operations

In Figure 9.5 an example of a patrolling and intercepting operation is presented for fifteen days. It is assumed that the vessel patrols at 8 kn, until a suspicious activity is detected. Then the helicopter and the RHIB are sent to chase the target, and the OPV follows them at 22 kn for more than 9 hours. When it intercepts the target, it lays still for a couple of hours, to then continue patrolling. After some days, again a threat is spotted and the same operation is repeated, after which it cruises back to port.

Figure 9.5: Example of operational profile for a patrolling and intercepting mission of an OPV.

Humanitarian and disaster relief missions

The last example of an operational profile is that of a humanitarian mission as shown in Figure 9.6. The vessel cruises for five days to the affected area to deliver aid, and stays after that in port for four days, after which it cruises to the next port, to stay there for one day. After ten days the vessel cruises back to its home port.

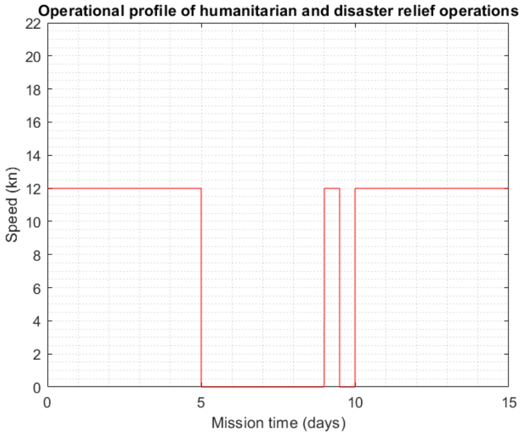

Figure 9.6: Example of operational profile for a humanitarian and disaster relief mission of an OPV.

9.8. Conclusion

In this chapter the reference design OPV used in this master thesis was presented. The reference design contains a slipway with a RHIB and a helideck, and an extra RHIB. These are used to support the OPV when higher speeds and manoeuvrability are required in certain operations.

The power plant of the reference design has a combined diesel and diesel (CODAD) configuration distributed in two separate engine rooms. There are two controllable pitch propellers and in each engine room two engines are located, making a total of four main diesel engines. For the auxiliary power four diesel generators are required, that are also distributed in the two engine rooms with their own switchboard. On top of that, on a higher position in the vessel there is an emergency diesel generator with its own switchboard.

The cooling system of the reference design is a seawater (SW)/ fresh water (FW) system. It consists of two loops of SW with three pumps each that through a plate heat exchanger (PHE) cool SW that goes to the main engines, gearboxes, and diesel generators. The PHE and the gearboxes are cross-connected, which allows that any of the system loops can go through these components.

The bulbous bow of the reference design was optimized to its dimensions, allowing to reach 22.6 kn at design draught and at full brake power instead of the 22.0 kn that were imposed by the client as the top speed. This reduction in required power to reach the 22.0 kn gives some design margin, since it would be possible to reach the maximum speed required by the client with a slightly larger draught. Moreover, the reference design has the availability to reach cruising speed (12.0 kn) with only one propeller driven by one main engine.

Regarding the electrical load balance of the reference design, the amount of auxiliary power depends on the mode that is desired. The total installed auxiliary power is 1,200 kW, but all modes can obtain enough power if three generators are running. That is, if one engine room is flooded and the generators in the other engine room have to be used combined with the emergency generator.

Throughout the entire design of the reference design it can be appreciated how redundancy is present in many systems. The vessel must remain operative in as many situations as possible to continue with the mission that it has been assigned. Therefore, the power plant consists of two separate engine rooms, with separated engines, diesel generators, and switchboards among them. Moreover, the vessel can lose one propeller and still be able to reach its cruise speed. Other systems like the cooling system have been also designed with a redundant philosophy, to allow that the failure of one of the heat exchangers does not affect the ability to remain operative. Redundancy is also appreciated in the watertightness of some components, like the gearboxes, that are sealed until the centerline of the output of the shaft. This level of flooding in one of the engine rooms allows the ship to keep operative.

The fact that the chosen vessel is an OPV means that signatures are not as relevant as other high-violence-spectrum vessels. In the case of the reference design class rules to reduce noise and vibrations have been taken, but are of commercial standards. RCS signatures are reduced by placing some outer panels under an angle.

Finally, three types of missions with their characteristics and specific requirements were presented. An OPV must be able to perform all of them. The three types of missions that were presented are: search and rescue missions, patrolling and intercepting operations, and humanitarian and disaster relief missions. While the first two require a rapid response and long sprints, the last one presents a much more constant speed profile since it is only cruising or laying still.

10

System Design

In this chapter, the system design of the concept design is carried out, to later implement it in the concept design. First of all, in section 10.1 the approach of the system design is presented, with the requirements that the new power plant must have. Second of all, in section 10.2 the SOFCs and the necessary support systems are designed. In section 10.3 the different peak power sources are considered and each configuration is designed. The different configurations consist of a combination of SOFCs and batteries, SOFCs and diesel engines, and SOFCs and methanol engines. Once all the different configurations have been designed, a final choice is made and in section 10.4 the electrical integration is done.

10.1. System Design Approach

The goal of this chapter is to design a power plant that makes use of SOFCs that are able to provide the load for the auxiliary power of the OPV and the propulsive power needed to reach cruising speed. On top of that, the new power plant must include an additional peak power source that is able to provide the propulsive power required to reach the maximum speed of the vessel. The chosen power plant must fulfil the requirements of the reference OPV as explained in chapter 9. These are:

- Cruising speed of 12 kn.
- Top speed of 22 kn.
- Rapid response after leaving port.
- Range of 4,500 nm.
- Sprints of at least 200 nm.
- Auxiliary power for each mode as shown in Table 9.5.
- At least the same level of redundancy as the reference design.

The system design starts with the SOFCs and their support systems. These elements are common for all the different power plant configurations that are considered in this chapter. The SOFCs do not only consist of the fuel cell stacks that form a fuel cell module, but also of the balance of plant (BoP) and a set of batteries required for peak load shaving to compensate the slow dynamic behaviour of SOFCs.

After having designed the SOFCs and their support systems, it is time to look at the additional peak power source. This additional power source must provide the propulsive power required to reach speeds above the 12 kn to cruise up to the 22 kn that were set as the maximum speed of the reference design. The peak power sources that are considered in this research are batteries (on top of the batteries that are always needed for peak load shaving of the SOFCs), diesel engines, and methanol engines. With this in mind, a certain configuration of power plant is chosen, that will be later designed in the concept design phase in chapter 11. Because the level of electrification of the power plant increases, after having chosen a certain type of propulsion, the integration of the entire electrical grid of the vessel is designed.

10.2. SOFC design and sizing

The goal is to design a system able to generate the auxiliary power and the propulsive power to reach 12 kn by SOFCs fuelled by methanol. In section 9.4 it was shown how the required brake power to reach the cruising speed of 12 kn in the reference design is equal to 1,075 kW. On top of that, the system should be able to provide the auxiliary power for all modes. Taking the full combat mode in Table 9.5, the SOFCs should be able to provide at least 855 kW of auxiliary power. Adding these two up is the minimum amount of power required for cruising and auxiliary power.

From section 6.3 it was concluded that there are not SOFCs on the market at this power output for marine applications. However, from the information of the existing SOFC designs and the prospects of the companies that manufacture them, assumptions can be made on the parameters of a SOFC system at a megawatt scale to be used in the power plant of a vessel. From all the manufacturers of SOFCs that were presented in subsection 6.3.3, the American company Fuel Cell Energy publicly presented its ambition to scale up SOFC modules to form a megawatt power plant making use of a Compact Solid Oxide Architecture (CSA) stack. This kind of stack increases its power to weight ratio and power to volume ratio by a factor of six and four respectively compared to its predecessors. It is also the kind of stack that was shown previously in Figure 6.8. The characteristics of the CSA stack by Fuel Cell Energy are shown in Table 10.1. Figure 10.1 shows how this stack can be integrated in a module.

Table 10.1: Specifications of the CSA by FCE (Ghezel-Ayagh, 2021).

CSA stack	
Stack power (kW)	7
Cell count	350
Fuel cell power (kW/cell)	0.02
Fuel cell voltage (V/cell)	0.85
Height stack (m)	0.44
Weight stack (kg)	15

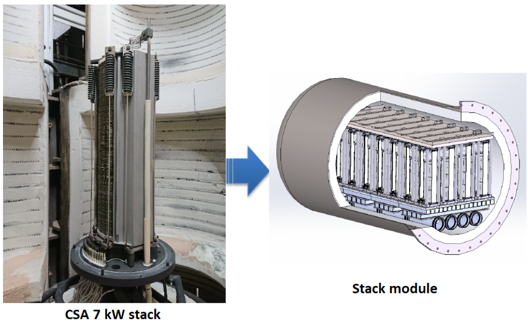

Figure 10.1: SOFC CSA stack and module (Ghezel-Ayagh, 2021).

Due to the decay in performance and the fact that the SOFCs in the OPV can only be replaced after five years, when the vessel has to dock, the SOFC system needs to be overpowered from the beginning. In subsection 6.3.3 it was mentioned that the current SOFC stacks present degradation rates of 0.26%/1,000 hours, but it is known that it is an industry target to keep these limited to 0.10%/1,000 hours. Therefore, this last value is used to overpower the SOFC plant. In reality, the decay of performance of the SOFCs also depends on how they are used, and especially how often they are cooled down. On the other hand, leaving them for long periods warm when they are not producing power (idling for example) also contributes negatively to their decay.

The module shown in Figure 10.1 includes a mounting base with insulation and the lines for exhaust and supply. It also requires some support systems, which require space. A prospect of what a Fuel Cell Energy 1,120 kW SOFC module could look like is shown in Figure 10.2. Here, four cylinders of 280 kW each are placed on the top, with the support systems on the bottom.

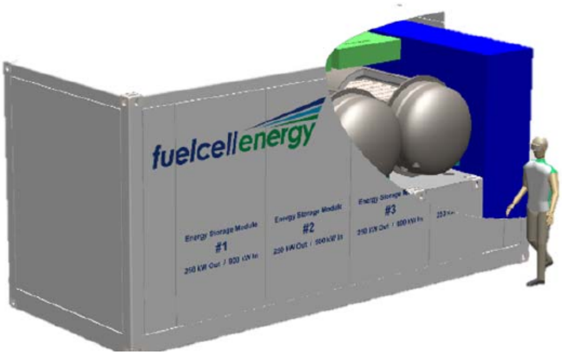

Figure 10.2: 20-foot 1,120 kW SOFC container of Fuel Cell Energy (Ghezel-Ayagh, 2021).

The system design of a SOFC container like the one presented in Figure 10.2 is shown in Figure 10.3.

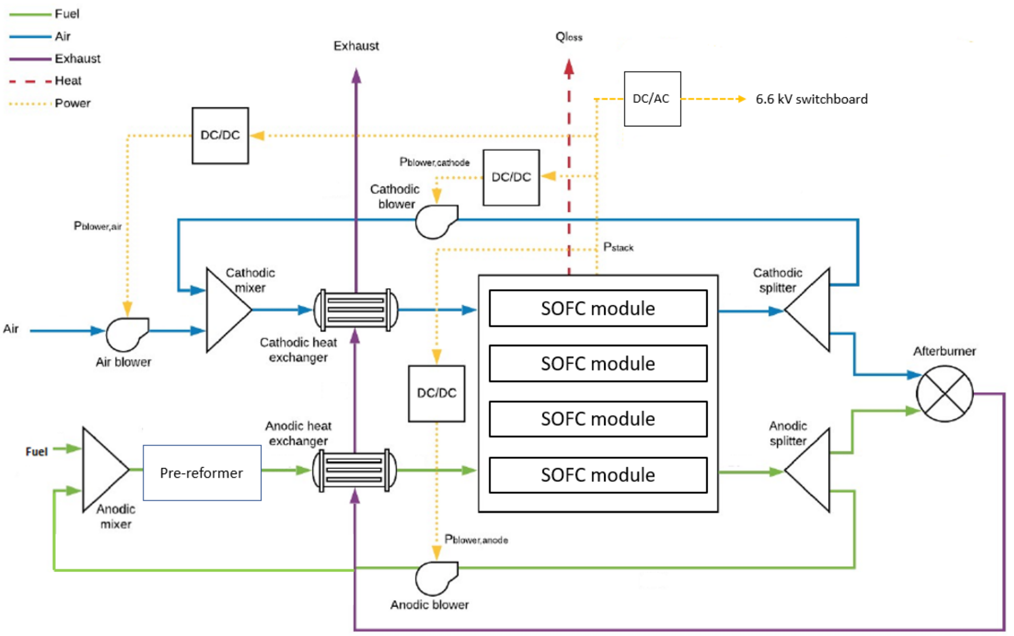

Figure 10.3: System design of SOFC container (modified from Henderik, 2020 with information from Ghezel-Ayagh, 2021 and van Veldhuizen et al., 2022).

In the lower half part of the container the balance of plant (BoP) is located. As can be seen, these support systems include the blowers, the pre-reformer for the methanol (which also makes use of the exhaust heat to evaporate the methanol to later reform it), and two heat exchangers. Also, an afterburner is placed at the outlet of the anode and cathode. This afterburner is used to increase the temperature of the exhaust. The exhaust gas goes then through the heat exchangers, that heat up both the methanol and the air that enters the fuel cells. By increasing the temperature at the inlet, the thermal stresses in the fuel cell can be reduced (Henderik, 2020). Moreover, both the anode and the cathode have a splitter at the outlet. This ensures a recirculation of the air and the methanol, which reduces the amount of air and fuel that has to be inserted in the system. Cathode off-gas recirculation has proven to reduce the primary airflow needed, which reduces the amount of heat required to preheat the air and improves the air-fuel ratio in the afterburner (van Veldhuizen et al., 2023). Regarding the amount of air that such a system requires, it is assumed that a SOFC container would require an equivalent air-to-fuel ratio (λ) of 2.5, a value that was also used in previous researches such as Fang et al., 2015 and that was consulted with Dr. ir. L. van Biert, expert in the field of SOFCs.

The efficiency curve is also one of the assumptions that need to be made for this research. The options in the market for SOFCs are quite limited at the moment, and manufacturers are not very prone to share detailed information since it is a technology being investigated. From the information presented in section 6.3 and the values gathered by van Biert, 2020, one can say that the efficiencies of a SOFC module oscillate between the 50-65%. Payne et al., 2009 presented an efficiency curve of a small SOFC module, where it was visible how at higher loads the efficiency lowers after the peak efficiency, due to the efficiency of the components in the BoP of the module. With this information, and after having consulted Dr. ir. L. van Biert, the efficiency curve of a SOFC module assumed for this research is shown in Figure 10.4. As can be seen, it is assumed that under 20% load the fuel cells are not able to produce any power. After that, at 20% the efficiency is approximated to 50%, that reaches its maximum at a load of 60% with an efficiency of 65% to later go back to an efficiency of 50% at a 100% load. In Figure 10.4 it can also be seen what the polynomial fit of the efficiency values is, that corresponds to a second degree polynomial that can be used to calculate the efficiencies at different loads. It is considered that an entire module (of 280 kW) always operates at the same load.

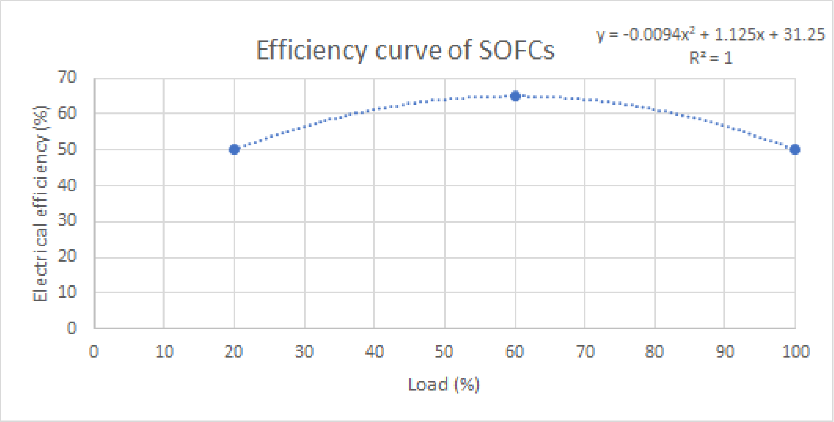

Figure 10.4: Assumed efficiency curve of a SOFC module.

10.2.1. Weight estimation of the SOFC container

In order to make a realistic estimation of the weight of a SOFC container, much more information than the weight of the SOFC stacks is required. As mentioned before, these fuel cells are not used yet at such a large scale, which implies that specific information about the weight of these kind of systems is limited. Therefore, due to the uncertainty that it implies, a conservative approach is used. In Table 10.1 the weight of the stacks was shown, but these are placed in a cylinder with insulation and fuel supply and exhaust pipes and under the SOFC module the support systems are located.

The only example of fuel cells at a large scale is the one presented in subsection 6.3.2, since Fuel Cell Energy offers power plants working on MCFC starting at 1,400 kW. From Ghezel-Ayagh, 2021 it is known that Fuel Cell Energy plans to use the same approach for power plants based on SOFCs. From drawings it can be seen that the balance of plant (BoP) is very similar. Therefore, the weights for the BoP of a 1,400 kW power plant of MCFC are used to calculate the weight of the support systems of a SOFC container by scaling them linearly.

Regarding the weight of the cylinder containing the stacks (the SOFC module), it is assumed that the weight of the cylinder and the insulation and fuel supply and exhaust pipes is equal to the proportional weight in terms of area of a 20-foot gas container.

The total weights of a 1,120 kW 20-foot container like the one shown in Figure 10.2 are:

Table 10.2: Weight breakdown of a SOFC 1,120 kW container.

Power (kW)	1,120
Dimensions L x W x H (m)	6.10 x 2.44 x 2.59
Weight SOFC stacks (t)	2.40
Weight cylinders (t)	3.04
Weight BoP (t)	27.5
Total weight (t)	**32.9**

In Appendix A a more detailed explanation of the calculation of the weight of a 20-foot 1,120 kW SOFC container is presented.

10.2.2. SOFC batteries

It is known that SOFCs are characterised by a bad dynamic behaviour, which means that they cannot react rapidly to transient loads. Therefore, they always require some batteries for peak load shaving.

With the information gathered from manufacturers and experts, it is expected that SOFCs can react within fifteen minutes to a change in load when kept idling. This means that they require this amount of time to go from idling to a 100% load. When idling, the fuel cells are kept in a stand-by mode, where they are warm (and therefore consume a little amount of fuel), but do not generate any electricity. When the fuel cells are cold, the amount of time to warm them up must be larger to avoid damaging the cells. The exact amount of time is dependent on the manufacturer, but it takes at least a couple of hours. Therefore, in order to not damage the cells it is better to keep them warm idling, instead of turning them off; unless they are not needed operative for a long amount of time.

This means that during those fifteen minutes that go from idling to full load, the vessel must be able to take that energy from another source. In this case, batteries are proposed to supply that amount of power because the power is immediately available and the duration of the time where they are used is limited to fifteen minutes.

The most extreme difference in power is taken, to ensure that the battery capacity is always enough. The mode with the highest power requirement is the full combat mode at 22.0 kn speed, and the one with the lowest is the hotel load where the vessel is standing still. In the worst case scenario in terms of power, the vessel would be making use of shore power and laying in port at hotel mode. In Table 9.5 it can be seen how the amount of power that can be taken from shore is 206 kW, meaning that the remaining 85 kW to get to hotel mode must come from one of the fuel cell modules. This means that at least one SOFC module is turned on when being ready to depart in port, and the other modules are kept idling, ready to be turned on. In Equation 10.1 the required power that must be provided by the batteries is calculated.

$$P_{batteries} = P_{fullcombatmode} - P_{SOFCmodule} = (1,075 + 855) - 280 = 1,650kW \tag{10.1}$$

This amount of power needs to be delivered during fifteen minutes, since that is the time that the fuel cells need to reach the 100% load from idling. The capacity of the batteries must be at least $1,650kW \cdot 0.25h = 413kWh$

A small literature research was performed comparing different manufacturers of batteries and an expert in the field was interviewed to validate the assumptions that are taken since this research is meant for the medium term and the development in battery technology is experiencing rapid improvements in the last years. Finally, the choice is made to use NMC (nickel manganese cobalt) lithium-ion batteries. These are one of the battery types with the highest energy densities and show promising results.

According to Houache et al., 2022 some manufacturers are already producing this kind of batteries which are used in the automotive industry, achieving energy densities of 250 Wh/kg. This is the energy density of a battery cell, but when multiple cells are combined to form a module, a packing factor is required to calculate the total energy density of the module. According to Los, 2017, this packing factor is 1.3 for the gravimetric energy density, and 1.6 for the volumetric energy density. That means that the gravimetric energy density of a battery module is reduced to 192.3 Wh/kg.

Having the type of battery and its energy density in mind, the next step is to look for manufacturers that sell similar products. Unfortunately, the information of the automotive batteries mentioned in

Houache et al., 2022 is not publicly available. Therefore, another manufacturer that sells NMC lithium-ion cells is used to find realistic values for the C-rate the batteries. The C-rate indicates the rate at which a battery can be charged/discharged. For example, a battery of 100 Ah can deliver 100 A at a C-rate of 1.

The company Kokam offers high-power NMC-lithium-ion batteries with an allowable discharging C-rate of up to 6C for temperatures between 10-25°C (Kokam, 2022). It is technically feasible to increase the rate of charge of the batteries, and according to the expert consulted the improvements in battery technology in the coming years will increase the C-rate limiting the degradation that the batteries experience. However, in order to be conservative, for this research it is assumed that the batteries can be discharged at 3C. On top of that, it is known that not charging the batteries at their fullest capacity allows to increase their cycle life time (Los, 2017). Kokam, 2022 advises to keep the DoD (depth of discharge), the amount of battery capacity that is used, limited to 90% to reach more than 6,000 cycles at 1C. Therefore, the DoD for the batteries used for peak load shaving is also limited to 90%.

Despite the measure taken to not charge the batteries at their fullest capacity to increase their life time, batteries experience a degradation in performance. According to Svens et al., 2022, a NMC-lithium-ion battery charged at 3C presented a decay in performance of 21% after 2,000 full cycles (so with a DoD of 100%). Therefore it is assumed that a battery discharged at 3C with a DoD of 90% would experience the same degradation (if not less), after 2,000 full cycles. 2,000 full cycles corresponds to more than a full cycle a day if the vessel were constantly run during five years. Since the full charge of the batteries would only occur in the extreme case as shown in Equation 10.1, it is assumed that a value of 2,000 full cycles is conservative for an OPV that operates for 5 years until having to dock.

In Table 10.3 the specifications used to calculate the batteries for the OPV are presented.

Table 10.3: Specifications of the assumptions made for the NMC-lithium-ion batteries (Kokam, 2022, Houache et al., 2022, Svens et al., 2022, Los, 2017).

Cell gravimetric energy density (Wh/kg)	250
Cell volumetric energy density (Wh/L)	468
Gravimetric packing factor	1.3
Volumetric packing factor	1.6
C-rate for 10-25°C	3
Depth of discharge (%)	90
Degradation at 2,000 full cycles (%)	21

Apart from the batteries themselves, at least an inverter is required to convert the DC to AC. On top of that, in order to keep the risk of fire limited, the lithium-ion batteries are placed in an enclosed steel box, that is connected to a special foam firefighting system. In the case some fire takes place inside the steel box full of lithium-ion batteries the firefighting system is activated and the foam is injected in the steel box extinguishing the fire. In Appendix A more details on the selection of the firefighting system for the batteries can be found.

10.2.3. Power sizing

Knowing that the required propulsive power to cruise is 1,075 kW and that the mode with the highest auxiliary power is the combat mode with 855 kW, one can make an estimation on the amount of 280 kW SOFC modules that are required for the concept design. Taking a power factor of 0.88 at full load for the electric motors required to reach cruising speed and a degradation of 0.10%/1,000 hours of the SOFCs for a period of five years, it is concluded that in total eight 280 kW SOFC modules are required, which is equivalent to two SOFC containers of 1,120 kW each.

Each of these SOFC containers requires a set of batteries for peak load shaving, and the lithium-ion batteries require a firefighting system to keep the risk of a fire in the engine room under control.

In Table 10.4 an overview of the amount of SOFC modules and their weight and that of the batteries and their firefighting systems is presented.

Table 10.4: Power sizing of the SOFCs.

Number of 280 kW SOFC modules	8
Number of SOFC containers	2
Total installed SOFC power (kW)	2,240
Weight SOFC containers (t)	65.8
Weight SOFC batteries (t)	3.82
Weight inverters batteries (t)	1.60
Weight Fifi systems SOFC batteries (t)	1.02

10.3. Selection of peak power source

Fuel cells have a lower power density and have a worse dynamic behaviour than ICEs. In order to reach higher speeds than cruising speed, another power source is needed. In this section, three different alternatives as peak power source are presented and compared, to finally end up with a choice that will be elaborated in the concept design phase.

10.3.1. SOFC and battery powered

Since the purpose of this research is to find a power plant for an OPV that reduces its emissions, batteries are considered as a peak power source. Apart from being used for peak load shaving, batteries can be used to provide power when higher speeds than cruising speed want to be reached.

Therefore, the batteries should provide enough power to reach 22.0 kn of speed. Since batteries have a certain amount of energy stored, the length of the sprint determines the amount of batteries that have to be carried on board. On top of that, depending on how fast they have to be recharged by the fuel cells, the SOFC system might have to be overpowered to be able to recharge the batteries in a certain amount of time to have the energy stored to sprint again.

The amount of batteries that are considered for this research are the same as used for peak load shaving with the specifications shown in Table 10.3.

Electric motors

When having a power plant based on fuel cells and batteries, the entire propulsion system needs to be electrified. This implies that the engines need to be replaced by electric motors. Since an OPV is mostly sailing at or below its cruising speed, a father-son configuration is chosen. This ensures that the small electric motor (the “son”) works at an efficient load when cruising, and that the larger motor (the “father”) can be turned on only when more power is required.

The electric motors that are considered are both Siemens motors with the characteristics shown in Table 10.5:

Table 10.5: Specifications of the Siemens electric motors chosen for the configuration of SOFCs and batteries (Siemens, 2022a).

	Simotics HV M 900	**Simotics HV M 3900**
Pb (kW)	900	3,900
rated speed (rpm)	1,483	993
number of engines	2	2
Weight motor (kg)	5,800	16,100
Weight variable-frequency drive (VFD) (kg)	3,970	4,700
Total weight (kg)	19,540	41,600

Emergency power

Since SOFCs are not able to react rapidly, it is considered that for this configuration batteries should be used for emergency power generation. That means that a stack of batteries must be carried on board that is always charged and is able to supply the required power in one time.

According to the rules of Bureau Veritas (Bureau Veritas, 2022a), the emergency power source must react within 30 minutes and provide the necessary required emergency power for 18 hours. From Table 9.5 it is known what the emergency power is, so the batteries must be able to supply the power required for this mode during 18 hours.

Power plant

The power plant of the configuration consisting only of SOFCs and batteries would look like diagram shown in Figure 10.5.

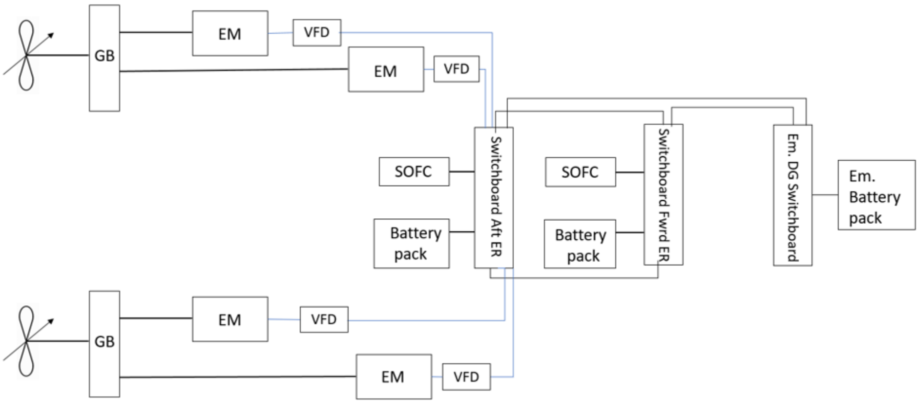

Figure 10.5: Power plant diagram of configuration with SOFCs and batteries.

10.3.2. SOFC and diesel engine powered

The current configuration of the reference design has diesel engines. From the literature review of this master's thesis, it is known that these react rapidly to load changes and are therefore a possible combination with SOFCs. Diesel generators were mentioned as a possibility to solve this issue, but in order to avoid losses in the conversion of mechanical to electrical to mechanical energy, one can think of coupling a diesel engine directly to the gearbox. Hereby, the power plant becomes more efficient, also in terms of the weight required. Therefore, the configuration would include a diesel engine per shaft that is used to sprint, combined with a smaller electric motor that is used with a power take-in (PTI) on the shaft to reach cruising speed.

Diesel engines

The two electric motors that are chosen for this configuration are shown in Table 10.6:

Table 10.6: Specifications of the electric motor and the diesel engine (Siemens, 2022b, MTU, 2022).

	Simotics HV A compact PLUS	**MTU 16V1163 M74**
Pb (kW)	710	4,800
rated speed (rpm)	1,782	1,250
number of engines	2	2
Weight motor (kg)	2,650	21,240
weight variable-frequency driver (kg)	3,280	-
Total weight (kg)	**11,860**	**42,480**

Auxiliary power

In order to provide auxiliary power in case of an emergency, the choice has been made to leave the existing diesel generator on board of the vessel. That is, a Caterpillar C9.3 diesel generator with a brake power of 325 kW. In the original design, the emergency diesel generator has its separate day tank with enough fuel to provide power according to class rules. Therefore, this tank that includes 2.0 t of diesel is kept constant.

Diesel

Because the SOFCs run on methanol, diesel has to be taken on board on top of the amount of methanol required to reach the range at cruising speed. This implies that the amount of time spent sprinting must be known beforehand, because it delimits the amount of diesel that is required for a certain mission. This has a negative effect on the operational flexibility of a vessel. While the current vessel that only carries diesel is “free” to choose how it sails, the configuration with SOFCs and diesel engines must be designed for a very specific operational profile. If the mission changes, it could happen that either the diesel runs up while there is still methanol, or that unnecessary diesel is carried on board that is not used. Therefore, depending on the amount of time that the vessel must sprint during a mission, the diesel that must be taken on board varies. Moreover, having two fuels on board (methanol for the SOFCs and diesel for the DE), complicates the logistics of refuelling, especially at sea.

Power plant

The power plant of the configuration of SOFCs and diesel engines is shown in Figure 10.6. As can be seen, batteries are still carried on board used to absorb the fluctuations of the SOFCs.

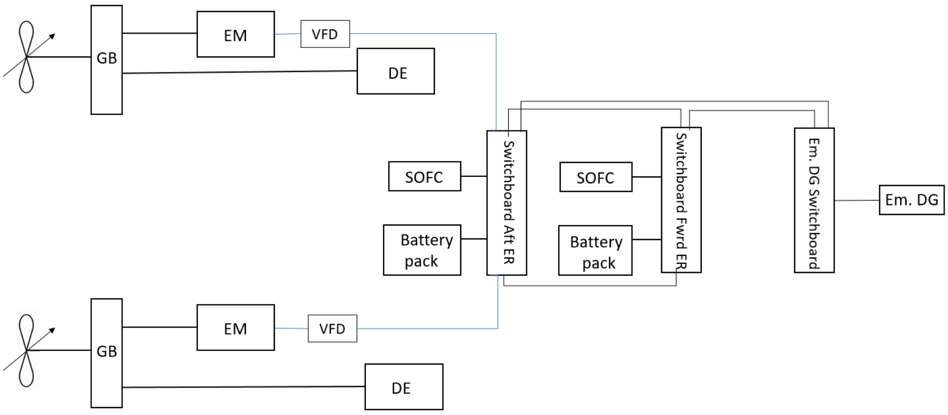

Figure 10.6: Power plant diagram of configuration with SOFCs and diesel engines.

10.3.3. SOFC and methanol engine powered

Having seen the challenges of having a configuration with SOFCs and diesel engines, because of the extra amount of diesel that has to be taken on board and thus the limitation in operational flexibility of the vessel, the choice is made to look at the possibility of using methanol engines.

Some manufacturers like Wartsila, are already offering methanol engines (Wärtsilä, 2022). The truth is that these engines are in reality dual-fuel engines, where methanol is mixed with diesel to ensure a combustion of the fuel at high pressures.

Methanol has the disadvantage that is has a very low cetane number. The cetane number is an indicator of the self-ignitability of a fuel (Li et al., 2014). While diesel has a cetane number of 45 to 60, methanol has a cetane number of 5. This means that methanol does not self ignite at high pressures. For that reason, many studies focus on the blend with diesel fuels, that increase the total cetane number of the blend.

According to Li et al., 2014, there are other ways to improve the self-ignitability of a fuel, such as redesigning the combustion chamber, adding an extra spark plug, increasing the compress ratio, etc. Opting for a blend of methanol and diesel is not considered feasible for this master’s thesis, since it would not eliminate the issues mentioned before, like the limitation in operational flexibility and the complications in the logistics of the replenishment.

Therefore, the choice of a spark-ignited methanol engine is studied. As mentioned before, methanol has a low cetane number; but at the same time it has a high octane number. The octane number indicates the anti-knock properties of a fuel. The higher the octane number is, the higher the pressure is that the fuel can withstand without detonating. The high octane number of methanol makes it a good candidate for a spark-ignited engine because it allows higher compression ratios that lead to a higher thermal efficiency, and helps to maintain optimal spark timing throughout the engine operating range (Agarwal et al., 2021). According to Agarwal et al., 2021, these effects help achieving a down-sizing of the spark-ignited engine without compromising the efficiency and power. Others like Brusstar et al., 2002 modified an automotive diesel engine adding port fuel injectors and spark plugs, and obtained efficiencies with methanol of 43%, higher values than the efficiencies than those achieved with diesel.

However, spark-ignited methanol engines also have disadvantages such as a poor lubrication and a poor cold starting (Agarwal et al., 2021). It is considered that these issues are solvable in the medium term, since this is the time range of this research. Therefore, it is assumed that in the medium term, similar engines to the current diesel ones (modified to have a spark plug) could work on pure methanol, obtaining the same engine efficiencies. For this reason, the engines chosen for the configuration with SOFCs and methanol engines are the same ones as for the configuration with SOFCs and diesel engines. These are shown in Table 10.7.

Table 10.7: Specifications of the electric motor and the spark-ignited methanol engine (Siemens, 2022b, MTU, 2022).

	Simotics HV A compact PLUS	**MTU 16V1163 M74 modified with spark plug**
Pb (kW)	710	4,800
rated speed (rpm)	1,782	1,250
number of engines	2	2
Weight motor (kg)	2,650	21,240
weight variable-frequency driver (kg)	3,280	-
Total weight (kg)	**11,860**	**42,480**

Emergency power
For the same reasons as mentioned above, it is assumed that a methanol generator of the same characteristics as the diesel generator used for the previous configuration can be used for the generation of the auxiliary power.

Methanol
For this configuration, only methanol would be required. In that sense, it is similar to the reference design OPV working only on diesel, because it only requires one type of fuel, which increases its operational flexibility and facilitates the logistics of refuelling. Keeping the same way of thinking, for this configuration the amount of methanol required is the one necessary to reach the range at cruising speed.

Power plant
The power plant of the configuration with SOFCs and methanol engines shown in Figure 10.7 has the same configuration as the one with diesel engines, with the difference that in this case the engines include a spark plug that allows them to work with pure methanol.

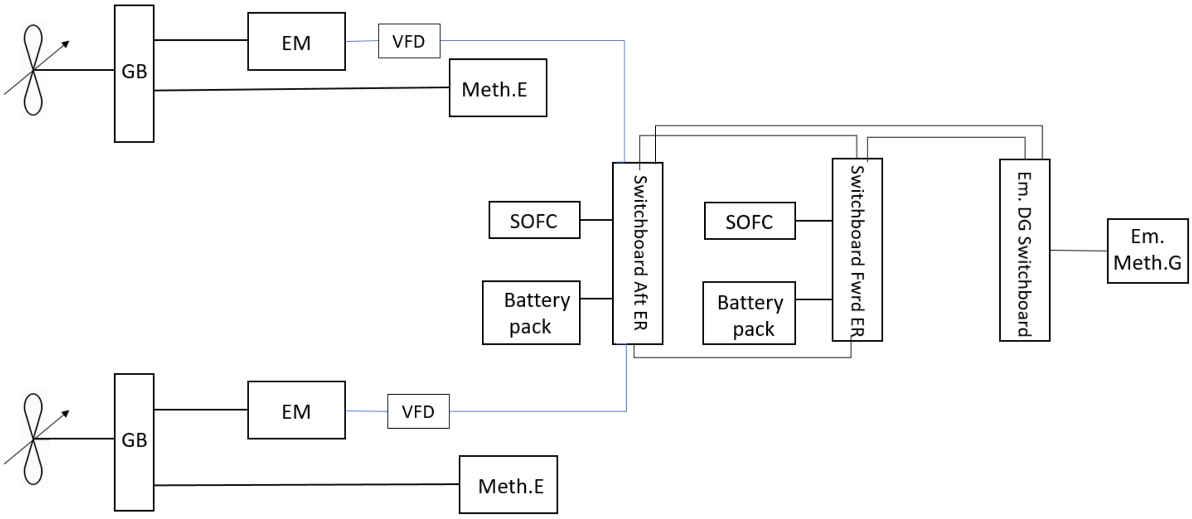

Figure 10.7: Power plant diagram of configuration with SOFCs and methanol engines.

10.3.4. Comparison between the different peak power sources

Once the system design of the three configurations has been done, their weight can be linked to the mission requirements. In section 10.1 the minimum requirements of the different types of missions that an OPV has to perform were presented. There, it was concluded that regarding the time spending sprinting, the OPV must be able to at least sprint 200 nm to reach the border of the EEZ in a straight line. For this reason, the (provisional) impact on the weight of the power plant of the different configurations is plotted against the duration of the sprint in Figure 10.8.

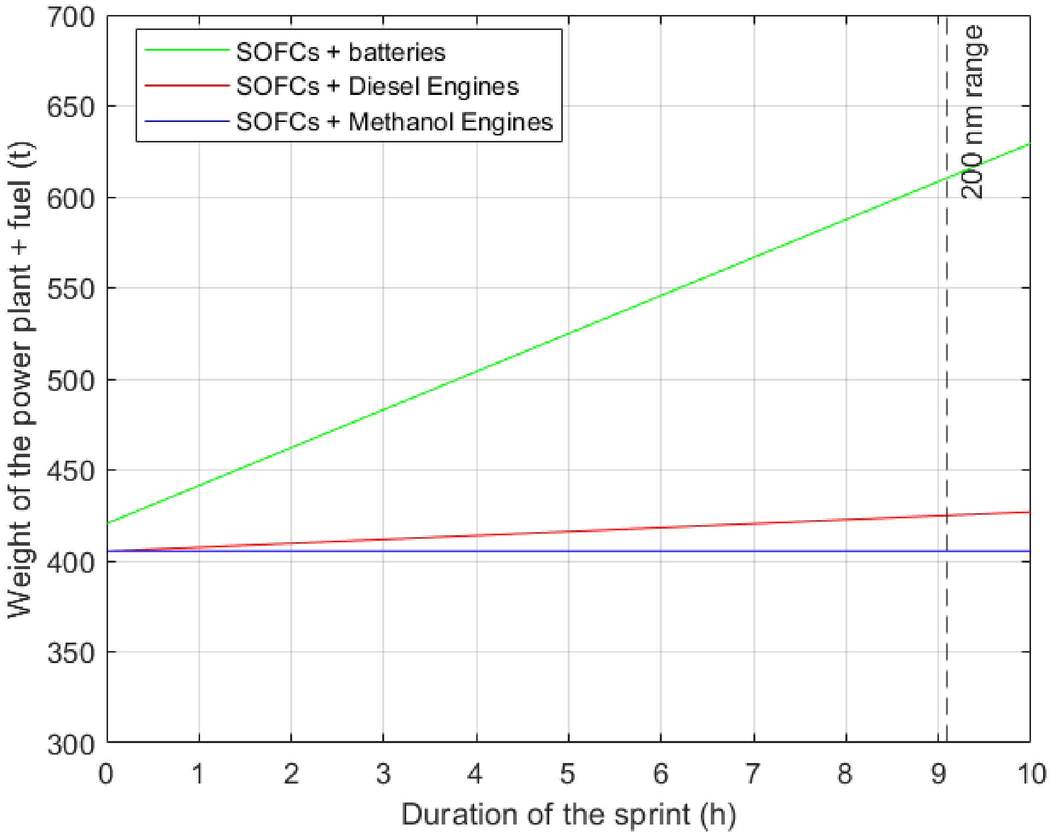

Figure 10.8: Overview of the weight of the different configurations of peak power source with respect to the duration of the sprint.

In Figure 10.8 a dotted vertical line shows the time that must be sprinted at 22 kn to reach the range of 200 nm. Mind that for this overview of the weight of the different power plants, many of the components such as the gearboxes and auxiliary systems have been kept constant. The chosen configuration will be studied further in the next chapters.

As can be seen, batteries exceed by far the weight of the combination with diesel engines and methanol engines. They are not even lighter at zero hours of sprint. This is because the two electric motors necessary for a power plant that is fully electrified are heavier than the combination of a small electric motor to reach cruising speed and a large internal combustion engine, which is the case of the other two configurations. On top of that, the SOFC power of the combination with batteries has not been increased to charge the batteries, which would increase the difference in weight of this configuration with respect to the other two.

As mentioned before, the combination with diesel engines requires that the operational profile of the vessel must be known in advance in order to know how much diesel must be carried on board. That is why, despite having the same initial weight as the combination with methanol engines, the red line ascends for longer sprint times, solely due to the extra amount of diesel that is required.

In the case of the combination with methanol engines, the weight of the power plant remains constant for every length of the sprint. This is what was referred before as operational flexibility. For this combination, like for the reference design, the amount of fuel is determined on the basis of the range required at cruising speed. Therefore, it is up to the vessel to “decide” how it sails and when it sprints, plus the fact that having only one fuel facilitates the logistics of refuelling.

Having analysed all the different configurations and their impact on the weight of the power plant and the fuel required, it is concluded that the best configuration is the one that consists of SOFCs and methanol engines. With this combination, the operational flexibility of the OPV is not affected despite the change in power plant and fuel.

10.4. Electrical integration

The partial electrification of the power plant implies that one electric motor per shaft has to be used in order to make use of the electricity generated by the fuel cells. It is known that the weight of all electrical components is directly related to the amount of current going through them. Therefore, in order to keep the weight of the electrical components of the power plant limited, the choice is made to choose an electric motor that operates at high voltage as the one shown in Table 10.7.

The output voltage of the fuel cells and the batteries can be chosen as such that it is connected to the 6.6 kVAC switchboards, which supply power to the electric motors. Keeping the voltage high, allows to lower the current, which results in lighter cables. From the 6.6 kV switchboard, a transformer is needed to convert the power to 440 V, which goes to the rest of the electric grid that stays unaltered.

In Figure 10.9 a complete overview of the electrical grid of the vessel can be seen, where the elements in red are the ones that have been added to the concept design. After having consulted the electrical team of Nevesbu, it is considered that only two panels are required per 6.6 kVAC switchboard. For redundancy purposes the 6.6 kVAC switchboards in the different switchboard rooms are connected with each other, and the transformers are designed as such that if one of them failed, the remaining transformer could convert the electricity generated for the two electric motors in the power plant.

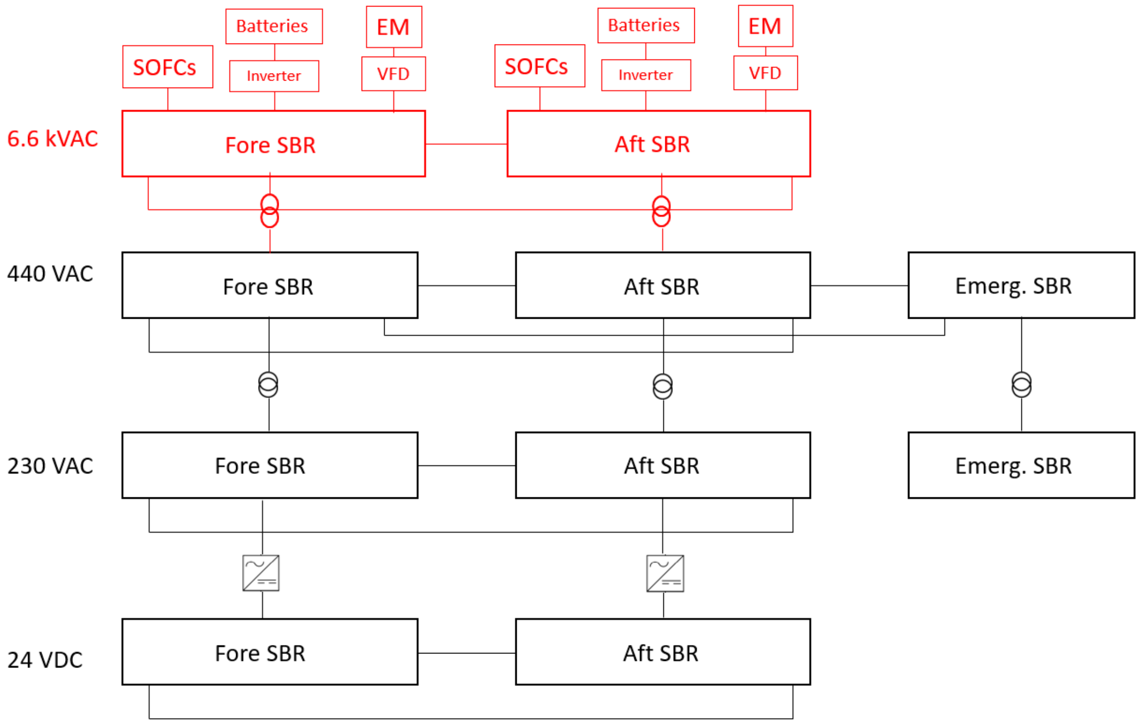

Figure 10.9: Simplified one line diagram for a SOFC-methanol engine configuration. The red parts show the added elements to the electric grid.

While a SOFC container already delivers AC current because an inverter is included in it (as shown in the system design in Figure 10.3)), batteries deliver DC current, which means that a separate inverter is required. For redundancy purposes, each battery pack has an inverter as shown in Figure 10.9.

Therefore, the added elements to the electrical system consist of batteries, inverters, transformers, 6.6 kV switchboards, and the variable-frequency drives and electrical motors that were already presented in Table 10.7.

The characteristics of the transformers and switchboards added to the electrical grid of the OPV are shown in Table 10.8.

Table 10.8: Weight and number of transformers and 6.6 kVAC switchboards.

Weight transformer (t)	4.4
Number of transformers	2
Weight 6.6 kVAC switchboard (2 panels) (t)	0.4
Number of 6.6 kVAC switchboards	2

10.5. Conclusion

In this chapter, the system design of the power plant for the concept design was done.

To start, in section 10.1 the approach of the system design was described. Here, the requirements of the new power plant were stated, reflecting on the capabilities of the reference design, and the different design steps were presented.

Next, in section 10.2, the SOFC modules were designed. The design entails not only choosing which kind of stacks are needed and their distribution among the different modules, but also their weight estimation, the components of the support systems, and the efficiency of the modules. Moreover, the amount of batteries required for peak load shaving was calculated. The calculation of the amount of batteries and SOFCs includes different margins and ensures that their lifetime reaches the five years that the vessel needs to spend until having to dock. Also, the inverters required to convert the current generated by the batteries to AC were selected. Finally, it can be said that a configuration consisting of a combination of 280 kW SOFC modules was chosen, where four modules (1,120 kW in total) can fit with their support systems inside a 20-foot container. In order to generate enough power for propulsion to reach the cruising speed and the auxiliary power required for all modes, the concept design needs to make use of eight 280 kW SOFC modules, which is equivalent to two SOFC containers.

In section 10.3 the different configurations of the peak power sources were analysed. These peak power sources must provide enough propulsive power to go from cruising speed to top speed. The three configurations that were studied to be used together with the SOFCs are: batteries, diesel engines, and methanol engines.

The configuration of SOFCs and only batteries implies that the full power plant is electrified, so all engines must be replaced by electric motors.

In the second configuration, the combination of SOFCs an diesel engines was studied, where the SOFCs drive a small electric motor used to cruise, and the diesel engines, directly connected to the gearbox, provide the power to reach the maximum speed. In this configuration, the amount of diesel that is taken on board on top of the necessary methanol is determined by the operational profile of the vessel. This limits the operational capabilities of the vessel, since the operational profile of the vessel must be known in advance, and complicates the logistics of refuelling because two different fuels (methanol and diesel) would have to be carried on board.

The third configuration that was analysed was one with methanol engines and SOFCs. A small literature review was performed about methanol engines. At the moment there are not engines that work on pure methanol, only dual fuel engines, where the methanol is mixed with diesel to ensure self ignition of the mixture. From the literature review it was concluded that spark-ignited engines of the same size of the current diesel engines could, from a technical point of view, work on pure methanol due to the high octane number of methanol and thus its anti-knocking properties. Therefore, for this combination it is assumed that the same diesel engines that were used for the combination with diesel engines could, with the addition of a spark plug, work on methanol in the medium term with very similar efficiencies.

Once all three configurations were elaborated, in Figure 10.8 the effect on the weight of the power plant of the different configurations with respect to the duration of the sprint of the OPV during a mission was shown. Referring to the minimum requirements that an OPV must have as explained in section 9.7, such as being able to sprint a minimum of 200 nm in one time, it was concluded that the combination of SOFCs and methanol engines is the most suitable for the concept design. In this configuration, the OPV maintains the highest flexibility in terms of which operations it can conduct. Moreover, having only one fuel on board facilitates the logistics of refuelling.

Finally, in section 10.4 the electrical integration of the power plant was done. In order to provide high-voltage power to the electric motors, a 6.6 kVAC switchboard is designed that is connected to the 440 VAC switchboard by a transformer. Keeping the same design philosophy as in the electrical grid of the reference design, each switchboard room has a 6.6 kVAC switchboard that is connected with the other switchboard room to increase the redundancy of the system. Also, one single transformer is able to convert all the propulsive power for cruising to a higher voltage in case the other transformer fails.

11

Creation of Concept Design

In the previous chapter (chapter 10) it was determined what the best power plant is in terms of weight and operational capabilities of an OPV. The goal of this chapter is to test how the chosen power plant—a combination of SOFCs and methanol engines—can be integrated in the OPV and how this affects the design.

11.1. Concept Design Approach

The system design in chapter 10 was done keeping in mind the requirements of the reference design as they were summarised in section 10.1. The objective of this chapter is to physically place all the necessary components of the new power plant in the vessel and to look at how this affects the design of the OPV.

The consequences on the arrangement of the different components in the new power plant are not the only relevant aspects. Other aspects such as the use of methanol and its impact on the design, the stability of the vessel, and the redundancy and the safety of the new design must be considered. Also, the effect on the auxiliary systems needs to be studied, and all the balances must be checked.

The results shown in this chapter are the outcome of an iterative process, where the design spiral was run through multiple times.

11.2. Methanol

The amount of methanol required for the new OPV is calculated on the basis of the range requirement stipulated in the contract. That is, that the vessel must reach a range of 4,500 nm at 12 kn.

With the assumptions in terms of efficiency of the SOFCs as explained in chapter 10, in order to generate enough power to reach cruising speed and its corresponding auxiliary power, all eight 280 kW fuel cell modules must run at a load of 88%. According to the efficiency curve shown in Figure 10.4 this load corresponds to an efficiency of 57% for all modules. Therefore, the amount of methanol required to reach the range at cruising speed is calculated with these parameters. The value obtained at design draught is 250 t of methanol.

11.2.1. Safety

In the concept design both the SOFCs and the engines run on methanol. As was explained in the literature review of hydrogen carriers in chapter 5, methanol is an alcohol fuel with composition CH_3OH that is liquid at ambient temperature. Due to its lower energy density, it is expected that it requires 2.3 times more space to store than diesel (van Kranenburg-Bruinsma et al., 2020). Methanol is also regarded as toxic for humans, and it has a flash point of 12°C, meaning that from that temperature in the presence of a spark it would ignite. In chapter 7 it was concluded that these characteristics make it still a suitable fuel to be used on board of an OPV, since this vessel operates in the lower violence spectrum. Despite the fact that it is considered to be suitable to be used on board of an OPV, additional measures must be taken in order to ensure the safety of the vessel and the crew and the vessel.

In August of 2022, Bureau Veritas published a set of rules for ships fuelled by methanol or ethanol (Bureau Veritas, 2022c). Since the reference design complies with the rules of Bureau Veritas, this new set of rules is used for the use of methanol in the concept design. A summary of the most relevant rules in Bureau Veritas, 2022c for a concept design is the following:

- “Tanks containing fuel are not to be located within accommodation spaces or machinery spaces of category A.”
- “Fuel piping that passes through enclosed spaces in the ship is to 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”, meaning that fuel piping must be double walled. In the annular space of the fuel piping either mechanical ventilation with at least 30 changes of air per hour must take place, or an inert gas must be used as an alternative to ventilation.
- The production plant of inert gas must be able to produce inert gas with an oxygen content not greater than 5%. In the case of fuel tanks, the oxygen level cannot exceed a percentage of 8%.
- “Any fuel preparation space is not to be located within a machinery space of category A, is to be gas a liquid tight to surrounding enclosed spaces and hold an independent ventilation system.” Meaning that the fuel preparation space must have its separate room from the engine room.
- “For fire integrity, the fuel tank boundaries are to be separated from the machinery spaces of category A and other rooms with high fire risk by a cofferdam of at least 600 mm.” Meaning that the spaces with which the fuel tanks adjoin cannot be machinery spaces or accommodation spaces.

This are the most important rules for the use of methanol as a fuel on board of a ship and they should be taken into account in the design of the new OPV. It is considered that this set of rules provides enough safety for an OPV, since the reference design is already built according to commercial standards.

11.2.2. Fuel cells on methanol

Apart from the rules of Bureau Veritas aforementioned on the use of methanol as a fuel on board of vessels, the same class association has a separate set of rules for the use of fuel cells on board of a vessel.

This set of rules (Bureau Veritas, 2022b) was published in January of 2022 and proposes new rules for those vessels making use of fuel cells. Apart from saying that the rules of the fuel type apply (in this case the rules for ships fuelled by methanol, Bureau Veritas, 2022c), the most controversial rule is one that states: “Fuel cell spaces are to be arranged outside the accommodation spaces, service spaces, machinery spaces not dedicated to fuel cell power installation and control stations.”

It is important to bear in mind that at the moment there are not examples of operative vessels running on fuel cells that make use of the same fuel that is used for the full propulsion. Moreover, the projects that are being announced at the date that this thesis is being written make normally use of PEMFCs, very often running on pure hydrogen which, as was explained in chapter 5, presents much higher safety risks than methanol.

Therefore, this author considers that the rules that Bureau Veritas presents at the moment would not make sense in a power plant where the internal combustion engines make use of the same fuel than the fuel cells. The measures regarding a safe use of methanol mentioned before will be implemented in the concept design, which should ensure also a safe use of the fuel cells. Therefore, it can be concluded that separating the SOFC modules fuelled by methanol from the internal combustion engines, fuelled by methanol as well, does not seem necessary to increase the safety of the new power plant, since the highest source of risk (methanol) is already tackled with multiple safety measures.

11.3. Diesel

In subsection 10.3.3 it was explained how methanol engines are a technically feasible option in the medium term if a diesel engine is adapted to have a spark plug. However, it is risky to say that an engine of the size of those used on board of RHIBs will be able to run on methanol in the medium term. Although technically feasible, it is doubted that the adaptation of diesel engines to methanol engines starts with the small engines, since the environmental benefits of using methanol instead of diesel as a fuel are higher in absolute terms for higher power ranges. Moreover, it should be studied whether it is safe to use methanol on board of a RHIB that is carried on board of an OPV, since the RHIB participates more directly in combat than the OPV itself. For the reasons aforementioned, it is considered that a separate diesel tank should be included on board of the OPV to provide fuel for the RHIBs, like it is already done with the aviation fuel for the helicopter.

In order to calculate the amount of diesel that needs to be taken on board, the range of the helicopter is analysed. In the operation of an OPV normally the helicopter has a higher range than the RHIB, so equalling these ranges should suffice the amount of fuel that is needed for the two RHIBs carried on board of the concept design.

The amount of aviation fuel carried on board the concept design allows the helicopter to travel in total almost 4,000 km. It is also known that the biggest RHIB has a range of 200 nm with 350 l of diesel. Therefore, it can be concluded that in order to have the same range as the helicopter, 3,780 l of diesel must be carried on board.

11.4. General Arrangement

In this section the general arrangement of the concept design is presented and discussed. The complete general arrangement of the concept design can be found in the confidential appendix in section C.2.

11.4.1. Tank arrangement

As was mentioned earlier, using methanol as a fuel entails new design rules. According to Bureau Veritas, 2022c, the fuel tanks have to be separated from machinery spaces and other rooms with high fire risk by a cofferdam of at least 600 mm. This means that the tank arrangement of the reference design needs to be rearranged in order to comply with these rules. In Table 11.2 the tanks used to store methanol are presented. Also, the volume of these tanks in the reference design is shown.

In order to comply with the rules for vessels fuelled by methanol, the location of some ballast water (BW) tanks and fuel tanks was swapped. That is the case of tanks 33, 34, and 35, which used to be ballast water tanks. The previous fuel tanks, that were forwards of the fore engine room, have become ballast water tanks in the concept design. This is done to ensure that the methanol tanks were not directly adjoining with machinery spaces. Also, in the height a cofferdam was placed to ensure that they keep 600 mm distance with respect with the accommodation spaces located one deck above. In the case of tanks 25 and 26, they do not adjoin with any sensible space in the length, but a cofferdam was again placed at the top of the tank to separate them from the accommodation spaces one deck above, hence the reduction in volume. In the case of tank 27, which used to be a ballast tank, the difference in weight is simply because not more fuel is required; thus the remaining volume can still be used as ballast tank. In Table 11.1 the total weight of the added cofferdams can be found. This has been calculated assuming that a steel plate of 8 mm would be used to make the cofferdams.

Table 11.1: Weight of added cofferdams to concept design.

Weight of added cofferdams to tanks (t)	6.10

It is a contractual requirement that the day tanks (tanks 7 and 8 in Table 11.2) and the bunker tanks (tanks 5, 33, and 34) have 10% and 3% fuel at arrival respectively. This adds 4.7 t to the 245 t of methanol that are required for the range condition. Therefore, the total amount of methanol that must be taken on board is equivalent to 250 t. On top of that, the departure condition is set at a level of the bunker tanks (tanks number 33, 34, and 35) of 95%, which means that $319\,\mathrm{m}^3$ of volume are required in total for the storage of methanol.

Table 11.2: Methanol tank arrangement.

Tank number	Old volume (m^3)	Vol net (m^3)	Weight (t)
8	7.6	13.2	10.5
7	7.6	13.2	10.5
33	60.7 (BW)	54.6	43.2
34	60.7 (BW)	54.6	43.2
5	24.4 (BW)	24.4	19.3
26	32.8	19.4	15.4
25	32.8	19.4	15.4
20	10	10.0	7.9
new tank	Storage room	45.8	36.3
27	84.4 (BW)	64.7	51.2
		319	**253**

It can be seen how all the requirements are met by the new arrangement of the tanks as shown in Table 11.2. In total, 250 t of methanol need to be carried on board to reach the range condition.

In section 11.3 it was mentioned how $3.8\,\mathrm{m}^3$ of diesel are required for the storage of the fuel required for the RHIBs that are carried on board the OPV. This amount of diesel is placed inside the tank that used to be the overflow tank in the reference design, under the aft engine room. The exact values are shown in Table 11.3.

Table 11.3: RHIB diesel tank arrangement.

Tank number	Old volume (m^3)	Vol net (m^3)	Weight (t)
19	12.1	4.00	3.36

Emergency generator room

In the system design of the configuration with SOFCs and methanol engines (subsection 10.3.3) it was explained that the emergency generator would be kept the same as in the reference design, assuming that it could work on methanol if a spark plug were added to it. In the reference design, a small diesel tank was placed in the emergency generator room. In the concept design, this fuel must be methanol, which has a lower energy density and requires cofferdams around the sides of the tank that adjoin machinery or accommodation spaces. Therefore, the emergency generator room of the concept design had to be slightly adapted, as can be seen in Figure C.11 of the confidential appendix (section C.2).

Due to the lower energy density of methanol, the amount of fuel that must be taken in the emergency generator has to be larger, to ensure that in total it stores the same amount of energy. The exact values can be found in Table 11.4. Apart from the lower energy density, the methanol tank must be separated from other spaces by cofferdams of $600\,\mathrm{mm}$. In Figure C.11 it can be seen how there are cofferdams placed separating the tank from the emergency generator room and the HVAC room. Also, a cofferdam is placed above the tank to separate it from the deck above. Since there was enough room and because this tank is placed on a higher deck than the rest of the tanks, although it is not required by class, for safety purposes it was chosen to isolate the tank by cofferdams on those walls limiting with the outer side of the vessel as well.

Table 11.4: Emergency methanol tank arrangement.

Tank number	Old volume (m^3)	Vol net (m^3)	Weight (t)
31	2.30	5.52	4.37

11.4.2. Engine rooms and fuel preparation space

The original idea was to place the fuel cells where the diesel generators were originally placed. Since eight 280 kW SOFC modules were required for auxiliary power generation and propulsive power for cruising speed, it was decided to split them between the two engine rooms to increase the redundancy of the system. One of the benefits of making use of fuel cells is their modularity, as was already stated in chapter 4. In chapter 10 it was explained how a 20-foot container can fit four 280 kW SOFC modules and their BoP. Knowing this, in the design of the engine rooms the arrangement of the BoP of the SOFCs was adjusted to the space requirement of each engine room, keeping the volume and height of the BoP equal, but playing with the surface it covers. Also, it was ensured that all SOFC modules were placed at places where the cylinders holding the fuel cells could be easily opened.

In Figure 11.1 the top view of the engine rooms can be seen.

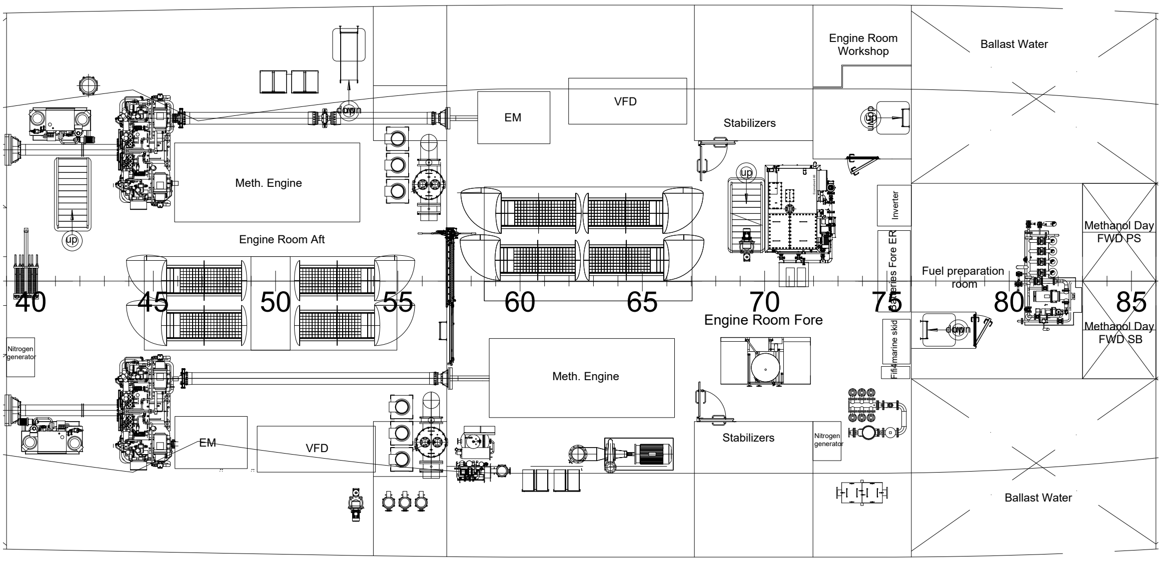

Figure 11.1: Top view of the engine room in the concept design.

Next, the arrangement of the engines had to be made. In terms of redundancy, it is better to have identical engine rooms, like it happened in the reference design. For this reason, in the concept design each engine room has an electric motor and a methanol engine with the characteristics as shown previously in Table 10.7. In order to be able to fit the methanol engine in the fore engine room, the aft walls of the stabilizer rooms had to be moved one frame (600 mm) forward. This is considered to be feasible, since there is still plenty of room inside the stabilizer room and these walls are not an continuous element of the structure of the vessel. The tween deck in the fore engine room is affected by this change, since it is also shortened also by one frame.

As can be seen in Figure 11.1, the design of each of the shaft lines would have to be different for this power plant, since the methanol engines are placed at different distances from the gearboxes. Although costs are considered to be out of the scope of this research, it is important to note that this arrangement is more complex than that of the reference design and that it therefore would imply more engineering time.

Behind each electric motor the variable-frequency drive (VFD) is placed. In the case of the fore engine room, because there is more space available, the batteries, the inverter, and the firefighting equipment for the lithium-ion batteries are placed at tanktop level like the SOFC modules.

According to the rules of Bureau Veritas, 2022c, the fuel preparation space must be placed in a separate room. According to Bureau Veritas, 2022c: "a fuel preparation space means any space containing equipment for fuel preparation purposes, such as fuel pumps, fuel valve train, heat exchanger and filters." Therefore, the fuel oil transfer system that was originally placed in the fore engine room, was moved to a separate room, that used to be the settling tank for diesel which is no longer needed, dedicated from now on to the preparation of the fuel as can be seen in Figure 11.1.

Gearbox

In the reference design, each shaft line was powered by two identical diesel engines. The gearbox that was used was a double input/single output that weighted $7.4\,\mathrm{t}$.

In the concept design, the engines providing power to the shaft are not identical, which might affect the optimal selection of a gearbox.

In order to find reliable advice, it was decided to contact the manufacturer of the gearbox of the reference design, Reintjes Powertrain Solutions. Thanks to their advice, it was concluded that given the engine selection of the concept design, the best option was to choose a single input/ single output gearbox with a power take-in (PTI) system for the electric motor. Given the difference in power of the engines that were selected, this seemed the most optimal and compact solution. Therefore, the electric motor would power the shaft by a PTI system to reach cruising speed, while the methanol engine would be only used to reach speeds above the $12.0\,\mathrm{kn}$.

From the information that was provided by Reintjes Powertrain Solutions, it is known that the new gearbox would be heavier, $12.0\,\mathrm{t}$ instead of $7.4\,\mathrm{t}$, slightly deeper and higher than the gearbox in the reference design. The gearbox still would fit in the aft engine room as was shown in Figure 11.1.

11.4.3. Switchboard rooms and tween deck

In both engine rooms, there is a tween deck that holds some of the equipment. Also, the switchboard rooms are placed at this level. In Figure C.7 of the confidential appendix a top view of the tween deck is shown.

As can be seen, the $6.6\,\mathrm{kV}$ switchboards and the transformers selected in the system design in chapter 10 have been placed inside each switchboard room. The aft switchboard room in the reference design had already enough space to accommodate these elements, but the fore switchboard room did not. For this reason the tween deck of the fore engine room had to be redesigned, making the electrical workshop $1.5\,\mathrm{m}^2$ smaller, which is considered feasible. This allowed the fore switchboard room to be larger to accommodate the new electrical components. On top of that, as was mentioned earlier, the tween deck of the fore engine room was shortened by one frame; while it used to start at frame 66 in the reference design, it starts now at frame 67 to make room for the methanol engine. The fresh water pumps and a heat exchanger placed on the tween deck would no longer fit, so it is chosen to extend the tween deck to port side (the side where the electric motor is placed) to make room for these components.

11.4.4. Maintenance routes

The SOFC modules have been designed as such that they have to be replaced once in the five years, when the vessel docks. Fuel Cell Energy, the manufacturer that made the prospect on which the fuel cells of this master's thesis are based, shows how the replacement of a the SOFC stacks could be done as can be seen in Figure 11.2.

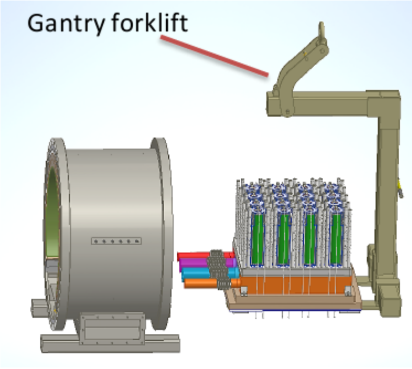

Figure 11.2: Replacement of the stacks of a SOFC module (Ghezel-Ayagh, 2021).

As explained in chapter 10, each 280 kW module, consists of forty 7 kW stacks. Each module weights 15 kg, so the replacement could be done one by one. However, this is not the most efficient way to do it, so something inspired in Figure 11.2 is designed.

The current power plant has two hatches in the aft engine room of 800 x 800 mm each that are meant to introduce big equipment in the engine room.

Each module consists of 10 stacks in the length and 4 stacks in the width. Therefore, by splitting the module in two, a 5 stack by 4 stacks unit would be obtained, where 20 stacks are placed in the same way as shown in Figure 11.2. This unit would measure 750 x 600 mm. In order to have some margin for the replacement of the SOFCs, it is proposed to enlarge the aft starboard hatch up to 1,000 x 800 mm to make sure they fit easily. The other hatch is not very convenient to use for the replacement of SOFCs, since the big methanol engine is placed between the tween deck and the modules.

A drawing of the maintenance route was done to check that the stacks would fit in the engine room to be accommodated inside the cylinders that hold the SOFC stacks. The maintenance routes of the SOFC stacks can be found in the drawing in the confidential appendix in section C.3.

11.5. Auxiliary systems

In this section the auxiliary systems of the power plant that experience changes are discussed. The only auxiliary systems that can be removed from the power plant of the reference design in the concept design are the two oil purifiers since these are not needed when using methanol as a fuel (Elleuch et al., 2016). Instead, in this section two additions to the auxiliary systems are discussed.

11.5.1. Fuel piping

According to the rules of Bureau Veritas, 2022c, all fuel piping when using methanol as a fuel must be double walled. Therefore, although this would not suppose a big impact in the arrangement in terms of volume within the vessel, it is decided to take this effect into account in the weight calculation of the OPV.

Table 11.5: Weight of the fuel piping.

	Weight (t)	
	Reference Design	Concept design
Fuel supply piping	0.169	0.337
Fuel transfer piping	4.28	8.55

11.5.2. Nitrogen generators

Bureau Veritas, 2022c stipulates that in the annular space of the double walled pipes, either mechanical ventilation must take place, or an inert gas must be used. Also, the oxygen level in the fuel tanks must not exceed 8% and the inert gas generation plant must be able to generate nitrogen with oxygen content at no time grater than 5%.

For the concept design, it was decided to make use of nitrogen as an inert gas. It is known that some manufacturers, like Wartsila, also suggest this kind of inert gas; in their case for diesel-methanol engines. The nitrogen content in air is around 78%, which means that it is relatively simple to generate nitrogen at high concentrations.

In order to calculate the amount of nitrogen that needs to be generated at a high percentage, the fastest mode for emptying the tanks was considered. This is the mode in which the vessel sprints until emptying its tanks. Assuming a volume of $300\,\mathrm{m}^3$ of methanol, sprinting for $205\,\mathrm{h}$ (4,500 nm at 22 kn) results in a fuel flow of $1.5\,\mathrm{m}^3/\mathrm{h}$. The inert gas plant must be able to generate this amount of volume of nitrogen at a high percentage.

After contacting some manufacturers, it was decided to choose a nitrogen generator of the German company Inmatec. This nitrogen generator is able to generate $5.8\,\mathrm{m}^3/\mathrm{h}$ of nitrogen at a purity of 99%. Since the nitrogen generator is relatively small, and due to the importance to ensure the safety of the vessel due to the use of methanol as a fuel, it was decided to incorporate another nitrogen generator, located in the other engine room of the vessel. The specifications of the nitrogen generators on board the concept design are shown in Table 11.6.

Table 11.6: Specifications of the nitrogen generator.

Dimensions LxWxH (mm)	750x810x1800
Power consumption (W)	150
Nitrogen flow at 99% purity (m^3/h)	5.8
Weight nitrogen generator (t)	0.15
Number of nitrogen generators	2

Since each fuel tank must be able to be inerted, there has to be a new piping system that is able to blow nitrogen to keep the oxygen level below 8%. In order to make an estimation of the weight that such system would cost, it was decided to double the weight of the sounding pipes, since these already go to each tank in order to manually measure the content of each tank. The weight of this system is shown in Table 11.7.

Table 11.7: Weight of the nitrogen supply system.

Weight of nitrogen supply piping (t)	1.39

11.6. Balances

In order to know the impact of a SOFC-based power plant on the design of the OPV, four types of balances must be calculated. These are: the heat balance, consisting of the heating ventilation and air conditioning (HVAC) systems, and the cooling water in the engine room; the electrical load balance, for the different modes in which the vessel has to sail; the volume balance of the components of the engine room; and the weight balance.

11.6.1. Heat balance

The heat balance consists of the HVAC and the cooling water needed for the different components in the engine room.

HVAC

Since the only modifications took place in the engine room and all other spaces have been maintained equal, it can be said that in the concept design only the ventilation of the engine room needs to be checked, while the HVAC systems of all other spaces in the vessel would remain equal.

The engine room is ventilated through funnels that are in charge of sucking the air required for the combustion in the engines and the evacuation of the heat emission of the different components in the engine room. The OPV has two funnels in each engine room. The funnel on port side sucks the air via two fans, and the funnel on starboard side lets the remaining air out, while the combustion engines let their exhaust out through exhaust pipes. Since the configuration of the two engine rooms of the reference design is identical, the calculations for the ventilation of the engine room are the same for both engine rooms, which is also the case of the concept design. The ventilation of the engine room in the reference design was calculated according to NEN-ISO 8861 rules. For this reason, for the concept design the same method will be used.

First of all, it is important to mention that since the fuel used in the concept design is different, the chemistry of the combustion (both in the methanol engine as in the fuel cell) changes. In Equation 11.1 it can be seen how the equivalent air-to-fuel ratio (λ) is calculated. For an ideal combustion, λ would have a value of 1, but in reality more air than fuel is needed to ensure a complete combustion of the fuel. For example, the diesel engines in the reference design have a $\lambda = 1.6$.

$$\lambda = \frac{AFR_{actual}}{AFR_{stoichiometric}} \tag{11.1}$$

On top of that, the stoichiometric air-to-fuel ratio (AFR) depends on the chemistry of the fuel that is being combusted. For example, diesel has an $AFR_{diesel} = 14.5 : 1$, meaning that 14.5 times more air as fuel are required to combust ideally the diesel. In the case of methanol (CH_3OH), due to the 50% oxygen content in its molecule (of molar mass), the air-to-fuel ratio is lower, namely $AFR_{methanol} = 6.47 : 1$. However, due to the lower energy density of methanol, more fuel is required to achieve the same power output in an engine.

Due to the lack of literature on the λ of a pure methanol engine, it is assumed that it would have the same equivalent air-to-fuel ratio as the diesel engines of the reference design, 1.6. The SOFCs, as mentioned in chapter 10, have a $\lambda = 2.5$, since they not only use this air for their chemical reaction, but also for cooling.

In Table 11.8 a calculation of the necessary air for the reference and concept design is shown.

The fuel consumption of the methanol engine is obtained from the manufacturer (and is corrected to the energy density of methanol), and the fuel consumption of the SOFCs is calculated for a situation in which they operate at full power until the fuel runs out. As can be seen, despite the lower energy density of methanol, the lower AFR results in a lower air requirement of a methanol engine. Also, the air for internal cooling and fuel of the SOFCs is calculated, and the amount of air to generate nitrogen as inert gas is included.

Table 11.8: Air flow required per engine room.

Component	**Air flow (m^3/h)**	
	Reference Design	**Concept Design**
Diesel engines	26,124	-
Diesel generators	2,964	-
Evacuation of heat emission	50,615	48,820
Methanol engine	-	20,300
SOFC container	-	4,818
Nitrogen generator	-	23.0
TOTAL	**79,703**	**74,099**

One might see a difference in the evacuation of heat emission of the reference and concept design. In Table 11.9 the different components can be seen.

Table 11.9: Heat emission per engine room of the concept design.

Methanol engine (kW)	105
VFD (kW)	27.8
Inverter batteries (kW)	10.0
SOFC container (kW)	22.4
Other components (kW)	67.6

First of all, the heat emission of the methanol engines is calculated, scaling that of the diesel engines to the brake power of the methanol engine. The heat emission of the VFD and the inverter is obtained from the manufacturers. In order to calculate the heat emission of the SOFC container there are many uncertainties. It is known that the SOFC modules are cylinders that keep the SOFC stacks isolated from the outside. The SOFC stacks are cooled by the same air that fuels them. This same air is then recirculated to the inlet, and the remaining air is combusted together with the rest fuel in the afterburner, to then go through the heat exchangers, after which it is let out through the exhaust pipes (see Figure 10.3). Therefore, it is assumed that this system is completely isolated from the rest of the engine room, and that only the BoP of the SOFC container emits heat to the environment. In the case of the inverter for the batteries, the losses are of 1.7%. The losses of the electrical components of the SOFC container are assumed to be 2%, and result in the value shown in Table 11.9.

In Table 11.8 it can be seen how, with the assumptions made, the air required for the concept design is 99% of that of the reference design. Therefore, it can be said that this system would not have to be adapted for the concept design, since the fans in the reference and concept design are able to suck up to 80.000 m^3/h of air per engine room.

In case the emitted air to the environment of the concept design were higher, it is known that the same fans can suck up to 60% more air by changing the pitch of the impeller blades. In that case, only the grillage at the inlet and outlet of the funnels would have to be increased. However, as explained, with the assumptions made it is considered that this would not be necessary.

Cooling water

In the power plant of the concept design, some elements are removed, and some new are added.

In the reference design each engine room consisted of two identical diesel engines and two identical diesel generators. These were the biggest elements that needed water cooling. Besides that, some smaller elements also made use of the water cooling such as: the oil cooler of the gearboxes, the fuel oil cooler, and the hydraulic power unit of the RHIBs and the stabilizers. These smaller elements are expected to remain constant in the concept design.

However, the diesel engines and the diesel generators are completely removed and are replaced by a methanol engine and an electric motor. The SOFCs do not require any water cooling, since the cooling of the fuel cells is done by the same air that is used as a fuel.

In Table 11.10 an overview of the different components of an engine room are shown for the reference and concept design.

Table 11.10: Cooling water balance per engine room.

Component	**Flow of fresh cooling water at 38 $^\circ$C** (m^3/h)	
	Reference Design	**Concept Design**
Diesel engine 1	90.0	-
Diesel engine 2	90.0	-
Diesel generator 1	12.0	-
Diesel generator 2	12.0	-
Other components	47.0	47.0
Methanol engine	-	171
Electric motor	-	5.40
TOTAL	**251**	**223**

As can be seen, the heat produced by the smaller components is kept constant. The heat cooling water flow for the methanol engine and the electric motor is obtained from the manufacturers. It is assumed that a methanol engine would require the same amount of cooling as a diesel engine of the same power output.

When one looks at the difference in required flow, it can be observed how the difference is not that big. The concept design requires $223\,\mathrm{m^3/h}$ of fresh water to cool all the components, while the reference design needed $251\,\mathrm{m^3/h}$. This is a difference of 11% in flow rate. Since this is not a substantial difference, and due to the uncertainties in the rest of the calculations because this design is still at concept phase, it is decided to keep the cooling systems in the concept design equal to those of the reference design.

11.6.2. Electrical load balance

Hitherto, all the different systems of the reference design that could experience adaptations in the concept design were analysed. In Table 11.11 it can be seen what the electrical load balance of the reference and the concept design are.

Table 11.11: Electrical load balance.

	Auxiliary power (kW)	
	Reference Design	**Concept Design**
Sailing (twin shafts)	587	578
Hotel load	291	282
Single shaft	535	526
Max speed	536	527
Combat mode	855	846
Emergency mode	146	137
Shore	206	197

As can be seen, the concept design has a slightly lower electrical load balance. This is mainly due to the removal of two oil purifiers that were needed when the vessel ran on diesel (4.8 kW each).

However, due to the use of methanol as a fuel, two nitrogen generators (of 0.15 kW each) were added to the electrical load balance.

11.6.3. Volume balance

Although in this chapter it has been proven that the SOFC-based power plant fitted in the engine room of the concept design without major modifications, from the literature it is known that fuel cells have a lower power density than internal combustion engines.

In Table 11.12 the volume of the main components of the engine rooms in the reference and concept design is shown. It can be seen how, despite the fact that both fit, the concept design has double the volume of the components of the reference design. The most voluminous component of the concept design is the SOFC container.

Table 11.12: Volume balance of the main components per engine room.

	Volume (m^3)	
	Reference Design	Concept Design
Diesel engines	32.4	-
Diesel generators	7.87	-
Fuel oil purifier	2.00	-
SOFC container	-	38.5
Electric motor	-	3.56
VFD	-	9.60
Methanol Engine	-	25.6
Batteries	-	3.20
Inverter	-	1.70
Fifi batteries	-	2.10
Nitrogen generator	-	1.46
TOTAL	**42.3**	**85.8**

This difference in volume does not come as a surprise. In chapter 6 it was already mentioned how authors like Minnehan and Pratt, 2017 discussed that in an engine room making use of fuel cells, 2.5 more volume could be effectively used due to the lower clearance that these require. Since one of the main advantages of fuel cells is that they do not require any maintenance, contrary to an ICE or DG, the space can be used more efficiently. The SOFCs are designed as such that they only have to be replaced once in the five years when the vessel has to dock, hence the maintenance routes to replace the SOFC stacks as shown in section C.3.

It is however important to mention that in the case of the concept design, the batteries and their firefighting equipment and the inverter would not always fit. In the case of the aft engine room these components had to be placed on the tween deck. In the fore engine room they were able to fit at the same level as the fuel cells because the fuel preparation equipment had made some room free because it was moved to a separate room. Also, the 6.6 kV switchboards and the additional transformer add some volume to the comparison, but these elements were placed in the separate switchboard rooms.

11.6.4. Weight balance

After having analysed all the different components and how they are affected by the design of a SOFC/methanol-engine-based power plant, the effect on the total weight of the ship can be discussed.

In Table 11.13 the final weights of the vessels are presented, for lightweight and departure condition. In the departure condition not only the fuel is included, but also the fresh water, the miscellaneous, the aviation fuel and, in the case of the concept design, the separate tank with diesel oil for the RHIBs.

Table 11.13: Weight balance.

	Reference Design				**Concept Design**			
	Weight (t)	**VCG (m)**	**LCG (m)**	**TCG (m)**	**Weight (t)**	**VCG (m)**	**LCG (m)**	**TCG (m)**
Lightweight	2154	6.55	39.4	0	2255	6.39	39.2	0
Deadweight	310	2.20	42.3	0	422	2.22	41.3	0
Departure condition	2464	6.01	39.8	0	2677	5.74	39.6	0

As can be seen, the lightweight of the concept design is 101 t heavier, due to the heavier power plant; hence the lower vertical center of gravity (VCG) and the longitudinal center of gravity (LCG), since the power plant is located behind the LCG of the reference design.

Due to the lower energy density of methanol compared to diesel, despite the higher efficiency of fuel cells, and the extra diesel that needs to be taken for the RHIBs, the amount of deadweight in the concept design is 112 t heavier.

11.7. Stability

With the weight values shown before, a stability analysis can be made.

In Table 11.13 it was shown how for both conditions the VCG was lower than in the reference design. This is mainly because the only increase in weight took place in the power plant, located in the lowest deck of the vessel. Therefore, in terms of transversal stability it can be said that the concept design has better stability than the reference design and that it therefore fulfils to this criterion.

Regarding the longitudinal stability, one must look at the location of the LCG. It can be seen how in lightweight, the LCG of the concept design is moved 0.2 m afterward. This is equal to 0.5% of the LCG of the reference design, and its effect is therefore considered solvable. Moreover, when one looks at the departure condition, the LCG of both configurations is almost equal, which means that the difference in trim would be zero.

Therefore, it can be said that the intact stability of the concept design is even better than the intact stability of the reference design, due to the lower VCG.

Regarding the damage stability of the vessel, it can be said that the changes in the concept design are expected to be negligible, since no compartments were made bigger.

11.8. Resistance

Since the concept design is heavier than the reference design, it has to be checked whether the vessel fulfils all design requirements at the new draught. In order to do so, a new resistance curve is needed. From the reference design, the resistance curve was shown in Figure 9.3. At Nevesbu, a resistance curve for the reference design with 124 t heavier was available. Therefore, since the concept design is 101 t heavier in lightweight, it was decided to interpolate linearly between these two resistance curves to obtain an approximation to the resistance curve of the concept design, which is how the resistance of the reference design was calculated in Figure 9.3. The power-speed curve of the concept design can be found in Figure 11.3.

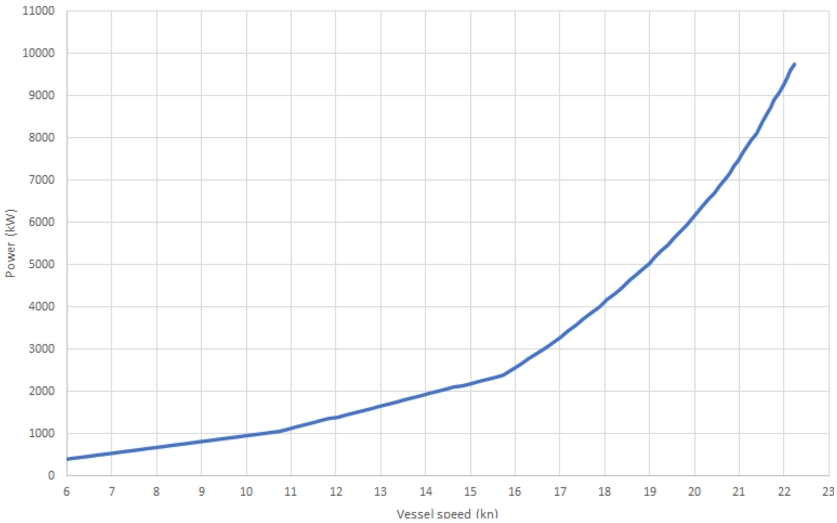

Figure 11.3: Power-speed of the concept design.

Using this power-speed curve, the values to reach cruising speed and top speed can be compared as shown in Table 11.14.

Table 11.14: Power-speed comparison.

	Reference Design	Concept Design
Draught (m)	3.75	3.85
Installed power (kW)	10,100	11,020
Power 12 kn (kW)	1,075	1,400
Power 22 kn (kW)	8,800	9,400

As can be seen, due to the heavier vessel, the concept design requires more power to reach the same speeds as the reference design. Looking at the installed power, it can be seen how the concept design can reach its maximum speed. Also, knowing that the required brake power to reach cruising speed is 1,400 kW, it can be said that this requirement is also fulfilled since the installed power in the electric motors is in total 1,420 kW.

11.9. Safety analysis

In chapter 3 it was stated how crucial safety can be for a naval vessel. During the creation of the concept design this aspect was always taken into account.

An OPV is in the lowest violence spectrum of naval vessels and therefore it was concluded that it would be suitable to make use of a slightly unsafer fuel such as methanol. Despite this consideration, all necessary measures have been taken to ensure that this change in the fuel does not put the vessel nor the crew at risk. The reference design was designed according to commercial standards. Therefore, these commercial standards have been applied as well in the creation of the concept design.

In order to prevent the leakage of methanol in the vessel, all fuel piping was made double walled and two nitrogen generators were installed in the engine rooms to produce inert gas for the annular space. On top of that, a nitrogen supply system was designed to provide each tank of inert gas to keep the oxygen level reduced, and to be able to fully inert a tank if necessary. The tank arrangement was also designed to minimize the risk of fire. Multiple fuel tanks were swapped with ballast water tanks to ensure that the methanol tanks did not adjoin any machinery or accommodation space. In those places where this was not an option, a cofferdam of 600 mm was built in between. Also, the fuel preparation station was moved to a separated room to keep the risk of fire under control.

Another element that could increase the risk of a fire is the use of lithium-ion batteries. As explained in chapter 10, these are placed in a steel box, that is as well connected to a special firefighting foam system that is able to mitigate a fire in the battery rack.

Finally, the fuel cell modules which also work on methanol are designed as such that the stacks are placed within a cylinder tank that is sealed, creating an isolated space for the fuel cells.

11.10. Conclusion

In this chapter the concept design of an OPV using SOFCs and methanol engines was made. The values that are shown are the result of an iterative process, in which the design spiral was run through multiple times.

It was concluded that it is feasible to design an OPV with a SOFC-based power plant that makes use of methanol engines as a peak power source.

The use of methanol entails that some safety measures must be taken in order to ensure a safe use of the fuel. The most relevant rules are regarding the fuel piping, which has to be double walled and must have the annular space inerted, the location of the fuel tanks within the vessel, and the creation of a separate fuel preparation space. The fuel tanks containing methanol cannot adjoin any machinery or accommodation space. Therefore, the tanks need to be rearranged to ensure that they adjoin only water or void spaces. When that is not possible, a cofferdam must be placed to create an extra barrier. Using methanol as a fuel for the SOFCs and the engines means that a separate small diesel tank must be included, to carry enough fuel for the RHIBs.

Regarding the arrangement of the engine room, it can be said that it was possible to include the SOFCs with their balance of plant in the engine rooms, choosing an identical configuration in terms of components among the two engine rooms of the OPV. Also, there is enough space in the engine room to replace the SOFC stacks in sets of 4x5 when the vessel has to dock every five years.

The effect on the heat balance, electrical balance, volume balance, and weight balance of the OPV was also studied. It was concluded that the heat balance (consisting of the ventilation of the engine room and the cooling water) and the electrical balance, experienced minor changes. The volume balance of the components showed how the volume of the SOFC-based power plant doubled the volume of the components of the reference design, proving that with fuel cells a more optimal use of the space can be made due to their lower required clearance. Regarding the weight balance, approximately a hundred tons were added to the lightweight, and another hundred tons to the deadweight with respect to the reference design. The addition of the weight to the lightweight comes from the new systems included in the engine room; so not only the SOFCs, but also the electric motors and their variable frequency driver, the methanol engines, and other support systems such as batteries, inverters, or transformers. The increase in deadweight has mainly to do with the lower energy density of methanol with respect to diesel.

Despite the heavier concept design, it can be said that the vertical center of gravity is lower than the one of the reference design, meaning that the stability of the concept design is not affected negatively. The increase in weight resulted in a larger draught and thus in an increase of the resistance, that the concept design is able to overcome. Therefore, it can be said that the concept design is feasible from a technical point of view, fulfilling all the design requirements.

12

Comparison study

Now that the concept design is finished, it is time to compare it with the reference design. In this chapter, the redundancy, operational capabilities and emissions of the two vessels are compared. To start, in section 12.1 the redundancy level of the vessels is analysed, for three different scenarios. After that, in section 12.2 the operational capabilities are compared, followed by an analysis of the emissions for different operational profiles in section 12.3. Next, in section 12.4 a qualitative analysis of the signatures is done. Finally, in section 12.5 the added value of the use of fuel cells in an OPV is discussed, by comparing the concept design to an hypothetical refit of the reference design to work on methanol engines only.

12.1. Redundancy

The redundancy level of the two vessels is compared by testing how they would perform in three different scenarios, which are:

- Failure of the aft engine room
- Failure of the fore engine room
- Failure of one propeller

In subsection 3.2.2 it was already discussed how the vulnerability of a a vessel can be improved by thinking of redundancy and robustness. Redundancy refers to the separation and duplication of systems, while robustness refers to how these are connected with each other. In the concept design, like in the reference design, the survivability level of the design was taken into account from the very beginning.

Both designs have in common that they have identical engine rooms in terms of main systems. That is for the concept design: one electric motor, one methanol engine, and four SOFC modules per engine room. On top of that, the concept design also takes this redundancy into account in the design of the electrical components. Fuel cells are in itself more redundant than a diesel generator. Each 280 kW SOFC module is formed by forty 7 kW stacks, which corresponds in total to 14,000 fuel cells per module. On top of that, apart from having identical switchboard rooms located in different engine rooms -like the reference design- the transformers are chosen as such that in case of failure of one transformer, the remaining one could transform the required power generated by the fuel cells.

In Table 12.1 the capabilities of the vessel for three kinds of failure are shown.

Table 12.1: Redundancy analysis for the reference and concept design.

	Reference Design					**Concept Design**				
	Available power (kW)					**Available power (kW)**				
Scenario	**DE**	**DG**	**Remaining aux. power (kW)**	**Available brake power (kW)**	**Max Speed (kn)**	**MethEng**	**SOFCs**	**Remaining aux. power (kW)**	**Available brake power (kW)**	**Max Speed (kn)**
1) Aft ER fails	5,050	900	900	5,050	19.5	4,800	1,120	900	4,994	18.9
2) Fore ER fails	5,050	900	900	5,050	19.5	4,800	1,120	900	4,994	18.9
3) One propeller fails	5,050	1,200	1,200	5,050	19.5	4,800	2,240	1,433	5,510	19.4

As can be seen, the reference design is able to reach slightly higher maximum speeds than the concept design. This is basically due to the larger draught of the concept design. Despite this, the speeds are very similar, all of them being around the 19 kn. Mind that in Table 12.1 it has been chosen to always keep 900 kW in the concept design free for auxiliary power. In reality this amount of power is only required for full combat mode, meaning that for other modes more propulsive power would be available for the electric motor and thus higher speeds could be reached.

It is therefore considered that the redundancy level of the concept design suffices the requirements of an OPV. Despite being able to reach slightly lower speeds than the concept design, the use of fuel cells in itself is a more redundant technology.

12.2. Operational capabilities

The concept design fulfils all the requirements of the reference design as presented in section 10.1. It is able to reach the top speed of 22 kn, it carries enough fuel to reach the range at cruising speed and it is able to react rapidly to load changes thanks to the batteries that are used combined with the SOFCs.

Therefore, it can be said that the concept design is able to perform the same kind of missions, like the ones showed in the operational profiles of section 9.7.

However, due to the higher energy density of diesel compared to methanol, it is very important to mention that, if desired, the reference design can carry up to 250 t of diesel, instead of the 140 t of diesel that it requires to fulfill the range condition. Therefore, it can be said that the reference design has enough tank capacity to increase the required range by 79%. In the case of the concept design this option is not available because of the lower energy density of methanol and the use of cofferdams to isolate the methanol tanks from crucial compartments. Only tank 27 in Table 11.2 has some extra volume available, which only would add 6.3% to the needed tank capacity of the concept design.

Since the amount of fuel is calculated on the basis of the range condition -that is: to reach a certain range at cruising speed- the efficiency of the source of power plays an important role. At cruising speed, the efficiency of the SOFCs is 56%, which is higher than the efficiency of the diesel engines in the reference design. This is translated to some differences in operational capabilities. Although both ships can cruise for the same amount of time, when the vessel stars sprinting, the time they can hold this mode is different.

The reference design uses the same engines to cruise than to sprint, but the concept design goes from electric motors powered by SOFC to cruise, to methanol engines to sprint. These methanol engines were assumed to have the same efficiency as a diesel engine of the same characteristics. Therefore, the reference design can sprint for 65 hours until it runs out of fuel, while the concept design can do this for slightly less time, 55 hours.

12.3. Emissions

For the three operational profiles presented in section 9.7, a comparison of the emissions is done in this section. Also, the emissions at range condition, when the vessel is constantly sailing at cruising speed, are presented.

As explained previously in section 5.5, each fuel produces a certain amount of CO_2. Therefore, the amount of CO_2 emissions is dependent on the amount of fuel that is used.

Regarding the SOx emissions, these come from the amount of sulphur present in the fuel. From the reference design it is known that the amount of sulphur present in diesel is limited to 1%. The amount of SOx emissions is calculated knowing that per kilogram of fuel with 1% sulphur, 20 g of SOx are produced (Woud et al., 2016). The concept design does not have any SOx emission, since there is no sulphur present in methanol. In the case of the particulate matter (PM), it is known that diesel has some, while methanol does not.

Regarding the level of NOx emissions the uncertainty is higher. It is known that the reference design is built according to Tier II regulations, so the maximum allowable values for this category are used to calculate the amount of NOx emissions. In the case of the concept design, in section 5.5 it was already explained how the amount of NOx emissions of SOFCs are negligible. However, the methanol engines could present some NOx emissions due to the higher temperatures reached in the cylinders. From the literature, no values for the NOx emissions of a spark-ignited methanol engine are found. The only literature available measures the emissions of a dual-fuelled diesel-methanol engine. From the literature found it was observed that dual-fuel engines presented lower NOx values than a diesel engine for low and medium loads (Xu et al., 2022, Yao et al., 2008). This is due to the higher latent heat of vaporization of methanol with respect to diesel, which absorbs a larger amount of heat, reducing the cylinder temperature. However, this same literature does not observe the same reduction at high loads. Therefore, because the methanol engines are running at a high load (86%) at 22 kn, and because of the lack of literature to quantify the possible reduction in NOx emissions, it is considered that the methanol engines emit as much NOx as a diesel engine of the same characteristics design to comply with Tier II regulations.

In figures 12.2, 12.4, 12.6, and 12.8, the normalised emissions for the different types of missions are shown. The exact details of the calculations can be found in Appendix B.

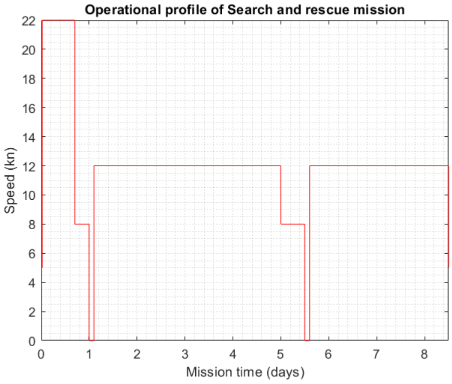

Figure 12.1: Operational profile for a search and rescue mission.

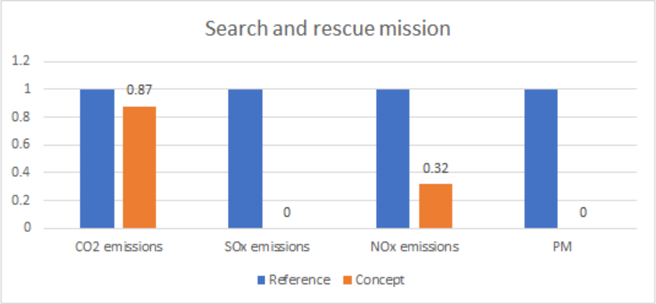

Figure 12.2: Emissions for a search and rescue mission.

Figure 12.3: Operational profile for a patrolling and intercepting mission.

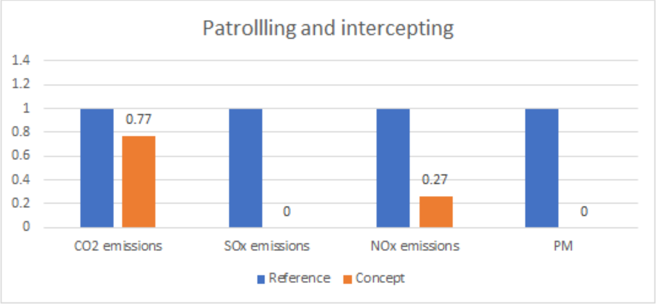

Figure 12.4: Emissions for a patrolling and intercepting mission.

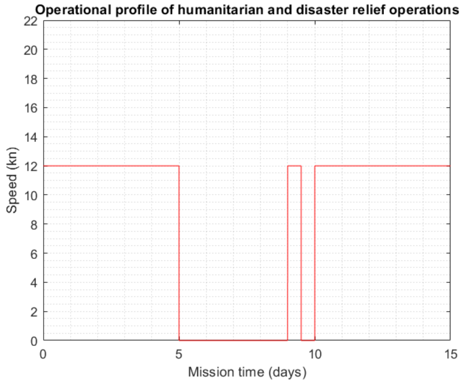

Figure 12.5: Operational profile for a humanitarian mission.

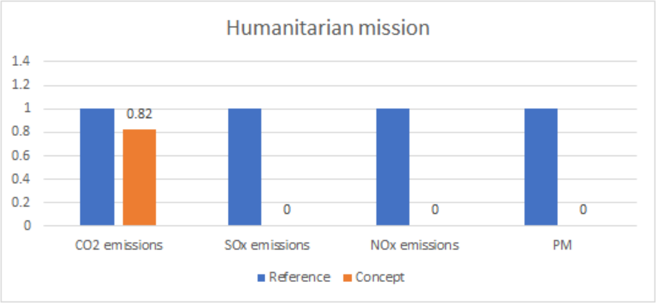

Figure 12.6: Emissions for a humanitarian mission.

Figure 12.7: Operational profile for range condition.

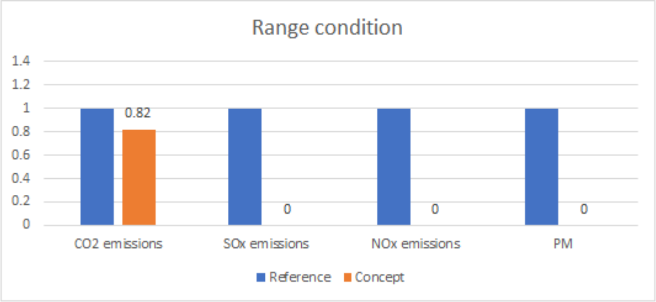

Figure 12.8: Emissions for range condition.

As can be seen, in general it can be said that the concept design presents a significant reduction in emissions compared to the reference design. Regarding the CO_2 emissions, these are lowered between 13-23%, depending on the type of mission. Despite the larger amount of brake power required for the concept design, the higher energy efficiency of the SOFCs and the lower CO_2 emissions of methanol result in a reduction of CO_2 emissions.

As mentioned previously, methanol does not contain sulphur in it, and does not emit any particulate matter. Therefore, the reduction in emissions of the concept design for SOx and PM is 100%.

Finally, the NOx emissions. Mind that these are the values with the highest uncertainty. However, a very conservative approach was taken to calculate the amount of NOx emissions of the concept design. With the assumptions that are taken, it can be seen that only the missions where the methanol engines have to be turned on produce some NOx. For these missions, the reduction in NOx emissions is between 68-73%, and for the missions where the methanol engine is not needed the reduction in NOx emissions is 100%.

12.4. Signatures

Comparing the signatures of both designs is quite complex, due to the difficulty to quantify them. However, a qualitative analysis can be done.

It can be said that the concept design has lower acoustic signatures than the reference design at cruising speed or lower. This is because at these speeds, the concept design does not make use of combustion engines, because only the SOFCs and electric motors are working. Moreover, it was proven that the air flow through the engine room stays more or less constant, which keeps the sound level of this source equal. At higher speeds, when the methanol engines are turned on, it is not expected that the reduction in acoustic signatures of the concept design would be so significant.

Regarding the infrared signatures, something similar can be said. The negligible NOx formation of SOFCs compared to a diesel engine seems to point out in the direction that the exhaust temperature of SOFCs is lower than that of a combustion engine. Moreover, the use of methanol in the engines, with its higher latent heat of vaporization, could mean that the exhaust temperature of a methanol engine is lower than the exhaust temperature of a diesel engine, reducing thus the infrared signatures.

Other signatures, like radar cross-section, are considered to stay equal, since nothing was changed to the hull or superstructure of the reference design. The magnetic signatures of the concept design could, however, increase due to the use of electric motors and other electrical components such as batteries.

12.5. Added value of fuel cells

At this point of the research, one might ask itself what the added value of fuel cells is. The implementation of SOFCs brought a high complexity into the power plant of the concept design, and it made the design around 100 t heavier.

In order to test what the added value of the use of fuel cells is, it was chosen to perform a quick study where the reference design is refitted to run on methanol engines.

Because the assumptions that were made earlier assumed that a diesel engine could, in theory, and when adapted to have a spark plug, work on methanol, the engines can be kept the same.

The only adaptations that need to be made to the reference design are all those concerning the use of methanol. Those are: cofferdams, double-walled fuel piping, and nitrogen generators. This results in a total of 12.5 t added to the lightweight of the ship.

In the same way that the resistance was scaled for the concept design, a new resistance calculation is done for this refit. The refit vessel lays 1 cm deeper in the water and requires 305 t of methanol to reach the range at cruising speed. This difference in methanol weight (compared to the 250 t of the concept design) is due to the difference in efficiency between SOFCs and methanol engines. It is doubted that this amount of methanol, given the special arrangement that this fuel requires, would fit in the current hull.

Knowing the amount of power required to reach the different speeds, the emissions for the multiple missions can be calculated to compare the refit to the reference design and the concept design.

In figures 12.9, 12.10, 12.11, and 12.12, the emissions of the refit compared to the reference design can be seen.

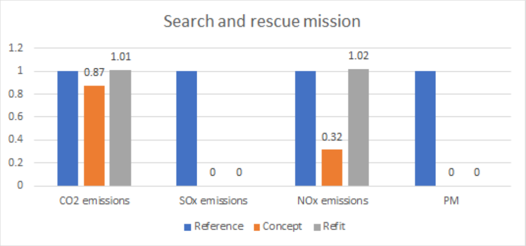

Figure 12.9: Emissions of the refit for search and rescue mission.

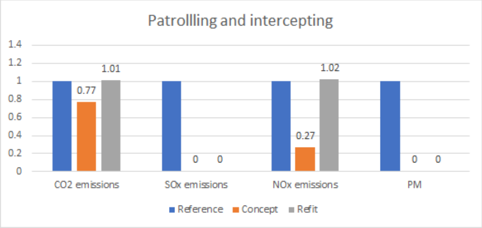

Figure 12.10: Emissions of the refit for patrolling and intercepting mission.

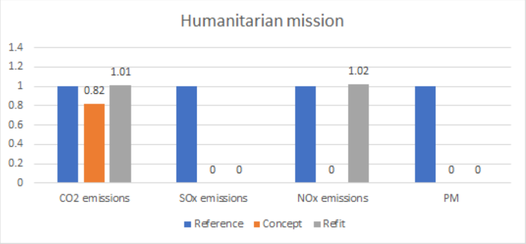

Figure 12.11: Emissions of the refit for humanitarian mission.

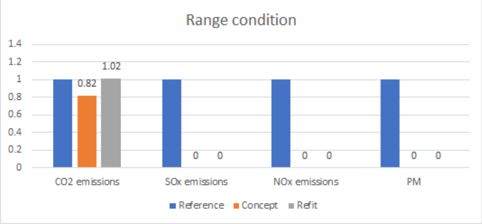

Figure 12.12: Emissions of the refit for range condition.

As can be observed, the refit does not perform better in terms of CO_2 emissions. Per unit of energy, methanol produces 7% less CO_2 emissions than diesel, as was shown in Figure 5.3. This is compensated by the slightly higher power that is needed for the refit due to the fact that it lays 1 cm deeper and the fact that at this new depth, the engines run at a slightly lower efficiencies. Therefore, it can be concluded that the reduction in CO_2 emissions of the concept design is due to the use of a more efficient technology such as SOFCs, and not only because of the use of methanol.

For the rest of emissions, such as SOx and PM, the refit performs as good as the concept design, since these are properties derived from the type of fuel. Regarding the amount of NOx, as explained previously, it is expected that the refit would perform better than the reference design due to the higher latent heat of vaporization of methanol, although quantifying them is case dependent and lacking in the literature. What can be concluded from the NOx values of the refit, is that these would be significantly higher than in the case of the concept design.

12.6. Conclusion

In this chapter, the comparison study between the reference and the concept design was made.

It can be concluded that the operational capabilities of the concept design are mainly affected by the use of methanol as a fuel. This is translated in a reduction of the extra tank capacity, additional to the one required to reach the required range, due to the lower energy density of methanol and the use of cofferdams. Also, the concept design presented a slightly lower sprinting time, due to the higher efficiency of SOFCs, which are only used to reach cruising speed. In terms of redundancy, both vessels perform similarly, although fuel cells themselves are a more redundant technology. For three given scenarios, the reference design is able to reach speeds around the 19.5 kn, while the concept design can reach speeds around 19 kn.

The goal of this research was to study the feasibility of the use of SOFCs fuelled by methanol on board of an OPV. Although the design seemed to be feasible in terms of weight and volume, the emissions had to be measured, because only when an improvement in the level of emissions is achieved, the new design would make sense. Therefore, the emissions for the three types of missions and for range condition were calculated. It can be concluded that the concept design performed better in terms of emissions. The achieved reduction in CO_2 emissions lays between 13-23%, depending on the type of mission. On top of that, by using methanol the reduction in emission of SOx and PM is 100%. Also, a significant reduction in NOx emissions is achieved, since the amount of NOx generated by the SOFCs is negligible and thus only the methanol engines produce some NOx.

Finally, in order to prove the added value of the SOFCs added to the power plant, the emissions for a hypothetical refit of the reference design to work on methanol engines were calculated. The results obtained for the refit with only methanol engines did not show a reduction in CO_2 emissions. Therefore, it can be concluded that the reduction in CO_2 emissions comes from the more efficient technology (fuel cells), rather than only from the use of a cleaner fuel, proving the added value of fuel cells.

13

Sensitivity analysis

In this chapter a sensitivity analysis is performed to quantify the effects of the uncertainty in the parameters of the concept design. By doing so, one can be aware of how different the design would be in case some of the parameters differ from the ones assumed for the concept design.

13.1. SOFC containers

The concept design performed in this report is meant for its medium-term implementation. At this point the chosen technology is still under development, which means that the information available is limited and many assumptions have to be made. These assumptions imply a level of uncertainty, which can affect the conclusions that were obtained.

The biggest uncertainty comes from the weight assumed for the SOFC containers, which is responsible for the majority of the weight increase in the lightweight of the concept design (approximately 69% of the lightweight increase). Although the approach that was taken to estimate the weight of a SOFC container is a conservative one, the chance of the SOFCs being lighter or heavier than the value of 32.9 t assumed in Table 10.2 is present, since the SOFC containers do not exist yet.

On top of that, it is uncertain whether the power of a SOFC container already includes the electrical load of its balance of plant or not. According to the prospects of Fuel Cell Energy, a SOFC container is able to deliver 1,120 kW, but if one assumes that it is formed by four 280 kW SOFC modules, there is no power left for the power required by the auxiliary components. This inconsistency in the values presented by the manufacturer stresses the importance of a sensitivity analysis.

The sensitivity analysis performed in this chapter reflects on the capabilities of the vessel for the combination of variations:

- ± 10% of weight of a SOFC container in steps of 5%.
- Electrical load of the BoP of the SOFC modules of the concept design of 0 kW (assuming that the BoP is already included in the 1,120 kW), 25 kW and 50 kW.

  The reason to choose these values for the electrical load of the BoP has to do with the largest consumers, mainly the blowers shown in Figure 10.3. Since their electrical load is unknown, a fuel pump of the reference design is taken as reference, which consumes 6.4 kW each. In each SOFC container there are three blowers, thus six in total, which would result in an electrical load of approximately 38.6 kW, hence the values of 25 and 50 kW taken in this sensitivity analysis as a lower and upper limit.

In order to test how these variations affect the vessel, it is chosen to keep the power plant of the concept design unaltered to study the effect on the maximum allowable cruising speed on SOFCs, the range, and the emissions of the vessel.

13.1.1. Impact on cruising speed

The results of the variations of the parameters can be seen in Figure 13.1, where the three diagonal lines show the impact on the cruising speed for the three loads of the BoP, for each weight variation of a SOFC container.

As can be seen in Table B.2 of Appendix B, at 12 kn the SOFC modules of the concept design are running at a load of 90%. Assuming a rate of degradation of 0.1%/1,000 hours means that if the modules were constantly turned on for five years, the decay of performance that they would experience is 4.4%. This leaves 5.6% of the SOFC power to absorb power fluctuations, since the values in auxiliary power used to calculate the electrical load are the mean value for each mode. It is considered that for all situations the margin of 5.6% of SOFC power is required. For that reason, in Figure 13.1 the increase in the power of the BoP leads to a reduction in the power that can be used for propulsion to reach cruising speed, leading to a slightly lower cruising speed.

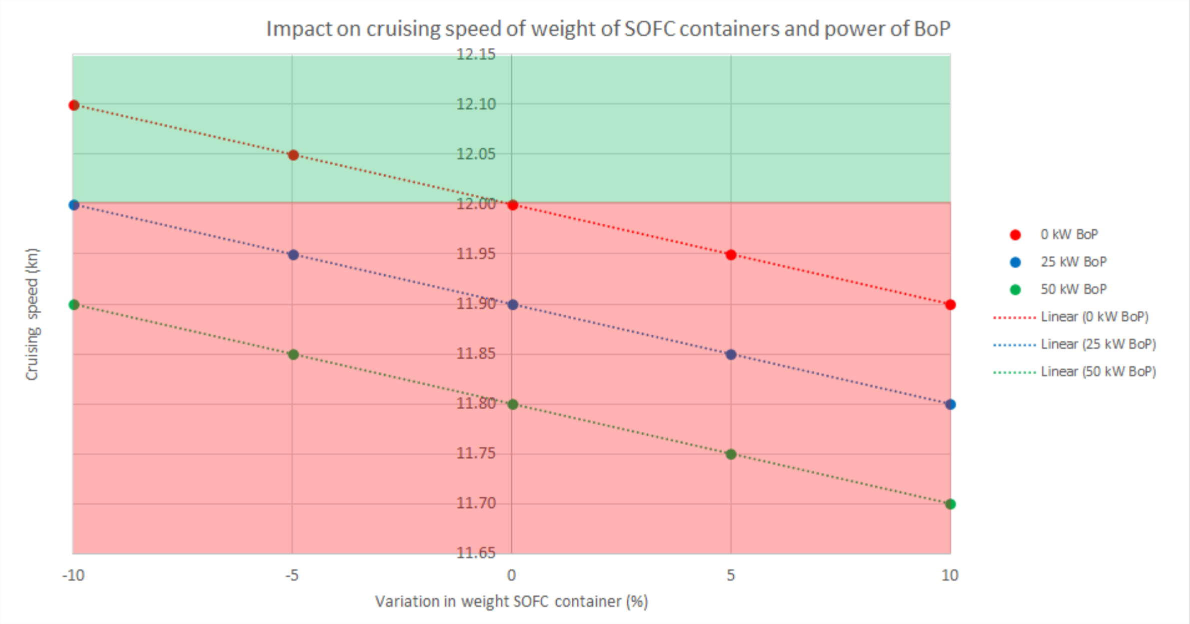

Figure 13.1: Impact on cruising speed on SOFCs depending on the weight of a SOFC container and the amount of power required for its BoP.

In the top left corner of Figure 13.1, the best case scenario can be observed. At this point, the weight of the SOFC container would be -10% than the one used for the concept design, and the BoP would be included in the 1,120 kW that a SOFC container is able to deliver. In the lower right corner of Figure 13.1 the worst case scenario is found. The SOFC container is in this case +10% heavier, and the total auxiliary power for the BoP of both SOFC containers is of 50 kW. This results in less power available to reach cruising speed only on SOFCs, which would reduce the cruising speed of the OPV from 12 to 11.7 kn.

In Figure 13.2 the normalised cruising speed of the best and worst case scenario with respect to the concept design can be observed. It can be seen how the combination of the higher weight of the SOFC containers together with 50 kW for their BoP has a more negative effect on the cruising speed than the reduction in 10% of the weight of a SOFC container.

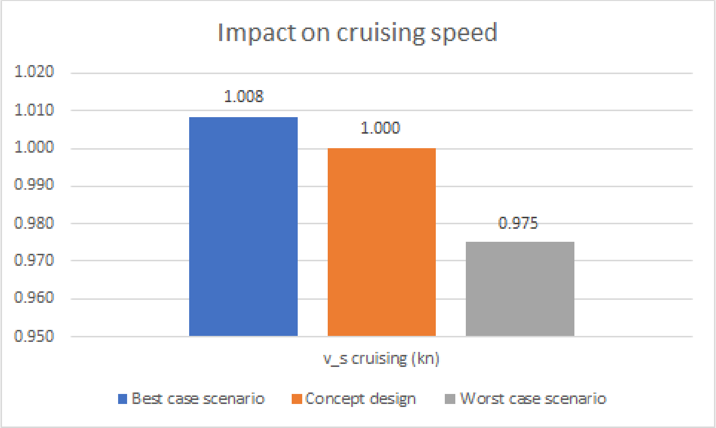

Figure 13.2: Normalised impact on the cruising speed of the best and worst case scenario from the values in Figure 13.1.

13.1.2. Impact on range

A variation in the cruising speed can imply a variation in the range; because if the vessel is cruising for the same time at a different speed, the distance travelled would be different. In order to try to meet the range requirement of the concept design (4,500 nm), some modifications were made. In the case of the worst case scenario where the maximum cruising speed on SOFCs was 11.7 kn, the time spent cruising was increased, which resulted in 6.25 t more of methanol required. In the case of the best case scenario, the cruising speed was kept at 12 kn, but due to the lower resistance and thus the lower fuel consumption, the amount of methanol was reduced by 4.80 t.

It is known that the concept design has 6.30% extra tank capacity, on top of the tank capacity needed to fulfil the range condition. In Table 13.1 tank capacity margin for each scenario is shown: that is, the tank volume available on top of the amount of fuel needed to reach the required range. As can be seen, all scenarios are able to meet the range requirement of 4,500 nm. However, the extra tank capacity and therefore the maximum theoretical range is affected.

Table 13.1: Impact on tank capacity and range of the worst and best case scenario of the values in Figure 13.1.

	Range (nm)	Max. theoretical range (nm)	Tank capacity margin (%)
Best case scenario	4,500	4,869	8.20
Concept design	4,500	4,784	6.30
Worst case scenario	4,500	4,671	3.80

13.1.3. Impact on emissions

For the considered variations in weight of a SOFC container and the electrical load of the BoP of such, the impact on the emissions of the vessel for the operational profiles presented in the comparison study in chapter 12 can be done. In order to obtain the new reduction of emissions, the operational profiles were corrected to the new cruising speed, like it was done when studying the impact on the range.

In Figure 13.3 the results can be seen. In the comparison study in chapter 12 it was already presented how for the chosen operational profiles the concept design would show a reduction in CO_2 emissions between 13-23%. As can be seen, this reduction would be between 11-22% for the worst case scenario, because the vessel would be sailing the same distance at 11.7 kn at the same load of SOFCs and thus would consume more fuel. For the best case scenario the reduction in CO_2 emissions would be slightly better than for the concept design, with values between 13-24%, due to the lower resistance to reach 12 kn.

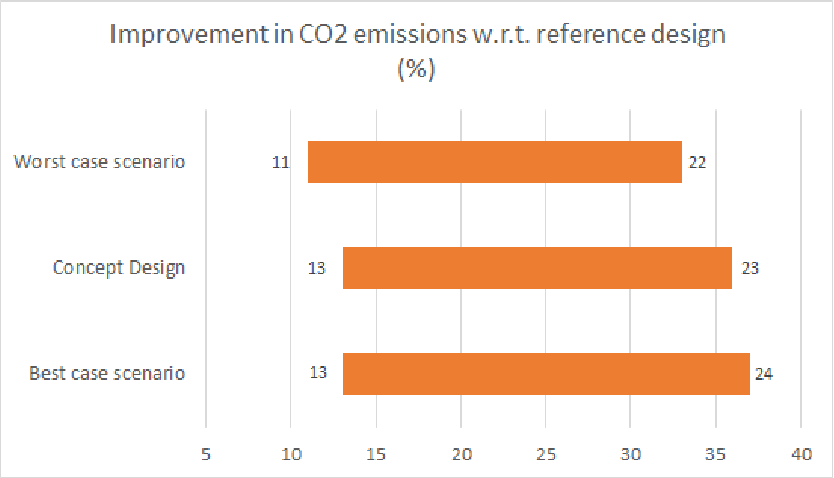

Figure 13.3: Improvement in CO_2 emissions with respect to the reference design for the concept design, and its best and worst case scenario.

13.2. Conclusion

In this chapter a sensitivity analysis was performed to quantify the impact of hypothetical variations of the most relevant parameters that were assumed in this research. Keeping the power plant of the concept design constant, the impact of variations of the weight of the SOFC containers and the electrical load of their balance of plant was studied. The effect of these variations was measured on the maximum allowable cruising speed of the vessel on SOFCs only, the range, and the emissions. On the basis of the variations in the parameters, a best and worst case scenario were defined and these were compared with the actual concept design.

It was concluded that the cruising speed would become 11.7 kn for the worst case scenario (+10% weight of SOFC containers and 50 kW of BoP), and could be 12.1 kn for the best case scenario (-10% of weight of SOFC containers) due to the lower resistance.

The change in cruising speed affected mainly the worst case scenario, because it would have to cruise for slightly longer time to reach the same range as the concept design. Despite this, both the best and the worst case scenario were able to fulfil the range of 4,500 nm due to the available tank capacity margin of the concept design.

Regarding the impact on emissions, some differences were observed. The concept design presented a reduction in CO_2 emissions with respect to the reference design of between 13-23%. This reduction was lowered to 11-22% for the worst case scenario, and was improved to 13-24% for the best case scenario.

14

Conclusion

In this report, a feasibility study on the use of fuel cells on board naval surface vessels was performed by testing it in a concept design phase. The study of naval surface vessels, fuel cells, and the different types of hydrogen carriers led to an optimal combination of these. This optimal combination was later tested in the concept design phase, where the fuel cells were integrated into the power plant of the vessel. To conclude whether this concept was feasible, the effect on the design, operational capabilities and emissions was studied comparing it to the reference design.

The main research question of this master's thesis and its answer are the following.

What combination of naval surface vessel, fuel cell, and hydrogen carrier is the most suitable for the medium-term implementation of a fuel-cell-based power plant, and what is the effect of the implementation of such a power plant on the design, operational capabilities, and emissions of the vessel?

An offshore patrol vessel (OPV) making use of a solid-oxide-fuel-cell-based power plant fuelled by methanol and using methanol engines as a peak power source is the most suitable combination in the medium term to be used on a naval surface vessel. This combination proved to be feasible in the concept design of the vessel, showing acceptable operational capabilities and a significant improvement in emissions with respect to the reference design.

To answer this main question, the research was divided into two parts. The first one, the literature review, aimed to find the optimal combination of naval surface vessel, fuel cell type, and hydrogen carrier.

Fuel cells can be in theory advantageous for naval surface vessels because they are more efficient than internal combustion engines. Moreover, they have other characteristics such as reduced infrared and acoustic signatures, reduced maintenance, and a modular and flexible design. For the different types of naval surface vessels, it was concluded that fuel cells can be especially interesting in mine warfare vessels and frigates to reduce their acoustic signatures, and on board of offshore patrol vessels to benefit from their constant base load. Regarding the types of fuel cells, it can be said that the most promising types are polymer exchange membrane fuel cells (PEMFC), and solid oxide fuel cells (SOFCs). While the first work at low temperatures and require very pure hydrogen to operate, the second work at high temperatures, have the highest efficiency, and are more versatile regarding the fuel to use because they are able to internally reform it. Due to their versatility and higher efficiency, it was concluded that SOFCs are a better choice for the medium term. The versatility of SOFCs allows for a wider choice of a hydrogen carrier. Taking aspects like flammability, toxicity, energy density and emissions into account, it was concluded that ethanol and methanol seem the best choice for a hydrogen carrier, but that their use should be limited to low-violence-spectrum vessels.

Therefore, after taking into account the availability of a reference design at Nevesbu in the first part of this research, it was concluded that an OPV making use of SOFCs fuelled by methanol seemed to be the most suitable combination of naval surface vessel, fuel cell type, and hydrogen carrier.

In the second part of the report, the concept design phase, the feasibility of the chosen optimal combination was tested. The following sub-questions can now be answered.

- *What are the characteristics of the OPV used as reference design?*

  The OPV used as reference design makes use of a combined diesel and diesel power plant (CODAD) consisting of two propellers, powered by two identical diesel engines each. It has four diesel generators and one emergency diesel generator for the supply of auxiliary power. Its cruising speed is of 12 kn and its maximum speed is 22 kn.
- *What is the impact on a systems level of the implementation of SOFC-based power plants in an OPV; and what is the optimal configuration of SOFCs and peak power source to be used on board of an OPV?*

  On a systems level, a SOFC-based power plant requires a power source to compensate the slow dynamic response of the fuel cells and a peak power source to reach higher speeds due to the low power density of SOFCs. To compensate the slow dynamic response of SOFCs, batteries were added to the power plant of the concept design. Due to the low power density of SOFCs, the use of a peak power source was deemed necessary to reach maximum speed, while the SOFCs are used to reach cruising speed and to generate auxiliary power. To reach higher speeds, a configuration of SOFCs and methanol engines gave the design the highest operational flexibility on top of being the lightest one. On a systems level the power plant of the concept design becomes more complex, mainly due to the partial electrification, with the addition of components that it entails.
- *What is the effect on the design of an OPV of the use of a SOFC-based power plant fuelled by methanol and what would that design look like?*

  The most relevant modifications to the design of the vessel arise from the use of methanol, with its separate fuel preparation room and its special tank arrangement to distance methanol tanks from machinery and accommodation spaces, among others. The new components of the power plant of the concept design were able to fit in the engine room and did not involve major changes on systems that existed in the reference design, such as the ventilation or the cooling systems. Due to the addition of components to the power plant, the lower power density of fuel cells, and the lower energy density of methanol, the concept design experienced an increase in lightweight and deadweight, each of approximately a hundred tons.
- *How are the operational capabilities of the OPV affected by the use of a SOFC-based power plant?*

  The lower energy density of methanol and the higher efficiency of fuel cells showed two interesting results regarding the operational capabilities of the concept design. Since the amount of fuel that a vessel carries is determined on the basis of range condition, and the concept design makes use of an efficient technology to reach cruising speed, but not maximum speed; it was observed that the time that the concept design can spend only sprinting is 15% less than the reference design. Also, although both vessels have the same range, it is known that the reference design has the ability to carry 80% more fuel due to the extra tank capacity, while the concept design can only extend its range by 6.30% due to the lower energy density of methanol and the special arrangement that this fuel requires.
- *How are the emissions of the OPV affected by the use of a SOFC-based power plant?*

  In terms of emissions, the concept design proved to perform significantly better than the reference design. The CO_2 emissions were reduced between 13-23%, depending on the type of mission. The SOx and PM emissions of the concept design were reduced by 100% due to the use of methanol, and the NOx emissions by at least 68%. By doing a refit of the reference design to work on methanol engines only, it was proven how the reduction in CO_2 emissions of the concept design comes from the use of a more efficient technology (fuel cells), and not only from the use of methanol.

Therefore, it can be concluded that it is feasible to use SOFCs fuelled by methanol in the medium term on board of an OPV. The concept design experienced an increase both in lightweight and deadweight due to the lower power density of SOFCs, the complexity in systems that a fuel-cell-based power plant implies, and the lower energy density of methanol. The concept design showed a significant reduction in harmful emissions and complied with the same design requirements as the reference design.

14.1. Discussion

As any concept study, this master's thesis is based on assumptions that add a level of uncertainty to the results presented. For this specific research, the uncertainty stems from the technology readiness level of the components of the power plant: mainly the SOFCs. Since the hypothetical implementation of SOFCs to the power plant of an OPV could only happen in the medium term, at this stage assumptions have to be made that will have to be checked once more information is available.

SOFCs

The SOFCs on which this research is based do not exist yet at such a large power scale. The stacks of 7 kW exist, but their integration into a 280 kW module, and the combination of four of these modules with their corresponding balance of plant to form a SOFC container is based on the prospects of the American company Fuel Cell Energy, but they have not been produced or tested yet.

The size of a 1,120 kW SOFC container was assumed to be equal to a 20-foot container. Due to the technology readiness level of SOFCs, none of the manufacturers that were considered is currently able to produce such a compact and light system. For example, if one compares the 325 kW Bloom Energy Server to the 1,120 kW SOFC container, an improvement of 3.3 and 1.7 times in volumetric and gravimetric power density respectively needs to be achieved in order to make the SOFC container a reality. Only when this is achieved, one can say that the conclusions derived in this master's thesis apply, and that a SOFC-based power plant fuelled by methanol on board of an OPV is feasible.

Although it has been paid careful attention to make conservative assumptions, aspects like the efficiency curve of a module (considering that all four modules of a SOFC container have the same efficiency curve despite sharing the same balance of plant), or the weight estimation of the SOFCs have the highest level of uncertainty. The range in efficiency between 50% and 65% of a SOFC module comes from already available information from the manufacturers.

The aspects on which no public information is available have to do with the electrical load of the balance of plant of a 1,120 kW SOFC container, and the weight of such. To quantify the effects of this uncertainty, in chapter 13 a sensitivity analysis was done that combined these two aspects. The impact on the range and cruising speed was analysed for variations of up to ± 10% in the weight of the SOFC containers, and for an electrical load balance of the balance of plant of the SOFC containers of 0 kW, 25 kW, and 50 kW. For both the best and the worst case scenario, it was concluded that the vessel would be able to fulfil the range of 4,500 nm, but not always the required cruising speed of 12 kn, since it would become 11.7 kn for the worst case scenario. The difference in weight would lead to a slight difference regarding the improvement of CO_2 emissions with respect to the reference design, showing a range of improvement of 11-22% for the worst case scenario, and 13-24% for the best case scenario.

Methanol engines

Besides the SOFCs, spark-ignited methanol engines do not exist at the moment either. Therefore, conservative assumptions were made regarding their efficiency, and other issues mentioned in the literature like the cold start-up and lubrication were considered to be solvable in the medium term. For this research it was assumed that a diesel engine could be adapted to have a spark plug and that such engine could work on pure methanol, with the same engine efficiency.

Electrical load balance

Another point that deserves some attention is the sizing of the SOFCs, which was done in order to comply with the range condition. That means that the fuel cells are able to provide enough power to reach cruising speed and its corresponding auxiliary power. However, the values for the auxiliary power that were used are a mean value of the power required in each mode, but in reality they would present some fluctuations when certain systems are turned on and off. In order to solve this issue, the batteries can be used for peak load shaving. However, it could happen that if in reality much more systems than as stated in the modes for the auxiliary power want to be used for a long time, the methanol engines have to be turned on, in order to “free” power coming from the SOFCs for additional auxiliary power and leave the propulsion to the combustion engines.

Emissions

It should be mentioned that the emissions of the reference, concept, and refit design were calculated as tank-to-wake emissions. This means that they only measure what the vessel emits, not taking into account how the fuel was produced. In the case of methanol, for example, if it is produced by green energy (the so-called *green methanol*) it is considered that the well-to-wake emissions (the sum of the upstream and downstream emissions) result in a carbon-neutral fuel, since the amount of CO_2 that it emits when being combusted, is the same as the amount of CO_2 that was absorbed to produce the fuel.

Finally, it should be noted that the improvement in emissions shown in chapter 12 is specifically with respect to the reference design used in this master’s thesis. That means, assuming that the reference design is an optimal design in terms fuel consumption, and thus emissions. Using common sense, one could argue that, for example, a father-son configuration of diesel engines would be a more optimal configuration for the reference design, considering that most of the time is spent at speeds of 12 kn or less, while the difference in weight of such power plant is not expected to be significant. These effects have not been taken into account, but one is aware that there might be room for improvement in the fuel consumption of a diesel-engine-powered reference design.

14.2. Recommendations

From the conclusions and discussion of this master's thesis, some recommendations arise that can be used for future research.

14.2.1. SOFCs

Based on the assumptions that were made in the system design, further research could be done at a marine/mechanical engineering level. The interaction between the balance of plant and the SOFC modules should be investigated, to better understand how the load of each SOFC module affects the efficiency of the auxiliary components of a SOFC container.

Also, in the literature review of this report it was mentioned how SOFCs allow some heat recovery, to increase the total efficiency of the system. Although this would increase the size and weight of the system, a higher efficiency implies that less fuel needs to be carried on board. This trade-off may have positive consequences for the fuel utilisation, which at the end would result in lower emissions.

During the execution of this research, more details were made available about the system that the new S-80 Plus submarine will use in order to reform bioethanol to then feed hydrogen to a set of PEMCs. The development in this field questions the advantages of the internal reforming capabilities of a high temperature fuel cell. Therefore, it would be interesting to study whether PEMFCs combined with an external reformer are also a feasible option for naval surface vessels and, if so, at what cost.

14.2.2. Fuel

From the comparison study, it was observed how the concept design made some concessions regarding the time that it could spend sailing at maximum speed. Due to the higher efficiency of fuel cells, and because these are used to reach cruising speed (which is also the condition at which the amount of fuel is calculated), but the maximum speed is reached on (less efficient) methanol engines, the concept design runs out of fuel earlier at maximum speed than the reference design. This is an interesting takeaway for the future hypothetical design of a fuel-cell-based power plant. In order to keep the operational capabilities of both vessels equal, more fuel than required for range condition needs to be carried in an OPV with a fuel-cell-based power plant.

The fuel chosen for the concept design was methanol, mainly due to its availability worldwide and its proven performance with SOFCs. However, as it was mentioned in the literature review, ethanol is a better alternative in terms of energy density. Regarding the implementation of ethanol to the design, nothing would have to be changed, since it follows the same rules as for methanol because they are both alcohol fuels. Therefore, if ethanol proves to perform equally with SOFCs and (meth)ethanol engines, the usage of this fuel should be considered in the future.

14.2.3. Power management system

The power plant of the concept design increased significantly in complexity. More systems are required than in a traditional ICE-based power plant, mainly due to the partial electrification, and the use of fuel cells and the support systems these require.

The values used to calculate the electrical load balance are the mean of the power required for each mode. In reality, these values would oscillate. A power management system would be needed to optimise these peaks in electrical load. For example, they can be either absorbed by the batteries (which have to be charged previously), by other SOFC modules, and when that is not possible, by freeing the SOFCs by leaving the propulsion to the methanol engines.

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A

SOFC design

In this appendix, the exact assumptions needed to design a SOFC container are explained.

From the prospects of Fuel Cell Energy, only the weight of the CSA 7 kW stacks is known. It was estimated on the basis of pictures from Fuel Cell Energy, that four 280 kW SOFC modules and their corresponding balance of plant would fit in a 20-foot container.

In order to assume the weight of a SOFC container, two main groups are found. First of all, the cylinder containing the fuel cell stacks, the necessary piping for fuel supply and exhaust, and the isolation material. Second of all, the components of the balance of plant.

The weight of the stacks is known, but the weight of the piping and isolation material is unknown. Therefore, a conservative approach was taken. Inspired by a 20-foot gas tank, meant to transport fluids at 4 bar that weighs 3,800 kg empty, the weight of the cylinders containing the SOFC stacks was scaled using their surface as a scaling factor. Since the tanks used to calculate this weight are able to withstand pressures of 4 bar, and the cylinders containing the SOFCs do not experience any pressure, it is considered that the weight includes the piping and isolation material.

Regarding the weight of the balance of plant, no examples of SOFC plants at this power scale were found that could be used as a reference. The only fuel cell power plant at a megawatt scale that was found is the one shown in Figure 6.5, which makes use of MCFC. These are fuel cells that also operate at high temperatures, and therefore the balance of plant is similar. The only difference is that MCFC require recirculation of CO_2 from the cathode to the anode, which can make the slightly more complex. However, in the system design of a SOFC container in Figure 10.3 it was shown how there is a splitter located out the outlet, that recirculates the rest fuel back to the inlet.

Therefore, and because both power plants (the one with MCFC at 1,400 kW and the SOFC container with 1,120 kW) are in the same order of magnitude in terms of power, it was decided to scale the weight of the balance of plant linearly. The weight decomposition of the two plants can be found in Table A.1.

Table A.1: Weight specification of the balance of plant of a SOFC container.

	MCFC power plant	**SOFC container**
Nominal power (kWe)	1,400	1,120
Weight Electrical BoP (t)	11.9	9.5
Weight main process skid (t)	22.5	18.0
TOTAL weight BoP (t)	**34.4**	**27.5**

A 3D drawing of a 20-foot SOFC container is shown in Figure A.1, where it can be appreciated what the size of the modules is compared to the balance of plant located in the bottom. The space that is empty on top of the modules can be used for the exhaust piping. The green block on the right indicates the size of the electronics module as stated in the prospects of Fuel Cell Energy.

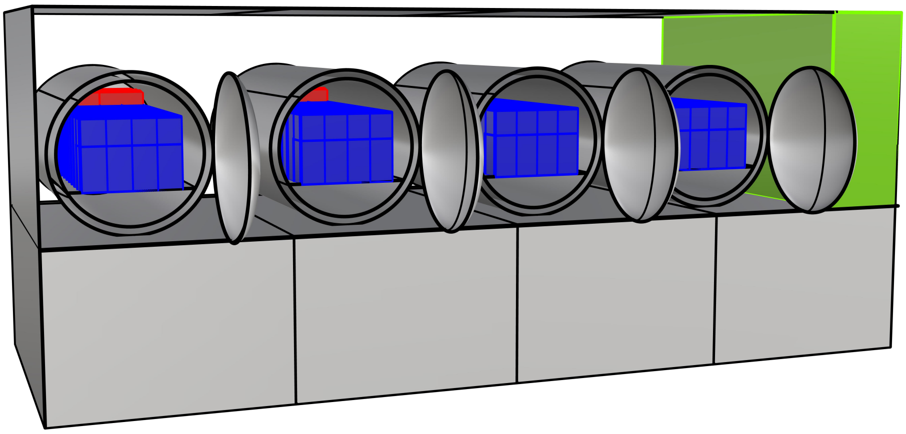

Figure A.1: Artist impression of a SOFC container.

A.1. Firefighting system for lithium-ion batteries

Due to the higher risk of fire of the lithium-ion batteries used to compensate the slow dynamic response of SOFCs, it was decided to enclose these in a steel box and to connect the battery cells to a firefighting system specially designed for this kind of technology.

The weight of such a system and its dimensions can be found in Figure A.2, where the 300 l module is shown.

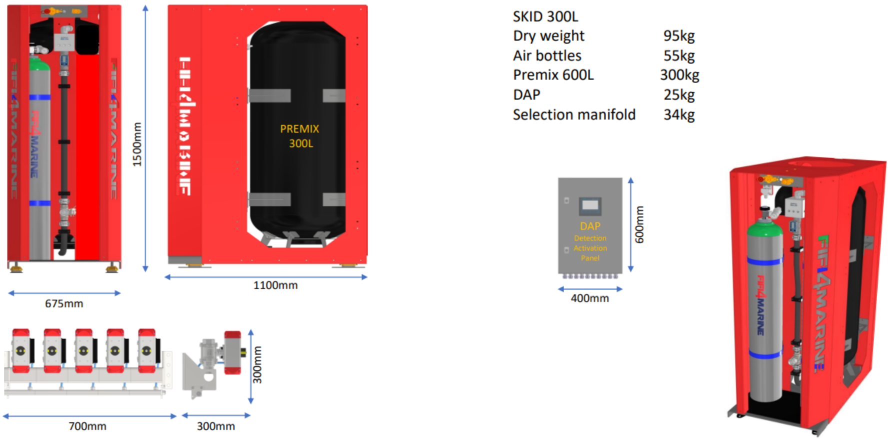

Figure A.2: 300 l firefighting skid from FiFi4Marine (Fifi4Marine, 2022).

Each engine room of the concept design is equipped with one of the modules as shown in Figure A.2. This system is able to inject foam in the battery rack, being able to mitigate any kind of fire.

B

Emissions calculation

In this appendix the values to calculate the emissions in chapter 12 are shown.

To start, Figure B.1 and Figure B.2 show the specific fuel consumption (SFC) assumed for the diesel and methanol engines.

The values for the diesel engine are obtained from the diesel engines used in the reference design, and the values for the methanol engines follow the same pattern, but are scaled to the energy density of methanol.

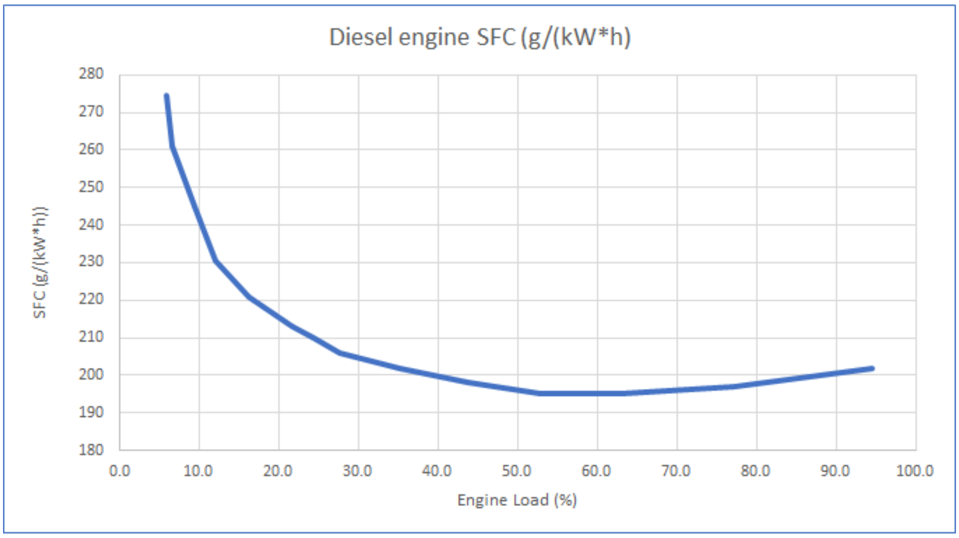

Figure B.1: Specific fuel consumption (SFC) of a diesel engine.

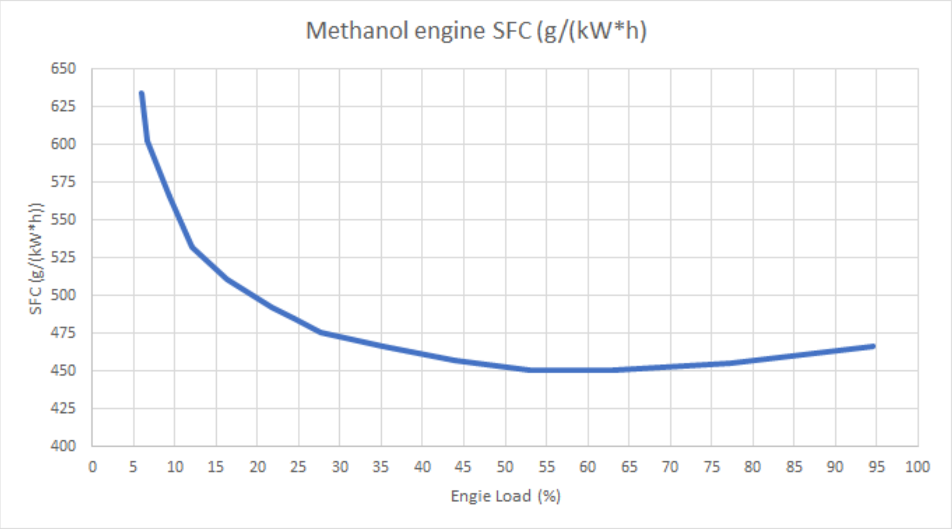

Figure B.2: Specific fuel consumption (SFC) of a methanol engine.

In order to calculate the fuel consumption of the SOFCs, the efficiency-load curve shown in Figure 10.4 is used. For each given speed, the load of the SOFC modules is calculated, which leads to the efficiency of the fuel cell modules. With the method explained in Woud et al., 2016, the mass flow of methanol can be calculated.

When a 280 kW module needs to be kept idling, it also consumes some fuel in order to stay at a high temperature. Due to the lack of information available in the literature, a value obtained informally from a manufacturer was used. This value corresponds to a 7 kW SOFC stack fuelled by natural gas, that required $0.06\,\mathrm{m}^3/\mathrm{h}$ to idle. This value was scaled to the energy density of methanol and to the size of a 280 kW module.

In Table B.1, Table B.2, and Table B.3, the exact parameters for the reference, concept, and refit design can be found. As can be seen, in the concept design idling of SOFC modules only occurs at 0 kn, when the only power that the fuel cells need to generate is the hotel load.

Tables B.4, B.5, B.6 and B.7 show the fuel consumption for the three designs for the different types of missions for each speed and mode. From these calculations, the CO_2 emissions can be calculated with the values shown in Figure 5.3.

Table B.1: Parameters to calculate the fuel consumption of the reference design.

	REFERENCE DESIGN											
Speed (kn)	Pb (kW)	Number of DE on	Load DE (%)	n DE (rpm)	NOx limit (g/kWh)	SFC DE (g/kWh)	P_aux (kW)	Number of DG on	Load of DG (%)	n DG (rpm)	SFC DG (g/kWh)	NOx limit (g/kWh)
0	0	0	0.00	0	0	0	291	2	48.50	1450	197	8.25
8	535	2	10.59	1000	8.98	240	588	3	65.33	1580	196	8.09
12	1075	2	21.29	1080	8.83	212	588	3	65.33	1580	196	8.09
22	8800	4	87.13	1800	7.85	200	855	4	71.25	1640	198	8.02

Table B.2: Parameters to calculate the fuel consumption of the concept design.

	CONCEPT DESIGN												
Speed (kn)	Pb (kW)	Number of EMs on	Load EMs (%)	Number of MethEng on	Load of MethEng (%)	n Meth eng. (rpm)	NOx limit (g/kWh)	SFC meth (g/kWh)	P_aux (kW)	Number of SOFC modules on	Load of SOFCs (%)	Efficiency SOFCs (%)
0	0	0	0	0	0	0	0.00	0	282	2	50.357	64.06487
8	680	2	47.887	0	0	0	0.00	0	578	8	57.100	64.83963
12	1400	2	98.592	0	0	0	0.00	0	578	8	90.237	56.22534
22	9400	2	78.535	2	86.3	1200	8.61	462	846	8	89.093	56.86635

Table B.3: Parameters to calculate the fuel consumption of the refit design.

	REFIT TO ONLY METHANOL ENGINES											
Speed (kn)	Pb (kW)	Number of ME on	Load ME (%)	n ME (rpm)	NOx limit (g/kWh)	SFC ME (g/kWh)	P_aux (kW)	Number of MG on	Load of MG (%)	n MG (rpm)	SFC MG (g/kWh)	NOx limit (g/kWh)
0	0	0	0.00	0	0	0	291	2	48.50	1450	455.07	8.25
8	560	2	11.09	1000	8.98	549.78	588	3	65.33	1580	452.76	8.09
12	1120	2	22.18	1100	8.79	487.41	588	3	65.33	1580	452.76	8.09
22	8870	4	87.82	1800	7.85	464.31	855	4	71.25	1640	457.38	8.02

Table B.4: Fuel consumption for a search and rescue mission.

		Reference Design		**Concept Design**		**Refit Design**	
Speed (kn)	Time (h)	Diesel prop (t)	Diesel aux (t)	Meth Engine (t)	Meth SOFCs (t)	Meth prop (t)	Meth aux (t)
0	4.8	0.00	0.28	0.00	0.54	0.00	0.64
8	19.2	2.47	1.94	0.00	6.92	5.91	5.11
12	163.2	37.19	18.81	0.00	107.21	89.09	43.45
22	16.8	29.57	2.84	64.30	10.77	69.19	6.57
			93.09		**189.75**		**219.96**

Table B.5: Fuel consumption for a patrolling and intercepting mission.

		Reference Design		**Concept Design**		**Refit Design**	
Speed (kn)	Time (h)	Diesel prop (t)	Diesel aux (t)	Meth Engine (t)	Meth SOFCs (t)	Meth prop (t)	Meth aux (t)
0	4.8	0.00	0.28	0.00	0.54	0.00	0.64
8	276.48	35.50	31.86	0.00	99.66	85.12	73.61
12	60.48	13.78	6.97	0.00	39.73	33.02	16.10
22	18.24	32.10	3.09	69.82	11.70	75.12	7.13
			123.58		**221.45**		**290.73**

Table B.6: Fuel consumption for a humanitarian mission.

		Reference Design		**Concept Design**		**Refit Design**	
Speed (kn)	Time (h)	Diesel prop (t)	Diesel aux (t)	Meth Engine (t)	Meth SOFCs (t)	Meth prop (t)	Meth aux (t)
0	108	0.00	6.19	0.00	12.04	0.00	14.30
8	0	0.00	0.00	0.00	0.00	0.00	0.00
12	252	57.43	29.04	0.00	165.55	137.57	67.09
22	0	0.00	0.00	0.00	0.00	0.00	0.00
			92.66		**177.60**		**218.96**

Table B.7: Fuel consumption for range condition.

		Reference Design		**Concept Design**		**Refit Design**	
Speed (kn)	Time (h)	Diesel prop (t)	Diesel aux (t)	Meth Engine (t)	Meth SOFCs (t)	Meth prop (t)	Meth aux (t)
0	0	0.00	0.00	0.00	0.00	0.00	0.00
8	0	0.00	0.00	0.00	0.00	0.00	0.00
12	375	85.46	43.22	0.00	246.36	204.71	99.83
22	0	0.00	0.00	0.00	0.00	0.00	0.00
			134.68		**246.36**		**304.55**