Electro-fuel solutions for the maritime sector

A model-based case study on the feasibility and impact of implementing e-fuels on the large offshore vessels of Heerema Marine Contractors

Master of Science Thesis

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TU Delft

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Preface

When I moved to Delft in 2015, I started my study career with a BSc Mechanical Engineering at the Delft University of Technology. Even though I really enjoyed my BSc, I realized I wanted to work on more up-to-date topics, therefore I decided to start the MSc Sustainable Energy Technology. As I learned more about the different facets of sustainability, my affinity for sustainability kept growing. Therefore, when I was offered the opportunity to conduct my thesis internship within the sustainability department of Heerema Marine Contractors and research the impact of implementing an e-fuel on one of the large offshore vessels of Heerema, I was immediately interested.
I was lucky enough to see and gain experience in several different facets of the sustainability sector and this is something I will be able to take with me further on in my career. Looking back at the last years of my studies and at the graduation project, it has been a very educational and interesting process. I hope that for any readers this report will be educational and interesting as well.

From the TU Delft, I would like to thank Dr. Jan Anne Annema for his frequent guidance and feedback during my graduation project. I would also like to thank Prof. Bert van Wee and Dr. Lindert van Biert for being part of my thesis committee and for their feedback on my report.

I especially would like to thank Hedzer Keulen, my daily supervisor from Heerema, who was actively involved in guiding and supporting me as well as providing me with feedback during my graduation. I would like to express my gratitude to the sustainability department of Heerema, who made sure I was able to work in a pleasant work environment and provided me with any information or help I needed. Lastly, I would like to thank Bram Hoeksma for his support and encouragement during my graduation, which kept me motivated during the entire process.

Finally, I would like to thank everyone who helped me throughout my whole study career, especially my family, who always supported me.
Grazie a tutti, e spero di poter festeggiare il raggiungimento di questo importante traguardo con tutti voi.

J.A. Carbutto
Amsterdam, June 8 2023

Abstract

Several global and European frameworks are set up to inhibit global warming and reduce greenhouse gas (GHG) emissions, such as the Paris Agreement and the Fit for 55 package, in which the European Union has set itself a binding target of cutting down emissions by 55% compared to 1990, by 2030. As the shipping industry is a significant source of GHG emissions, it faces sustainability challenges and is subject to regulations set by the International Maritime Organisation (IMO), which set a goal to reduce 70% of CO_2 emissions per transport by 2050. Additionally, the European Commission has suggested including emissions from the maritime sector in the European emission trading system (EU ETS). The general expectation is that these set targets and regulations will only become stricter in the coming years, thereby emphasizing the need for the maritime sector to adopt GHG abatement solutions.
Electro-fuels (e-fuels) are a potential zero-carbon alternative fuel option for the maritime sector. However, e-fuels still face several challenges, as currently, their production costs are high, and the implementation of e-fuels in the marine sector is still in a research and development phase.

This study focuses on the impact that implementing an e-fuel has for both the vessel and vessel owner, from a techno-economic perspective. Since this research is performed at Heerema Marine Contractors (HMC), the focus is on large offshore construction vessels. Through findings obtained from literature research and a case study, a general indication is obtained regarding the impact of implementing an e-fuel on a large offshore vessel. Several KPIs are defined to quantify and evaluate this impact by comparing them to a fossil base case.
During literature research, e-fuel characteristics and relevant energy characteristics of a large offshore vessel are identified, as well as several feasible e-fuel conversion pathways that are expected to be able to be implemented on a large offshore vessel within a time frame of approximately 10 years set for this study. The data obtained during the literature phase of this study is utilized as input for the technical as well as financial evaluation.

To implement an e-fuel on a large offshore vessel operating on MGO, modifications are required, except in the case of e-diesel, as it is a drop-in fuel and has similar characteristics as MGO. The modifications vary per e-fuel and are required to ensure safe fuel storage, fuel handling, and energy conversion. During the technical evaluation, the main focus is on the fuel storage tanks, energy conversion unit, and fuel piping system, as these are the main components of the energy infrastructure of a vessel.
Based on expected e-fuel, MGO and EU ETS price developments, 2030 - 2035 is projected as period in which it would be financially more attractive to operate on an e-fuel than on MGO, solely based on the fuel price. However, since this study focuses on retrofitting existing vessels, modifications required to the vessel operating on MGO should also be considered. Even though large capital expenditures (CapEx) could affect the financial attractiveness of implementing an e-fuel, on overage, the CapEx only contributes to approximately 17% of the total implementation costs of the financially most attractive e-fuel pathways, shown in Table 1. Thereby the OpEx is the main financial driver.

The results of the case study, performed on one of the semi-submersible crane vessels of HMC, are utilized to give a general indication regarding the impact for both the vessel and the vessel owner when implementing an e-fuel on a vessel operating on MGO. Table 2, gives a general indication regarding how each e-fuel performs on the set KPIs, where green is the best-performing e-fuel, followed by yellow, orange, and lastly red is the worst-performing e-fuel.
For the carbon-containing e-fuels to realize a 100% CO_2 abatement of a specific capacity, they must be produced from renewable electricity and CO_2 originating from a renewable source. If this is not the case, they can not adopt a zero CO_2 WTW emission factor and can be disregarded as an emission abatement option.

The levelized cost of energy (LCOE) of each e-fuel is compared to an MGO with a carbon capture storage (CCS) system pathway to determine if implementing the e-fuel is a financially attractive abatement option. Since the OpEx of each pathway is the main financial driver in selecting which e-fuel to implement, pathway efficiencies and the expected e-fuel prices for 2032 have a large impact on the vessel owner. Most pathways that include a CCS system make use of a proton exchange membrane fuel cell (PEMFC), or where the e-fuel is converted to hydrogen, can be disregarded as their LCOE is greater than that of the MGO with CCS pathway. Hereby implementing an e-fuel with an internal combustion engine (ICE) poses the least impact for the vessel owner, from an LCOE perspective. The financially most attractive pathways and their LCOE are shown in Table 1.
Since this study adopts a zero CO_2 WTW emission factor for each e-fuel, the abated emissions are similar for the levelized cost of carbon abatement (LCoCA) of each e-fuel, and the LCoCA and LCOE results are similar. By comparing the LCoCA of each e-fuel to the assumed EU ETS price of 2032, insights are created regarding how an e-fuel performs as an abatement option compared to regulations set for the marine sector. The LCoCA of the financially attractive pathways is shown in Table 1.

Table 1: Pathways with an LCOE below the MGO with CCS pathway. *(With an expected EU ETS price of 155 Eur /mT CO_2)*

(E-)fuel	**MGO** (Base case)		**E-diesel**	**E-LNG**	**E-hydrogen**		**E-methanol**		**E-ammonia**
Pathway	ICE	ICE + CCS	ICE	DF ICE	DF ICE	PEMFC	DF ICE	$H_2 \rightarrow$ DF ICE	DF ICE
LCOE *[Eur /kWh]*	0.34	0.51	0.39	0.48	0.29	0.49	0.33	0.37	0.40
LCoCA *[Eur./mT CO_2]*	-	-	70	207	-80	212	-24	46	90

Implementing any of the e-fuels on an MGO-fuelled vessel, except for e-diesel, requires additional storage capacity or an increase in the bunkering frequency. E-hydrogen has the largest impact, as the largest additional storage capacity is required. Depending on the vessel, expanding the fuel storage tanks or increasing the bunkering frequency might not be feasible, thereby certain e-fuel pathways can be disregarded as viable abatement option.
Implementing any of the e-fuels on an MGO-fuelled vessel, except for e-diesel, requires additional health and safety measures. The hazard of an e-fuel does not result in any e-fuel being disregarded, it only imposes a safety challenge on the vessel and additional CapEx for the vessel owner. E-ammonia is the most hazardous e-fuel and poses the largest impact.

A general indication of the impact of each e-fuel on the above-mentioned KPIs is shown in Table 2. Depending on the large offshore vessel and on KPIs that stakeholders regard as more or less relevant, a decision could be made regarding what e-fuel to implement. However, implementing e-diesel on an MGO-fuelled vessel has the smallest impact on the vessel, whereas implementing e-hydrogen has the smallest financial impact on the vessel owner. E-methanol can be seen as the most viable option, as it has a relatively small financial impact on the vessel owner and a relatively small impact on the vessel compared to the other e-fuels.

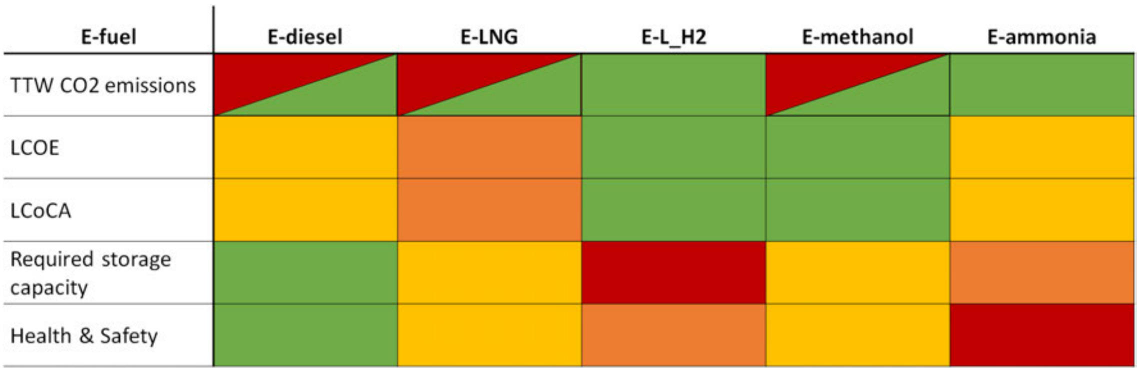

Table 2: Overview of the e-fuels impact on the set KPIs

Contents

Glossary

BAU	Business As Usual
BOG	Boil-Off-Gas
CapEx	Capital Expenditures
CCS	Carbon Capture Storage
CH_4	Methane
CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon dioxide
CRF	Capital Recovery Factor
DCV	Deepwater Construction Vessel
DMFC	Direct Methanol Fuel Cell
DNV	Det Norske Veritas
DP	Dynamic Positioning
EDF	Environmental Defense Fund
E-fuel	Electro-fuel
EU	European Union
EU ETS	European Emissions Trading Scheme
FAME	Fatty Acid Methyl Ester
GHG	Greenhouse Gas
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
H_2	Hydrogen
HFO	Heavy Fuel Oil
HMC	Heerema Marine Contractors
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
KPI	Key Performance Indicator
LCoCA	Levelized Cost of Carbon Abatement
LCOE	Levelized Cost Of Electricity
LFO	Light Fuel Oil
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MOB	Mobilization
mT	metric Ton
N	Nitrogen
NH_3	Ammonia
NO_x	Nitrous oxides
O_2	Oxygen
OpEx	Operating Expenditure
PBU	Pressure Build up Unit
PEMFC	Proton Exchange Membrane Fuel Cell
ppm	Parts per million
PS	Portside
R&M	Repair and Maintenance

SB	Starboard
SO_x	Sulphur oxides
SOFC	Solid Oxide Fuel Cell
SSCV	Semi Submersible Crane Vessel
TRL	Technological Readiness Level
TTE	Tank-to-Exhaust
TTW	Tank-to-Wake
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WTT	Well-to-Tank
WTW	Well-to-Wake

List of Figures

List of Tables

1 Introduction

To limit global warming as much as possible and hereby inhibit climate change, a set of different frameworks were set up on a global, European, and sector level. One of the best-known is the Paris Agreement, which was implemented during the United Nations Framework Convention on Climate Change (UNFCCC) in 2015. The Paris Agreement is a legally binding international agreement signed by 196 different parties, making it the first binding treaty to align almost all countries. The agreement's main aim is to halt climate change and ensure that global warming will not exceed 2 degrees Celsius, compared to pre-industrial levels. Ideally, global warming will be limited to 1.5 degrees Celsius, as this would significantly reduce climate change effects. However, to do so, emissions should be cut down substantially and reach net zero by the middle of this century [109].
Another framework is the Fit for 55 package, which is part of the European Green Deal and therefore only effective in Europe. In this packet, the European Union (EU) has set itself a binding target of cutting down emissions by 55%, compared to 1990, by 2030 and reaching climate neutrality by 2050 [41].

International shipping is also facing considerable sustainable challenges, following global regulations for the protection of the aquatic environment and the prevention of emissions. Even though the shipping industry plays an important role in the global economy, it is also a substantial source of Greenhouse Gas (GHG) emissions. The International Maritime Organisation (IMO) has set out several Business As Usual (BAU) scenarios, which indicate the emissions from the shipping sector in case no regulations were to be adopted, and concluded the emissions originating from the shipping sector will only increase in the coming years [121]. Therefore the IMO has been actively involved in reducing these emissions and in 2018 agreed on an initial reduction strategy. The central goal of this initial reduction strategy is to reduce 40% of CO_2 emissions per transport, compared to 2008 levels. Additionally, the IMO has set the goal to reduce 70% of CO_2 emissions per transport in 2050, compared to 2008 levels [75]. The prediction is that the currently set targets by the IMO will only get stricter in the coming years [138].
In addition to the goals set by the IMO, the European Commission has suggested including any emissions originating from the maritime sector to the European Emissions Trading Scheme (EU ETS) as mentioned in the Fit for 55 package. As a result, ETS allowances will have to be bought as offset for each tonne of carbon dioxide (CO_2) emitted [39].

All these frameworks and regulations are set up to incentivize the shipping sector to improve energy efficiencies, focus on low-carbon alternatives, and thus lower GHG emissions. Companies active in the shipping industry must look at GHG abatement solutions, to lower their emissions. Heerema Marine Contractors (HMC) is an offshore marine contractor and thus active in the shipping sector. HMC has its own fleet with several large offshore construction vessels, which are currently still excluded from the framework set up by the IMO. However, since HMC is a company where sustainability is embedded in their way of working, they have set up their own GHG abatement ambition and targets for the coming years.
An overview of the ambitions set by each framework as well as a business-as-usual scenario, can be seen in Figure 1.1.

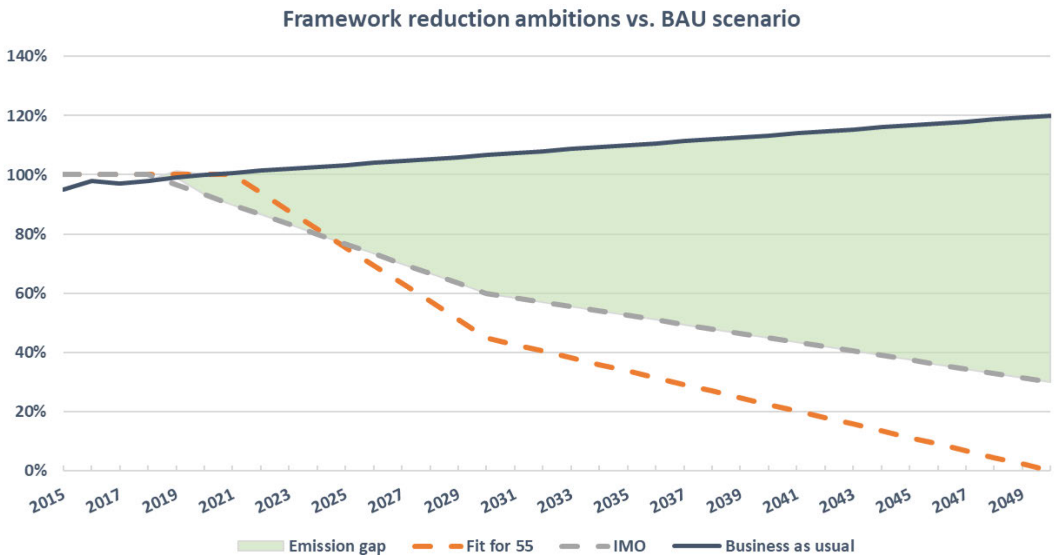

Figure 1.1: The abatement ambitions of the different frameworks compared to the BAU scenario.

1.1. Problem background

The GHG emissions, originating from the maritime sector, have seen a 9.6% increase from 2012 to 2018. These GHGs include CO_2, methane (CH_4), nitrous oxides (NO_x), and sulphur oxides (SO_x), which are indirect GHGs. It is essential to consider all GHG emissions, as all these gasses are damaging to the environment, to human health and have their own global warming potential. This increase in emissions resulted in the share of shipping emissions, to the global anthropogenic emissions, increasing as well and reaching approximately 3% in 2018. According to several plausible long-term scenarios set out by the IMO, these emissions will continue to increase by approximately 0% - 40% by 2050 compared to the global emissions in 2018 [121]. Figure 1.2 gives an overview of historical and projected emissions originating from the shipping industry.
Currently, the most conventionally used fuels in the shipping industry are marine gas oil (MGO), heavy fuel oil (HFO), light fuel oil (LFO), and liquefied natural gas (LNG). In the last few years, LNG has gained increasing interest, as natural gas was abundantly available, hereby also realizing the competitive costs of LNG and due to the fact that using LNG can decrease GHG lifecycle emissions significantly compared to other fossil fuels [52]. However, all these fuels emit GHGs and will therefore not provide a viable solution to reducing emissions according to the Fit for 55 or the IMO goals. The shipping industry is therefore forced to look at other abatement options or alternative fuels to lower their emissions.
When emissions originating from the shipping industry are further examined, it becomes clear that a large fraction of those emissions can be traced back to a specific category of vessels, which are large offshore vessels [32]. The fact that they are a significant contributor to the emissions of GHGs in the shipping industry, is not only caused by the fact that they are the largest fuel consumers but is also because these types of vessels are almost always operational and, therefore, almost always emit GHGs. The vessels of HMC are mostly large offshore construction vessels and thus also fall within this category. So, to reduce emissions from the shipping industry a big impact can be made in making these large offshore vessels more sustainable [32].

Although numerous methods exist to lower emissions from these large offshore vessels, not every method is suitable or will have the same impact. For example, slow steaming, where the speed of the vessel is reduced to save fuel, or any energy-saving technologies implemented on a vessel, will only have a limited impact and will not be able to result in a net-zero emission vessel. In addition, batteries will neither form a suitable solution as the amount and the size of the batteries would have to be too substantial to make an impact. This is because of such vessels' high and long power demand [101]. Therefore, to reduce emissions from these large vessels, and from the shipping industry, the focus should be on alternative fuels [101].

One alternative fuel option, could be biofuels, such as fatty acid methyl ester (FAME) or hydrotreated vegetable oil (HVO). Biofuels are now mainly looked into as a drop-in fuel solution, meaning that the biofuel is blended, up to 100%, into an existing fuel mixture. Therefore no changes to the infrastructure of the vessel will be necessary. Even though CO_2 is still emitted during combustion, these fuel mixtures can reduce GHG emissions, as biomass is used as feedstock to produce these biofuels, which absorbs CO_2 during its lifetime. Therefore, these fuel mixtures would be net-zero if the CO_2 absorbed during the lifetime of the biomass is equal to the CO_2 emitted by the fuel and originates from a renewable source.
Besides the fact that biofuels still emit GHGs, the general assumption is that biofuels will only provide a temporary solution for the shipping industry and play a role as a transition fuel. The expectation is that the maritime sector will have to compete with other sectors, such as the food industry or the aviation or freight sectors, which will also need to look at alternative fuels to decarbonize. This future competition, regarding biofuels, has caused the presumption that the demand will increase, while the supply will remain limited, causing biofuels prices to increase significantly in the coming years, up to a point where it will no longer be financially attractive to utilize these biofuels for the offshore shipping industry [90].

Another alternative fuel option, for reducing GHG emissions, are e-fuels (electro-fuels), such as e-hydrogen, e-ammonia, and e-methanol. These are all low-carbon fuels, which are produced from green electricity, hydrogen, and captured CO_2 or nitrogen. Some of these fuels do contain carbon and thus will emit CO_2, however during the production of these e-fuels use is made of CO_2 which is captured from the air, thereby making them potentially net-zero fuels.
Even though much is known regarding their characteristics, related technologies, and production of these type of fuels, more research is required regarding the implementation of e-fuels on large offshore vessels before they can actually be implemented. Additionally, the techno-economical impact that this implementation will have on the vessel and on the vessel owners is also still unclear. This knowledge gap is filled during this study and will be further discussed in section 1.2.
Since e-fuels are seen as a potential zero-carbon solution that can be utilized to decarbonize the shipping industry completely and due to the fact not all complications and challenges regarding implementing these e-fuels in the shipping industry are known, further research into this alternative fuel type is justified.

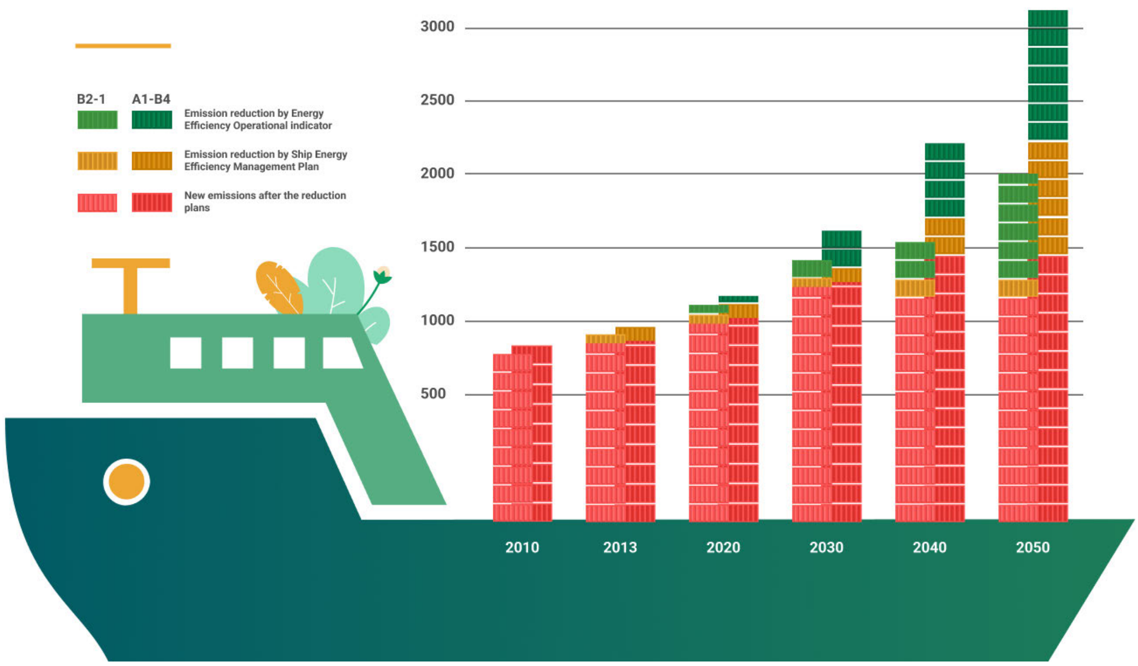

Figure 1.2: Projected CO_2 emissions from the shipping sector [167]

1.2. Research gap

Several organizations, such as the Environmental Defense Fund (EDF) and Det Norske Veritas (DNV), have already identified the potential of e-fuels as an alternative fuel to decarbonize the maritime sector in two published papers [51] [98]. Both papers state that e-fuels are among the leading solutions with a high potential of decarbonizing the marine sector. However, both papers also state the need for significant investments in the production of renewable energy to realize affordable e-fuels and to make them compatible with currently used fossil fuels in the future. Additionally, regulations, such as the EU ETS, are also necessary to reduce the financial attractiveness of currently utilized fossil fuels and make e-fuels more cost competitive.

The potential of e-fuels as an alternative fuel is reiterated in many published articles, which cover various aspects of these e-fuels, such as the technologies associated with various e-fuels.
For example, in the article from Ababned and Hameed, which gives an overview of recent developments regarding the chemistry and technologies involved in the production of e-fuels [2]. This article is based on a study and review done on recent literature and states that these production processes suffer from several disadvantages, such as their low tolerance to a varying energy supply. However, much research and development is currently carried out regarding these production processes to overcome these challenges and ensure more reliable production technologies.
In a paper written by Taljegård et al. on behalf of the Swedish Environmental Research Institute, an overview is given of the current status of e-fuel-related technologies, their efficiencies, and costs. The paper also discusses the feasibility of a high enough e-fuel production capacity to decarbonize the marine sector. The paper states that considering the potential competition for biofuels, e-fuels might be the only option to decarbonize the marine sector. However, the paper also expresses that safety issues and other practical problems regarding the implementation of an e-fuel are not taken into account and should be considered [151].

The investment and production costs of different e-fuels are also discussed in many articles. In two articles by Grahn et al., the costs and environmental impact of several e-fuels for the transport sectors are discussed, and the production and investment costs of several e-fuels are compared [66] [65]. The articles state that e-fuels in combustion engines and the usage of hydrogen in fuel cells could become cost-competitive. However, the investment costs for certain energy conversion units should be able to be spread out over many operating hours. Grahn et al. also mentions that the production costs of e-fuels are strongly related to the fluctuating production of renewable energy, which in turn depends on the location the renewable energy is produced.
In addition, the article by Brynolf et al. assesses the production costs of different e-fuels by performing a literature and a supporting study to review the costs and efficiencies of the production steps of each e-fuel. At the end of the paper, these costs are compared as well [22]. Brynolf et al. state that the production costs of e-fuels, found in previous literature, have a very broad range from 10 up to 3500 Eur./MWh (Euro per MWh), however in their calculations, they found a production cost range between 80 and 2700 Eur./MWh in 2015 and between 50 and 750 Eur./MWh in 2030, based on various scenarios. They also mention that the production costs of e-fuels come with high uncertainty.

Several publications discuss the potential of e-fuels in the shipping sector specifically. For example, the article by McKinlay et al. discusses important considerations, decisions and technical challenges regarding storing several e-fuels on-board [101]. The article states that methanol requires the least gravimetric and volumetric storage and that it is easier to store than hydrogen. McKinlay et al., however, also state that other factors, such as the toxicity of ammonia, the carbon content of methanol, and the complex storage of hydrogen, should also be considered in further studies regarding the potential and implementation of e-fuels.
Another example is the paper from Lindstad et al., which discusses the feasibility, GHG reduction potential, energy utilization and costs of each e-fuel, compared to fossil fuels, for the decarbonization of the marine sector [95]. Firstly, the paper states that producing e-fuels will be a costly process, mostly depending on electricity costs. Secondly, the paper mentions that the GHG emissions from e-fuels, such as e-hydrogen or e-ammonia, are significantly lower than for alternative fuels produced in other ways.

Even though several articles are already published regarding the characteristics of different e-fuels, technologies, and costs related to e-fuels and their potential in the shipping sector. There has yet to be a study that combines these already researched aspects of e-fuels and combines them to eventually perform a techno-economical study regarding the implementation of these e-fuels on large offshore construction vessels. Additionally, no study has yet been performed where a case study is executed on a large offshore vessel by means of a model that is able to quantify the impact, from a techno-economic perspective, that the implementation of e-fuel has on the vessel as well as on the vessel owner.

This report aims to design a methodology that can be utilized as a supportive tool to quantify and evaluate the techno-economic impact of implementing an e-fuel by stakeholders of decarbonizing the marine sector. Several set key performance indicators (KPIs) will form the model's output and are utilized to quantify and evaluate the impact of implementing an e-fuel on a large offshore vessel. Once the working principles of the model are defined, and necessary initial input values are obtained through a literature study and from in-house data available within Heerema, a case study is performed on one of the vessels of Heerema. The results of this case study will give a general indication regarding the impact of implementing an e-fuel on the vessel and are also utilized to give an indication regarding the impact of implementing an e-fuel on other large offshore vessels.

1.3. Research questions

To evaluate the implementability of an e-fuel and the impact, from a technical and financial perspective, that implementing an e-fuel has on the vessel as well as for vessel owners, a research question and several sub-questions are formulated.

1.3.1. Main question

Resulting from the aforementioned problem definition and the knowledge gap, the following research question was formulated:

What impact, from a technical and financial perspective, will the implementation of low-carbon e-fuels have on large offshore construction vessels?

"A case study based on the technological and financial feasibility of implementing e-fuels on the current crane vessels of Heerema Marine Contractors."

1.3.2. Sub-questions

Besides the main research question, several sub-question are setup, which will help answering the main research question:

1. *How can the techno-economic impact, for both the large offshore construction vessel and the vessel owner, of implementing an e-fuel be evaluated?*
2. *Which e-fuels are suitable and expected to be available to implement on large offshore construction vessels?*
3. *What energy characteristics of a large offshore construction vessel should be considered when implementing an e-fuel?*
4. *What technological adjustments are required in order to implement the selected e-fuels, and what are the associated costs?*

1.4. Heerema Marine Contractors

This research is performed at Heerema Marine Contractors, hereby, the knowledge gap of this research will be filled within the context of HMC. Additionally, the set research questions of this study will be answered by using available knowledge and data within HMC.

Heerema is a Dutch company that is part of the Heerema Group, which was founded in 1948 and has its headquarters in Leiden. Figure 1.3, shows the HMC office in Leiden. Heerema is one of the leading marine contractors, mainly active in the oil, gas and renewable industry. The main activities of HMC consist of the installation of offshore wind farms, the transport and installation of offshore structures and the decommissioning of offshore facilities. To carry out all these activities, Heerema has a diverse fleet, consisting of the world's largest and second-largest semi-submersible crane vessels (SSCV), a heavy lift vessel, tugboats and barges.

Sustainability is an essential aspect within Heerema and is deeply embedded in their way of working; not only was Heerema the first carbon-neutral marine contractor, but they also incorporated a roadmap to prevent, reduce and compensate all their CO_2 emissions in the coming years.
The road map is based on the sustainable development goals set by the United Nations (UN) and the International Maritime Organization. To decrease their percentage of emissions, which is compensated, and thus increase the percentage of reduced and prevented emissions, Heerema is looking at different solutions to mitigate and prevent their greenhouse gas emissions. Therefore Heerema is looking into alternative fuels to replace the currently used fossil fuels, and they acknowledged that e-fuels could play an important role in powering their vessels. Heerema has chosen to investigate the feasibility of implementing an e-fuel and the impact that the implementation of an e-fuel will have, from a technological and financial viewpoint, when implemented on their large offshore crane vessels.

Figure 1.3: HMC office in Leiden

1.5. Research method

The methodical decision was made to conduct this study within HMC since it is a company with its own fleet that is active in the maritime sector and actively involved in making its vessels more sustainable. To obtain the methodology as well as the information and data required for this study, several experts within and outside of HMC were consulted. An overview of these experts and their area of expertise is shown in Appendix A. By combining the obtained data and knowledge and performing a case study on one of their vessels, an answer to each of the sub-questions and eventually to the main research question is obtained. This section gives an overview of the methodology used to answer each sub-question and the main research question. Besides the main and sub-question, a research objective is defined as well and is stated below:

To support companies and other stakeholders, actively involved in reducing emissions from large offshore vessels, in the selection of what e-fuel to implement based on a techno-economic evaluation.

Figure 1.4 shows the applied methodology used to answer the research questions and hereby realize the research objective. The research is divided into four phases, during which the research questions are answered. The four phases are elaborated on in the following sections.

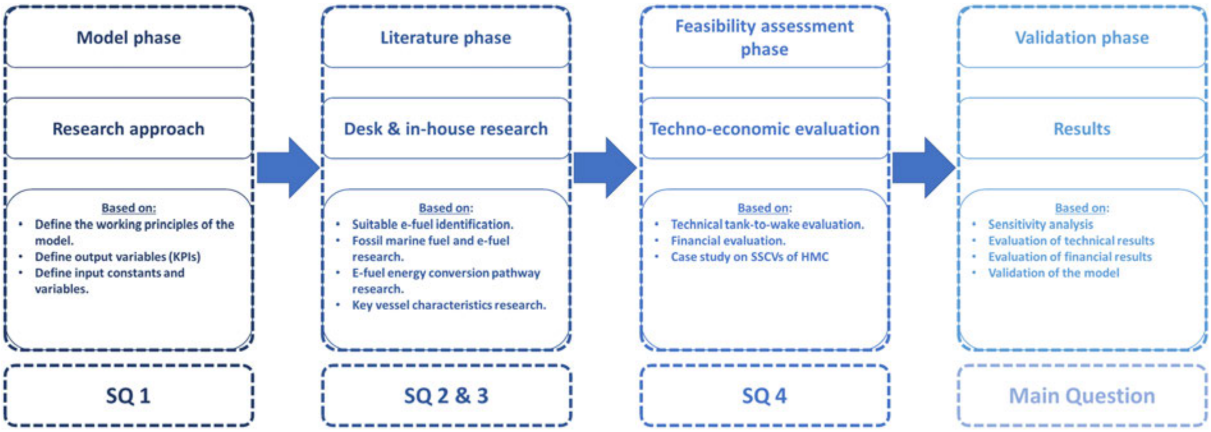

Figure 1.4: Applied methodology during this research

Phase 1 - Model

During the model phase of this research, the first sub-question is answered, and hereby how the techno-economic impact for both the vessel and the vessel owner can be evaluated and quantified. The first phase of this study is performed in several steps:

1. **Define the KPIs used to quantify and evaluate the impact.**
   After consulting several sustainability experts, a set of KPIs is identified that are used to determine and quantify the impact of implementing an e-fuel. These KPIs cover factors that are important to a company active in the maritime sector when evaluating the implementation of an alternative fuel on their vessels. Such companies can use the KPIs to base decisions on regarding what e-fuel to implement. By comparing the KPIs of an e-fuel to the KPIs of a fossil base case, the impact of implementing an e-fuel is obtained.
2. **Define how to obtain and quantify the KPIs.**
   Since previous research within HMC, regarding the implementation of abatement technologies, was executed by using a model, the choice was made to use a model for this study as well. A model is identified as the most suitable tool to quantify and evaluate the set KPIs, as it offers flexibility to the user. The model can be customized to reflect the user's specific needs. In the case of HMC, the model can be used as an extension to previously executed research. The model can be used as a supportive tool to assist stakeholders in making large offshore vessels more sustainable, in determining the impact of implementing an e-fuel, and hereby selecting which e-fuel is most viable to implement. The model can provide the desired KPIs as output based on various input variables and constants.

3. **Determine necessary input.**
The input variables and constants required to quantify the set KPIs, by making use of the model, are obtained by performing a literature study, an in-house study within HMC and by consulting the various experts, stated in Appendix A. These input values are subdivided into three different categories:
    - ***External conditions**, values such as fuel availability, pricing, and regulations. These values are relevant as they can be utilized to simulate different scenarios and hereby, the uncertainty of the model can be accounted for. Additionally, these conditions affect the OpEx of each e-fuel.*
    - ***Fuel characteristics**, values such as emission factors and energy densities. E-fuel and fossil fuel characteristics are compared to obtain the abated emissions but also the required technical modifications on the vessel.*
    - ***Vessel characteristics**, values such as the energy profile and infrastructure of large offshore vessels. These values are used to set up a base case, to determine what capacity is retrofitted and what modifications are required on the vessel.*
4. **Set up the base case.**
Based on information and data gathered online and within HMC, a base case is set up, which is also used as input for the model. The base case represents the current fossil scenario, as it includes the fuel infrastructure, fuel use, and emissions of the vessel. By comparing the KPIs of each e-fuel to the base case, the impact that implementing an e-fuel has can be evaluated.

The model and its working principles will be further elaborated on in Chapter 2. Through the steps mentioned above, several KPIs are set up, as well as the methodology and input values required to obtain the set KPIs, which are used to quantify and evaluate the techno-economic impact of implementing an e-fuel on a large offshore vessel. Hereby sub-question one of this study is answered.

Phase 2 - Literature study

The second phase of this research is a literature study, where information and data regarding the necessary input values of the model are collected. During this phase, several informational resources are consulted, such as recent online literature, knowledge from experts, and internal documents and data available within HMC.
Through online literature research, on previously published papers, theses, and studies, regarding the characteristics of e-fuels and the energy characteristic of large offshore construction vessels, an overview of the input variables and constants is created. During the online literature research, the repository of the Delft University of Technology is used, where theses, dissertations, and other research papers written at the university are published. Studies published by organizations such as DNV, IMO, and EDF, which elaborate on the future of the maritime sector and ways to make the sector more sustainable by making use of e-fuels, are also utilized. Lastly, the Google Scholar database is used, which gives access to many scientific publications. The keywords listed below are utilized during the online literature study to obtain the required information and data.
During the conversations with experts, stated in Appendix A, notes are taken, which are hereafter analyzed by comparing them to findings from the online literature research. Hereby more insights are created regarding certain technologies, and required input values for the model are obtained.
Since HMC is a company with its own fleet, much data and knowledge are present within the company, which are utilized to help form the fossil base case. This data is available within the internal database of HMC and is available for all employees.

Keywords - *Electrofuels for shipping, marine fuel, e-diesel, e-LNG, e-methanol, e-ammonia, e-hydrogen, sustainable shipping, fuel storage, fuel piping, marine diesel engine, PEMFC, SOFC.*

During the literature phase, the second and third sub-questions of this research are answered, and similar to the model phase, this phase is also performed in several steps:

1. **Identify currently used fossil fuels on large offshore vessels.**
To identify the currently used fossil fuels and obtain their characteristics, use is made of the databases and studies mentioned above and of the in-house knowledge present within HMC, as their vessels currently operate on fossil fuels. It is important to look into the fossil fuels currently used on large offshore vessels, as the characteristics of these fuels will form input for the base case, to which the e-fuels will, later on, be compared.
2. **Form initial selection of available and suitable e-fuels.**
Various e-fuels that are available and suitable to be implemented on large offshore vessels are identified, and a general description, as well as an overview of their properties, is given. Additionally, the possible e-fuel conversion pathways that are expected to be available within the set time frame of this study and their efficiencies are given as well. The properties, pathways, and efficiencies are used to determine the required modifications on the vessel and are compared to fossil fuel properties to eventually obtain the KPIs and the impact of implementing an e-fuel.
3. **Examine and identify the energy characteristics of large offshore construction vessels**
The energy characteristics of a vessel that are considered in this study are the energy profile and Tank-to-Exhaust (TTE) energy infrastructure. These characteristics are obtained by examining the large offshore vessels of HMC. The energy profile of a large offshore vessel is used to determine the energy consumption and emissions within a certain time period and, eventually the capacity to be retrofitted. The energy infrastructure gives an overview of several components, such as the fuel storage, fuel piping and energy conversion unit, of a vessel operating on a fossil fuel. This energy infrastructure will form the basis of the technical evaluation and is used to determine what modifications are required to implement an e-fuel.
Since HMC has several large offshore construction vessels in its fleet, many documents, data, and knowledge are available. Therefore, mostly an in-house study within HMC is performed to create an overview of the energy profile and energy infrastructure.

The knowledge and data obtained during this phase of the study are utilized as input constants and variables for the model. Additionally, the energy profile and infrastructure of a large offshore construction vessel are used, together with the characteristics of the fossil fuel, to create the base case.

By identifying several e-fuels, their possible energy conversion pathways, and the time frame within which they are expected to be ready to be implemented on a large offshore vessel, sub-question two is answered. Additionally, by identifying energy characteristics of large offshore vessels that are relevant in the case of implementing an alternative fuel, sub-question three is answered. The literature study exists out of Chapter 3 and Chapter 4.

Phase 3 - Feasibility assessment

The third phase is the feasibility assessment phase. During this phase, all data and knowledge obtained during the literature phase is utilized to perform a technical and financial evaluation. During the technical evaluation, modifications to the fossil base case required to implement an e-fuel are identified. Hereafter, the total costs of implementing an e-fuel are determined. By combining both evaluations and utilizing the results as input for the model, the impact of implementing an e-fuel can be determined on the vessel as well as for the vessel owner.
During the feasibility assessment phase, sub-question four of this research is answered.

1. **Technical evaluation.**
Each e-fuel requires a specific energy infrastructure, which must be compatible with the e-fuel and in line with health and safety measures. By using the TTE infrastructure and energy profile of the fossil base case in combination with the characteristics of an e-fuel, the modifications required to implement an e-fuel are obtained. Since the TTE infrastructure contains many components, the focus is on the largest components likely to have the largest impact, which are the fuel storage tanks, the energy conversion unit, and the fuel piping.

2. **Financial evaluation.**
   The costs of implementing an e-fuel are identified during the financial evaluation. These costs consist of capital expenditures (CapEx) of each modification, operational expenditures (OpEx) of the components, and OpEx related to the e-fuels. By the CapEx and OpEx of each e-fuel, the financially most attractive e-fuel can be determined. Through an online study as well as by talking with cost experts within and outside of HMC, assumptions are made regarding the future e-fuel, MGO, and EU ETS prices, and values are obtained for the CapEx and OpEx of the modifications and components.

The technical and financial evaluation are conducted in a case study on one of the large offshore construction vessels of HMC, as it will represent the group of large offshore construction vessels. The results of the case study are utilized to give a general indication regarding the impact of implementing an e-fuel on other large offshore vessels. Additionally, the case study falls within the context of HMC and is executed such that the results can be validated by sustainability, retrofit, and cost experts within HMC, familiar with the vessel. During this case study, all obtained data during the literature phase, together with a technical and financial evaluation performed on the vessel, are used as input for the model. Relevant data or information required of the vessel to execute the case study is obtained from an in-house database within HMC. The model is then utilized as a supportive tool to determine the set KPIs, with which, in the end, the impact of each e-fuel can be obtained.

An overview of the required modifications is created by evaluating what modifications are required to implement an e-fuel on a vessel operating on a fossil fuel. The total implementation costs are obtained by identifying the OpEx and CapEx associated with implementing each e-fuel pathway, and an answer to sub-question four is obtained. The feasibility assessment is further touched upon in Chapter 5, 6 and 7.

Phase 4 - Evaluation

The last phase of this research is the validation phase. In this phase, the results from the case study are all obtained and compared to a fossil base case to obtain the impact of implementing an e-fuel. Additionally, the results are evaluated to ensure that the input values, method, and model used in this study do not contain any inaccuracies and the results potentially represent a real-life scenario. If the results are validated, the model could be used on other large offshore vessels and by other companies and organizations active in the maritime sector.

Prior to the evaluation, a sensitivity analysis is performed. During this sensitivity analysis, variable input values that are estimated and thus form an uncertainty in the model, such as the e-fuel prices, are altered to better understand the influence that these estimated values have on the results. By performing a sensitivity analysis, insights are created regarding how the impact of implementing an e-fuel varies, with deviating input values.

The input values, the methodology, and hereby also the results are evaluated through an input and face validation, hereby a group of experts, mentioned in Table A.1, examines the input values, the model, the results of the technical as well as financial evaluation and the results [117]. The experts within HMC are familiar with the vessel on which the case study is performed and all have expertise on making large offshore construction vessels more sustainable, making them suited to evaluate the results.

Lastly, a discussion and conclusion are written regarding the findings of this research. The assumptions and flaws of this study are discussed in the discussion, and in the conclusion, the key findings of this research are summarised. Lastly, several considerations for future research are given as well.

In the evaluation phase, the main research question is answered. By obtaining the results from the case study, validating them, and comparing them to a fossil base case, the techno-economic impact that the implementation of an e-fuel has, both on the vessel and the vessel owner, is obtained. The validation phase is further touched upon in Chapter 8, 9, and 10.

1.6. Scope of the research

To answer the sub-questions and, ultimately, the main research question of this study, a research scope is defined to set the broad outlines of the project. By doing so, several boundary conditions are set regarding different aspects of the research, which are discussed below.

- **A time frame of 0-10 years is utilized in this study**
  This time frame is chosen, in discussion with sustainability experts, as it is a realistic time frame within which several e-fuel energy conversion pathways, will be ready to be implemented on a large offshore construction vessel.
- **Assumptions are made regarding the future MGO, e-fuel as well as the future EU ETS price and e-fuel availability.**
  Since a time frame is chosen between 0-10 years, certain assumptions will have to be made regarding the future availability of each e-fuel. This research assumes that each e-fuel will be available in the set time frame. The future e-fuel, MGO and EU ETS prices are based on historical data as well as market outlooks adopted from literature.
- **This study will only focus on large offshore construction vessels.**
  As this study is performed within the context of HMC, and their SSCVs are the most carbon-intensive vessels in their fleet, HMC is looking into making these vessels more sustainable to reach its carbon abatement goals. Besides, large offshore vessels are significant contributors to GHG emissions originating from the maritime sector and since the SSCVs of HMC fall within this category, they are looked into and will represent this category.
- **Only the technical and financial aspects of implementing an e-fuel are considered.**
  The method and model used and designed for this study are mainly intended for companies active in the maritime sector, however, they could also be adopted by organizations and other stakeholders active in the maritime sector. Since the implementation of an e-fuel will mostly affect them financially, which depends on the technical modifications on the vessel, only these two aspects are considered.
- **The KPIs set for this study are particularly relevant for companies active in the maritime sector and with their own fleet.**
  The KPIs are obtained after consulting sustainability experts within HMC. This study uses HMC as a generic example of other companies active in the maritime sector. Therefore, the KPIs, which are set up together with HMC, are taken as generic for every company active in the maritime sector and with large offshore vessels in its fleet.
- **Only required modifications to the TTE infrastructure are considered during the technical evaluation.**
  Only modifications necessary to the TTE infrastructure will have an impact on the vessel or vessel owner. During the technical evaluation, only components, such as piping, energy conversion unit and fuel storage, that are selected after consulting retrofit experts within HMC, are taken into account during this study.
- **The model and methodology of this study are designed to evaluate the impact of implementing an e-fuel on one vessel at a time.**
  The model and methodology can be utilized by companies or other stakeholders involved in making large offshore vessels more sustainable by implementing an e-fuel, as a supportive tool to base decisions on regarding what e-fuel to implement. Due to the fact that certain input values of the model are vessel specific, the actual impact for the vessel owner and for the vessel is also vessel specific. Therefore, the model and methodology can only be used to base decisions on one vessel at a time.

By making use of the methodology, discussed in sub-chapter 1.5, the research gap, discussed in sub-chapter 1.2, is filled and answers to the research questions are obtained, within the scope of this research. By answering the research question and designing a methodology as well as a model to evaluate and quantify the impact of implementing an e-fuel on large offshore vessels, this study academically and scientifically contributes to research and development regarding the implementation of e-fuels, and the challenge of decarbonizing the marine sector.

1.7. Structure of the research

In this section, the structure of this research is shortly elaborated on. The four phases, discussed in section 1.5, will form the guideline for the following chapters of this research.

The model phase is discussed in Chapter 2, which will elaborate on the working principles as well as the input and output of the model. In this chapter, an answer to the first sub-question is given as well.

The literature phase is discussed more extensively in Chapter 3 and Chapter 4, where information and data regarding the various fuels as well as large offshore construction vessels is obtained. In these chapters, answers to the second and third sub-question are given as well.

The feasibility assessment phase is discussed in Chapter 5, Chapter 6 and is completed by Chapter 7. Initially, the technical evaluation is touched upon, followed by the financial evaluation and lastly, both evaluations are executed in a case study. In these chapters, an answer to the fourth research question is given as well.

The validation phase is discussed in Chapter 8, where the results of the case study are shown and elaborated on. Additionally, the results are also validated in this chapter.

Lastly, the conclusion and discussion, including recommendations for future research, are touched upon in Chapter 9 and Chapter 10. In the conclusion, the answers to the sub-questions as well as to the main research questions, are given.

2 Evaluation model

In this chapter, a description of the working principles and methodology behind the model used in this research are given. During this research, a model is used as a supportive tool, which makes use of several input variables and constants to obtain the set KPIs. The KPIs are the model's output and are used to quantify and evaluate the impact of implementing an e-fuel on large offshore vessels.

The model is intended as a tool for stakeholders that are actively involved in reducing emissions from the maritime sector, such as companies like HMC, that operate in the maritime sector and have large offshore vessels in their fleet. The model can be used to determine the impact that the implementation of an e-fuel has on the vessel as well as for the vessel owner. Based on multiple conversations and brainstorming sessions with sustainability experts, the factors that are important to a company with large offshore vessels when looking into implementing an alternative fuel are determined. These factors are quantified in the form of several KPIs by making use of a model. Based on these KPIs, vessel owners can substantiate certain decisions related to reducing vessel emissions by making use of an e-fuel.

Initially, in sub-chapter 2.1, the required input variables and constants to obtain the set KPIs are touched upon. Hereafter, in sub-chapter 2.2, the output of the model, which in this research are several KPIs, are elaborated on. Lastly, the working principles regarding how certain KPIs will be obtained by using the model's input values will be elaborated on in sub-chapter 2.3. In the final phase of this study, the model and the results of a case study performed on one of the SSCVs of HMC are evaluated by sustainability, retrofit, and cost experts within HMC.

In Figure 2.1, a structured overview of the necessary input values for the model and the set KPIs is given. As can be seen, the input values are categorized into three different groups and are used to perform the technical and financial evaluations.

This chapter answers the first sub-question, which was mentioned in section 1.3.2:

- *How can the techno-economic impact, for both the large offshore construction vessel and the vessel owner, of implementing an e-fuel be evaluated?*

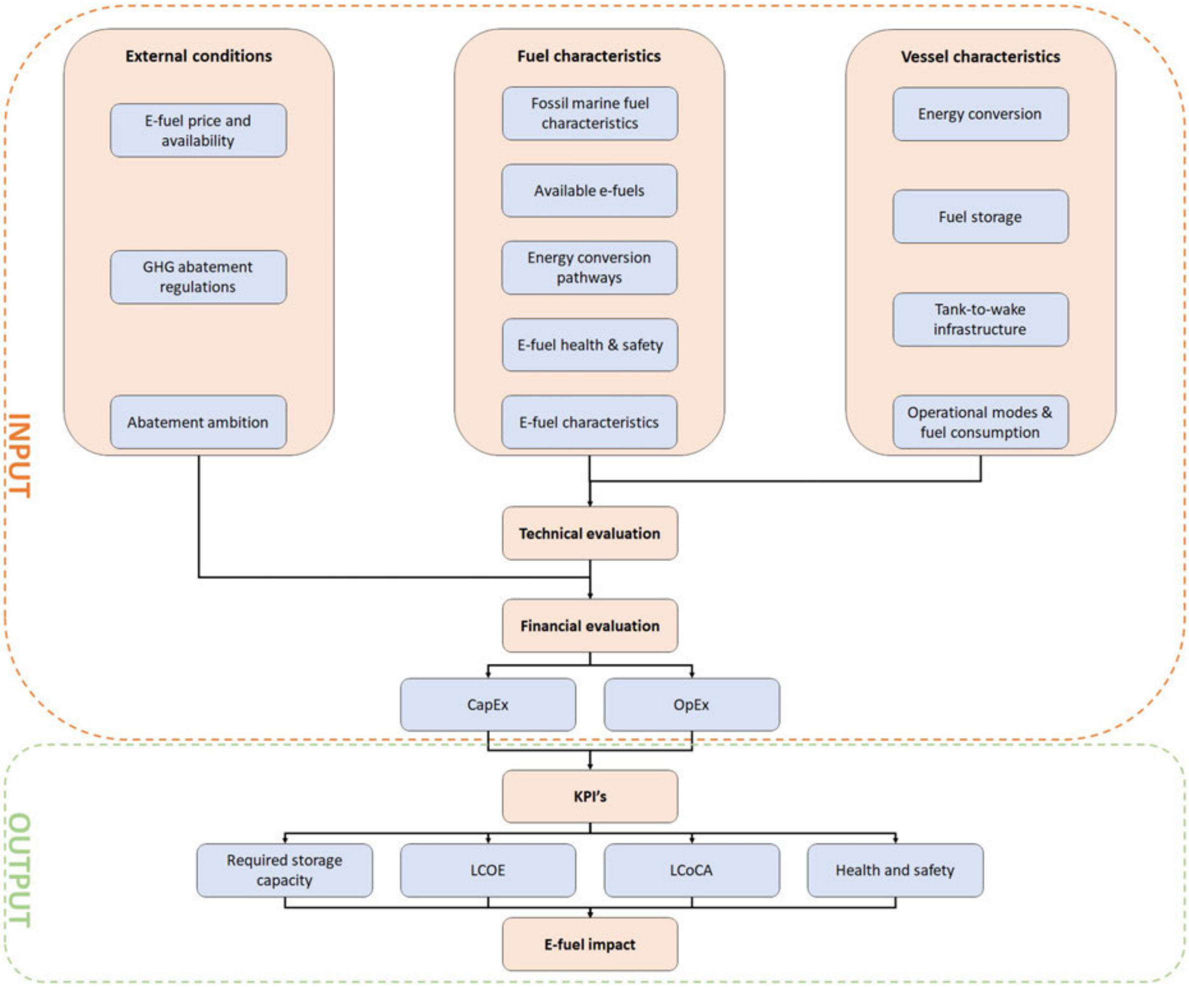

Figure 2.1: Structured overview of the input and output of the model

2.1. Input

In this section, the different input variables and constants necessary to determine the set KPIs and, eventually, the impact that implementing an e-fuel has, are shortly discussed. As could be seen in Figure 2.1, the input values are divided into three different categories, which are all discussed in this section. The input values from the three categories are used to create a base case and perform the technical and financial evaluation. The technical and financial evaluation results are also used as input in the model. The model combines all these input values to obtain the set KPIs eventually.
Initially, the input from the scenario conditions is touched upon in section 2.1.1, followed by the fossil marine fuels & E-fuels and vessel characteristics in sections 2.1.2 and 2.1.3. Lastly, the financial and technical evaluation is discussed in sections 2.1.4 and 2.1.5.

2.1.1. External conditions

In this study, the external conditions are utilized to simulate several future scenarios. The external conditions are input variables such as abatement ambitions, GHG abatement regulations, and future e-fuel prices as well as availability. Due to the time frame of 0-10 years used in this research, certain assumptions regarding these external conditions will have to be made based on current and historical data.
The external conditions are included in this research as they have a financial impact on the vessel owner, as a higher e-fuel price will have a larger impact and will therefore be less attractive to implement. Based on the fossil fuel, e-fuel, and EU ETS price, the financial incentive of implementing an e-fuel can be determined. The external conditions are shortly elaborated on below.

- **E-fuel price and availability**
  As a time frame of 0-10 years is set for this study, assumptions will have to be made regarding the e-fuel price and availability. The e-fuel price significantly impacts the KPIs, as e-fuels with low acquisition costs will be financially more attractive to implement than e-fuels with high acquisition costs.
  In this study, the assumption is made that every e-fuel is available within the set time frame since the production process of these e-fuels is known, and thus the only limiting factor will be the available green energy and CO_2 from a renewable source.
- **GHG abatement regulations**
  Regulations covering GHG emissions in the maritime sector are factors that companies such as HMC do not influence, however still affect them. The maritime sector is likely to be included in the EU ETS, for example, resulting in companies having to pay for the CO_2 they emit and higher fossil fuel prices. As such regulations will have an effect on fossil fuel prices, they are included in this study.
- **Abatement ambition.**
  The abatement ambition indicates how much of the vessel emissions should be abated by making use of an e-fuel. Based on this ambition, the capacity to be retrofitted can be determined, which has an effect on the required amount of e-fuel as well as on the required modifications on the vessel. The abatement ambition is a variable input value as each model user has its own ambition.

2.1.2. Fuel characteristics

The next category of input values is input from the currently used fossil fuels, on large offshore vessels, and from the e-fuels. These input values range from properties of the fuels to efficiencies that are associated with certain production processes. Initially, fossil fuels are touched upon, followed by e-fuels.

Currently used fossil fuels

An overview is created of the fossil fuels used in the maritime sectors as well as by HMC. Since this study is performed within the context of HMC and a case study is executed on of their vessels, the fossil fuels used on HMC's vessels are mainly focused on. Once these fuels are identified, their characteristics are obtained and used as input for a fossil base case. The base case describes the current situation on board of a large offshore vessel and is used as input for the model as a reference scenario to which each e-fuel scenario can be compared. By comparing the characteristics of a fossil fuel with the characteristics of an e-fuel the required modifications on the vessel as well as the realized emission abatement can be obtained.

E-fuels

Just as with the currently used fossil fuels, literature research is executed and combined with in-house knowledge present within HMC, to identify available and suitable e-fuels that could replace the currently used fossil fuels.
Through online literature research, characteristics that are relevant during the implementation of an e-fuel are summarized. These characteristics act as input for the model, where they are used to obtain the set KPIs. However, these characteristics are also used to determine if a certain component in the fuel infrastructure of a fossil-fuelled vessel is compatible with the e-fuel.
Besides the characteristics of the e-fuels, the hazards, such as toxicity and flammability, posed by each e-fuel are also looked into. These factors are important since health and safety measures currently equipped on a vessel operating on a fossil fuel might not be sufficient in case an e-fuel is implemented.

Lastly, each e-fuel has several options regarding how the chemical energy stored in the e-fuel can be converted into mechanical energy and utilized on the vessel. The possible pathways depend on the e-fuel, as some can only be utilized directly in an energy conversion unit, whereas others can also function as a hydrogen carrier. The efficiencies associated with each pathway are also obtained, and based on the total pathway efficiency, the amount of an e-fuel required to retrofit a certain capacity can be determined.

Each pathway's Technological Readiness Level (TRL) is also looked into. The TRL of each pathway is obtained in multiple discussions with sustainability experts and is used to identify which pathways are available to be implemented on a large offshore vessel within the set time frame of this study.

2.1.3. Vessel characteristics

The vessel characteristics are subdivided into the energy infrastructure and the energy profile of a large offshore vessel.
Initially, the TTE energy infrastructure of a large offshore vessel is investigated, and components that play a role in case an e-fuel is implemented are identified. The focus is on the energy conversion unit, the fuel storage tanks and the fuel piping infrastructure, as these are the main components. Modifications to these components will have the largest impact both on the vessel and vessel owner. To evaluate the required modifications to these components in case an e-fuel is implemented, the characteristics of these components, such as the materials they are made of and certain health and safety measures, are investigated as well. The TTE energy infrastructure of a vessel operating on a fossil fuel is part of the base case and is the starting point for the technical evaluation. Based on the fossil TTE energy infrastructure, the fossil fuel characteristics, and the characteristics of an e-fuel, the required modifications to implement an e-fuel are obtained.
To get a better understanding of the energy profile of a large offshore vessel, the fuel consumption during each operational mode and the occurrence of each operational mode is looked into. Additionally, the loads present on a large offshore construction vessel and their occurrence during the operational modes are also obtained. Based on this data, the emissions per operational made are determined, as well as the average load present during an operational mode. Hereby, the capacity to be retrofitted to comply with a certain abatement ambition is obtained.

2.1.4. Technical evaluation

In the technical evaluation, data from the fuel and vessel characteristics are combined to evaluate what modifications are necessary if an e-fuel is implemented on a vessel. The base case, which includes the energy profile and infrastructure of a vessel operating on a fossil fuel, is the starting point of the technical evaluation. The modifications are determined based on the characteristics of an e-fuel combined with the efficiencies of the e-fuel's pathway.
The output of the technical evaluation, which are the required modifications, is utilized as input for the financial evaluation, which is the consecutive step of the research. The technical evaluation is performed on one of the large offshore construction vessels of HMC in a case study.
The required technical modifications to implement an e-fuel have an impact on the vessel as well as on the vessel owner, as additional CapEx is needed, which increases the total implementation costs.

2.1.5. Financial evaluation

The financial evaluation is the last source of input values required for the model. The associated costs can be obtained when all technical modifications related to a certain e-fuel pathway are identified. The CapEx are costs related to modifications or replacements of components in the energy infrastructure. Whereas the OpEx is related to the repair and maintenance of specific components as well as the costs related to the acquisition of an e-fuel. The CapEx, as well as the OpEx, are used as input in the model, as together they form the implementation costs of an e-fuel and they influence the financial KPIs.
Just as the technical modification, the financial evaluation is executed on one of the large offshore construction vessels of HMC in a case study.

2.2. Output

This section discusses the model's output, which is in the form of several set KPIs. Once the case study results are obtained, a sensitivity analysis is performed to see how the results change in case certain input variables are modified. Lastly, the input values, the methodology, and the model are evaluated by sustainability, retrofit, and cost experts, to determine if the results are representative of a real-life scenario.

2.2.1. Key Performance Indicators (KPIs)

All the aforementioned input values are combined to obtain the KPIs. The set KPIs are determined after consulting sustainability experts within HMC and are factors on which companies active in the maritime sector and with their own fleet, can base decisions on when looking into implementing an e-fuel to reduce their vessel emissions. The KPIs are used to quantify the techno-economic impact that implementing an e-fuel pathway has on the vessel as well as for the vessel owner.
An overview of the KPIs considered in this study and their unit of measure as well as a short description of each KPI is given below.

1. **Required storage capacity *[L or m^3]***
   - Indicates the volume occupied by the entire storage system of an e-fuel on the vessel.
   - Considered since there might be a limit regarding the available storage space on a vessel, which might complicate implementing an e-fuel pathway.
   - Used to evaluate if the volume of the fossil fuel storage is sufficient in case an e-fuel is implemented. Modifications to the fuel storage system have an impact on the vessel and on the vessel owner, as additional CapEx is required.
2. **Tank-to-wake CO_2 emissions *[Kg CO_2]***
   - Indicates the emitted CO_2 in case use is made of a fossil fuel as well as the abated CO_2 in case a certain capacity is retrofitted by making use of an e-fuel.
   - Considered since companies with their own fleet will be sanctioned for the amount of CO_2 they emit [47].
   - Used to evaluate the abated emissions by making use of an e-fuel as well as the environmental impact of an e-fuel. The abated emissions have an impact on the vessel owner, as fewer carbon offsets will have to be purchased.
3. **Health and safety *[1<x<10]***
   - Since the health and safety factors of an e-fuel have no unit of measure, a value (x) between 1 and 10 is used to evaluate the e-fuel, where 1 indicates the least hazardous e-fuel and 10 the most hazardous.
   - Considered since the energy infrastructure must be compliant with health and safety measures and the working crew on the vessel as well as aquatic life, should be protected at all costs.
   - Used to evaluate the hazards of each e-fuel compared to the currently used fossil fuel and if the fossil fuel infrastructure is compliant with the required health and safety measures of an e-fuel. Health and safety modifications have an impact on the vessel and on the vessel owner as additional CapEx is required.
4. **The Levelized Cost Of Electricity (LCOE) *[Eur./kWh]***
   - Indicates a price per amount of energy, as the sum of the costs over the lifetime of the system is divided by the sum of the energy produced by the system over its lifetime.
   - Considered as it takes the total costs as well as the required energy of an e-fuel pathway into consideration, and thus indicates a financial incentive of implementing an e-fuel compared to a fossil fuel.
   - Used to evaluate the financial incentive of implementing an e-fuel compared to a fossil base case.

5. **The Levelized Cost of Carbon Abatement (LCoCA)** ***[Eur./Kg CO_2]***
    - Indicates the investment necessary to abate one mT of CO_2. An actual reduction of CO_2 must be realized, therefore each e-fuel pathway is compared to the fossil base case.
    - Considered since the investment costs and abated carbon for each e-fuel pathway are combined and can be compared to each other as well as to a base case.
    - Used to evaluate the costs as well as abated emissions with a fossil base case, hereby indicating a financial incentive to implement an e-fuel.

Based on the outcome of the aforementioned KPIs, certain e-fuel pathways could be labeled as less suitable, as their implementation is less realistic from a technical or financial perspective. This can be done to narrow down the number of pathways and eventually select several pathways that show the highest potential to be implemented.

2.3. Model methodology

This sub-chapter discusses the methodology behind the model regarding how the input values are utilized to determine the set KPIs. Several formulas are shown that are used in the model to determine intermediate values or the set KPIs.

Initially, the required energy is calculated in the model, which indicates the energy needed for each e-fuel energy conversion pathway to make a certain capacity more sustainable. The required energy is calculated by making use of Equation 2.1. After determining a capacity to be retrofitted, by making use of an e-fuel, this capacity is multiplied by the bunkering frequency of the vessel, the average engine utilization and the power requirements of a CCS system, which is an optional addition. Dividing by the total pathway efficiency results in the energy required for each e-fuel pathway.
Hereafter the required storage capacity is obtained by making use of Equation 2.2, where the required energy is divided by the volumetric energy density of the e-fuel.

By making use of the required energy and properties of the e-fuel, the tank-to-wake CO_2 emissions can be determined. The emitted CO_2 is calculated by making use of Equation 2.3 and is determined for the same period of time as the required energy was calculated for, which is the bunkering frequency. To completely ensure a zero-carbon e-fuel or realize a negative-carbon e-fuel, a carbon capture storage system (CCS) can be added to the energy conversion pathways of the carbon-containing e-fuels, however, adding a CCS system is optional. If the abatement ambition, the amount of emitted CO_2, and the efficiency of the CCS system are all known, the CCS system can be sized such that the necessary amount of CO_2 is captured to comply with the abatement ambition.

The variables for the three equations, as well as their unit and a short description, are given below the equations.

$$E_{\text{required}} = \frac{C \,*\, f_{\text{bunkering}} \,*\, U}{\eta_{\text{TTW}}} * (1 + P_{\text{CCS}}) \tag{2.1}$$

$$V_{\text{storage}} = \frac{E_{\text{required}}}{E_{\text{D-volume}}} \tag{2.2}$$

$$E_{CO_2} = \frac{E_{\text{required}}}{E_{\text{D-gravimetric}}} \,*\, EF_{\text{TTW}} \tag{2.3}$$

Symbol	Unit	Explanation
$\mathbf{E_{required}}$	*MWh*	*Energy required to retrofit a capacity.*
C	*MW*	*Capacity that is retrofitted*
$\mathbf{f_{bunkering}}$	*Hrs.*	*Period of time between refuelling*
U	*%*	*Utilization of the engines*
η_{TTW}	%	*Total TTW efficiency of e-fuel pathway*
$\mathbf{P_{CCS}}$	%	*Power requirement of the CCS system (optional)*
$\mathbf{V_{storage}}$	m^3	*Volume required for storage system*
$\mathbf{E_{D\text{-}volume}}$	kWh/m^3	*Volumetric energy density of e-fuel*
$\mathbf{E_{CO_2}}$	mT CO_2	*Emitted tonnes of CO_2*
$\mathbf{E_{D\text{-}gravimetric}}$	kWh/m^3	*Gravimetric energy density of e-fuel*
$\mathbf{EF_{TTW}}$	kg CO_2/kg e-fuel	*Ratio of emitted kg CO_2 per kg fuel*

The LCOE is a KPI where the CapEx and OpEx, related to the implementation of an e-fuel pathway, are divided by the energy produced by the energy converters in case a specific e-fuel pathway is implemented.
The produced energy by the energy converters is calculated in the same way as the required energy is calculated, however, the TTW efficiency is left out. Due to the sums, present in the LCOE, the calculation can be split up. The produced energy remains the same, however, a separate LCOE can be calculated for each modification. In the end, all these separate LCOE can be summed up again to obtain the total LCOE for an e-fuel pathway.
Equation 2.4 is used to calculate the LCOE and below the equation the input variables, their unit and a short description is given.

$$LCOE = \frac{sum\ of\ cost\ over\ lifetime}{produced\ energy\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2.4}$$

Symbol	Unit	Explanation
LCOE	Eur./kWh	*Levelized Costs Of Electricity*
$\mathbf{I_t}$	Eur.	*Investment costs*
$\mathbf{M_t}$	Eur.	*Operating and maintenance costs*
$\mathbf{F_t}$	Eur.	*Fuel costs*
$\mathbf{E_t}$	MWh	*Energy produced by system*
r	%	*Discount rate*
t	Year	*Operational year of the system from 1 to n years*
n	Years	*Total lifetime of the system*

As the LCoCA is only valid in case there is an actual reduction of CO_2, the e-fuel pathways must be compared to the fossil base case [36]. The LCoCA is a KPI that compares the costs as well as the emissions of an e-fuel pathway with those of the fossil base case and gives insight into how large of an investment is required to abate one mT of CO_2.
As becomes clear from Equation 2.6, the value of the LCoCA can become negative if either the costs related to implementing an e-fuel pathway are lower than they are for the base case, or if the CO_2 emissions for an e-fuel pathway are higher than they are for the base case.
As the LCoCA is determined on a yearly basis, the CapEx of each pathway is annualized and spread out over the lifetime of the pathway, for which in this study the lifetime of the energy conversion unit is adopted. To obtain a yearly CapEx payment, a capital recovery factor is used, which gives a ratio of a constant series of payments at equal intervals with a certain discount factor and is depicted in Equation 2.5. For this study a discount factor of 8.5% is adopted, which also used by HMC.

$$CRF = \frac{i(1+i)^{\mathrm{n}}}{(1+i)^{\mathrm{n}}-1} \tag{2.5}$$

$$LCoCA = \frac{(C_1 - C_0)}{(E_{\mathrm{CO_2\text{-}0}} - E_{\mathrm{CO_2\text{-}1}})} \tag{2.6}$$

Symbol	Unit	Explanation
CRF	-	*Capital Recovery Factor*
i	%	*Discount factor*
n	Years	*Lifetime of the pathway*
LCoCA	Eur./mT CO_2	*Levelized Cost of Carbon Abatement*
$\mathbf{C_1}$	Eur./year	*Yearly cost of implementing an e-fuel pathway*
$\mathbf{C_0}$	Eur./year	*Yearly cost of base case*
$\mathbf{E_{CO_2\text{-}1}}$	mT CO_2	*CO_2 emissions of e-fuel pathway*
$\mathbf{E_{CO_2\text{-}0}}$	mT CO_2	*CO_2 emissions of base case*

3 Fuels

This chapter gives an overview of the currently used fossil fuels in the maritime sector and the available and suitable e-fuels. Sub-chapter 3.1 elaborates on the currently used fossil fuels in the maritime sector. This is done to see where the industry is currently at and to form a fossil base case used to compare the e-fuels, in this research. Hereafter, in sub-chapter 3.2, several e-fuels, that are suitable and available, are further examined. Initially, a short description of each e-fuel is given, followed by their characteristics and health and safety properties. Some pathways also include a CCS system, which is elaborated on in section 3.2.6. To summarize this chapter, an overview of all possible energy conversion pathways of the selected e-fuels is given as well as a conclusion in sub-chapter 3.3.

This chapter answers the second sub-question, which was mentioned in section 1.3.2:

- *Which e-fuels are suitable and expected to be available to implement on large offshore construction vessels?*

3.1. Currently used fossil fuels

Currently, the most commonly used fuels in the shipping industry are fuel oils, such as heavy fuel oil (HFO), light fuel oil (LFO), MGO, and LNG. All these fuels contain carbon and thus emit CO_2 as well as other greenhouse gasses. The amount and type of GHG (CO_2, SO_x, NO_x or CH_4) that is emitted, depends partly on the fuel type and efficiency during combustion and partly on the combustion characteristics and the after-treatment system used in combination with the engine. Due to increasingly strict regulations regarding emission limits of these GHGs, shipowners and stakeholders are forced to look at alternative fuel options, to comply with these regulations. In 2020 only a very small percentage, approximately 0.09%, of the shipping industry was powered by alternative fuels [123]. An overview of the fuel share of the most used fossil fuels in the shipping sector in 2020, is depicted in Figure 3.1.
In 2020 the total fuel consumption of the marine sector was approximately 202.5 million mT, which mostly consisted of either HFO or LFO [150]. Additionally, the fuel share of HMC is also depicted and as can be seen, in 2022 HMC only operated on MGO and LNG. The share of HMC to the total fuel consumption of the marine sector is approximately [redacted].

Since this study is performed at HMC and a case study is executed on one of the SSCVs of HMC, only MGO and LNG are shortly touched upon. Information regarding the other currently utilized fossil fuels in the marine sector, is given in Appendix B.

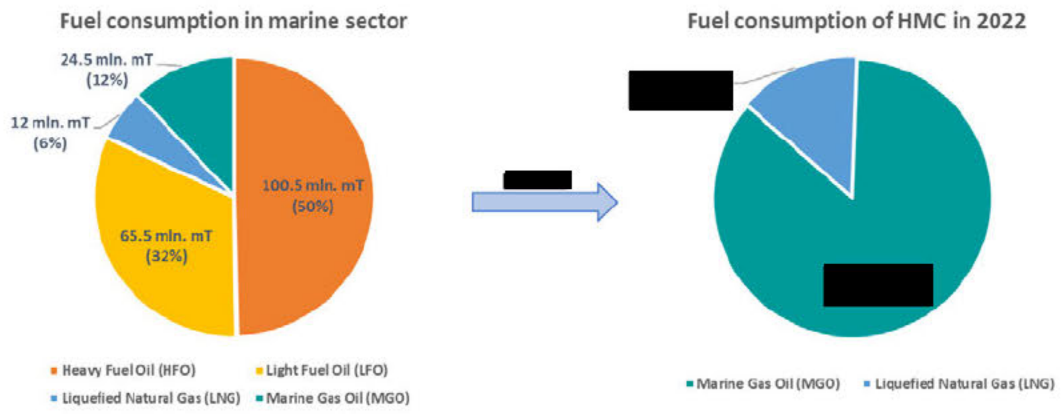

Figure 3.1: Maritime sector fossil fuel share in 2020 and the 2022 fuel share of Heerema

3.1.1. Fuel oils

HFO, LFO and MGO are all different types of fuel oil. As shown in Figure 3.1, fuel oils are currently the most dominant fuels in the shipping industry. These types of fuels started to gain traction after the Second World War and because vessels are known to have long lifetimes, a large share of the vessels currently operational still use fuel oils. These fuel oils often go hand in hand with high sulfur content, resulting in high SO_x emissions, in addition to the large CO_2 emissions. Over time, more sophisticated fuel oils were developed to meet the stricter emission regulations [89].

Marine Gas Oil

MGO is a distillate fuel, as it consists entirely or partly out of a blend of distillates, which are components from crude oil that evaporate during distillation and are then condensed back to a liquid oil. Marine Diesel Oil (MDO) is a fuel that is very similar to MGO, the only difference is that MGO entirely consists of several distillate blends and MDO consists out of a mixture of distillate blends and HFO [159]. MGO can be produced with ranging degrees of sulfur, however its maximum lies below that of HFO, in some cases, MGO can even be considered an ULSFO. On the other hand, MDO has a sulfur content of approximately 2%, and is thus less popular due to the new IMO limits. Both MGO and MDO do not require any heated storage or preheating before being used due to their viscosity [13].

3.1.2. Liquefied Natural Gas

LNG is obtained by cryogenically storing natural gas at a temperature below -162 °C and at atmospheric pressure, thereby liquefying the gas. LNG is a mixture of various gases in a liquid state, however, it consists between 70% and 99% by mass, out of CH_4 [4]. The uptake of LNG as a marine fuel has gained more attention in the last few years, not only because it was commercially appealing and globally available, but also because the implementation of LNG can significantly reduce the NO_x emissions by approximately 85%, whereas the CO_2 emissions are not necessarily reduced, [52]. In addition, since LNG does not contain any sulfur, the SO_x emissions decrease by 100% [52].

Even though the GHG emission reduction advantages of LNG, the usage of LNG as a shipping fuel is still debatable. Due to the high methane content present in LNG, the methane slip, which is the event where methane gas escapes during production, storage or combustion, is higher than for oil-based fuels. Methane slip is extremely harmful to the environment as it has a higher global warming potential than the other GHGs, resulting in more trapped solar radiation and a more negative global warming effect [4].

An overview of several characteristics of the currently used fuels in the shipping sector are listed in Table 3.1, together with their unit and source.

Table 3.1: Characteristics of currently used fuels in the shipping sector

Characteristic	Unit	HFO	LFO	MGO	LNG	Source
Density	*kg / L*	0.938	0.836	0.840	0.440	[134] [125] [108] [124]
Gravimetric energy density	*kWh / kg*	11.22	12.22	11.86	13.67	[16] [155]
Volumetric energy density	*kWh / L*	10.51	10.19	9.96	5.95	-
CO_2 WTW emissions factor	*kg CO_2 / kg fuel*	3.11	3.15	3.21	2.76	[141]
NO_x WTW emissions factor	*kg NO_x / kg fuel*	1.70e-4	1.80e-4	1.80e-4	1.40e-4	[33]
CH_4 WTW emissions factor	*kg CH_4 / kg fuel*	4.04e-3	4.53e-3	4.66e-3	5.34e-2	[33]
CO_2-eq WTW emissions factor	*kg CO_2-eq / kg fuel*	4.01	n.d.	3.25	3.65	[63]

As becomes clear from Table 3.1 each fossil fuel has its own specific emission profile. An important consideration is that the emission factors, shown in Table 3.1, only give a general indication regarding the emitted GHGs, as engine and drive train characteristics also influence the emission factors. By making use of this emission profile as well as other characteristics of the fossil fuels, a base case is created to which the e-fuels can be compared.
Different processes within the production and consumption of a fuel have different emission factors, in this case the emission factors are stated for the well-to-wake process, meaning that emissions in the whole process of fuel production, bunkering and use on the vessel are taken into account. The Well-to-Wake (WTW) process can be subdivided into well-to-tank (WTT) and tank-to-wake (TTW). WTT includes emissions associated with the acquisition of the raw materials used to produce the fuel, production of the fuel, transport and storage of the fuel and lastly, the bunkering of the fuel. TTW includes all onboard emissions associated with fuel storage, energy conversion, and the transfer of energy to the propeller to power the vessel. An overview of the WTW process can be seen in Figure 3.2.

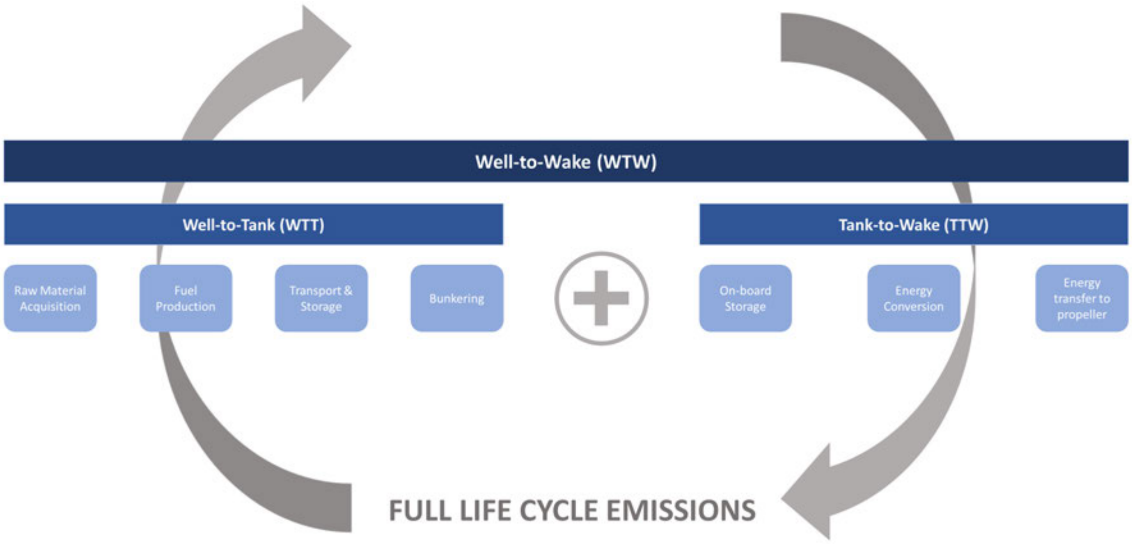

Figure 3.2: Well-to-Wake process for shipping fuels [158]

3.2. E-fuels

In this sub-chapter, several e-fuel are discussed, and their potential to be implemented on large off-shore vessels is examined. First, the working principles of an e-fuel are touched upon in section 3.2.1, hereafter each e-fuel and its production technology are discussed in section 3.2.2. Subsequently, an overview is given of relevant characteristics and health and safety properties of the e-fuels in sections 3.2.3 and 3.2.4. Lastly, the possible energy conversion pathways of each e-fuel are discussed in section 3.2.5. The working principles of the energy conversion units considered in this study are touched upon in Appendix B.

3.2.1. Working principles of e-fuels

E-fuels are a category of synthetic fuels that are characterized by the fact that they are produced from electricity, water and carbon dioxide or nitrogen. Synthetic fuels are fuels that are produced from syngas, which is a blend of carbon monoxide (CO) and H_2 [153]. To realize e-fuels that have a net-zero carbon footprint, the electricity should be generated by renewable sources, such as wind or solar, and the CO_2, used in the production process must be equal to the CO_2 emitted during transport, distribution, storage and combustion of the e-fuel [153]. Additionally, the CO_2 shoul originate from a renewable source. If all conditions are met, an e-fuel can adopt a zero CO_2 WTW emission factor [48], which is also adopted in this study.

There are two main categories where e-fuels can be grouped in, carbon-based and non-carbon-based e-fuels. The carbon-based e-fuels can be produced by combining hydrogen with carbon monoxide or carbon dioxide in diverse chemical processes. Since these type of e-fuels contain a form of carbon, they emit CO_2 during combustion [98].

Non-carbon-based e-fuels, do not contain carbon and thus will not emit any CO_2 during combustion, however they might still emit other GHGs [98]. In the schematic overview, depicted in Figure 3.3, the production routes for different e-fuels are shown.

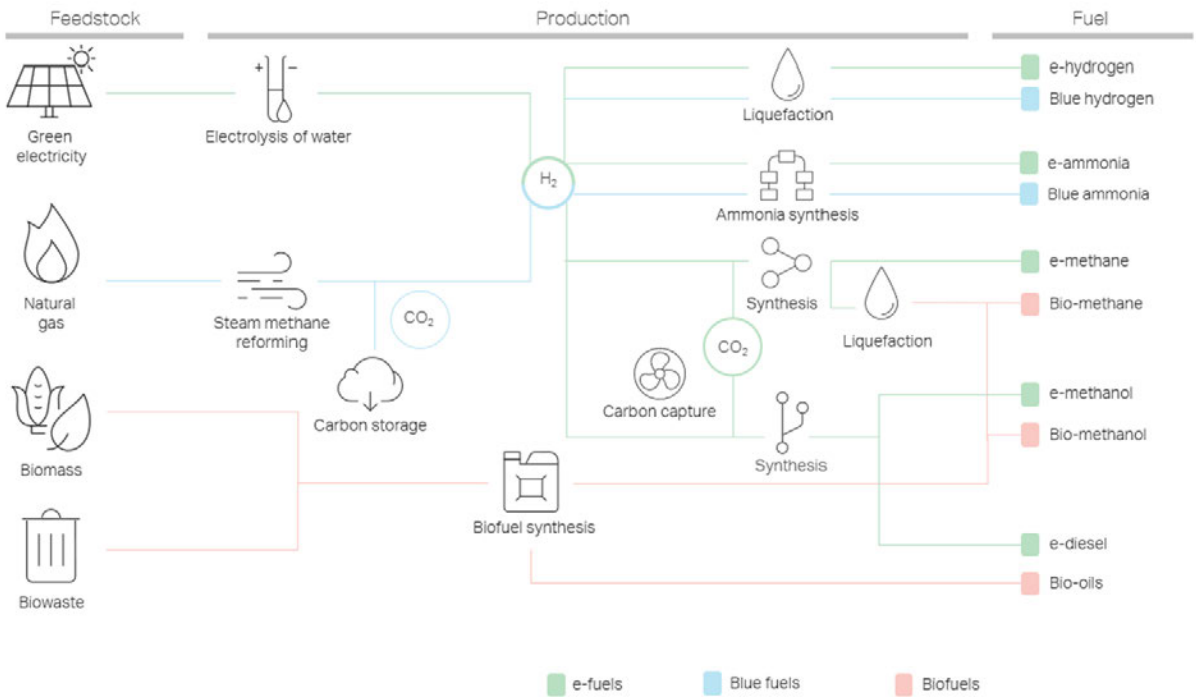

Figure 3.3: Schematic overview of the different e-fuel production routes [26]

3.2.2. Available e-fuels

As mentioned before, there are several different type of e-fuels, all with their own production pathways, properties and associated technologies. In this section, a brief description is given of each e-fuel, first, e-hydrogen is discussed since all e-fuels can be produced from e-hydrogen. Hereafter the carbon-based e-fuels, e-diesel, e-LNG and e-methanol are discussed and lastly, e-ammonia is touched upon. In addition to the e-fuels, liquid organic hydrogen carriers (LOHC) and borohydrides, which are two types of compounds that can chemically store hydrogen, are discussed in Appendix B. At the end of this section, an overview is given of the efficiencies associated with each production step of the e-fuel, in Table 3.2.

E-Hydrogen

E-hydrogen (H_2) does not contain any carbon and will therefore not emit any CO_2 during combustion. The production process of H_2 makes use of mature technologies which are proven at a large scale [98]. The production process is schematically shown in Figure 3.4 and can be divided into several steps.

1. H_2O is split into H_2 and oxygen (O_2) in an electrolyser and by making use of green electricity at an efficiency of approximately 73% [115].
2. The gaseous e-hydrogen is liquefied to obtain liquid e-hydrogen, by a vaporizer or chiller.

Only with modifications and adjustments to an ICE, can e-hydrogen be used as an alternative shipping fuel in an ICE [101]. However, the most efficient way to extract energy from H_2, would be by making use of a fuel cell, whereby the only by-product is water [101].
H_2 is gaseous at ambient conditions and has a critical temperature at -253 °C and can either be stored as a gas or as a liquid. As a gas, H_2 has a very low volumetric energy density, which can be increased by storing the gas under high pressurized (700 bar) conditions. Storing H_2 as a liquid will increase its volumetric energy density, however, a constant temperature of approximately -253 °C is required, thereby increasing the energy demand of the vessel [101].
Some disadvantages of H_2 are its high flammability and high explosion risk and the fact that H_2 is non-toxic, invisible and has no scent, which makes any leaks hard to detect. These characteristics result in additional health and safety measures and regulations that have to be taken onboard of the vessel [101].

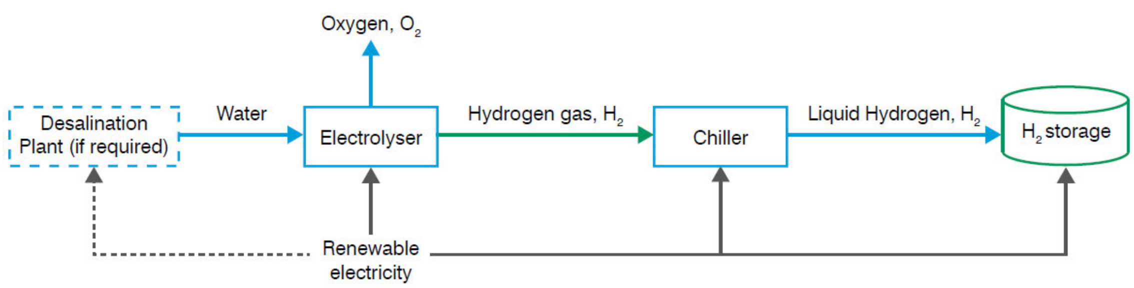

Figure 3.4: Schematic overview of e-hydrogen production [98]

E-diesel

Electro-diesel (e-diesel), is a fuel that is part of the carbon-based e-fuels and thus emits CO_2 when combusted. Since E-diesel and fossil diesel have similar properties the drop-in quality of e-diesel is excellent. Therefore none, or only minor, modifications are required to the energy infrastructure of a vessel operating on MGO and the existing tank-to-wake infrastructure can all be used [103].

A difference between fossil diesel and e-diesel is that e-diesel has a lower content of hydrocarbons, resulting in less NO_x and particle emissions and thus a cleaner combustion. In addition, e-diesel also is a low-sulfur e-fuel, causing the SO_x emissions to be close to zero [17].

The production process of e-diesel is shown in Figure 3.5, and is performed in two consecutive steps.

1. Syngas ($CO + H_2$) production from captured CO_2 and green H_2 through electrolysis.
2. Production of e-diesel through the Fisher-Tropsch process at an efficiency of approximately 50% [160], or through methanol-to-diesel synthesis.

Depending on the e-diesel grade and the fuel cell system, several processing steps will be necessary to obtain an e-diesel with a high enough purity to be used in a fuel cell system. These purification steps will lower the power density and the system's overall efficiency [18]. Even though e-diesel is an inconvenient e-fuel to be used in fuel cells, it is still one of the most researched fuels for marine fuel cell applications, as it is energy-dense and the infrastructure is already fully available.

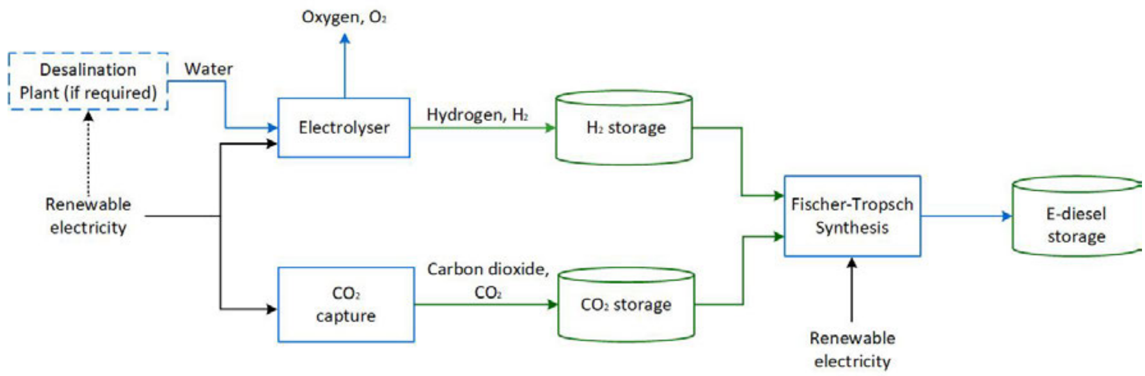

Figure 3.5: Schematic overview of e-diesel production [11]

E-LNG

Electro-LNG (e-LNG), is also part of the carbon-based e-fuels, and just like fossil-LNG, almost entirely consists out of CH_4. Due to the fact that e-LNG consists of the same compounds as fossil-LNG, their characteristics are similar as well. The production process of e-LNG is shown in Figure 3.6 and can be divided into several steps.

1. Syngas ($CO + H_2$) production from captured CO_2 and green H_2 through electrolysis.
2. Sabatier reaction, where natural gas (methane) and water are produced at an efficiency of approximately 83% [93].
3. Liquefaction of natural gas at temperatures below -162 °C, at atmospheric pressure and at an efficiency of approximately 90% [106], to obtain e-LNG.

To obtain e-LNG, natural gas must be liquified at temperatures below -162 °C, therefor storing e-LNG poses similar difficulties as e-hydrogen storage. Like e-diesel, e-LNG is fully blendable with fossil LNG and can therefore be used in existing engines, TTW piping and fuel storage of a vessel operating on fossil LNG [153].
When LNG is in a gaseous state extra safety measurements will have to be taken, as ignitable mixtures could be formed when LNG is mixed with other gases. An advantage of LNG is that it is lighter than air and therefore diffuses quickly [153].

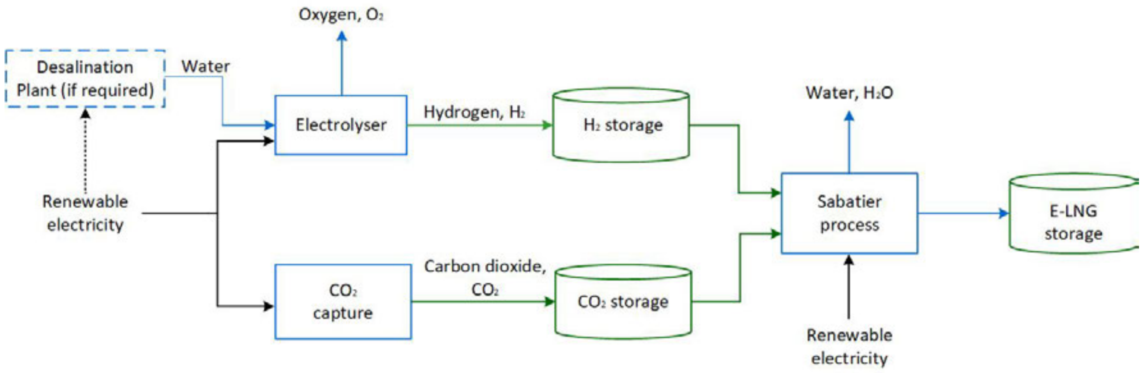

Figure 3.6: Schematic overview of e-LNG production

E-Methanol

Like e-diesel and e-LNG, e-methanol (CH_3OH) is also a carbon-containing e-fuel. However, the CO_2 TTW emissions from e-methanol are 18% lower than when e-diesel is utilized [98].
The production process of e-methanol is shown in Figure 3.7 and is performed in two consecutive steps.

1. Syngas (CO + H2) production from captured CO2 and green H2 through electrolysis.
2. E-methanol production from syngas and green energy through a methanol synthesis process, at an efficiency of approximately 65% [81].

Advantages of e-methanol are that it is a liquid at ambient temperatures which simplifies its storage compared to other e-fuels. Some disadvantages of methanol are that it is corrosive towards certain materials that are currently used in a vessels infrastructure and that e-methanol is toxic to humans, resulting in extra health and safety matters that should be considered [98].

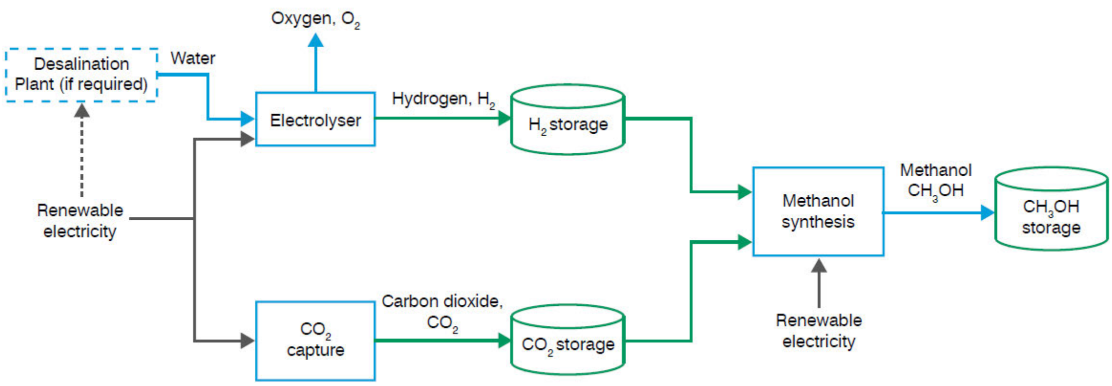

Figure 3.7: Schematic overview of e-methanol production [98]

E-Ammonia

Just as e-hydrogen, e-ammonia (NH_3) is part of the non carbon-based e-fuels, thus resulting in zero CO_2 that is emitted during combustion. The production process of e-ammonia is commercially mature and well understood, the process is schematically shown in Figure 3.8, and can be divided into several steps.

1. Capture of nitrogen through air separation and production of green H_2.
2. Synthesis of H_2 and N through the Haber-Bosch process at an efficiency of approximately 76% [101].

At a temperature of -33 °C and at ambient pressure, e-ammonia is a liquid, with an energy density slightly lower than that of e-methanol, however 1.6 times higher than that of liquid H_2 [18].
A major disadvantage of e-ammonia is that it is highly toxic for humans as well as for marine life. Because ammonia is already available worldwide, there are already international safety protocols in place regarding the transport and storage of ammonia, however, more research will be necessary to put safety protocols in place for use and storage on board of vessels.

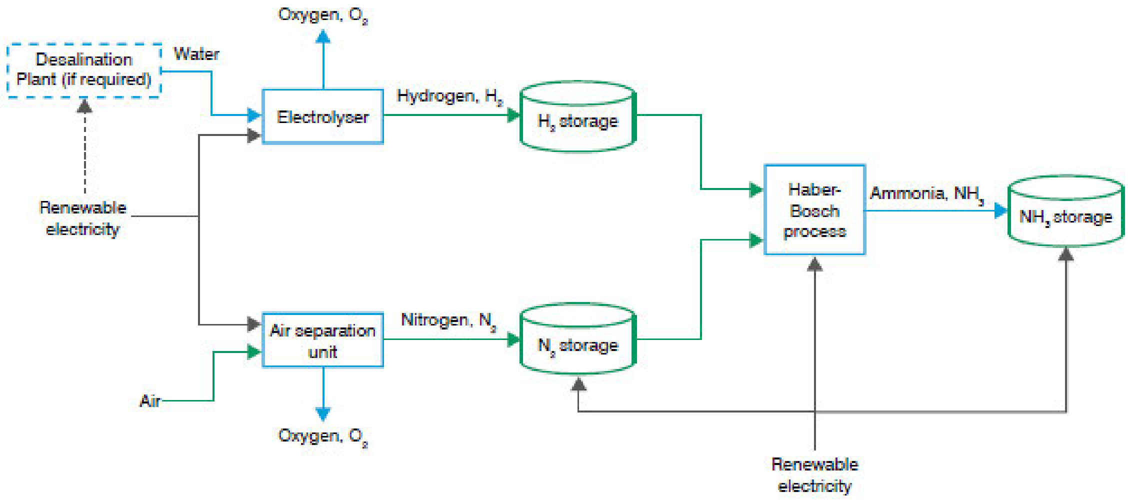

Figure 3.8: Schematic overview of e-ammonia production [98]

Table 3.2 gives an overview of the efficiencies associated with the production steps of each e-fuel, including the liquefaction of the e-fuel, which is only relevant for e-hydrogen and e-LNG. E-hydrogen (L) indicates the liquefied form if e-hydrogen. Additionally, the overall production efficiency of the e-fuel is given as well.

Table 3.2: E-fuel production efficiencies

	RES to e-hydrogen	**E-hydrogen to e-fuel**	**Liquefaction of e-fuel**	**Total production efficiency**	**Reference**
E-diesel	73%	50%	-	37%	[160]
E-LNG	73%	83%	90%	55%	[78] [106]
E-hydrogen (L)	73%	-	70%	51%	[116]
E-methanol	73%	65%	-	47%	[86]
E-ammonia	73%	76%	99% [1]	55%	[101]

[1]Own assumption

3.2.3. E-fuel characteristics

This section gives an overview of some key characteristics of the e-fuels and hydrogen carriers, discussed in section 3.2.2. These characteristics are used to compare the e-fuels with a fossil fuel and are used as input for the model, later on in this study.
In Table 3.3 all key characteristics are listed, with their associated unit and source and a short description of each characteristic is given below.

- **Density *[Kg/L]***
  - Both the gravimetric *[kWh/Kg]*, as well as the volumetric *[kWh/L]* energy density, are included, which are used to determine the required storage volume or the mass of the stored e-fuel.
- **Emission factors *[Kg CO_2/Kg e-fuel]***
  - Utilized to determine the amount of CO_2 that is abated compared to the fossil base case, within a certain time period, for the vessel.
- **Hydrogen content *[wt.-%]***
  - Since most e-fuels can be utilized as potential hydrogen carriers, the hydrogen content, given in mass fraction [wt.-%], together with the energy conversion pathways could be utilized to determine the best hydrogen carrier.
- **Storage conditions *[Bar] & [°C]***
  - The storage conditions are utilized to determine if storing the e-fuel poses challenges and if the currently installed storage tanks can withstand the conditions.
  - The storage conditions are also utilized to obtain the overall efficiency of the storage system, since storing some e-fuel will require energy and therefore additional fuel.
- **Auto-ignition temperature and flash point *[°C]***
  - The auto-ignition temperature of an e-fuel is utilized to determine if it can be combusted in an engine operating on a fossil fuel.
  - The flash point is an important factor utilized to determine the health and safety measures that need to be taken in the energy infrastructure of an e-fuel.

Table 3.3: Characteristics of various e-fuels

Characteristic	Unit	E-Diesel	E-LNG	E-Methanol	E-Ammonia	E-hydrogen (Liquid)	Dibenzyltoluene	Sodium Borohydride	Source
Formula	-	$C_{12}H_{23}$	CH_4	CH_3OH	NH_3	H_2	H_{18}-DBT	$NaBH_4$	[111] [136]
Density	*kg / L*	0.840	0.440	0.790	0.683	0.042	0.91	1.035	[108] [124] [102] [96] [111] [114]
Gravimetric Energy Density	*kWh / kg*	11.9	13.7	5.6	5.2	37.0	2.1	9.9	[16] [144] [95] [162] [114]
Volumetric Energy Density	*kWh / L*	9.96	5.95	4.42	3.53	2.22	1.9	10.34	[68] [12] [58] [111]
CO_2-eq Well-to-Wake emissions	*kg CO_2-eq / kg e-fuel*	3.250	3.650	2.080	1.600	1.092	-	-	[37] [95] [63] [129]
CO_2-eq Tank-to-Wake emissions	*kg CO_2 / kg e-fuel*	3.237	2.945	1.449	0.100	0	-	-	[63] [43] [95]
CO_2 Well-to-Wake emissions	*kg CO_2 / kg e-fuel*	0	0	0	0	0	-	-	[48]
CO_2 Tank-to-Wake emissions	*kg CO_2 / kg e-fuel*	3.206	2.755	1.375	0	0	-	-	[121] [30]
Hydrogen content	*wt.-%*	14.0%	25.1%	12.5%	17.7%	100%	6.2%	10.8%	[74] [140] [56] [111] [107]
Storage method	-	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Solid	
Storage pressure	*Bar*	1	1	1	1	1	1	1	[27] [59] [112]
Storage temperature	*°C*	18	-162	18	-33.4	-253	25	18	[27] [59] [62] [112] [114]
Auto-ignition temperature	*°C* (at 1 bar)	257	537	470	651	585	-	-	[44] [8]
Flash point	*°C*	>55	Flammable gas	9.7	132	Flammable gas	-	-	[1] [149] [143] [142] [94]

3.2.4. E-fuel environment, health & safety assessment

An import aspect that should also be considered during this research is the environmental, health and safety issues related to the different e-fuels. Environmental issues are not only related to the emissions originating from combusting a fuel but are also related to the effects a fuel will have in case of a spill. Health and safety issues have to do with certain characteristics of a fuel that can do damage to either certain materials or to humans who come into contact with the fuel. Therefore, when implementing an e-fuel, all hazards related to the e-fuel, should be known and the vessel, including its crew members, should be compliant with environmental, health and safety regulation setup for each e-fuel. Based on the environmental, health and safety hazards of each e-fuel, the necessary safety measures for the energy infrastructure can be determined. A short description of several hazards of each e-fuel are given and in the end, an overview of the hazard statements per e-fuel is given as well.

The Globally Harmonized System of Classification and Labelling of Chemicals (GHS), is a system that is used to address a classification to chemicals, based on hazards. By doing so the GHS has identified three main hazard categories:

1. **Physical hazards**, displayed with H2 at the beginning of the hazard statement;
2. **Health hazards**, displayed with H3 at the beginning of the hazard statement;
3. **Environmental hazards**, displayed with H4 at the beginning of the hazard statement.

These hazard categories all include several hazard statements, that are allocated to a fuel in case it is applicable. The hazard statements also have hazard categories, that indicate the severity of the hazard. The lower the hazard category, the greater the hazard [61]. The hazard statements and the hazard categories of the e-fuels, touched upon in section 3.2.2 are shown in Table 3.4.

E-hydrogen

- E-hydrogen is labelled as non-toxic for the environment as well as for humans [94].
- E-hydrogen is lighter than air, when in a gaseous phase, therefore it dissipates quickly when released, however, it can cause irritation to the eyes [94].
- Due to its low storage temperature e-hydrogen can cause cryogenic burns [94].
- E-hydrogen is extremely flammable as gas burns with an invisible flame and should therefore be kept away from heat, flames, ignition sources and releases of electric current [94].

E-diesel

- Toxic to humans and aquatic life, with long-lasting effects [1].
- Storage spaces must be ventilated and free of any heat, flame or ignition sources [1].
- Flammable and at temperatures above 55 °C e-diesel is able to form an ignitable mixture with surrounding air [1].
- In case of a fire or if heated, the pressure inside an e-diesel storage tank will increase, causing the tank to burst or explode. Vapour from e-diesel residues may form a highly flammable atmosphere inside the storage tank [1].

E-LNG

- Gases originating from the incomplete combustion of e-LNG, are dangerous in high concentrations but non-toxic for the environment as well as for humans [149].
- In a gaseous phase, e-LNG can have anaesthetic or suffocating effects as the gas replaces the oxygen, thus e-LNG needs to be stored in well-ventilated spaces [149].
- Contact with e-LNG should be avoided as it may cause cryogenic burns.
- LNG is an extremely flammable fuel that must be kept away from heat, flames, ignition sources and releases of electric current [149].
- In case of heating, boil-off gas generation is stimulated in the storage tank, which may cause the tank to burst [149].

E-methanol

- E-methanol can cause damage to organs and is toxic for humans when inhaled, in contact with skin or when orally ingested. Therefore protective gear needs to be worn when handling the fuel and it needs to be stored in well-ventilated places [143].
- E-methanol is highly flammable as gas and as liquid and needs to be kept away from heat, flames, ignition sources and releases of electric current [143].
- E-methanol is a corrosive fuel, thus only certain materials can be used to store or transport the fuel [143].

E-ammonia

- E-ammonia is extremely toxic to aquatic life as well as to humans at very low concentrations of above 5000 ppm (parts per million). Exposure to ammonia gas with air can cause eye, throat and nose burns [142].
- E-ammonia must be stored in highly ventilated spaces and ammonia detection systems should be installed. Personnel handling the fuel should be well instructed and wear protective equipment to avoid contact or inhalation [142].
- E-ammonia is a highly corrosive material and therefore, just as with methanol, only certain materials can be used when handling the fuel [142].
- E-ammonia is only flammable in a gaseous state [142].

Table 3.4: E-fuel hazard statements, adapted from Hagen [69]

Hazard statement	**Hazard category**	**E-Diesel**	**E-LNG**	**E-methanol**	**E-ammonia**	**E-LH$_2$**
H220: Extremely flammable gas.	1A		X			X
H221: Flammable gas.	2				X	
H225: Highly flammable liquid and vapor.	2			X		
H226: Flammable liquid and vapor.		X				
H280: Contains gas under pressure; may explode if heated.					X	
H281: Contains refrigerated gas; may cause cryogenic burns or injury.	Refrigerated liquified gas		X			X
H301: Toxic of swallowed.	3			X		
H304: May be fatal if swallowed and enters airways	1	X				
H311: Toxic if in contact with skin.	3			X		
H314: Causes severe skin burns and eye damage.	1B				X	
H315: Causes skin irritation	2	X				
H331: Toxic if inhaled.	3			X	X	
H332: Harmful if inhaled.	4	X				
H370: Causes damage to organs.	1			X		
H373: May cause damage to organs through prolonged or repeated exposure	2	X				
H410: Very toxic to aquatic life with long lasting effects.	1				X	
H411: Toxic to aquatic life with long lasting effects.		X				

3.2.5. E-fuel energy conversion pathways

Each e-fuel has several possible options, regarding how its chemical energy can be converted into mechanical energy and used onboard of a vessel. However, in this study, only these three types of power conversion units are considered, which are an ICE, Solid Oxide Fuel Cell (SOFC) and a Proton Exchange Membrane Fuel Cell (PEMFC). These three are chosen as an ICE is currently used on the vessels of Heerema, and the SOFC and PEMFC are two of the most studied alternative power conversion units for the maritime sector. Even several SOFC and PEMFC projects are already operational, to assess their potential [7]. The SOFC and the PEMFC were also identified as the two of the most promising fuel cell technologies by several studies, such as a study on the manufacturing costs by the U.S. Department of Energy [55], and the fuel cell application study carried out by DNV [7].

This section gives an overview of the possible energy conversion pathways, their associated TRL and efficiencies. It is important to get an understanding of the efficiencies of each pathway, as it indicates how much energy is lost and thus how much additional energy should be stored on a vessel to comply with the energy demand of the vessel. Thereby, the efficiencies play an essential role in the required fuel quantity, which affects the fuel storage system's size and the overall implementation costs of a pathway. An important consideration is that for this study an average efficiency is adopted to get an indication of the conversion or production efficiency of the e-fuels. The efficiency of a conversion or production step sits within an efficiency range and depends on multiple factors.
In Figure 3.9 the different possible pathways and their associated efficiencies, for the selected e-fuels are shown. E-fuels that contain carbon emit CO_2 and a CCS system is added to the energy conversion pathways of these e-fuels, which is optional. In this study the assumption is made that the same amount of CO_2 is emitted if a carbon-containing e-fuel is reformed or cracked to extract the stored hydrogen, as when the e-fuel is combusted in an ICE. A CCS system's working principles and power requirements are shortly discussed in section 3.2.6. Lastly, the technology used to convert the chemical energy into mechanical energy for each e-fuel route is color coded. The colors indicate the timeline in which the technology is expected to be available to be implemented on a large offshore vessel.

E-hydrogen

Each e-fuel pathway starts with a Renewable Energy Source, such as solar or wind, from which green hydrogen is produced. Hydrogen can be produced through electrolysis at an efficiency of approximately 73% [115]. By combining the green hydrogen with CO_2 or N_2, extracted from the air, all the selected e-fuels can be produced in several chemical processes. Whereby each e-fuel production process has its own efficiency.
Besides all the hydrogen carriers that can transport and store hydrogen, e-hydrogen can also be used on its own in several energy conversion units. In case no use is made of hydrogen carriers, the e-hydrogen needs to be stored and transported as a fuel itself. Hydrogen storage can induce complications due to its low volumetric energy density and low liquefaction temperature. The storage of e-hydrogen can also be done chemically, in a LOHC or borohydride, where the hydrogen is stored in and released from the material. The overall efficiencies for hydrogen storage and release in a LOHC are 99% and 74% respectively [112] and 40% [169] and 80% [113] for borohydrides, however the production efficiency might in practice even be lower.
In case e-hydrogen is stored as a fuel, it can either be stored cryogenically, as a liquid, or compressed as a gas. Both storage methods are energy intensive and therefore have an associated efficiency that should be considered. The conversion from e-hydrogen to liquefied e-hydrogen and hereafter storing the fuel, occurs at an efficiency of 70%, whereas compressing the e-hydrogen and hereafter storing it occurs at an efficiency of 95% [9].
Hydrogen has three possible energy conversion pathways that can be implemented on a large offshore vessel, which are elaborated on below.

1. ICE, modifications to an ICE are required to convert it to a DF ICE able to operate on a fossil fuel and H_2. Currently, a H_2 fuelled ICE is able to operate at an efficiency of approximately **42%** [119]. The advantages of hydrogen-fuelled ICEs are that less pure H_2 can be used, in comparison to fuel cells, which reduces the fuel costs [119]. Since much research has been performed regarding this technology and institutes such as TNO have also acknowledged its potential in the shipping industry [154], the pathway is labeled orange.

2. PEMFC, the utilization of a H_2 fuelled PEMFC onboard of vessels is already demonstrated on several projects, such as ZEMSHIPS or the Nemo H_2 project [161]. Research and development regarding hydrogen-fuelled PEMFC, has continued and the technology is relatively mature. Therefore, the pathway is labeled green. A H_2 fuelled PEMFC is able to operate at an efficiency of about **55%** [18].
3. SOFC, even though H_2 fuelled SOFC have gained much attention in recent years, a lack in development, high costs, and a high mechanical vulnerability have limited the implementation of SOFCs on large offshore vessels. Further developments and research are necessary and the pathway is labeled red. SOFCs can be applied as a stand-alone system or can be used in a combined operating system with a gas turbine [18], a stand-alone H_2 fuelled SOFC can operate at efficiencies of about **60%** [15].

E-diesel

E-diesel can be produced from hydrogen at an efficiency of approximately 50% [160], and has several energy conversion pathways. Since e-diesel contains carbon an optional CCS system is added to its pathways. In case e-diesel is utilized in a SOFC, CO_2 emissions are significantly reduced however still occur, therefore a CCS system can be installed to even further reduce emissions [35]. The e-diesel pathways are described below.

touched upon below.

1. ICE, since e-diesel has similar properties as fossil diesel, the same onboard fuel infrastructure can be utilized and the ICE pathway is depicted as available. E-diesel is also combusted at the same efficiency as fossil diesel, which is approximately **40%** [104].
2. SOFC, e-diesel is not an ideal fuel to be utilized in a SOFC, but it is feasible. Further research and development are necessary, regarding the usage of e-diesel in a SOFC. E-diesel can be converted in a SOFC at an efficiency of approximately **50%** [18].

E-LNG

Green hydrogen is utilized to produce natural gas, through the methanation reaction at an efficiency of approximately 83% [78], after which the natural gas is liquefied. The liquefaction of natural gas is an energy-efficient process that has an efficiency of approximately 90% [106], resulting in an overall e-LNG production efficiency of 75%. E-LNG has two possible pathways and since it contains carbon an optional CCS system is added to both pathways, as CO_2 also occurs in case use is made of a SOFC [83]. The e-LNG pathways are touched upon below.

1. ICE, since e-LNG and fossil-LNG have similar properties and fossil LNG is already used as fuel in DF ICEs on large offshore vessels, the ICE pathway is set as available. E-LNG can be converted at an efficiency of approximately **40%** [165].
2. SOFC, similar as to the PEMFC, SOFCs are being developed to operate on e-LNG, with efficiencies of about **60%** [25]. The SOFC technology is still being developed and after consulting fuel cell experts, the pathway is set to be available in 10-20 years.
3. H_2, e-LNG can also be used as a hydrogen carrier, where e-LNG is converted back to hydrogen through a methane steam reforming process, with an efficiency of approximately **70%** [130]. During this process, CO_2 is also released [82], and thus a CCS system is added to the pathway.

E-methanol

Just as with e-diesel and e-LNG, e-methanol also contains carbon and thus emits CO_2, hereby an optional CCS system is added to its pathways. Emissions are reduced in case e-methanol is utilized in a PEMFC or SOFC, however CO_2 emissions still occur and a CCS system can be utilized [72], [128]. E-methanol has four possible energy conversion pathways, which are shown below.

1. ICE, ICEs that can operate on e-methanol are already available. These ICEs often have dual-fuel capabilities, meaning either e-methanol or a fossil fuel, such as MGO can be utilized [137]. The efficiency of an ICE fuelled by e-methanol is approximately **40%** [168].

2. PEMFC, E-methanol can also be used in a direct methanol fuel cell (DMFC), which is a type of PEMFC. The DMFC is able to convert the chemical energy, stored in e-methanol, at ambient temperature [81] and at an efficiency of approximately **30%** [46]. The low efficiency is caused by e-methanol passing through the membrane to travel from one electrode to the other [18]. Further research and development are required before an e-methanol fuelled PEMFC can be implemented on large offshore vessels, thus the technology is set to be available in 10-20 years [81].
3. SOFC, several projects have already proven the usage of an e-methanol-fuelled SOFC for transport applications, such as the METHAPU project [120]. However, similar to the PEMFC further research and developments are necessary and thus the pathway is also labeled available in 10-20 years [81]. A SOFC is able to convert e-methanol at an efficiency of about **54%** [120].
4. H_2, e-methanol can also be used as a hydrogen carrier, where the hydrogen is released through a methanol steam reforming process at an efficiency of about **90%** [67]. In this process, CO_2 is also released and thus a CCS system is included in the pathway.

E-ammonia

Since e-ammonia does not contain any carbon no CCS system is needed and it can directly be used in a fuel cell, without the risk of CO poisoning the catalyst. However, e-ammonia can not be utilized in a PEMFC since the e-ammonia itself poisons the membrane of a fuel cell [18]. E-ammonia has three possible energy conversion pathways, that are touched upon below.

1. ICE, e-ammonia-fuelled ICEs are being developed and are expected to be commercially available by 2024 [148]. However, due to the high toxicity of ammonia extra health and safety measures will have to be taken before the e-fuel can actually be implemented on large offshore vessels, therefore the pathway is labeled orange. The combustion of e-ammonia in a DF ICE has an efficiency of approximately **40%** [166].
2. SOFC, some complications, regarding the lifetime and volumetric density, inhibit the implementation of e-ammonia-fuelled SOFCs on large offshore vessels, therefore the pathway is depicted as red. A SOFC fuelled by e-ammonia is able to operate at an efficiency of approximately **60%** [166].
3. H_2, e-ammonia can be used as a hydrogen carrier, where temperatures ranging from 250 to 700 °C are required to extract the hydrogen from the e-ammonia. The extraction is done through an ammonia cracking process, with the conversion rate of e-ammonia to H_2 increasing with the temperature and lays between approximately 90% up to 99%, however, this conversion is energy intensive and has an energy efficiency of approximately **76%** [20].

3.2.6. Carbon Capture Storage (CCS)

Even though e-fuels are labeled as zero-carbon fuels, a CCS system can still be added to the pathway of the carbon-containing e-fuels. A CCS system is only relevant in case no zero CO_2 WTW emission factors can be adopted for the e-fuels and carbon offsets will have to be purchased. Additionally, a CCS system could be added to take a certain redundancy into account in case only fossil-produced e-fuels are available and an e-fuel pathway is already implemented. Hereby a CCS system can be added to ensure that in case a fossil-produced e-fuel is utilized the emissions are minimized and the EU ETS costs as well. Additionally, any emission originating from a fossil pilot fuel, required for each e-fuel, are also abated by implementing a CCS system. In case a CCS system is implemented a negative emission e-fuel can also be realized, which indicates more CO_2 is abated than emitted and has a positive effect on the environment.

The capture of CO_2 from the exhaust gas is an energy-intensive process and the power requirement of the CCS system depends on the fuel that is utilized. The power requirement of the CCS system is lowest for an LNG-fuelled vessel as the power requirement of the systems depends on the thermal energy available in the exhaust gas [133]. The engine is able to provide rest heat for the capturing process and the low temperature of the LNG can be utilized to liquefy and store the captured CO_2 [133]. The power requirements to capture CO_2 from the carbon-containing e-fuels are listed below.

A CCS system is not only added to pathways where a carbon-containing e-fuel is combusted, but also to pathways where a carbon-containing e-fuels function as a hydrogen carrier, as during the process of extracting hydrogen from the e-fuel CO_2 is also released. In this study, the assumption is made that the CO_2 emissions from the combustion and the conversion of an e-fuel are similar.

When carbon-containing e-fuels are utilized in a SOFC or a PEMFC CO_2 emissions are significantly reduced, however still present. Therefore, in order to realize an even higher CO_2 abatement, a CCS system can be implemented as well. The energy conversion pathways of the carbon-containing e-fuels that make use of a SOFC or PEMFC therefore also contain a CCS system, which is optional.

The energy conversion pathways where a CCS system is added are shown in Figure 3.2.5.

- E-diesel, **42%** additional energy is required, to obtain a capture rate of 74% [100].
- E-LNG, **20%** additional energy is required, to obtain a capture rate of 78% [100].
- E-methanol, **38%** additional energy is required, to obtain a capture rate of 75% [100].

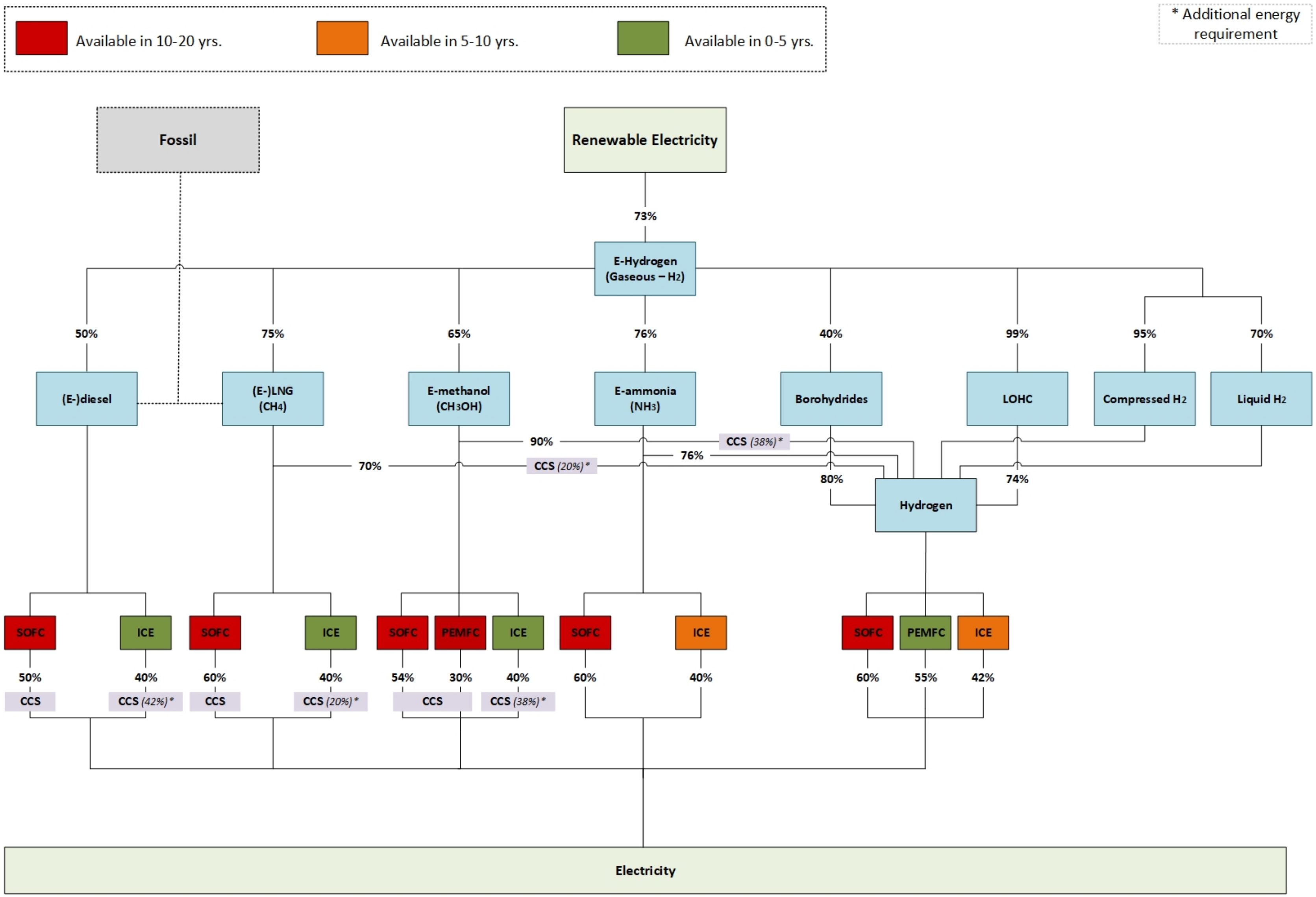

Figure 3.9: Schematic overview of the possible energy conversion pathways for the selected e-fuels

3.3. Conclusion Fuels

The goal of this chapter was to create an understanding of the current, fossil, state of the maritime sector, as well as identify possible e-fuels to be implemented on large offshore vessels. Thereby this chapter gave an overview of the currently used fossil fuels in the maritime sector as well as of the possible e-fuels that could be used to decarbonize the maritime sector. The production processes and various characteristics of these e-fuels were touched upon as well as the possible energy conversion pathways that are assumed to be available in the 0-10 year time frame, set for this study.
Some conclusions obtained from this chapter are stated below.

Certain poor-performing characteristics of the e-fuels, compared to the currently used fossil fuels, might complicate the implementation of the e-fuels. For example, e-fuels with a low volumetric energy density will require much more storage space on the vessel, or e-fuels with a low auto-ignition temperature will need some sort of pilot fuel to start the ignition. Additionally, e-fuels that pose a high safety, health, and environmental risk, will also be more complex to implement on a vessel, due to additional safety measures that have to be taken.
All in all, poor performing characteristics of an e-fuel, are likely to result in significant modifications required on the vessel, hereby complicating the implementation of the e-fuel and requiring additional investments.

Efficiencies of the e-fuel pathways play an important role regarding the required e-fuel quantity on the vessel and thereby also on the OpEx. E-fuel pathways with a low conversion efficiency are much less attractive from an e-fuel storage as well as OpEx perspective. To compensate for the energy loss during the conversion of the e-fuels, additional fuel is required, to still comply with the energy demand of the vessel. Thereby, additional storage volume on the vessel as well as additional OpEx, related to the acquisition of the e-fuel is required. Additionally, from an OpEx and e-fuel storage perspective, implementing a CCS system is not very attractive, due to its additional power requirement, which results in extra OpEx and fuel storage.
However, for this study, all possible pathways that are available within the set time frame are considered and an overview of these pathways, the time frame within which they will be available and the notation used in this study, are given below.

- **E-diesel**

  → ICE (already available) [*E-diesel ICE*]
- **E-LNG**

  → ICE (already available) [*E-LNG DF ICE*]
  → Conversion to H_2
- **E-methanol**

  → ICE (available in 0-5 years) [*E-methanol DF ICE*]
  → Conversion to H_2
- **E-ammonia**

  → ICE (available in 5-10 years) [*E-ammonia DF ICE*]
  → Conversion to H_2
- **E-hydrogen**

  → ICE (available in 5-10 years) [*E-LH2 DF ICE*]
  → PEMFC (available in 0-5 years) [*E-LH2 DF ICE*]

4
Key Vessel Characteristics

In this chapter, insights are provided regarding some key energy characteristics of large offshore construction vessels that are of importance during the technical and, eventually, the financial evaluation. The vessels of HMC are used to create a generic overview of a large offshore construction vessel and further, in this research, a case study is carried out on one of the vessels.
The research on these vessels is executed to get a better understanding of what the energy infrastructure of such large offshore construction vessels, that operate on MGO, looks like. This chapter creates a generic overview of the possible energy infrastructure of a large offshore construction vessel that operates on MGO, which is also used in the case study. Additionally, insights are created regarding the operational modes and loads that are present on a large offshore construction vessel.
To begin with, in section 4.1, the vessels of HMC are introduced and some dimensional characteristics of each vessel are given, in sub-chapter 4.2, the onboard energy infrastructure is looked into, hereafter in sub-chapter 4.3 the different operational modes and their occurrence on each vessel is depicted and in sub-chapter 4.4 the different energy consumption profiles of each vessel are touched upon. Lastly, a conclusion of the chapter is presented, in sub-chapter 4.5, to summarize the key takeaways.

This chapter answers the second sub-question, which was mentioned in section 1.3.2

- *What energy characteristics of a large offshore construction vessel should be considered when implementing an e-fuel?*

4.1. Fleet introduction

The operational fleet of Heerema consists of several different vessels, all with different dimensions, services and lifetimes. The fleet ranges from SSCVs to anchor handling tugs, however, in this study, only the large vessels in HMCs fleet will be examined. An SSCV is a vessel that is able to partially submerge itself to perform heavy lift operations such as the installation or decommissioning of subsea equipment.
In this section, the large offshore vessels of Heerema are introduced and some general information is given regarding their activities, lifetime and dimensions. At the end of this section, the general characteristics of each vessel are depicted in Table 4.1. In Figure 4.1 the four large offshore vessels of Heerema are shown.

Figure 4.1: The large offshore vessels of Heerema

Sleipnir

The Sleipnir is the world's largest crane vessel, equipped with two heavy lift cranes, each with a lift capacity of 10,000 mT, and that can be operated together to lift 20,000 mT. The Sleipnir has a length and width of 220 and 102 meters, respectively, these dimensions are also shown in Table 4.1. Additionally, the draft, which is the distance between the deepest point of the vessel and the waterline, is also depicted, during operations as well as during transit.
The Sleipnir is equipped with 12 four-stroke dual-fuel engines that provide the vessel with continuous power, each engine has a capacity of 7.8 MW. Because the Sleipnir is equipped with dual fuel engines, it is able to operate on MGO as well as on LNG.

Thialf

Like the Sleipnir, the Thialf is also an SSCV of Heerema and is currently the world's second-largest SSCV. The Thialf is equipped with two heavy lift cranes that are able to jointly lift 14,200 mT. The dimensions of the Thialf are shown in Table 4.1.
The Thialf is equipped with 12 diesel engines with different capacities, 6 engines with a capacity of 4.9 MW, 4 of 4.5 MW and 2 of 6 MW. The Thialf uses MGO as operational fuel, however, in 2020, the first pilot tests were performed to test the vessel's performance when making use of gas-to-liquid and HVO.

Balder

The Balder is Heerema's Deepwater Construction Vessel (DCV) and was the world's first SSCV, as it was constructed in 1978. A DCV is a vessel that can execute complex operations in very deep water while also providing a high lift capacity in less deep waters. The Balder is fitted with two heavy lift cranes, which are able to perform a tandem lift of 6,300 mT. The dimensions and some extra characteristics of the Balder are shown in Table 4.1.
The Balder is fitted with 7 diesel engines, each with a capacity of 3.5 MW, and with a propulsion system that consists of 2 thrusters with a capacity of 4.4 MW each.

Aegir

The Aegir is the fast-moving heavy lift vessel of Heerema and it is one of the world's largest monohull crane vessels, which was constructed in 2012. The Aegir is able to operate in any water depth and because of its high transit speed, the Aegir is able to mobilize itself globally. The Aegir is equipped with a single heavy lift crane that has a lift capacity of 5,000 mT. The dimensions and other characteristics of the Aegir are stated in Table 4.1.
The Aegir is fitted with a power plant consisting of 6 diesel engines of 8 MW each and one emergency diesel generator with a capacity of 1.7 MW, both make use of MGO as operating fuel.

Table 4.1: Heerema vessel characteristics

Characteristic	**Sleipnir**	**Thialf**	**Balder**	**Aegir**
Vessel type	SSCV	SSCV	DCV	Heavy lift vessel
Construction year	2019	1985	1978	2012
Installed capacity [MW]	93.6	59.4	24.5	48
Length [m]	220	201.6	154	211
Width [m]	102	88	86	46
Operational draft [m]	12.0 - 32.0	11.9 - 31.6	11.0 - 25.0	8.0 - 11.2
Transit draft [m]	12.0	12.5	11.0	8.0
Lift capacity [mT]	20,000	14,200	6,300	5,000

4.2. Vessel infrastructure

In this sub-chapter, the onboard infrastructure of a large offshore vessel is investigated by studying the aforementioned vessels of Heerema. This section aims to create a general overview of a possible TTE infrastructure of a vessel operating on MGO or LNG, as these are commonly used fuels in the maritime sector and are also used on the vessels of HMC. To begin with, these key components are identified by performing a literature study and in-house research, hereafter a description of these key components is given. The generic overview of a large offshore vessel's infrastructure is used to better understand what components are likely to be replaced or modified, in case an e-fuel is implemented. Additionally, the MGO infrastructure is used as starting point for the technical evaluation, in Chapter 5.
The infrastructure that is looked into during this research will only entail the TTE infrastructure, which is the infrastructure starting from the fuel storage until the exhaust of the vessel.
Only components relevant to this study are considered, which are the fuel storage, which is discussed in section 4.2.1, the energy conversion unit, which is discussed in section 4.2.3 and the piping infrastructure, which is discussed in section 4.2.2. Additionally, several additional components of the infrastructure, that are of less relevance to this study are discussed in Appendix C.

Figure 4.2 gives an overview of a possible TTE infrastructure configuration of a large offshore vessel, operating on MGO. Not all components of the TTE infrastructure are of shown since not all components are relevant for this study or will have to be modified when implementing an e-fuel. The overview only shows components that are in contact with a fuel, residuals of the fuel or emitted gasses of a fuel and are therefore likely to be modified in case an e-fuel is implemented. An overview of a possible TTE infrastructure of a vessel operating on LNG is shown in Appendix E.

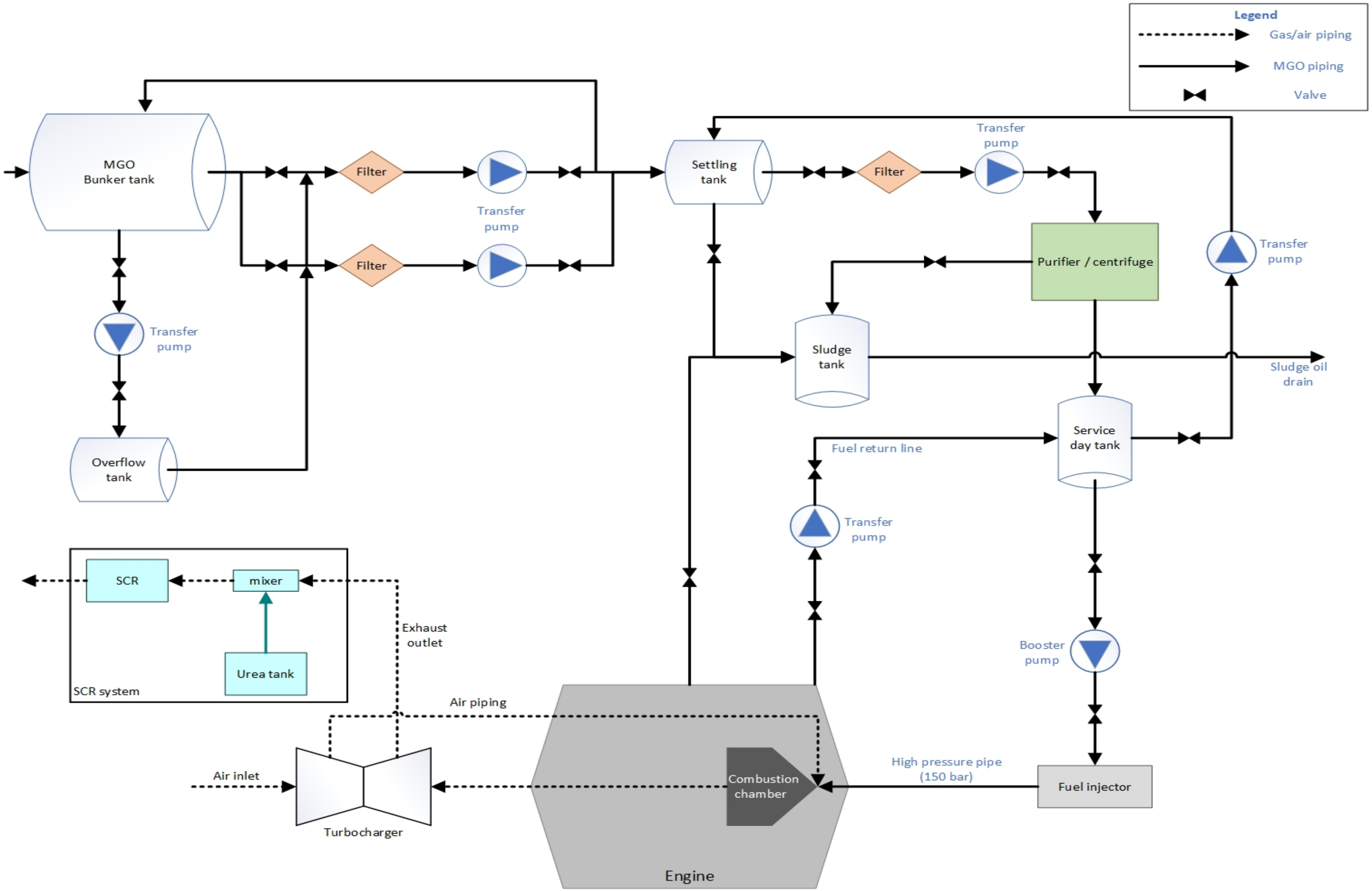

Figure 4.2: Example of an energy system of a vessel operating on MGO

4.2.1. Fuel storage

The first key component of a vessel's infrastructure is the fuel storage system, which includes the fuel tank and its additional components. The characteristics of the fuel storage system depend on the type of fuel, the bunkering frequency and the amount of space available on the vessel. Some fuel storage systems require additional components to store the fuel in certain conditions or to comply with certain health and safety measures. Based on the fuel used on the vessel, the fuel storage system and the space it is in must meet certain restrictions to comply with health and safety issues.
As was mentioned earlier, all HMC vessels operate on MGO, with the Sleipnir being the only exception, as it can also operate on LNG. To begin with, a short description of an MGO storage system is discussed, and hereafter, a short description of the LNG storage systems is given.

MGO

As can be seen in Figure 4.2, multiple fuel tanks are present on a large offshore vessel operating on MGO. Each fuel tank has its own function, capacity, and additional components, however, they all have similar characteristics. A short description of the tanks present on a vessel operating on MGO is given in Appendix C.
The most important tank on the vessel is the fuel storage tank, as it requires the most space. Below some key characteristics of an MGO storage tank are given.

- MGO storage tanks are made out of corrosive-resistant materials, such as (stainless) steel or other iron-based materials [70].
- To prevent any contaminants from mixing with the fuel as well as any metallic interaction, storage tanks can be coated with an inert coating [70].
- To prevent an accelerated degradation of the fuel tanks, no copper (alloys) or zinc (alloys) should be used as tank material or come into contact with MGO [70].
- The tanks are single-walled and depending on the capacity of the tank, a certain thickness is required [70].
- The tanks should be separated from other spaces on the vessel either by gas and water-tight spaces or by well-ventilated and drained cofferdams [76].
- The tanks are insulated but do not require additional heating since the viscosity of MGO is low enough to flow through the piping at temperatures below room temperature [70].
- Fill, return and vent piping or openings must be located on the topmost surface of the tank, only openings and piping for supply, cleaning and level gauges are allowed at the side or bottom of the tank [70].
- The tanks must be placed as close as possible to the engine rooms and reinforced as well as supported to prevent any movement [70].
- The tanks must also be electrically connected to a common ground to prevent any static build-up, which may cause a spark [132].

LNG

Similar to the MGO infrastructure, multiple tanks are present, with similar characteristics. Due to the fact that an LNG-fuelled vessel also makes use of MGO, the MGO fuel infrastructure is still present on the vessel. Below a short description of the characteristics of an LNG storage tank is given.

- Type C tanks are cylindrical and can be fully or partially pressurized [87].
- In case type C tanks are utilized, the hold space can be considered as a cofferdam, and can be filled with dry air or an inert gas [87].
- The tanks are double-walled, the inner tank is made out of stainless steel and the outer tank is made out of carbon steel [87].
- The space between the walls is filled with insulation material and is kept under vacuum to ensure a temperature of -162 °C [87].
- Boil-Off-Gas (BOG) line is installed to extract the natural gas from the tank and maintain the required pressure [87].

  - *Even though the LNG tanks are well insulated, a small amount of heating of the temperature inside the tank, will cause the LNG to evaporate, creating a BOG [87].*
  - *The gas can either be sent to the engine to be utilized or can be re-liquefied and pumped back in the tank, this method requires energy and is not preferred [87].*
- The tanks can also contain a Pressure Build-up Unit (PBU), instead of a BOG line, which is used to maintain the LNG tank at the desired pressure [87].
  - *The PBU pumps LNG out of the tank, heats it, thereby turning it into gas and hereafter pumps it back into the tank [87].*

4.2.2. Tank-to-Exhaust piping

The TTE piping system present on a vessel needs to be compatible with the fuel used to power the vessel. Depending on the fuel and its associated characteristics, the pipelines need to be of a specific material and need to comply with certain health and safety measures. Additional to the piping, certain components integrated into the piping system are necessary and vary also per fuel, used on the vessel. In this section, the piping system and relevant components of an MGO, as well as LNG fuelled vessel, are discussed.

MGO

Below a short description of several characteristics of the piping system of a vessel operating on MGO is given.

- The MGO piping system is usually made out of (carbon) steel, which is, just like the MGO storage tanks, an iron-based material that is non-corrosive [70].
- To prevent an accelerated degradation, no copper (alloys) or zinc (alloys) should be used as material for the piping system [70].
- The piping system is entirely made out of single-walled pipes and almost entirely made out of low-pressure pipes [70].
- All pipes should be insulated to ensure MGO stays at the desired temperature, however, no trace heating is required, since the viscosity of MGO is compatible with filters and combustion [70].
- To prevent the insulation around the MGO pipes to degrade, piping should not be located in wet spaces or in spaces where condensation is likely to occur. However, if this is the case they should be equipped with a shielding layer [70].
- All spaces the MGO piping system passes should be vented and the system should avoid spaces containing generators,or electric motors and should be kept away from hot surfaces [70].
- The pipes should run as directly as possible between each fuel system component [70].
- The piping system is equipped with several pumps used to transport MGO through the fuel system [70].
- The piping is equipped with valves, which are used to regulate the MGO flow. By opening or closing certain valves the amount and the direction of the MGO can be controlled [70].

LNG

Below several characteristics of the LNG piping system are given.

- The piping system for e-LNG consists entirely of double-walled pipes since the e-LNG will only be handled in enclosed areas [87].
- The inner as well as outer pipes are made out of stainless steel [87].
- The space between the inner and outer pipe is kept at a negative pressure by an extraction ventilation system, where dry air is ventilated between the pipes.
  - *In case of a leakage the ventilation air will contain natural gas and extract it [147].*
  - *The space between the pipes can also be maintained at a pressure higher than the fuel pressure, with an inert gas, such as nitrogen [147].*
- A monitoring system is added which can detect any leakage and shut off the supply to the engine by closing the shut-off valve [147].

- An inert gas, such as nitrogen, is used to purge and cool the fuel system, hereby the fuel pipelines are cleaned of any mixtures that may cause a combustion.
  - *Nitrogen is used since it is an inert gas, has a lower boiling point than LNG in a liquid phase, and is non-combustible [157].*
- Drip trays, as well as a gas detection system, should be added, however only in areas where leakages are a risk, such as the bunkering station and in areas where the fuel is prepared [157].

4.2.3. Energy conversion unit

The energy conversion unit is one of the most important components of the TTE infrastructure, as this is where the chemical energy, present in a fuel, is converted into mechanical energy and utilized to power the vessel. As has become clear from section 4.1, all vessels of Heerema make use of MGO as operating fuel, only the Sleipnir is able to use LNG as fuel as well, due to its dual-fuel engines.
All vessels of HMC are equipped with multiple ICEs that are compatible with MGO as fuel, the working principles of such an engine are touched upon in Appendix B. The energy conversion unit, and its characteristics, depend on the fuel used to power the vessel. However, the working principles and certain components of an engine, which are not in contact with the fuel, remain the same. In this section, a short overview of the components, that are relevant for this research, of an ICE operating on MGO or an ICE operating on LNG, are discussed.

MGO

- The cylinder of an MGO fuelled ICE, is usually made out of cast iron and is the section of the engine where MGO is combusted and power is generated by the pistons moving in a vertical direction, thereby increasing and decreasing the pressure in the combustion chamber [70]. A schematic overview of the cylinder of an ICE is shown in Figure 4.3.
- The pistons form the bottom of the combustion chamber and are usually made of cast iron as well [70].
- The upper part of the engine, which is referred to as the head, contains the air and exhaust valves, the fuel injector, and the relief valves. This component of the engine must be internally cooled and is usually made of cast iron or steel [70].
- A fuel injector sprays MGO at high pressure into the combustion chamber. Fuel injectors consist of materials that can withstand high pressure and that are compatible with MGO [70].

LNG

When natural gas is used as fuel in an ICE, two engine types are available, gas-only engines and DF engines, that operate on MGO as well as on LNG. Both engines are already commercially available. A significant difference between the two types of engines is that the gas-only engine makes use of a spark plug to ignite the natural gas, whereas the DF engine makes use of a pilot fuel, which is often MGO, to start the ignition [156]. A pilot fuel is required due to the low cetane number, which is an indication of the combustion speed as well as the auto-ignition temperature of a fuel [4].
In case an MGO engine is retrofitted to a DF engine operating on MGO and LNG, several options are possible, below a short description is given of a DF LNG engine.

- LNG can either be supplied to a gas mixer or it can directly be supplied to the combustion chamber. The latter is more suitable for large offshore vessels since it has the ability to convert MGO engines up to 20 MW [71].
  - *In the gas mixer LNG is mixed with air and transported to the combustion chamber through the turbocharger.*
  - *Through the gas admission valve LNG can directly be supplied to the engine.*
- The DF engine must be equipped with gas admission valves, which regulate the amount of natural gas fed to the combustion chamber and ensure that no natural gas is supplied to the combustion chamber in case the engine operates on MGO [156].

- All pipes connected to the engine that supply natural gas, must be double-walled and consist of the same materials as the LNG piping infrastructure [156].
  - *When the engine switches from LNG to MGO mode, the piping as well as the engine is purged with an inert gas [156]*
- Since all connecting pipes are double-walled the DF engine can be installed in engine rooms similar to MGO engine rooms, which must contain a ventilation and a minimum of two gas and fire detection systems [156].

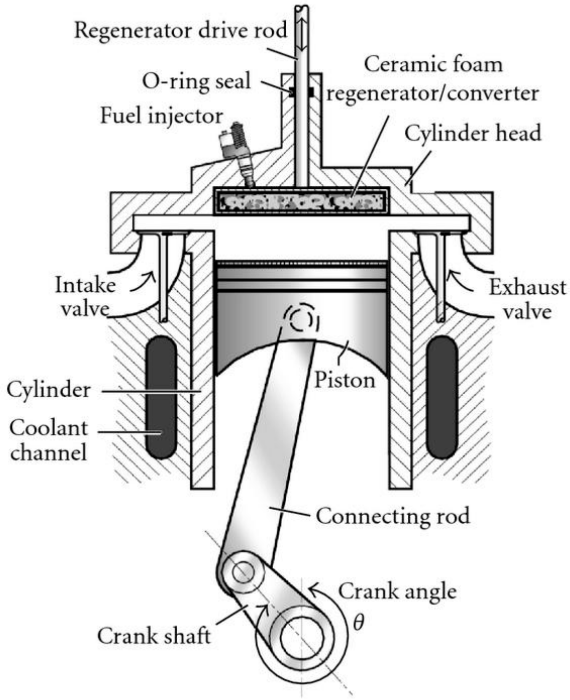

Figure 4.3: Schematic overview of the cylinder of an ICE [105]

4.3. Operational modes

The various operational modes of a large offshore vessel, with each their own frequency of occurrence, energy consumption and GHG emissions, are considered in this study. A distinction is made between the following operational modes: Mobilization (MOB), work, sail, idle and Repair and Maintenance (R&M). Table 4.2 gives a short description of the operational modes.

It is essential to examine the different operational modes a vessel can operate in to better understand the energy required during such an operational mode. When the frequency of occurrence, as well as the average daily energy consumption of an operational mode, are known, the total required energy as well as the emitted GHG for a certain period of time can be determined. Additionally, as the amount of required energy is known for a certain time period, as well as the efficiencies of the energy conversion unit of the vessel, the necessary amount of e-fuel can be obtained as well, which could be used to scale the fuel storage tanks. Therefore, in this sub-chapter, the above-mentioned operational modes, their energy consumption, and their frequency of occurrence are elaborated on.

Some of the operational modes on the vessels can be subdivided into multiple modes, within the operational mode. For example, the sail operational mode can be subdivided into two different transit modes, namely, a high-speed transit and an eco-speed transit mode. During high-speed transit, the vessel sails faster and therefore has a higher power demand in comparison to the eco transit speed.
The work operational mode can also be subdivided into different dynamic positioning (DP) modes, namely DP2 mild weather, DP2 medium weather and DP3 extreme weather. During DP, several position reference sensors and the autopilot, are used to make sure that the vessel stays in the same position without any mooring lines and in any weather conditions. The DP system is active when the vessel is engaged in construction, deconstruction, or any other offshore activities. The difference between the three DP operational modes is that they all take different redundancy measures into account, to ensure that the vessel remains in its current position and is still able to operate.

DP2 mild weather is the most commonly used operational profile when the vessel is engaged in any offshore activities, during this operational mode the systems account for the failure of a single active component, and therefore engine loads are generally low (below 50%). To account for any failure, redundancy measures are taken, which during DP2 means that at least one extra engine is always running. During DP2 the vessel mostly handles relatively light equipment.
DP2 medium weather, is similar to DP2 mild weather, however, the vessel operates in more turbulent weather conditions and therefore more power is required to keep the vessel in its position.

DP3 takes the redundancy measures of DP2 one step further, resulting in an additional engine that is available in case of emergency, meaning two engines in total are available as a backup. The two engines are located in a different engine room each, which ensures that the vessel will not lose its DP control system, in the case of any failure, flooding, or fire emergencies.

	MOB	Work	Sail	Idle	R&M
Characteristics	• Different activities to prepare before a project • Combining operational modes • Transit between projects	• Consists of three subcategories: *1. DP1, at mild weather conditions* *2. DP2, at medium weather conditions* *3. DP3, at extreme weather conditions*	• Vessel sails long distances • Two subcategories: *1. High transit speed* *2. Eco transit speed*	• Vessel is anchored or moored • No DP system required • Only one engine is operational for small loads	• R&M is performed on the vessel • Vessel is in idle mode • Extra power required for R&M

Table 4.2: Characteristics of the several operational modes on an offshore construction vessel

In Figure 4.4, an overview is given of the daily energy consumption for each operational mode per vessel of HMC, additionally, the frequency of occurrence, of these operational modes, is depicted as well. The frequency of occurrence is obtained by determining the number of days a vessel is operating in a specific mode. By making use of this data, the energy consumption for a certain period of time can be determined. Figure C.1 in Appendix C shows the yearly average energy consumption of the vessels of Heerema, based on the daily energy consumption and the frequency of occurrence.
By examining all four vessels of Heerema, more insight is created regarding the modes a large offshore vessel primarily operates in and its associated energy consumption. Additionally, since the fuel consumption per day is known for each operational mode, the emitted CO_2 and the fuel's generated energy can be determined by using the emission factor and the energy density of the fuel. The CO_2 emissions for each vessel of HMC are shown in Appendix C.

An important consideration is that even though the fuel consumption during an operational mode is known, this does not mean that all fuel, and thus generated energy, is utilized to perform a specific operation. Different loads are present during each operation, each with its own consumption profile. The different loads that are present on a large offshore vessel will be touched upon in sub-chapter 4.4.

[redacted]

Figure 4.4: The frequency of occurrence and daily energy consumption of the different operational modes

4.4. Energy consumption profiles

A distinction can be made between the different loads present during an operational mode. It is relevant to understand when certain loads are present, to better understand how significant the impact is in case a specific capacity is retrofitted, and to get an understanding of the energy consumption, during these loads. Examining the loads gives a better insight into what the primary energy consumers are during the operational modes and how much of the load is responsible for a certain amount of GHG emission. Hereby, it will be possible to apprehend how much emissions can be reduced by making the vessel more sustainable up to a certain capacity.

Initially, the different loads are identified and shortly discussed in this section. The loads that are present on the vessels are the hotel load, thruster load, crane load, pump load and the handling crane load. These loads are present on all large offshore vessels of Heerema and therefore give a good representation of what loads will be present on other large offshore construction vessels.

The characteristics of the various load present on a large offshore construction vessel are listed in Table 4.3. Some loads fluctuate highly, whereas others are relatively constant and do not require a high ramp-up. Additionally, in Table 4.4 an overview is given regarding which loads are present during the operational modes, mentioned in section 4.3.

	Hotel	**Thruster**	**Crane**	**Pump**	**Handling crane**
Characteristics	• Constant load • Always present • Relatively low • Electrical power for always consuming appliances	• Electrical power for thrusters • Load depends on the transit speed or DP mode • Fluctuates and varies over time	• Electrical power for large cranes • Highly fluctuating • High and fast ramp up required	• Relatively constant • Electric power for ballast and anti-heeling pumps	• Low load • Electrical power for smaller cranes • Less irregular and high than crane load

Table 4.3: Characteristics of the several loads on an offshore construction vessel

Active load	Hotel	Thruster	Crane	Pump	Handling Cranes
Mobilization	√	√	×	×	×
Work	√	√	√	√	√
Sail	√	√	×	×	√
Idle	√	×	×	√	√
R&M	√	√	√	√	√

Table 4.4: Active loads during several operational profiles

4.5. Conclusion key vessel characteristics

The goal of this chapter was to identify vessel characteristics that are relevant in case an e-fuel is implemented on a large offshore vessel. These characteristics were obtained by examining the energy infrastructure and energy profile of the large offshore vessels of HMC.
A generic energy infrastructure was created of a vessel operating on MGO, which will be used in the technical evaluation of this study. Additionally, the operational modes and loads present on a large offshore construction vessel were identified as well.
Several key takeaways from this chapter are summarized and touched upon in this sub-chapter.

Depending on the fuel infrastructure already present on the vessel, implementing certain e-fuels might be more convenient than others. Since certain fossil fuels and e-fuels have similar characteristics, resulting in fewer or no modifications required to the TTE infrastructure of the vessel, thereby also resulting in a lower CapEx. An overview of the characteristics of an MGO and LNG fuel infrastructure is given in Table 4.5.

Even though the emission abatement would be large, it is not likely that the entire capacity of the vessel is retrofitted to operate on an e-fuel. To take redundancy into account a DF ICE is likely to be installed, additionally, due to the highly fluctuating loads with a high ramp up fossil fuels are likely to be still required as their cetane number is higher compared to e-fuels and thus have a higher combustion speed.

Since the hotel load is present during each operational mode, retrofitting a capacity similar to the hotel load will firstly result in emissions being abated during each operational mode and secondly will result in the largest abatement as the load is always present.

Component	(E-)Diesel	(E-)LNG
Fuel storage	• Corrosive resistance material (steel/iron based). • Inert coating for inner tank. • Single walled and insulated tanks, with no extra heating. • Separated from other spaces by gas and water tight spaces or cofferdams.	• Type C tanks. • Hold space is considered as cofferdam. • Double steel walls, with insulation and vacuum between walls. • BOG or PBU installed to maintain desired pressure.
TTE piping	• Corrosive resistance material (steel/iron based). • Mostly low-pressure single-walled pipes. • All pipes are insulated, without trace heating. • Shielding layer required in case piping is located in wet or damp spaces. • All passing spaces should be ventilated.	• Double-walled steel piping required. • Space between pipes is kept at vacuum, or at higher pressure with inert gas. • Nitrogen system is added to purge and cool the piping system. • Leakage monitoring system required.
Energy conversion unit	• Cylinders as well as pistons are mad out of cast iron. • Head of the ICE is made out of cast iron or steel. • Fuel injectors, must be compatible with high pressure and MGO and often steel is used.	• DF engine with gas admission valves • Pilot fuel is required to start combustion. • LNG is either supplied to a gas mixture or directly to combustion chamber.

Table 4.5: Overview of the MGO and LNG energy infrastructure

5 Technical evaluation

The technical evaluation, used to evaluate the key components of the energy infrastructure discussed in Chapter 4, is looked into in this chapter. In the previous chapters, data is gathered necessary to perform the technical evaluation. In the technical evaluation the energy infrastructure of a vessel operating on MGO, depicted in Figure 4.2, is utilized as starting point. By making use of previously gathered information and data, the modifications on a large offshore vessel, necessary to implement an e-fuel, are identified. These modifications depend on the key vessel characteristics as well as the type of alternative fuel that is implemented, this chapter discusses the modification required to implement an e-fuel.

The technical evaluation is later on in this research utilized in the case study, where the necessary modifications to implement an e-fuel on one of the large vessels of HMC are assessed. This chapter is divided into three sub-chapters, which represent the key infrastructural components of the fuel system. In each sub-chapter the characteristics of and modifications to the fuel storage tank, fuel piping and energy conversion unit, for each e-fuel are discussed.
In sub-chapter 5.1, the fuel storage tanks are looked into, in sub-chapter 5.2 the piping infrastructure of the fuel system is touched upon and in sub-chapter 5.3 the energy conversion unit is discussed. At the end of this chapter, an overview is given of the characteristics of the above-mentioned components per e-fuel as well as a conclusion of the technical evaluation in sub-chapter5.4.

Each energy infrastructure also requires some additional components, necessary to maintain the fuel at the right storage conditions, to filter the fuel or to ensure certain safety aspects on the vessel. In this study the focus is on the larger components of the energy infrastructure as they are likely to have a larger impact on the KPIs, however, a short description of some additional components for the energy infrastructure of each e-fuel is mentioned in Appendix D.
This chapter partly answers the fourth sub-question, which was mentioned in section 1.3.2:

- *What technological adjustments are required in order to implement the selected e-fuels, and what are the associated costs?*

5.1. Fuel storage evaluation

The first component of the energy system that is looked into is the onboard fuel storage. Important considerations that should be taken into account are, the volume of an e-fuel tank, that is necessary to comply with the energy demand of the vessel, if the materials used in the fuel storage system are suitable to handle the specific e-fuel, if the health and safety measures of the current fuel storage system are sufficient to store the e-fuel and lastly if the e-fuel storage requires additional components that are not included in the current fuel storage system.

Depending on the energy demand of the vessel between bunkering periods, the efficiency of a pathway and the volumetric energy density of an e-fuel, the fuel storage tanks can be sized. The necessary volume of an e-fuel is calculated according to Equation 2.2 in the model. Hereafter, the currently installed fuel storage system, which was looked into in section 4.2.1, is examined. Based on the characteristics of the fuel storage system and based on the properties of the specific e-fuel the necessary modifications to the fuel storage system are identified.

Additionally, based on the extra e-fuel required to comply with the energy demand of the vessel and based on additional components required for the fuel storage system of an e-fuel, a volumetric and gravimetric evaluation is also performed. The additional volume required by the fuel storage system, hereby thus also including extra components of the system, could affect the feasibility of implementing an e-fuel, since available space on a vessel could be a limiting factor. Besides, the additional mass which is added to the vessel, in case an e-fuel is implemented, could affect the displacement of the vessel, and should, therefore, also be taken into account.

E-hydrogen

E-hydrogen can either be stored in a gaseous state, where it is compressed at 350 or 700 bar, or in a liquid state where it is stored at ambient pressure and at a temperature of -253 °C. During this study, the focus is on the cryogenic storage of hydrogen, as the energy density of this storage type is approximately 1.5 times higher compared to storing hydrogen in gaseous pressurized conditions.

The conditions that are required to ensure e-hydrogen stays in its liquid state make it a challenging fuel to store. One of the challenges is keeping e-hydrogen at the right temperature, thereby minimizing evaporation. The evaporation of e-hydrogen has two downsides, the first one is that the pressure increases inside the storage tank due to the boil-off gas and the second downside is the loss of spent energy used to store the hydrogen in its liquid state. Some characteristics of e-hydrogen storage tanks are listed below.

- The tanks must be designed to minimize BOG production, which can be done according to two different methods:
  1. *Maximizing the volume to surface ratio of the tank, which is obtained by using cylindrical tanks [77].*
  2. *Insulating the tank. To minimize heat transfer, the tanks must be double-walled with a vacuum between the walls. Insulation materials, such as perlite, are placed inside the vacuum to reduce heat transfer through radiation [10].*
- Type C storage tanks should be utilized, similar to the e-LNG tanks, however, a higher grade material is needed for the inner wall of the tank, such as high-grade stainless steel (SUS304L) [69] or aluminum alloys [29].
  - *Since hydrogen molecules are significantly smaller than methane molecules, the material used must be able to block the small hydrogen molecules from leaking through the tank, as well as be able to withstand the low cryogenic temperatures and embrittlement [69].*
  - *The temperature of the tank materials will increase as the hydrogen tank gets emptier. This temperature increase can lead to stress and deformations in the system and eventually to failure, therefore a minimum amount of hydrogen needs to be present in the tank [69].*

E-diesel

As mentioned before, since the properties of fossil diesel and e-diesel are similar, no modifications are necessary to the fuel storage system of a vessel operating on MGO. The current fuel storage system, including all additional components, can be utilized in case e-diesel is implemented on a large offshore vessel. The fuel infrastructure of a vessel operating on MGO was discussed in sub-chapter 4.2.

E-LNG

Just as with, e-diesel and fossil-diesel, the properties of fossil-LNG and e-LNG are similar, therefore a storage system for fossil-LNG can also be utilized in case e-LNG is implemented. A description of the characteristics of an LNG storage tank was given in sub-chapter 4.2.

E-methanol

Since methanol is a liquid at ambient temperature and pressure it does not require special pressurized storage tanks. Additionally, since e-methanol is not classified as a marine pollutant, by the IMO storing e-methanol offers some flexibility. A short description of the characteristics of an e-methanol storage tank is given below.

- Double-walled tanks equipped with a zinc or epoxy coating to prevent corrosion, in case the e-methanol contains contaminants or moisture [164].
  - *Methanol can contain a percentage of water that may cause cracking due to corrosion, thus corrosion-inhibiting additives or specific coatings are required to reduce corrosion [5].*
- The tanks can be placed either in the vessel or the storage tanks can be hull-integrated [164].
  - *If the tanks are hull-integrated, no double-bottom is required, and the bulkheads of the e-methanol storage tanks, which is the upright area within the tank, can form the shell plating of the vessel, however only below the waterline [164].*
- A tank connection space on top of the tank, which is an enclosed area where all valves, openings and monitoring equipment are placed, is required [164].
- Cofferdams, which are air-tight void spaces around the tank, are required [164].
  - *Cofferdams provide an additional layer of protection against the leakage of e-methanol and prevent the creation of a mixture of explosive gasses [164].*
  - *The cofferdams are purged and filled with an inert gas, such as nitrogen, which lowers the oxygen content hereby preventing the reaction of methanol with oxygen and thus the creation of an explosive gas mixture [164]. The cofferdams can also be filled with water [126].*
- Inerting system is required to provide an inert blanket on top of e-methanol and hereby ensure an inert tank at all times [164].
- A minimum of two ventilation inlets and outlets for gas purging and gas freeing, which are placed on the highest point of each fuel tank, are required [99].
- Tanks must be equipped with pressure and vacuum relief valves, to limit the pressure or vacuum in the tank [99].
- Additional monitoring and control systems are required, such as liquid and gas detection systems, overfill and shutdown alarms and areas adjacent to the storage tanks should be equipped with fire detection systems [99].

E-ammonia

Liquid e-ammonia can either be stored at ambient pressure and at a temperature of -33.4 °C, or at ambient temperature and at a pressure of approximately 20 bar [92]. Therefore, depending on the storage method either an atmospheric tank or a pressurized tank is required. Both storage methods have their advantages and disadvantages. The low-temperature storage method is used on a large scale, however, additional energy is required to maintain the e-ammonia at the desired temperature. Additionally, due to the continuous evaporation of the e-ammonia a boil-off gas is generated, just as with e-LNG, which will increase the tank pressure if not controlled [3]. The characteristics of an e-ammonia storage tank are given below.

- Only corrosive-resistant alloys, such as iron, (nickel-) steel, and carbon-manganese can be utilized as a material for the storage tanks [92].
- Type A, type B, and membrane tanks are compatible with storing e-ammonia at ambient pressure and at -33.4 °C [6].
  - *Type A and membrane tanks must be fully double-walled, with a fully inerted annular space [6] Type B only requires a partial double-wall and is equipped with fatigue analysis tools that are able to manage small leaks with a cryogenic barrier protection and the management of an inert gas in the space between the walls [6].*
- Type C tanks, similar as to the e-LNG tanks, are compatible with storing e-ammonia under pressurized conditions [3].

  - *No re-liquefaction equipment is necessary and no double-walls either. However, due to their cylindrical form much space is lost [3] and additional safety measures must be taken due to the pressurized ammonia [6].*
  - *The hold space should be filled with an inert gas or with dry air [6].*

- E-ammonia storage tanks, except for type C, must be separated from other spaces with a cofferdam of at least 900 mm or more [6].
- A tank connection space, similar to e-methanol, is located in the fuel supply space system space [6]
- In e-ammonia storage spaces, measures are required to ensure the solidity of the equipment and insulate it from external damage, these areas are restricted for personnel [31].
- Safety measures should be taken to minimize the possibility of a leakage, such as gas leak detection and shut-off systems [31].
- Spaces where e-ammonia is never present, must be isolated by one or two boundaries or by a minimal distance from the areas where e-ammonia is present [31].

The storage volume required to store an adequate amount of fuel that is compliant with the energy demand of the vessel, is an important factor in the technical evaluation. As mentioned earlier, the available space on a vessel could be a limiting factor, resulting in some e-fuel pathways being less realistic to implement. The necessary storage volume depends on the volumetric energy density of the fuel, the efficiency of an e-fuel pathway as well as the additional components necessary for the fuel storage system of the fuel. Figure 5.1, gives an overview of how much energy is stored in each e-fuel per cubic meter, which is indicated by the orange line. Additionally, the extra volume necessary to store the fuel is shown as well and hereby e-diesel is taken as baseline as it has similar characteristics as MGO. The extra volume is shown for only the fuel and for the entire fuel system as well. As can be seen, the lower the volumetric energy density of the fuel, the more storage volume is needed, however, the extra volume occupied by the entire system also plays a big role.

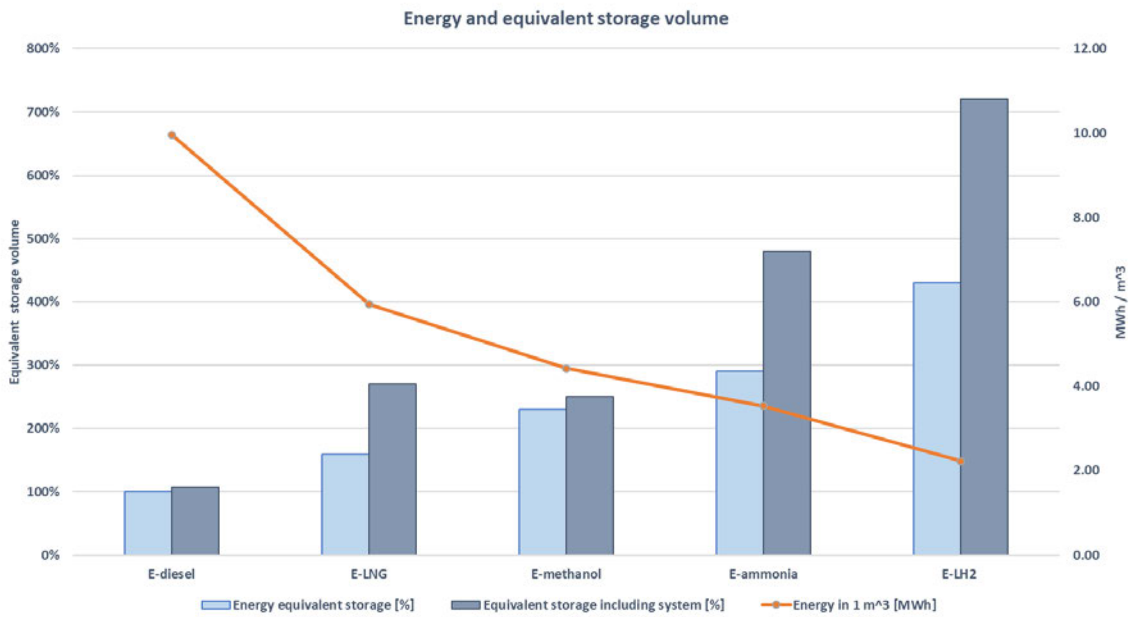

Figure 5.1: The equivalent storage volume of the e-fuels compared to e-diesel and the energy stored in 1 m^3 [164]

5.2. Fuel piping evaluation

The same evaluation that is performed for the fuel storage system is performed for the TTE piping infrastructure. Important considerations, when looking at the piping infrastructure, are the piping materials, if the pipes must be single or double-walled and if the health and safety measures currently equipped on the vessel are appropriate for the e-fuel. As could be seen in the possible energy infrastructure of a vessel operating on MGO and LNG, in Appendix E, the piping system of the fossil fuel and the secondary fuel are separated.

Based on the characteristics of a specific e-fuel, as well as on the characteristics of the piping infrastructure currently present on the vessel, the fuel piping system is evaluated.
The focus is specifically on the piping and additional components, that are part of the fuel piping system, such as transfer pumps are not considered during the technical evaluation.

E-hydrogen

The piping infrastructure of e-hydrogen must comply with several safety measures since it is a highly explosive fuel and can impose physical damage on humans. A short description of the characteristics of an e-hydrogen piping system is given below.

- The piping system must be double-walled and should consist of materials that are able to withstand the cryogenic temperature, as well as hydrogen embrittlement, such as stainless steel or aluminium [50].
- The piping system is equipped with control, shut-off and pressure relief valves, that are utilized to regulate the pressure in the piping system [50].
- A detection system should also be included, which alarms in case of a leakage and the shut-off systems shuts the supply of e-hydrogen to the engine off [50].
- A blowdown system should also be installed, which in case of a spill the blowdown systems blows the hydrogen to a safe location, which is often outside of the vessel, where it will rise and disperse [50].

E-diesel

Just as with the fuel storage system, the MGO piping infrastructure is also compatible with e-diesel, and therefore no modifications are required. The piping infrastructure of a vessel fuelled by MGO was discussed in sub-chapter 4.2.

E-LNG

Similar as to the e-LNG storage tanks, a fossil LNG piping system is also compatible with e-LNG, due to similar characteristics. A description of the LNG TTE piping system was given in sub-chapter 4.2.

E-methanol

The piping infrastructure for e-methanol must be separated from all other piping systems onboard of the vessel, besides the piping system must maintain a minimum distance of 760 millimeters from the sides of the vessel. A short description of an e-methanol TTE piping system is given below.

- The entire piping system must be made gas-free and inert before operating and drip trays must be installed below possible leakage points [99].
- A zinc or epoxy coating must be applied to the MGO piping system to protect against corrosion [5].
- The piping system consists out of double-walled pipes to protect against mechanical damage as well as against leakage [164]. Only within cofferdams can the piping be single-walled [126].
- All piping is low-pressure, up to the high-pressure pump room, after which the e-methanol is transferred to the engine [126].
- The outer pipe is gas and watertight, and the space between the double walls must be ventilated to the open air and equipped with appropriate sensors for leakage detection [99].
- The space between the double-walls must be kept at a pressure lower than the fuel pressure but higher than ambient pressure and must contain an inert gas [126].

- Direct e-methanol supply lines to the engine are equipped with automatically operated master valves and shut-off valves, which are located outside of the engine room [99].
- The piping system is equipped with several pumps located in pump rooms outside of the engine room.
  - *The pump rooms must be gas as well as watertight and vented to open air [99].*
  - *The additional valves and pumps present in the piping system result in many possible leakage points that need extra safety measures [99].*

E-ammonia

Since e-ammonia is an extremely dangerous substance, handling the fuel must be done with extreme caution. To prevent any e-ammonia spill and hereby exposure to humans or the environment, the pipes should be located at a minimal distance from the hull, for example, with a distance of the breath of a vessel divided by 5 [163]. A short description of an e-ammonia piping system is given below.

- Only alloys that are resistant to ammonia, such as iron, can be utilized as a material for the piping system [31].
- The piping system must be double-walled to ensure that a single failure within the piping infrastructure will not lead to a leakage [31].
- The outer pipe must contain a continuous flow of ventilation air, which can get rid of any leaked e-ammonia [31].
- The piping system must contain an ammonia detection system and isolation valves which can be closed in case of an ammonia leak [163].
- The entire piping system must be purged with an inert gas, such as nitrogen [6].

5.3. Energy conversion evaluation

In all e-fuel pathways, except for e-diesel, where an ICE is utilized to extract the chemical energy, a DF ICE is used. This is done to take redundancy into account in case an e-fuel is not available and the vessel will still need to operate. During the technical evaluation, the parts of the ICE, with which the e-fuel comes into contact, are examined to see if they are suitable for the combustion of an e-fuel. Due to the low cetane number of the e-fuels, all require a pilot fuel, such as MGO, to start the combustion. If a PEMFC is utilized as an energy conversion unit, which is only relevant for e-hydrogen in this study, the ICEs currently utilized on the vessel will be replaced. During this evaluation, an important consideration is the required volume, in case a fuel cell stack, with a capacity in the MW regions, is installed.

E-hydrogen

As became clear from the energy conversion pathways, there are two possible pathways for the conversion of e-hydrogen that fall within the scope of this research. The first option is the combustion of e-hydrogen in a DF ICE. The main challenges of e-hydrogen combustion are related to its low methane number, low ignition energy, high auto-ignition temperature and high flame speed, which leads to a high pressure and temperature increase [146]. A brief description of an e-hydrogen fuelled ICE is given below.

- E-hydrogen can either be supplied to a gas mixer or it can directly be supplied to the carburetor at the supply ports of the ICE. The latter is preferred as it showed higher efficiencies and reduced emissions [45].
  - *In the gas mixer, e-hydrogen is mixed with air and transported to the combustion chamber through the turbocharger [45].*
  - *In the carburetor, the hydrogen is mixed with air and supplied to the cylinder [45].*

The second option is making use of a PEMFC to convert the chemical energy into mechanical energy that can be utilized onboard the vessel. The gravimetric and volumetric power density of a hydrogen-fuelled PEMFC are between 0.25-1 kW/kg and 300-1,550 kW/m^3 [18]. The requirements for an e-hydrogen-fuelled PEMFC are shortly described below

- The fuel supply lines should be similar to the piping system and thus be double-walled and of high-quality stainless steel [64].
- The space where the PEMFC system is located must be gas-tight and should be able to contain any fuel leakages [64].
- The space should be equipped with a mechanical ventilation system to avoid the accumulation of leaked fuel gases [64].
- The ceiling of the PEMFC system space should have a ceiling sloping towards the ventilation outlet, as in the case of hydrogen, the leaked gas will rise [64].
- A control, monitoring, and safety system that detects any leakages of gaseous fuel and that automatically shuts off the fuel supply line towards the PEMFC should be installed as well as a fire and smoke detection system [64].

E-diesel

In the possible energy conversion pathways for e-diesel, the only feasible option that falls within the time frame set for this study, is the pathway that includes an ICE. The ICE used for e-diesel is similar to the ICE used for MGO, which was already discussed in sub-chapter 4.2.

E-LNG

When natural gas is used as fuel in an ICE, two engine types are available, gas-only engines and DF engines that operate on MGO as well as on LNG. Both engines are already commercially available as well as compatible with e-LNG. These engines were discussed in sub-chapter 4.2.

E-methanol

If e-methanol is implemented on a large offshore construction vessel, two options are available regarding the energy conversion, either a methanol-only or a DF engine could be implemented. The DF ICE is focused on in this study and will be the preferred choice, since it includes a certain type of redundancy, as in the scenario where e-methanol will not be available, the vessel is still able to operate. However, due to the low cetane number of e-methanol, a pilot fuel is necessary to start the combustion [54]. A short description of a DF e-methanol ICE is given below.

- The DF ICE should be equipped with an e-methanol common rail system, which is a type of fuel injection system that is separate from the MGO fuel injection [99].
  - *The common rail system contains e-methanol booster injectors, a liquid gas injection block, which contains a control valve that regulates the injection of e-methanol, and several inlet and outlet valves [99].*
- The cylinder of the MGO-only ICE will have to be replaced by a special cylinder compatible with e-methanol as well as MGO [5].
- Inerting system is required to purge the DF engine before and after using e-methanol [54].

E-ammonia

Due to the slow flame velocity, high auto-ignition temperature, lower heat of combustion and small flammability range, implementation of e-ammonia is a difficult process, however, engine manufacturers are working on addressing these issues [3]. E-ammonia can be combusted in a DF ICE, in combination with a pilot fuel, such as MGO. Since the combustion of e-ammonia requires a high compression rate and temperature, much NO_x is emitted during combustion. A brief description of a DF e-ammonia ICE is given below.

- The same materials that must be avoided for the fuel storage and piping system of a vessel operating on e-ammonia, should also be avoided in an e-ammonia fuelled ICE [6].
  - *Components such as the combustion chamber, supply valves and lines, and exhaust gas systems should all be modified to operate on e-ammonia [6].*
- A suitable ventilation system should be installed, including fans and air ducts that can remove any e-ammonia fumes or leaks [6].
- The engine must be equipped with shut-off and pressure relief valves and shut-off switches, to shut off any fuel supply to the engine [6].
- The e-ammonia can either be premixed with air and hereafter supplied to the engine or directly injected into the compressed air in the combustion chamber [31].
- A high-pressure injection system, separate from MGO, is utilized, which also minimizes ammonia slip [3].

5.4. Conclusion technical evaluation

This chapter aimed to identify the technical modifications required to implement the selected e-fuels. By looking at the technical requirements of the fuel storage system, fuel piping and energy conversion unit of each e-fuel, the required modifications to the MGO base case are obtained. Table 5.2, summarizes the technical evaluation discussed in this chapter.
Several conclusions obtained from this chapter are stated in this sub-chapter.

Since redundancy is an important aspect, when implementing an e-fuel, it is important to understand what e-fuels are compatible with the TTE infrastructure of MGO and other e-fuels. Hereby, in case a specific (e-)fuel is not available, the vessel owner has an understanding of what other fuels are compatible with the TTE infrastructure and could be implemented to power the vessel.
Based on the storage conditions and characteristics of the storage tank of each e-fuel an overview of the compatible storage tanks for each e-fuel is given in Table 5.1.
MGO storage tanks are not compatible with e-LNG, e-hydrogen or e-ammonia, as their storage conditions differ too much, and type C tanks are required. MGO and e-methanol have similar storage conditions, therefore, MGO tanks can be used for e-methanol storage in case a second wall, additional cofferdams, and a zinc or epoxy coating are applied.
Storage of MGO in a type C tank is possible, however, the materials used must be iron or steel-based, storage of MGO in a methanol tank is not possible as the coating used MGO is not compatible with zinc.

Another redundancy measure taken is the fact that DF ICE engines are used, therefore, both MGO as well as an e-fuel can be utilized to power the vessel. Each of the e-fuels requires MGO as pilot fuel and the cylinders must be of a material compatible with the e-fuel as well as with MGO.
The piping infrastructure for an e-fuel is mostly separate from the MGO piping, as can be seen in Figure E.1, however in case another e-fuel is to be implemented, certain modifications are required depending on the e-fuel.

Retrofit to → / Currently installed ↓	Fuel storage tank				
	(E-)diesel	(E-)LNG	E-L_H2	E-methanol	E-ammonia
(E-)diesel		Type C required	Type C required	Double wall + coating + cofferdam required	Type C required
(E-)LNG			High grade steel required	Coating required	
E-L_H2				Coating required	
E-methanol	Not compatible with zinc	Type C required	Type C required		Type C required
E-ammonia			High grade steel required	Coating required	

Table 5.1: Overview of the compatible storage tanks for each e-fuel

Component	(E-)Diesel	(E-)LNG	E-hydrogen	E-methanol	E-ammonia
Fuel storage tank	• Steel/Iron based materials. • Inert coating for inner tank. • Single walled and insulated tanks. • No extra heating is required. • Separated from other spaces by gas and water tight spaces or cofferdams.	• Replace MGO tanks with type C tanks. • Double steel walls, with insulation and vacuum between walls. • BOG or PBU installed to maintain desired pressure.	• Replace MGO tanks with type C tanks. • Vacuum and insulation. material between walls. • High grade stainless steel.	• Apply zinc or epoxy coating to MGO tank • Add double-wall to MGO tank • Tank connection space on top of tanks. • Cofferdams around the tank. • N_2 inerting system.	• Replace MGO tanks with type A, B, C or membrane tanks. • Cofferdams, required if no type C tank. • N_2 inerting system.
Fuel piping	• Steel/Iron based materials. • Mostly low-pressure single-walled pipes. • Insulation required, but no trace heating. • Shielding layer required in case of wet or damp spaces. • All passing spaces should be ventilated.	• Double-walled steel piping required. • Space between pipes kept at vacuum, or at higher pressure with inert gas. • Nitrogen system is added to purge and cool the piping system. • Leakage monitoring system required.	• Double-walled pipes. • Same materials as storage tank. • Control, shut-off and pressure relief valves present • Detection and blowdown system. • N_2 inerting system.	• High and low pressure double-walled pipes. • Zinc or epoxy coating. • Ventilation and leakage monitoring system. • Pumps outside engine room. • N_2 inerting system.	• Double-walled pipes. • Same materials as storage tank. • Continuous ventilation. • Ammonia detection system. • N_2 inerting system.
Energy conversion unit	• Cylinders as well as pistons are made out of cast iron. • Head of the ICE is made out of cast iron or steel. • Fuel injectors, must be compatible with high pressure, often steel is used.	• DF engine with gas admission valves • Pilot fuel is required to start combustion. • LNG is either supplied to a gas mixture or directly to combustion chamber by fuel injector.	ICE • Pilot fuel necessary. • Mixed with air in gas mixer or carburetor. • Cylinder must be compatible with e-hydrogen. PEMFC • Gas tight space with ventilation • Leakage monitoring system	• Pilot fuel necessary. • Common rail system required, for separate fuel injection. • Cylinder must be compatible with e-methanol. • N_2 inerting system.	• Pilot fuel necessary • Cylinder must be compatible with e-ammonia • Ventilation system. • Separate high pressure injection system.

Table 5.2: Overview of the required technical modification

6 Financial Evaluation

In this chapter, the financial evaluation and the methodology used to assess the costs associated with the implementation of an e-fuel are discussed. Since the assumption was made that an e-fuel will be implemented in the coming 10 years, assumptions are made regarding the future MGO, e-fuel, and EU ETS prices based on historical data and published market outlooks.
Since the CapEx of a technical modification, the OpEx of a component and the OpEx related to the fuels, affect the LCOE and LCoCA and, therefore, the impact of implementing an e-fuel, they must be considered. Therefore, this chapter provides a generic overview of the costs related to the implementation of an e-fuel pathway.

The information gathered during this financial evaluation is later used in the case study on one of the large offshore vessels of HMC. Initially, in sub-chapter 6.1, the e-fuel prices are determined, in sub-chapter 6.2, the CapEx of each modification is touched upon, and in 6.3, the OpEx related to the components of energy infrastructure is discussed.
This chapter partly answers the fourth sub-question, which was mentioned in section 1.3.2:

- *What technological adjustments are required in order to implement the selected e-fuels, and what are the associated costs?*

6.1. E-fuel & ETS pricing

The e-fuel price influences the OpEx of each pathway and, thereby also the LCOE and LCoCA. Whereas the EU ETS price affects the fossil fuel prices and thus the OpEx of the MGO base case, to which the e-fuels are compared. Therefore both are considered and used as input values for the model. Even though the production of e-fuels is developing fast, it is still under development and several major challenges still need to be overcome, before e-fuels will be globally and abundantly available [22]. As became clear from sub-chapter 3.2, the production route for each e-fuel starts from renewable electricity, which is utilized to produce H_2 and that is combined with captured CO_2 or N_2 to produce an e-fuel. The future production and price of the various e-fuels will, therefore, largely depend on the available renewable electricity and the prices as well as on the available CO_2 and N_2 [51].

Since this study assumes that e-fuels will be implemented on large offshore vessels in the coming 10 years, certain assumptions will also have to be made regarding e-fuel prices. Based on recent literature and published market outlooks, data is gathered regarding the price of each e-fuel. In a study published by Brynolf et al., an overview is created of recent literature regarding the production costs of e-diesel, e-LNG and e-methanol [22]. Additionally, in several market outlooks, published by IRENA, the current and expected e-methanol, e-ammonia, and e-hydrogen prices are stated [81] [80] [79]. DNV published a maritime forecast, in which they estimated both fossil and e-fuel prices for 2050, by looking at production as well as distribution costs of the fuels and taking the average of 10 different regions [51].

From the gathered data, multiple e-fuel prices are obtained, and a range is created within which the price for each e-fuel is expected to lie. The range for the e-fuel prices in 2022 and 2032 is shown in Figure 6.1, together with the MGO price in 2022 and 2032. For the MGO price, the yearly average is taken, which was approximately 0.089 Eur./kWh in 2022 [24], as can be seen, this price is lower than the average e-fuel prices in 2022.
Currently, e-fuel prices are high, compared to the MGO price, which is caused by the production processes of the e-fuels still being under development, renewable electricity not being abundantly available and the small-scale use of direct air capture. However, the assumption is that due to increasing efficiencies of the production processes of e-fuels, an increase in renewable energy sources and large-scale implementation of direct air capture, e-fuel prices will decline in the coming years [51]. This price decline is also depicted in Figure 6.1, where the range and the average e-fuel price for each e-fuel declines.
In contrast, fossil fuel prices are likely to increase due to the implementation of new regulations, such as including CO_2 emissions from the shipping sector to the EU ETS. The EU ETS creates a financial incentive, as it sets a cap on the total amount of GHGs that a sector can emit each year. A fixed number of emission allowances are issued and companies must purchase sufficient emission allowances to cover their emissions, additionally, the cap is lowered over time, to stimulate an emission reduction. By lowering the cap, the assumption is that the EU ETS price will increase, and hereby also the fossil fuel prices, as the user has to pay for the fuel and the GHGs it emits [38]. Even though some e-fuel still emit CO_2, the EU ETS allows using a zero WTW emission factor for e-fuels and thereby exempts them from the EU ETS [49]. The fossil fuel price increase is depicted in Figure 6.1, where the MGO price increased compared to 2022.

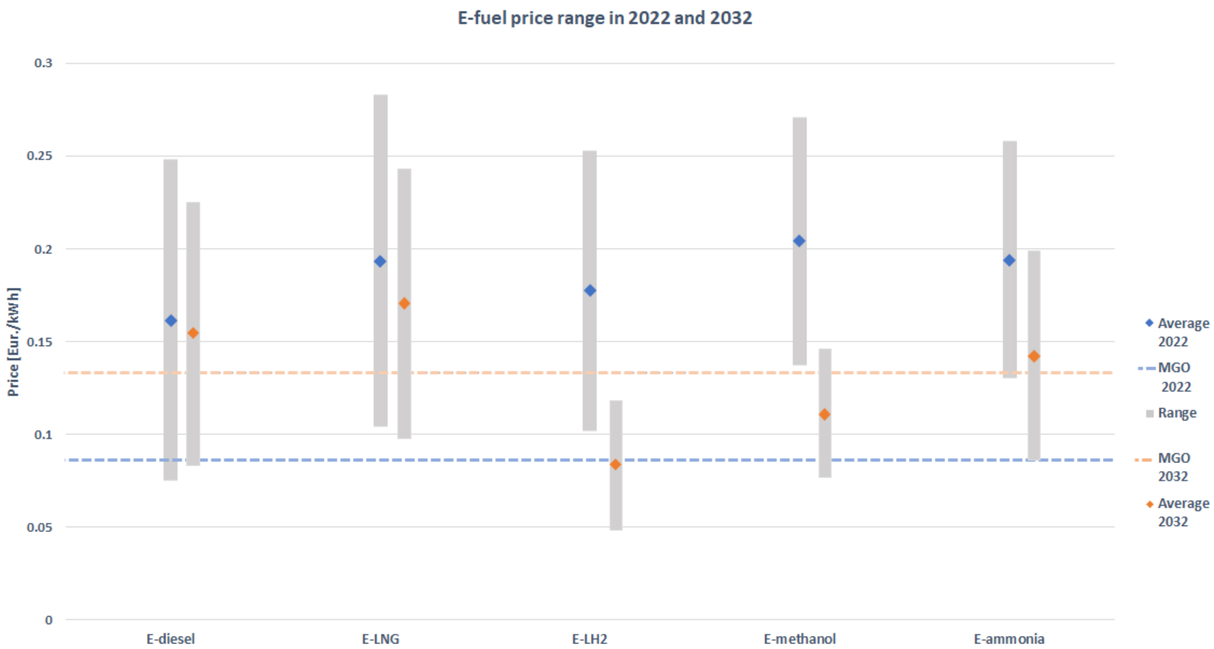

Figure 6.1: 2022 and 2032 E-fuel price range, obtained from literature, compared to MGO price

Due to an expected increase in fossil fuel prices and a decrease in e-fuel prices, a break-even point will be reached where it is no longer financially attractive to operate on MGO, as its price exceeds the price of an e-fuel. Based on the average fuel prices, shown in Figure 6.1 and on market outlooks for the various e-fuels an assumed forecast is created, regarding the e-fuel prices up to 2050, which is shown in Figure 6.2. In Figure 6.2, the minimum, maximum, as well as the average e-fuel price, are shown. As mentioned before and as can be seen, the assumption is that e-fuel prices will decline in the coming years due to several technological advancements. A more detailed description of the e-fuel price forecasts and the data used is given in Appendix D.
The price developments of MGO are also given in Figure 6.2, and even though the MGO price is expected to increase with approximately 0.63% per year [73], the addition of CO_2 emissions, originating from the marine sector, to the EU ETS will likely result in the MGO price increasing at a more rapid pace.

The emissions of the marine sector will be added to the EU ETS gradually, in 2027 40% of emissions will be added, in 2028 70% and in 2029 the marine sector will have to pay offsets for 100% of its CO_2 emissions [40]. This gradual transition is also visible in the MGO price developments, which increase as a percentage of the emissions is added. The EU ETS price is currently set at approximately 100 Eur./mT CO_2 [53], and the expectation is that this price will increase in the coming years by approximately 5% per year [110].

A break-even point is determined by using the MGO price developments as well as the average e-fuel price, indicated with the red dashed line. Even though the price decrease varies per e-fuel, as shown in Appendix D, the average price is utilized to get an understanding of the approximate timing and price at which an e-fuel becomes more financially attractive to use than MGO. The period within which it is expected to be financially more attractive to use an e-fuel instead of MGO, is 2030 - 2035. The break-even point occurs after 2031, which is in line with the time frame set for this study, and at an e-fuel price of approximately 0.135 Eur./kWh.
Further in this research, the assumed e-fuel as well as EU ETS prices for 2032 are utilized in the financial evaluation of the case study. An important consideration is that assumptions are made regarding the future fuel and EU ETS price and therefore, a level of uncertainty is incorporated in this study. Additionally, variations of the prices will affect LCOE and LCoCA, therefore during the sensitivity analysis in Chapter 8, this effect is examined and in Chapter 10, this uncertainty in the values is reflected on.

Figure 6.2: Fuel price forecast until 2050

6.2. CapEx

Implementing a specific e-fuel pathway requires certain modifications to or replacements of equipment on the vessel, which are accompanied by an associated CapEx. The modifications necessary on a vessel, to implement a certain e-fuel pathway, and therefore also the related CapEx are vessel specific. Depending on the already present energy infrastructure and the energy profile of the vessel the necessary modifications can be determined as well as the necessary investments.

Even though the CapEx of each e-fuel pathway is vessel-specific, several initial values regarding the investment costs can be obtained and indicate the implementation costs. These values are depicted in Table 6.1. The initial CapEx values are subdivided into investments necessary to the energy conversion unit, investments necessary to the storage system, investments necessary to the piping system and lastly investments necessary for additional components. As can be seen, almost all values, except the CapEx values of the piping system, depend on the energy profile of the vessel.

In the case study, these initial CapEx values are utilized, together with the energy profile characteristics of the vessel, to determine the CapEx related to a specific e-fuel pathway. Hereafter these CapEx values are used to determine the LCOE as well as the LCoCA.
To obtain the total CapEx of an e-fuel pathway, Equation 6.1 is utilized, depending on whether the e-fuel is reformed or cracked to obtain hydrogen a fuel reformer is included in the CapEx or not.

$$CapEx = C_{\text{En. conversion unit}} + C_{\text{Fuel storage}} + C_{\text{Fuel handling}} + C_{\text{Fuel reformer}} + C_{\text{SCR}} \tag{6.1}$$

Symbol	Unit	Explanation
$\mathbf{C_{\text{En. conversion unit}}}$	Eur.	*CapEx related to the energy conversion unit*
$\mathbf{C_{\text{Fuel storage}}}$	Eur.	*CapEx related to the fuel storage system*
$\mathbf{C_{\text{Fuel handling}}}$	Eur.	*CapEx related to the fuel handling system*
$\mathbf{C_{\text{Fuel reformer}}}$	Eur.	*CapEx related to the fuel reformer*
$\mathbf{C_{\text{SCR}}}$	Eur.	*CapEx related to the SCR*

6.3. OpEx

Each component that is installed in the energy infrastructure of a vessel has an associated OpEx, which indicates reoccurring costs. These are costs such as repairs or maintenance on the specific component or the replacement of the fuel cell stack in case a fuel cell is utilized as an energy conversion unit. The OpEx of a component of the energy system is strongly related to the operating hours of the specific component and, thus, to the energy profile of the vessel. The OpEx is, therefore, often a value in euros per a certain time period. In this study, the OpEx is denoted as a percentage of the CapEx per year. The Opex values related to the components of a specific e-fuel pathway are depicted in Table 6.1 and are obtained from recent literature as well as from conversations with manufacturers.

The costs associated with the acquisition of an e-fuel also fall under the OpEx of an e-fuel pathway, as they are costs that reoccur within a certain time period. However, in this study, the OpEx associated with an e-fuel is looked at separately from the OpEx costs associated with the energy infrastructure.

The OpEx values obtained are utilized as input in the model, together with the OpEx of the e-fuels as well as the CapEx. These financial input values have an essential contribution to determining the LCOE and LCoCA.
To obtain the total OpEx of an e-fuel pathway, Equation 6.2 is utilized. The OpEx related to the acquisition of carbon offsets is only relevant for fossil fuels.

$$OpEx = C_{\text{Fuel}} + C_{\text{EU ETS}} + C_{\text{Components R\&M}} \tag{6.2}$$

Symbol	Unit	Explanation
$\mathbf{C_{\text{Fuel}}}$	Eur./year	*OpEx related to the acquisition of a fuel*
$\mathbf{C_{\text{EU ETS}}}$	Eur./year	*OpEx related to the acquisition of carbon offsets*
$\mathbf{C_{\text{Components R\&M}}}$	Eur./year	*OpEx related to R&M of fuel infrastructure components*

Table 6.1: Initial CapEx and Opex values for components of the energy infrastructure

	Component	CapEx	Unit	Source	OpEx	Unit	Source
Energy Conversion Unit	E-diesel ICE	240	*[Eur./kW]*	*[88]*	2%	*[% * CapEx/yr.]*	*[23]*
	E-LNG DF ICE	470	*[Eur./kW]*	*[88]*	3%	*[% * CapEx/yr.]*	*[23]*
	E-methanol DF ICE	540	*[Eur./kW]*	*[151]*	3%	*[% * CapEx/yr.]*	*[23]*
	E-ammonia DF ICE	550	*[Eur./kW]*	*[85]*	3%	*[% * CapEx/yr.]*	*[23]*
	E-LH2 DF ICE	700	*[Eur./kW]*	*[14]*	3%	*[% * CapEx/yr.]*	*[23]*
	E-LH2 PEMFC	2500	*[Eur./kW]*	[1]	4.5%	*[% * CapEx/yr.]*	[1]
Fuel storage system	E-diesel storage system	0.083	*[Eur/kWh]*	*[14]*	1%	*[% * CapEx/yr.]*	[2]
	E-LNG storage system	0.31	*[Eur./kWh]*	*[14]*	2%	*[% * CapEx/yr.]*	[2]
	E-methanol storage system	0.14	*[Eur./kWh]*	*[14]*	2%	*[% * CapEx/yr.]*	*[69]*
	E-ammonia storage system	0.18	*[Eur./kWh]*	*[131]*	2%	*[% * CapEx/yr.]*	*[69]*
	E-LH2 storage system	0.83	*[Eur./kWh]*	*[14]*	2%	*[% * CapEx/yr.]*	*[69]*
Fuel handling system	E-diesel piping system	30	*Eur./kW*	[2]	2%	*[% * CapEx/yr.]*	[2]
	E-LNG piping system	178	*[Eur./kW]*	*[139]*	3%	*[% * CapEx/yr.]*	[2]
	E-methanol piping system	57	*[Eur./kW]*	*[139]*	3%	*[% * CapEx/yr.]*	*[69]*
	E-ammonia piping system	57	*[Eur./kW]*	*[139]*	3%	*[% * CapEx/yr.]*	*[69]*
	E-LH2 piping system	178	*[Eur./kW]*	*[139]*	3%	*[% * CapEx/yr.]*	*[69]*
Additional components	Methane reformer	370	*[Eur./kW]*	*[14]*	2%	*[% * CapEx/yr.]*	[118]
	Methanol reformer	370	*[Eur./kW]*	*[14]*	1%	*[% * CapEx/yr.]*	*[85]*
	Ammonia cracker	250	*[Eur./kW]*	*[14]*	1%	*[% * CapEx/yr.]*	*[85]*
	SCR	42	*[Eur./kW]*	*[69]*	3%	*[% * CapEx/yr.]*	[69]
	CCS system	2778	*[Eur./kW]*	[3]	6.5	*[Eur./mT CO_2]*	[133]

[1] *Obtained from Nedstack data*
[2] *Own assumption*
[3] *Obtained from manufacturer data*

6.4. Conclusion financial evaluation

The goal of this chapter was to identify the cost of implementing an e-fuel pathway. By looking into the CapEx associated with each modification as well as the OpEx of each pathway the total costs of implementation can be determined. The OpEx was subdivided into an OpEx related to the components of the infrastructure as well as an OpEx related to the fuels, which entails the acquisition of an e-fuel. Several conclusions obtained from the financial evaluation are stated in this sub-chapter.

Since a significant number of vessels are already compatible with e-diesel and e-LNG, the demand for these e-fuels will likely be the highest in the beginning. Therefore, even though e-fuel prices will decline, the high demand for e-diesel and e-LNG will result in their e-fuel prices being higher compared to the other e-fuels and, therefore, less attractive to implement.

The high CapEx and OpEx of a PEMFC make it a much less attractive energy converter to implement compared to a DF ICE even though having a higher efficiency.
A CCS system is especially relevant for fossil fuels, however, its high CapEx and OpEx withhold the implementation of the technology. The CapEx should be compared with money saved from abated emissions to determine if there is a financial incentive to implement a CCS system. Therefore, it is only relevant for fossil fuels. Additionally, an MGO pathway that makes use of a CCS system should be compared to the e-fuels pathways to determine if it is a viable solution to abating emissions.
E-fuel pathways that do not make use of a CCS system, a PEMFC or convert the e-fuel to hydrogen are likely to be the most financially attractive pathways. These pathways require the least CapEx, OpEx related to the components and OpEx related to the fuels as one less conversion step is required.

7
Case study

This chapter elaborates on the case study performed during this research. The case study is performed on the Thialf, which is one of the semi-submersible crane vessels owned by HMC and is shown in Figure 7.1. Initially, this chapter introduces the Thialf and provides some characteristics of the vessel such as its energy infrastructure as well as its energy profile. These characteristics are elaborated on in sub-chapter 7.1. Hereafter, the technical and financial evaluation are performed to gather input data for the model. The technical evaluation is discussed in sub-chapter 7.2 and the financial evaluation in sub-chapter 7.3. Once all necessary input data is collected, the model is utilized to obtain the results of the case study, which is elaborated on in Chapter 8.
All data regarding the Thialf is obtained from the in-house database of HMC, which gives insights regarding the energy infrastructure and energy profile of the vessel. Additionally, sustainability and retrofit experts within HMC that are familiar with the Thialf are also consulted to ensure correct and up-to-date information regarding the vessel is utilized.

Figure 7.1: The Thialf performing an installation of a wind turbine generator

7.1. The SSCV Thialf

The Thialf is one of four large offshore vessels within the fleet of HMC. Since the case study of this research is performed on the Thialf, this first sub-chapter introduces the vessel and elaborates on some characteristics relevant to this study. All characteristics of the Thialf, elaborated on in this sub-chapter, are obtained from an in-house database within HMC. Initially, some general dimensions and specifics of the vessel are touched upon in section 7.1.1 to get a better understanding of the size of these types of vessels. Hereafter, the energy infrastructure and the energy profile of the Thialf are discussed in sections 7.1.2 and 7.1.3.

7.1.1. Thialf introduction

As was already shortly mentioned in sub-chapter 4.1, the Thialf is one of the SSCVs within the fleet of HMC. The hull of the Thialf consists of two parts, the upper part of the hull and the lower part of the hull, which contains two submersible pontoons. Eight columns extend from the top of the lower hull to the bottom of the upper hull. The engine rooms, machinery rooms as well as living quarters are located in the upper hull, whereas the compartments in the pontoons are mostly utilized as tanks for ballast water or fuel. The compartments in the columns are utilized as ballast water tanks, however also as storage space for certain tools.
The Thialf is a multifunctional vessel designed to meet various installation needs and is therefore equipped with a class III dynamic positioning system, meaning the highest level of redundancy is present when the vessel is operating.

An overview of the dimensions of the Thialf is given in Table 7.1. The deadweight tonnage indicates the mass the Thialf is able to transport, store or bunker.

Table 7.1: Overall dimensions of the Thialf

	Dimensions of the Thialf
Length	201.6 m
Width/Breath	88.4 m
Depth to work deck	49.5 m
Operational draft	11.9 - 31.6 m
Transit draft	12.5 m
Deadweight tonnage	125508 mT

7.1.2. Thialf energy infrastructure

The Thialf only operates on MGO, and therefore, the generic fuel infrastructure shown in Figure 4.2 is taken as basis for this case study.

The electrical plant on the Thialf converts the chemical energy, stored in MGO, into electrical energy according to a three-stage process. In the first step, the diesel engines convert the chemical energy into mechanical energy. In the second step, the generators convert the mechanical energy into electric energy. In the final step, the electric energy is converted into AC electrical energy by the alternator and hereafter distributed to the various energy users. The distribution of the electrical energy is performed by the main switchboards, which are installed in each engine room. The separate switchboards are in line with the redundancy requirements for DP3, which indicates that each engine room should be able to function individually and not cause a total system failure.

The Thialf is equipped with 12 diesel-generator sets, divided over 3 separate engine rooms, that provide the vessel with the required power. The diesel generator sets consist of a diesel engine and an electric generator that is equipped with an alternator. The diesel generator sets have a combined maximum power output of 56.4 MW. The specifications of the diesel engines and diesel generators are as follows:

- *6x 4,900 kW each,* [redacted] *engine*
- *4x 4,500 kW each,* [redacted] *engine*
- *2x 6,000 kW each,* [redacted] *engine*
- *6x 4,600 kW each,* [redacted] *generator*
- *4x 4,300 kW each,* [redacted] *generator*
- *2x 5,800 kW each,* [redacted] *generator*

The engine rooms are located in the upper hull at portside (PS), starboard (SB), and in the former boiler room of the vessel, which is located close to the aft. Each engine room has a volume of approximately 3,770 cubic meters and contains four varying diesel-generator sets. All engines are equipped with their own drive train system, which among others, exists out of the fuel system, pumps, and a heating and control system.
The separation of the engines is done to meet the DP3 requirements, which state that one engine or engine room should be able to fail without resulting in other engines or systems failing as well. Hereby, these requirements take a certain level of redundancy into account and ensure that the vessel is still able to operate and stay in its exact position, even if an engine or system fails.
Another redundancy measure that is taken to prevent any power shortages, is that the necessary electricity must be produced with a minimal number of engines. This is done to ensure the required power can still be produced even if one engine fails, hereby preventing a failure. During certain operational modes, the minimal number of engines that are required to operate is higher than the number of engines actually necessary to perform a specific operation. During these operations, engines run on partial load, which results in the Thialf operating at lower engine efficiencies but at higher redundancy levels.

To get a general indication regarding the performance of the various engines installed on the Thialf a general specific fuel oil consumption curve is generated, which shows the average performance of the installed engines. Even though the engines are already operational for several years, the assumption is made, after consulting retrofit experts, that the performance of the engines has not degraded, as the components of the engines are replaceable. Therefore, no efficiency degradation is included in the average engine curve. As seen in the curve in Figure 7.2, the efficiency increases as the load increases.

[redacted]

Figure 7.2: Engine efficiency vs load curve of the engines on the Thialf

The Thialf is equipped with similar fuel storage tanks, fuel service tanks, and fuel settling tanks, as shown in the generic MGO infrastructure in Figure 4.2. In total, the Thialf is equipped with two large fuel storage tanks and one smaller tank, two settling tanks, and two service tanks. The two large MGO storage tanks of the Thialf are located in the pontoons of the vessel and MGO is transferred from the storage tanks to the settling tanks by a transfer pump. Hereafter, the MGO is transferred to the service tanks, from which the MGO is supplied to the main engines by supply and booster pumps. Any excess MGO is returned to the service tank through the relief valves of the engine.
Table 7.2 gives an overview of the volume and weight of the above-mentioned fuel tanks. Additionally, the energy that can be stored in the tanks is also shown in MWh. However, only the fuel tanks are utilized to actually store fuel and therefore, the total tank storage volume on the Thialf is approximately 8,350 m^3, which can store 83,194 MWh of energy.

Table 7.2: MGO fuel tanks of the Thialf

Fuel tank	**Volume *[m³]***	**MGO mass *[mT]***	**Energy *[MWh]***
Fuel tank (S)	[redacted]	[redacted]	[redacted]
Fuel tank (P)	[redacted]	[redacted]	[redacted]
Fuel tank (Aft)	[redacted]	[redacted]	[redacted]
Fuel settling tank (P)	[redacted]	[redacted]	[redacted]
Fuel settling tank (S)	[redacted]	[redacted]	[redacted]
Fuel service tank (P)	[redacted]	[redacted]	[redacted]
Fuel service tank (Aft)	[redacted]	[redacted]	[redacted]
Total	**8506**	**7654**	**84,748**

The Thialf is also equipped with a ballast system, which controls the trim, list, draught, stability and stresses of the vessel. The Thialf contains 42 ballast tanks, of which 12 are in the portside lower hull, 12 in the starboard lower hull, 9 in the four portside columns and 9 in the four starboard columns. The ballast system has a total tank capacity of approximately 135,632 m^3, of which about 72,305 m^3 is located in the lower hull tanks and 63,328 m^3 in the columns.

7.1.3. Thialf energy profile

To get a better understanding of the energy profile of the Thialf, historical data of last year as well as future data, based on already scheduled projects, is utilized present within HMC's database. This data gives an overview of the fuel consumption per day as well as the operational mode the vessel is in. The operational modes touched upon in sub-chapter 4.3, are also present on the Thialf.
By making use of the fuel consumption data of the Thialf, the energy consumption and CO_2 emissions are obtained. The fuel consumption data of the Thialf, from January 2022 to March 2023, is depicted in Figure 7.3. Additionally, the daily energy consumption and daily CO_2 emissions are shown as well. Within this time period, the Thialf had a fuel consumption of approximately [redacted] mT/year which equals [redacted] MWh/year and resulted in about [redacted] mT CO_2 emissions.

[redacted]

Figure 7.3: Total fuel consumption and CO_2 emissions for a two year period of the Thialf

Since the fuel consumption data also included the operational mode the Thialf was in, the frequency of occurrence, in % of days per year, of an operational mode is determined as well as the daily average fuel consumption during an operational mode. The frequency of occurrence and daily average fuel consumption for the operational modes of the Thialf are shown in Figure 7.4. Since the fuel consumption depends on various factors, irrespective of the operational mode the vessel is in, such as weather conditions or other electrical users onboard of the vessel that consume energy, the average fuel consumption per operational mode is determined and utilized during the case study.

[redacted]

Figure 7.4: Fuel consumption and frequency of occurrence of the operational modes of the Thialf

7.2. Technical evaluation on Thialf

In this sub-chapter, the characteristics of the Thialf, such as its energy infrastructure and energy profile, obtained from an in-house database, are utilized together with information and data obtained from the literature study, to determine the required technical modifications to implement an e-fuel pathway. In section 7.2.1, the energy conversion unit is evaluated, followed by the fuel storage, in section 7.2.2 and lastly, the TTE piping infrastructure, in section 7.2.3. Even though these are the largest components of the energy infrastructure, some additional components, which were discussed in Appendix C, are added to the case study as well.

The first step of the technical evaluation is to utilize the energy profile data and thereby determine the capacity that should be retrofitted by making use of an e-fuel. This is the first step, as the capacity to be retrofitted influences the number of energy conversion units to be retrofitted as well as the necessary e-fuel storage. This capacity is determined by looking at the normal distribution of the occurrence *[% of days]* as well as of fuel consumption *[% of fuel]*, of each operational mode, per power load.

To obtain a normal distribution for each operational mode, initially, the average power load during each operational mode is determined by making use of Equation 7.1.
The load factor of the engines of the Thialf is obtained from HMC data and is only based on the engines that are operational during the specific mode, which varies due to redundancy reasons. Since the load factor differs per operational mode, and the efficiency depends on the engine load, the efficiency also varies per operational mode. By making use of the load factor per operational mode and the specific fuel oil consumption curve, shown in Figure 7.2, the efficiency for each mode is determined.
Since the average fuel consumption, as well as the engine efficiency for each operational mode on the Thialf, are known, the average power for each operational mode is determined by making use of Equation 7.1. The load factor, engine efficiency, power requirement, and several other characteristics of the operational modes are shown in Table 7.3.
The standard deviation is determined with consult from sustainability experts within HMC and is based on the power fluctuations of each operational mode. The average fuel use of each operational mode is expressed as a percentage of the total fuel used on the Thialf.

$$P = \frac{\eta_{\text{engine}} * F_{\text{cons.}} * E_{\text{D-gravimetric}}}{t} \tag{7.1}$$

Symbol	Unit	Explanation
P	MW	*Average power requirement*
η_{engine}	%	*Engine efficiency*
$F_{\text{cons.}}$	mT/day	*Fuel consumption*
$E_{\text{D-gravimetric}}$	kWh/kg	*Gravimetric energy density of MGO*
t	Hrs./day	*Hours per day*

Table 7.3: Characteristics of the operational modes of the Thialf

	Unit	Sail	MOB	Work	R&M	Idle
Load factor	*% of load*	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Engine efficiency	*%*	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Avg. occurrence	*% of days*	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Avg. Fuel use	*% of fuel*	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Avg. Power	*MW/day*	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Std. deviation	-	0.5	1	1	0.3	0.1

To gain insights regarding how often a certain power load occurs during an operational mode on the Thialf, a normal distribution is generated of the occurrence of each operational mode. This normal distribution is generated by making use of the average power, the occurrence, and the standard deviation per operational mode.
To gain insights regarding how much of the total fuel is consumed by a certain power load during an operational mode on the Thialf, a normal distribution of the fuel use is generated. Since the emissions of the Thialf depend on the fuel use, the normal distribution of the fuel use also gives insights regarding the percentage of the total emissions of the Thialf that can be allocated to a certain power load during an operational mode. The normal distribution of the fuel use is generated by making use of the average power, the percentage of fuel, and the standard deviation per operational mode.
By combining the two normal distributions, an overview is created regarding what percentage of the time a certain power load is present and how much of the emissions can be allocated to this power load. The two normal distributions are shown in Figure 7.5. In Appendix F, the normal distribution of the emissions is shown in a separate chart.

[redacted]

Figure 7.5: Normal distribution of the occurrence and emissions of the Thialf.

As can be seen from Figure 7.5, idle and R&M are modes that, even though they have a high occurrence, only account for a small percentage of the emissions. Additionally, the work mode accounts for the largest share of the emission on the Thialf, with also the largest power distribution, which is caused by its high standard deviation compared to the other modes. From the normal distributions, the average power load that occurs on the Thialf is also obtained, which is approximately 10.3 MW. Depending on the operational mode the Thialf is in, the power is distributed over a number of engines, and a spinning reserve might be present to take redundancy into account.

In order to determine what capacity should be retrofitted by an e-fuel, a cumulative distribution is generated from both normal distributions. The cumulative distribution of the occurrence gives insight into how often a power load less than or equal to a certain capacity is present on the Thialf and how this power load is distributed over the operational modes. Whereas the cumulative distribution of the emissions gives insights into the contribution of a power load less than or equal to a certain capacity to the total emissions of the Thialf and also how these emissions are distributed over the operational modes. Figure 7.6 shows the cumulative distribution of the occurrence of the Thialf. The cumulative distribution of the emissions of the Thialf is shown in Figure F.2 in Appendix F.

As becomes clear from the cumulative distribution of the occurrence, a capacity of up to 4.3 MW is always present on the Thialf, which is the hotel load. From the cumulative distribution of the emissions, a capacity of up to 4.5 MW was identified as having a 100% contribution to the total emissions of the Thialf.

[redacted]

Figure 7.6: Cumulative distribution of the occurrence of the Thialf

To determine the capacity to be retrofitted, the cumulative distribution of the emissions is integrated, which gives an overview regarding what percentage of the total emissions can be allocated up to a certain capacity. By dividing a specific capacity of the Thialf by the percentage of emissions allocated to that capacity, a ratio is obtained which gives insights regarding how much the emissions increase per power load. This ratio is indicated as abatement effectiveness and is shown in Figure 7.7, together with the integration of the cumulative distribution of the emissions.

The abatement effectiveness is used to find an ideal capacity to retrofit on the Thialf. An optimum can be found by identifying where the highest abatement can be realized with the lowest capacity. As can be seen, the abatement effectiveness decreases slowly and reaches approximately 0.09 at 9 MW, hereafter the abatement effectiveness decreases more rapidly per MW. Therefore, approximately 9 MW can be seen as the optimum capacity to retrofit, which corresponds to an abatement of approximately 80% of the Thialf's emissions.
However, due to the lifespan of the Thialf and the time frame within which is assumed e-fuels will be available to implement on large offshore vessels, a capacity of 5.4 MW is obtained as suitable for the Thialf. This capacity of 5.4 MW corresponds to an abatement of 50% of its emissions and is almost equal to the always present hotel load of the Thialf. Retrofitting a capacity of 5.4 MW is solely based on the abatement effectiveness, however, it might be the case that from a technical or financial perspective, this might not be the ideal capacity to retrofit. During the case study, a capacity of 5.4 MW is maintained and in the discussion, this capacity is reflected on.

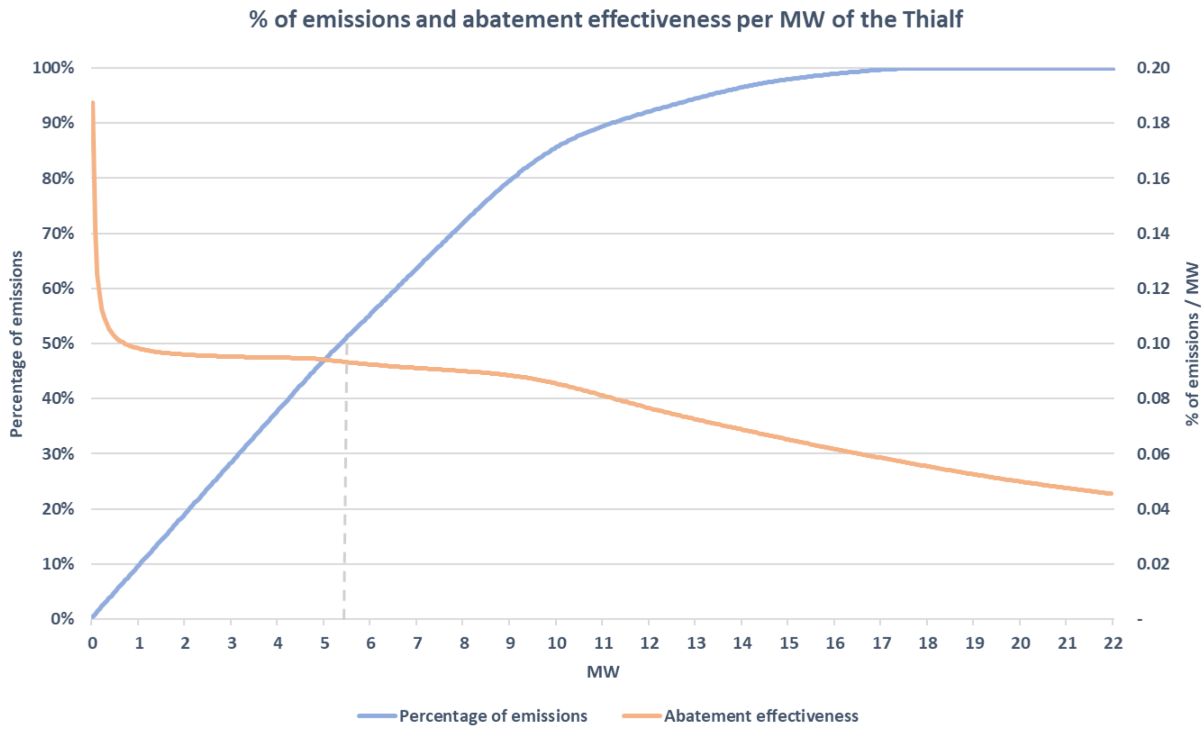

Figure 7.7: The percentage of emissions as well as the abatement effectiveness per MW on the Thialf

7.2.1. Thialf energy conversion unit

A consideration that should be taken into account when retrofitting the energy conversion units of the Thialf is the load factor and up-time of the engines. Since the load factor indicates what percentage of the capacity the engines are operating on, and the up-time indicates what percentage of time the engines are actually operational, they both affect the capacity that is actually retrofitted on the Thialf. As the load factor, depicted in Table 7.3, varies for each operational mode, an average load factor is utilized of 44%.

For redundancy reasons, a minimal number of engines are operational, which are utilized to supply the Thialf with the required power. The number of engines that is operational depends on the operational mode the Thialf is in. This study assumes that an engine of the Thialf is operational approximately 50% of the time, which is expressed in the up-time.

By combining the average up-time with the average load factor of the engines of the Thialf, an average engine utilization, which indicates what percentage of the time and at what power the engines operate, is obtained. The average engine utilization on the Thialf is 22%. Therefore, in order to retrofit a capacity of 5.4 MW with an e-fuel, a total capacity of 24.5 MW should actually be retrofitted to realize an abatement of 50% of the emissions. Hereby, approximately 5 engines on the Thialf should be retrofitted to actually realize making 5.4 MW of the Thialf more sustainable by making use of an e-fuel.

In case 5 ICEs of the Thialf are retrofitted to a DF ICE that is able to operate on MGO as well as on an e-fuel, the characteristics and health and safety measures mentioned in section 5.3, should be taken into account. Additionally, the required modifications to an MGO-fuelled ICE, mentioned in Table 5.2, should be executed to ensure the ICE is compatible with MGO and the e-fuel. The costs related to this retrofit are discussed in sub-chapter 7.3.

An important consideration, according to fuel cell experts, is that the efficiency of a PEMFC decreases at higher loads, hereby showing an opposite effect compared to an ICE. Even though high loads on the Thialf do not occur regularly, as concluded from Figure 7.6, the scenario where a very high load occurs should be accounted for. Since the efficiency of a fuel cell decreases at higher loads, a sizing factor is utilized to take this efficiency degradation into account and ensure that the required power during these high loads can still be supplied. After consulting fuel cell experts, a sizing factor of 1.2 is adopted for this study. To obtain the actual capacity required by a fuel cell, to retrofit 5.4 MW, the same utilization of 22% is used in combination with the sizing factor.
In case use is made of a PEMFC, the ICEs will be replaced by one or multiple PEMFC stacks with a total capacity of 29 MW. The characteristics of PEMFC, which were mentioned in section 5.3, as well as the necessary modifications shown in Figure 5.2, should be taken into account.

In conclusion, to retrofit a capacity of 5.4 MW and hereby realize an abatement of 50% of the emissions of the Thialf, two options are available:

1. 5 ICEs should be retrofitted, with a capacity up to **24.5 MW**.
2. A PEMFC stack should be installed with a capacity of **29 MW**.

7.2.2. Thialf fuel storage

Since the capacity to be retrofitted on the Thialf is determined, the required quantity of stored e-fuel, in volume and mass, can be obtained for the bunkering period. Even though the bunkering period varies in reality, since the operational modes the Thialf is in are not the same for every bunkering period, HMC tries to pursue a bunkering period of approximately six weeks, which is therefore also utilized in this case study.
To determine the required e-fuel volume, which complies with the energy demand of a capacity of 5.4 MW during the bunkering period, Equation 2.2 is utilized. However, in Equation 2.2, only the volume of the required e-fuel is determined, whereas the volume of the entire storage system should be considered. By making use of the increase factors, shown in Figure 5.1, the required volume of the entire storage system can be determined for each e-fuel pathway.

Since the capacity that is retrofitted by making use of an e-fuel, is only part of the entire capacity installed on the Thialf, MGO is still required to comply with the total energy demand during the bunkering period. To determine the necessary volume of the still required MGO, use is made of the available fuel storage on the Thialf, which is 8,350 m^3. The installed tanks on the Thialf were designed by considering safety factors, which oversize the tanks and therefore ensure that a sufficient amount of fuel, and thus energy, is stored on the vessel. To determine the quantity of MGO still necessary on the Thialf, the current energy storage capacity of 83,194 MWh, is used as a reference. By making use of Equation 7.2, the still required MGO storage volume is determined.

$$V_{\text{MGO}} = \frac{(E_{\text{stored}} - E_{\text{required}})}{E_{\text{D-volume}}} \tag{7.2}$$

Symbol	Unit	Explanation
$\mathbf{V_{MGO}}$	m^3	*MGO volume still required during bunkering period*
$\mathbf{E_{stored}}$	MWh	*Energy storage of the Thialf*
$\mathbf{E_{required}}$	MWh	*Required energy of retrofitted capacity during bunkering period*
$\mathbf{E_{D\text{-}volume}}$	kWh/m^3	*Volumetric energy density of MGO*

By combining the volume required for the e-fuel and MGO storage, the total volume of the storage systems on the Thialf is determined and the volume increase, compared to the currently installed storage system, is obtained as well. The available storage space on the Thialf is a limiting factor and could result in several e-fuel pathways being less suitable to be implemented. An overview of the required volume for the entire fuel storage of the Thialf is shown in Figure 7.8.

A similar calculation is performed to obtain the mass of the stored e-fuel, in this case, use is made of the gravimetric energy density. By combining the mass of the e-fuel with the mass of the still required MGO and comparing that quantity with the current mass of the MGO installed on the Thialf, insights are created regarding the weight increase on the Thialf. The mass of the required e-fuel, as well as MGO quantity, are shown in Figure 7.9.

When retrofitting the existing fuel storage tanks to be compatible with an e-fuel, the characteristics mentioned in sub-chapter 5.1 and the required modifications shown in Figure 5.2, for each e-fuel storage tank must be considered. In case cylindrical tanks are necessary, which is the case with e-LNG and e-hydrogen, the MGO tanks must be replaced. Whereas, in the case of e-methanol some modifications are sufficient, such as placing a double wall, adding a coating as well as an inerting system.

Figures 7.8 and 7.9, show the volume and mass of each e-fuel pathway, such that it complies with the energy demand during the bunkering period. As can be seen, the volume required for e-hydrogen is significantly higher, compared to MGO, hereby making the e-hydrogen pathways less attractive from a volumetric viewpoint followed by the e-ammonia pathways.
From a gravimetric perspective, e-methanol and e-ammonia are the least attractive, however, the additional mass should be compared with the deadweight tonnage of the Thialf to determine if it actually has an effect on the Thialf.

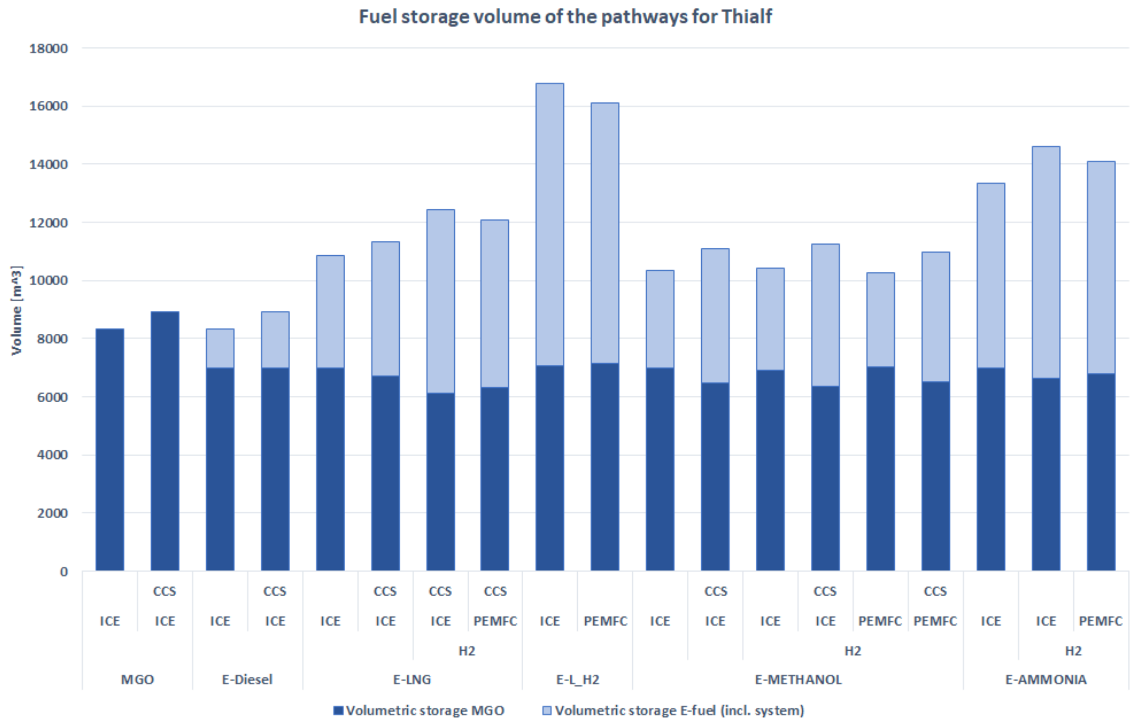

Figure 7.8: E-fuel storage volume for the poss ble pathways on the Thialf.

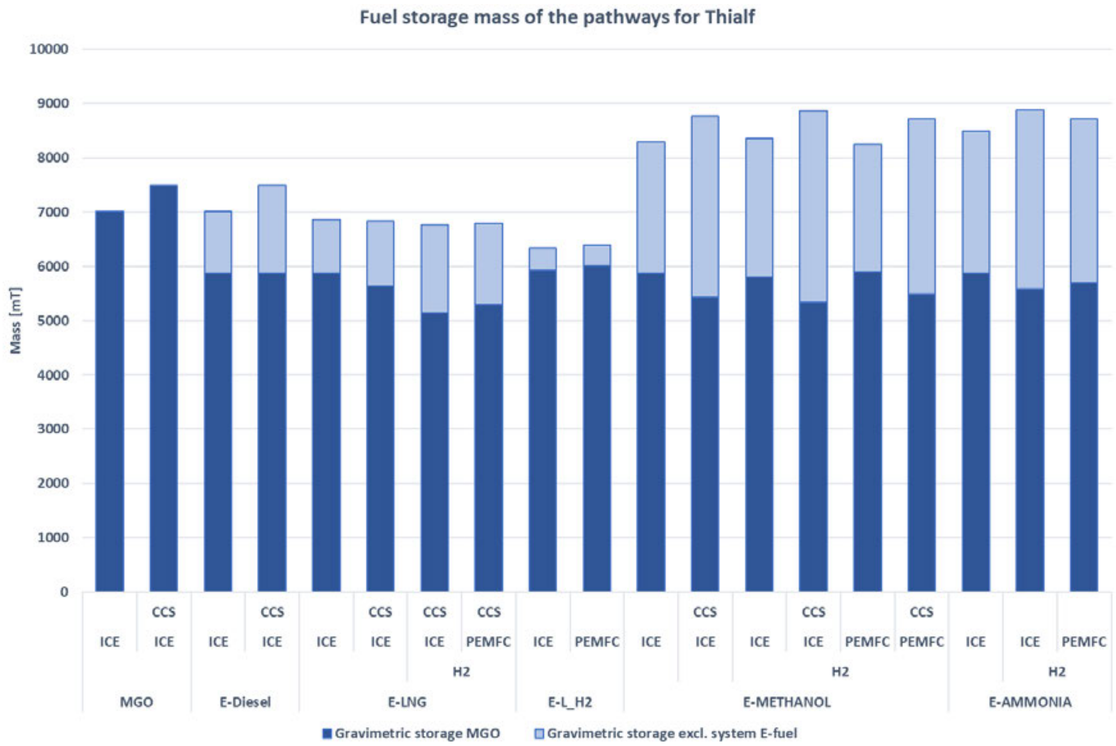

Figure 7.9: E-fuel storage mass for the possible pathways on the Thialf.

7.2.3. Thialf piping infrastructure

In order to implement a piping structure on the Thialf, which is compatible with one of the e-fuels, the characteristics mentioned in sub-chapter 5.2 and the required modifications shown in Figure 5.2, should be taken into account. One of the safety measures that should be considered, and is required for almost every e-fuel pathway, is a double-walled piping system. The material of the inner and outer pipes depends on the e-fuel implemented. In some cases, a coating is sufficient for the piping system to be compatible with an e-fuel, whereas in other cases, a different material must be utilized, which requires major changes for the piping system to be compatible. Additionally, almost every e-fuel requires an inerting system, to ensure no combustible gas mixtures are formed, as well as an appropriate detection and shut-off system.

7.3. Financial evaluation on Thialf

In this sub-chapter, data from the technical evaluation on the Thialf is used in combination with the financial evaluation performed in Chapter 6. In the financial evaluation, an overview is given of the CapEx and Opex associated with implementing an e-fuel energy conversion pathway on the Thialf. Initially, the CapEx associated with the implementation of each pathway is shown in section 7.3.1 and hereafter the associated OpEx of each pathway is shown in section 7.3.2.

7.3.1. Thialf CapEx

By making use of the data from table 6.1 the CapEx of each e-fuel pathway is determined and compared to the CapEx of the MGO pathways. For the energy conversion unit, fuel handling system and additional components, the capacity to be retrofitted, determined in technical evaluation 7.2, is utilized to determine the necessary investments. The CapEx of the energy storage system, however, depends on the required energy during the bunkering period, which varies for each pathway as it depends on the pathway efficiency and additional power requirements.

Figure 7.10, shows the breakdown of the CapEx of each e-fuel pathway. As becomes clear, the CapEx of the pathways is mostly dominated by one or two components of the energy infrastructure, whereas the other components only have a small contribution to the CapEx. The CapEx of a CCS system and of a PEMFC are significantly larger than those of the other components, which results in the pathways that make use of either one or both of these technologies greatly exceeding the CapEx of pathways that only make use of an ICE without a CCS system. Since an e-fuel is already labeled as a net-zero fuel and a CCS system is not required but only additional, it is unlikely that one is implemented as the e-fuel pathways become less financially attractive, based on the CapEx, to implement on a large offshore construction vessel.
As can be seen, the e-diesel pathways have a CapEx similar to that of the MGO base case, since e-diesel is a drop-in fuel, and thus is already compatible with the currently installed MGO infrastructure of the Thialf.
The CapEx of each pathway is utilized to determine the LCOE and LCoCA, which are touched upon in Chapter 8.

From the CapEx analysis, several initial conclusions can be obtained, stated below.

- Implementing a CCS system on the Thialf will result in a high CapEx, hereby worsening the attractiveness of implementing a CCS pathway, from a CapEx perspective.
- Implementing a PEMFC on the Thialf will result in a high CapEx, hereby worsening the attractiveness of implementing a PEMFC pathway, from a CapEx perspective.
- A high CapEx will have a negative effect on the LCOE as well as on the LCoCA.

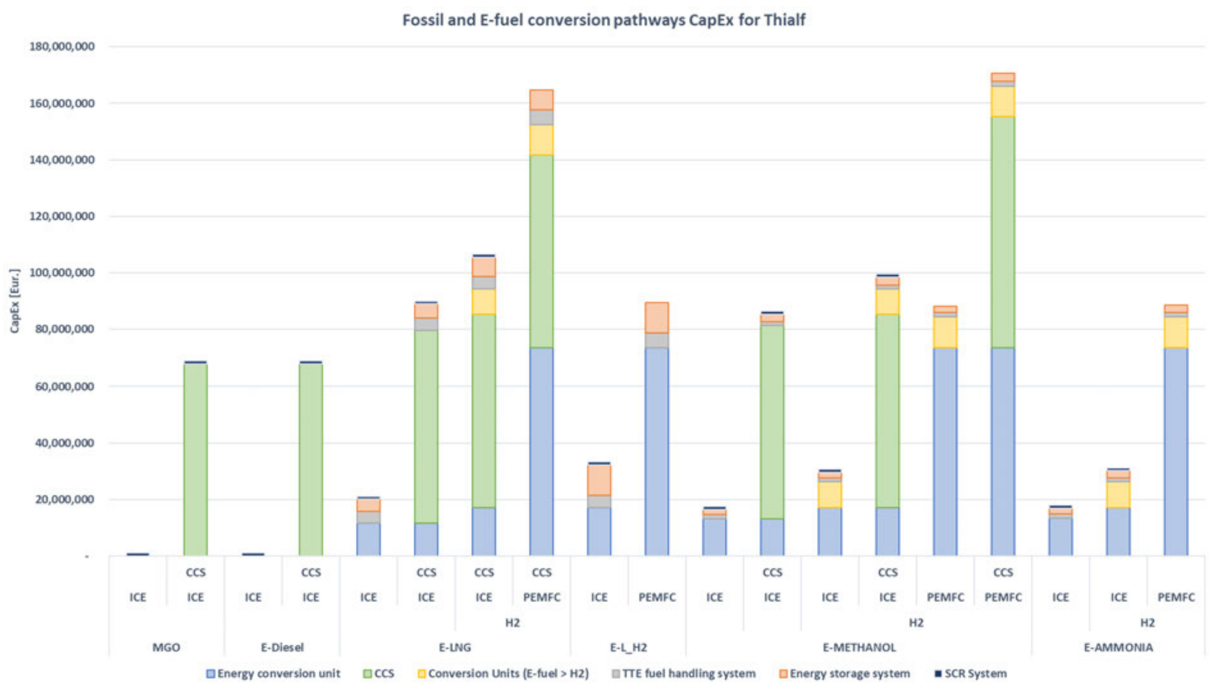

Figure 7.10: CapEx breakdown for the various e-fuel pathways on the Thialf.

7.3.2. Thialf OpEx

When looking at the OpEx of the fossil and e-fuel pathways, a distinction is made between the OpEx related to the components of the energy infrastructures and the OpEx related to the e-fuels. The Opex related to the components of the energy infrastructure is mostly maintenance, repair or replacement costs which are specific for each component. The OpEx related to the e-fuels are the costs of the acquisition of the e-fuel and of the EU ETS in case a fossil fuel is used.
A breakdown of the OpEx for MGO, as well as e-fuel pathways, is shown in Figure 7.11. The OpEx of each pathway is utilized to determine the LCOE and LCoCA, which are touched upon in Chapter 8.

In the OpEx evaluation, an average MGO, EU ETS and average e-fuel prices for 2032 are utilized, based on assumptions from literature. The 2032 prices are utilized as the e-fuel as well as MGO price assumptions showed, in Chapter 6, that from 2032 it would be financially more attractive to implement an e-fuel instead of MGO.

As becomes clear from Figure 7.11, the OpEx of each pathways is mainly dictated by the OpEx related to the e-fuels, the OpEx of a PEMFC is the only component that shows a significant impact on the overall OpEx compared to OpEx of other components. The PEMFC OpEx includes repair and maintenance costs but also costs related to the stack replacement of a PEMFC. As was mentioned earlier, e-fuel prices are expected to decrease in the coming years, also after 2032, which will result in a lower OpEx related to the acquisition of an e-fuel and, thus a lower overall OpEx.
Due to the fact that the OpEx of each e-fuel pathway is a yearly reoccurring cost and the average lifetime of an ICE and a PEMFC are about 25 and 15 years, according to retrofit and fuel cell experts, the total OpEx could become significantly high compared to the CapEx of each e-fuel pathway. This would suggest that the financial aspect of implementing an e-fuel pathway is dominated by its OpEx and that, if a decision on implementing an e-fuel route is based solely on a financial incentive, a pathway with a low OpEx is more attractive to implement.
From the OpEx analysis, several initial conclusions can be obtained, as stated below.

- E-fuels with high acquisition costs are less attractive to implement on the Thialf, as it is the main contributor to the overall OpEx.
- Eventhough, a PEMFC is more efficient, and thus requires less fuel compared to an ICE, its high OpEx results in a higher LCOE compared to pathways that use an ICE.
- The additional power requirement of a CCS system results in a larger OpEx and thus a higher LCOE for each pathway.
- E-hydrogen, e-methanol and e-ammonia are the most attractive to implement on the Thialf, from an OpEx perspective.
- Several e-fuel pathways show a better OpEx than MGO, caused by an assumed high MGO and EU ETS price in 2032.

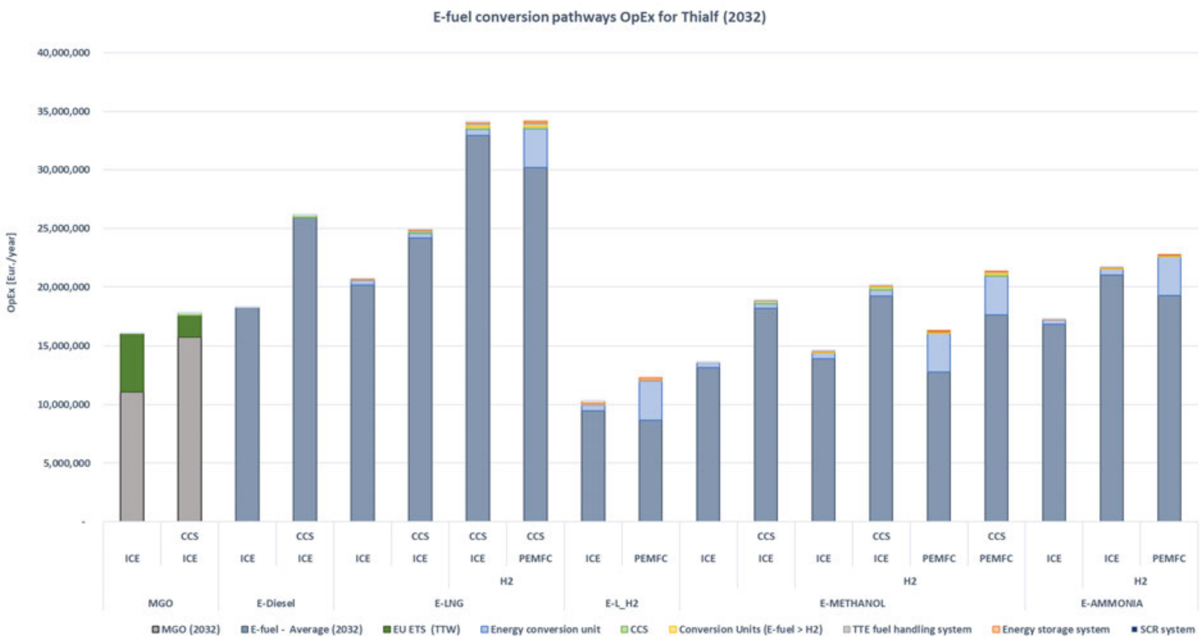

Figure 7.11: OpEx breakdown for the various e-fuel pathways on the Thialf.

8 Results

In this chapter, the results of the case study are shown and elaborated on. By making use of all data obtained during the literature phase of this study, a technical and financial evaluation are performed on the Thialf. The KPIs set at the beginning of this research are obtained by combining data acquired during the literature phase with results from the technical and financial evaluation and utilizing both as input for the model. By comparing these KPIs with the MGO base case the impact of implementing an e-fuel pathway on a large offshore vessel can be determined.

Initially, the KPIs and thus the results of the case study are discussed, to begin with, the storage capacity is touched upon in sub-chapter 8.1, followed by the TTW CO_2 emissions, LCOE and LCoCA, in sub-chapter 8.2, 8.3 and 8.4 lastly the health and safety factors are discussed in sub-chapter 8.5. Additionally, a sensitivity analysis is carried out in sub-chapter 8.6 and a conclusion is given in sub-chapter 8.8. The results of the case study are hereafter evaluated, summarized to draw several conclusions from and eventually discussed in Chapter 9

8.1. Storage capacity

During the case study, in Chapter 7, the required storage volume of the e-fuel pathways was already touched upon. The total required volume of the e-fuels as well as for the additional required MGO was shown in Figure 7.8. For each pathway, the additional required volume, compared to the currently installed storage volume on the Thialf is obtained and shown in Figure 8.1. Additionally, the percentage of the total additional required storage volume, compared to the total ballast volume, is shown as well.

As becomes clear from Figure 8.1, additional volume is required for each e-fuel pathway, The pathways where use is made of CCS system or where the e-fuel is converted into hydrogen required more storage volume than the other pathways, due to extra required fuel, to compensate for the energy loss during these processes. In case an e-fuel pathway is implemented, either the currently installed fuel storage tanks must be expanded, hereby retrofitting a certain percentage of the ballast tanks, or the bunkering frequency of the Thialf must be increased.
The required volume for both e-hydrogen pathways is considerably larger compared to the other e-fuel pathways and shows that a maximum of 6.2% of the total ballast tank volume will have to be retrofitted in case e-hydrogen with an ICE is implemented. Based on the required storage volume, both e-hydrogen pathways are the least suitable to implement on the Thialf, followed by the e-ammonia pathways.

The mass of each pathway, which included MGO as well as the e-fuel, was also looked into and compared to the mass of the MGO currently stored on the Thialf, an overview was shown in Figure 7.9. Hereby, the additional mass for each pathway is obtained as well as its percentage of the deadweight tonnage of the Thialf and is shown in Figure 8.2.
The additional mass for the worst-performing pathway only accounts for approximately 1.5% of the total deadweight tonnage and is therefore considered as having an insignificant impact on the feasibility of implementing one of the pathways on the Thialf.

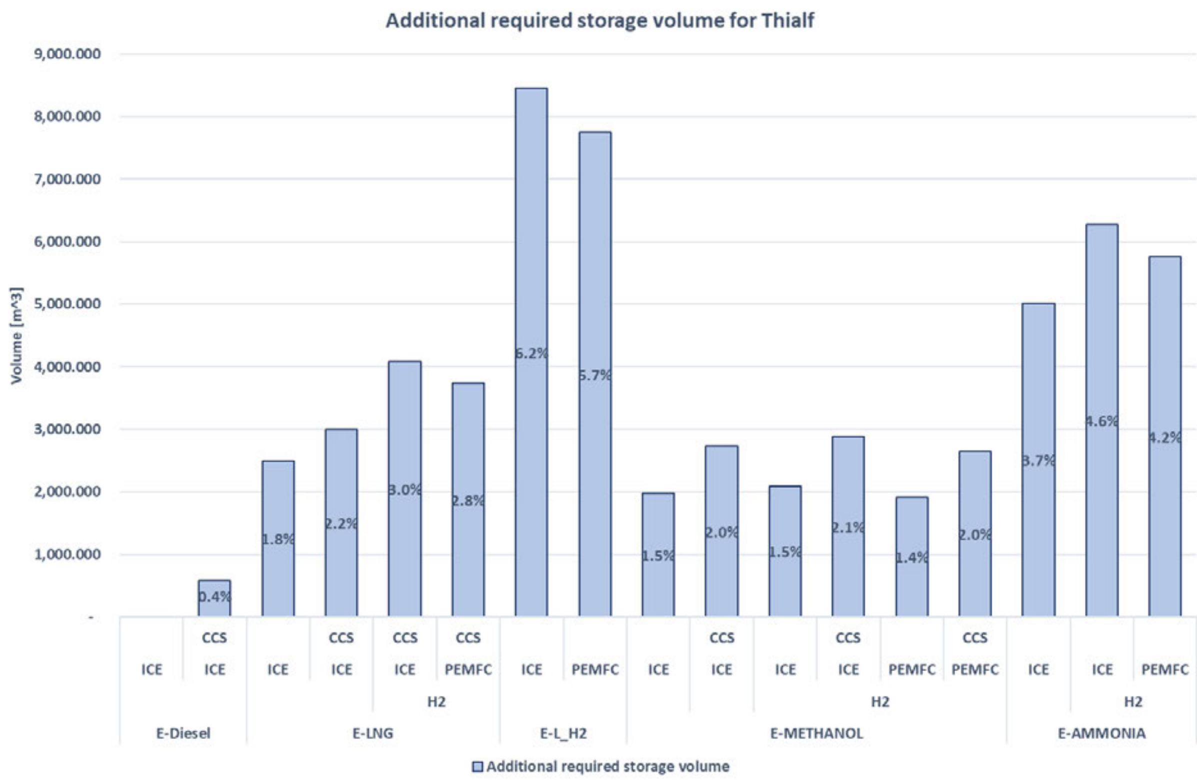

Figure 8.1: Additional required storage volume for each pathway on the Thialf

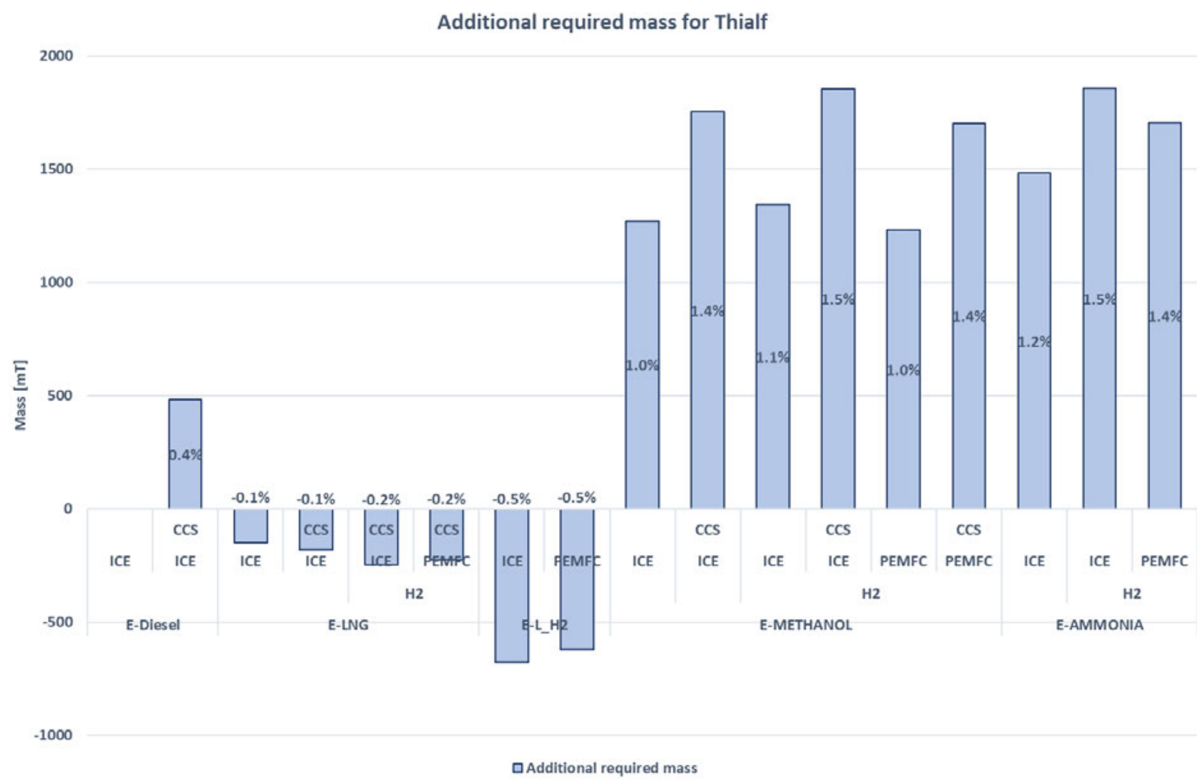

Figure 8.2: Additional required mass for each pathway on the Thialf

8.2. TTW CO_2 emissions

By making use of the data obtained from the Thialf, regarding the fuel consumption, as well as of Equation 2.3, the yearly emitted CO_2 of each e-fuel pathway is determined for the retrofitted capacity of 5.4 MW and compared to the MGO base case. The TTW CO_2 emissions of each pathway are shown in Figure 8.3. As can be seen, the e-hydrogen pathways as well as the e-ammonia pathways do not emit CO_2 and the emission of the pathways where a CCS system is included are significantly lower compared to the other pathways. Due to similar characteristics between e-diesel and MGO, the e-diesel pathway that only makes use of an ICE, shows the same emissions as the Thialf currently would, by operating on MGO.
The pathways where an e-fuel is converted to hydrogen and hereafter used in an energy conversion unit, show larger emissions compared to the other pathways. This emission increase is caused by the additional fuel required by the pathway due to the efficiency loss of the e-fuel conversion. Additionally, in this research, the assumption was made that the emission occurring from the conversion of an e-fuel to hydrogen are similar to the combustion of an e-fuel.

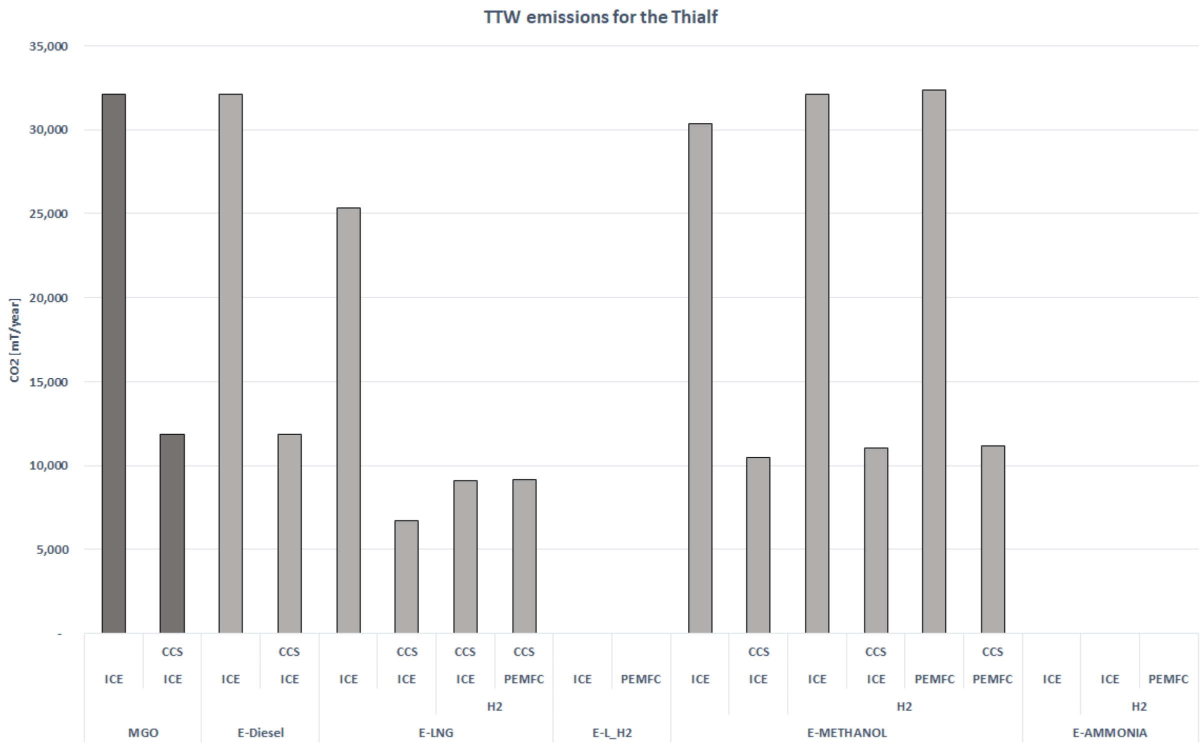

Figure 8.3: TTW CO_2 emission for the retrofitted capacity of the Thialf

8.3. LCOE

The LCOE is determined by making use of Equation 2.4 and obtained for the CapEx, OpEx and for both combined. The LCOEs are also determined for the MGO base case, such that the e-fuel LCOEs can be compared to the current scenario. Initially, the LCOE of the CapEx is looked into and can be seen in Figure 8.4.

The high CapEx of pathways that use a CCS system or a PEMFC, shown in sub-chapter 7.3.1, causes the LCOE of these pathways to be significantly higher than the pathways that do not make use of these technologies. Thereby, from a CapEx LCOE perspective, the pathways that make use of a CCS system, a PEMFC or both are much less attractive to be implemented, compared to pathways that do not make use of these technologies. However, since the LCOE also consists out of an OpEx part, this should also be considered to get a better understanding of the financial attractiveness of implementing a pathway.

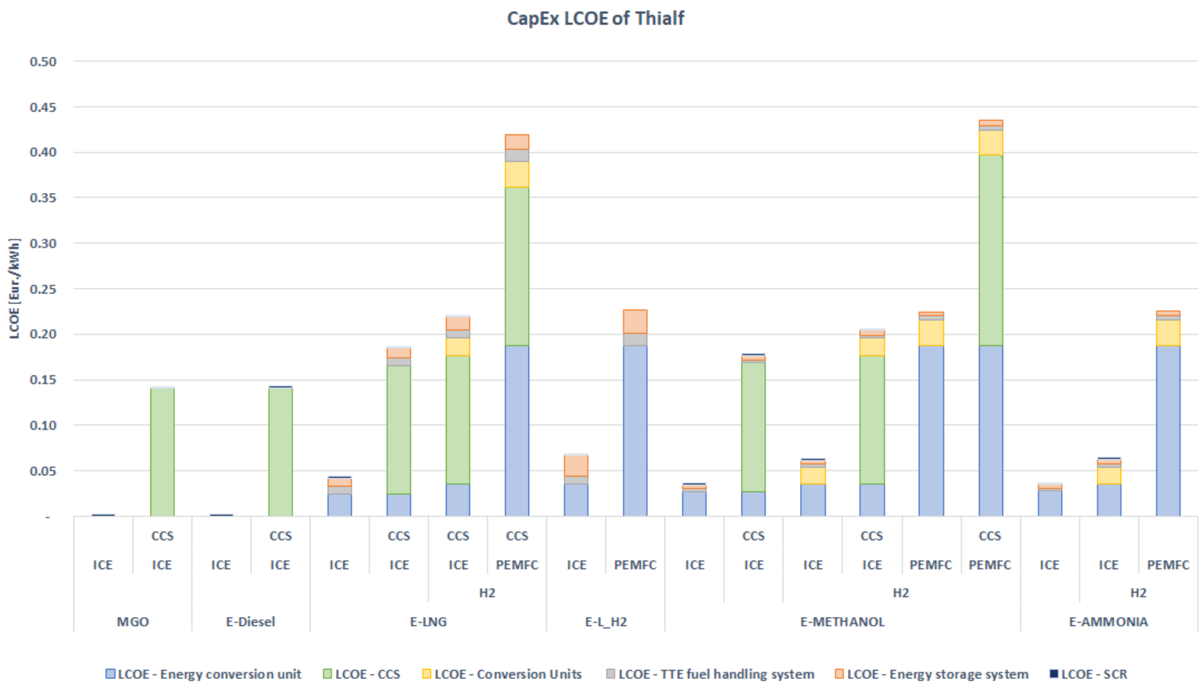

Figure 8.4: CapEx LCOE breakdown for the e-fuel pathways on the Thialf

As was mentioned during the case study, the OpEx of each pathway is divided into an OpEx related to the components and an OpEx related to the e-fuels. Initially, the OpEx LCOE of the components is looked into, which is shown in Figure 8.5.
As can be seen, the OpEx LCOE of the components is much lower than the CapEx part of the LCOE and thus has a small contribution to the total LCOE and an even smaller impact on the implementation of an e-fuel pathway. The OpEx LCOE is for most pathways dominated by the OpEx of the energy conversion unit, especially for the pathways where a PEMFC is implemented.
Similar to the CapEx LCOE, pathways that make use of a PEMFC are much less financially attractive to implement on the Thialf, from a components OpEx LCOE perspective.

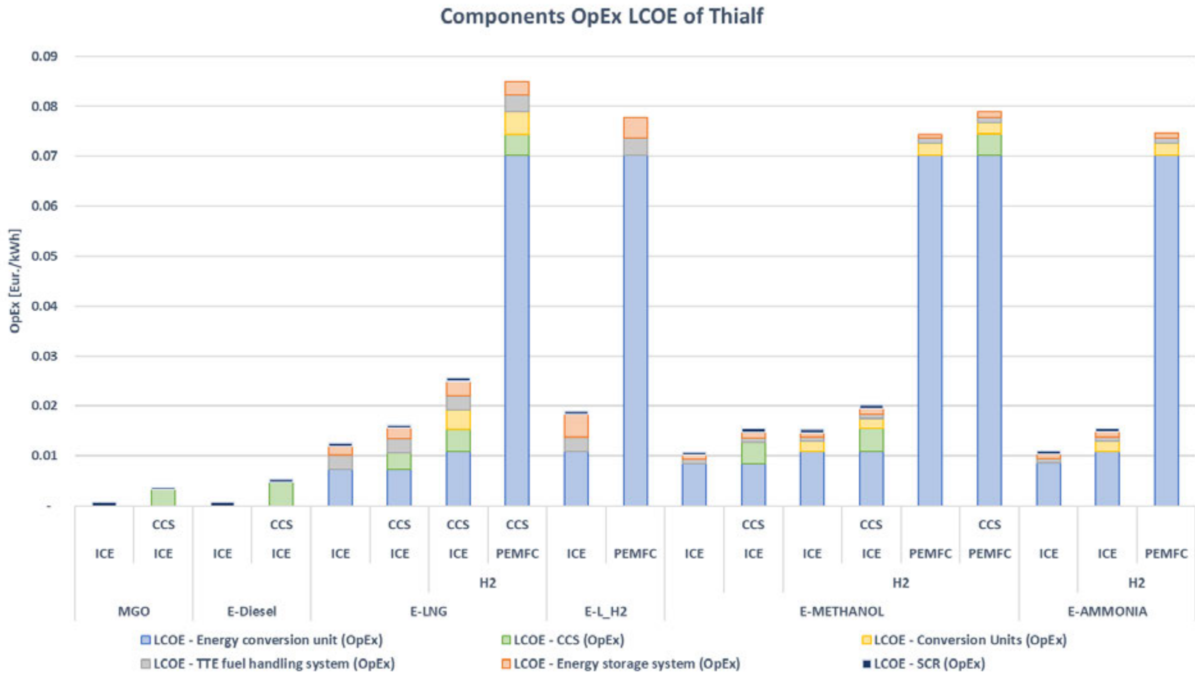

Figure 8.5: OpEx LCOE breakdown for the components of the e-fuel pathways on the Thialf.

Lastly, the LCOE of the e-fuels is determined, which is related to the actual acquisition of an e-fuel. The LCOE of the OpEx related to MGO as well as to the e-fuels is shown in Figure 8.6. The e-fuel OpEx LCOE is obtained by dividing the total costs associated with the acquisition of an e-fuel by the energy produced by the retrofitted capacity during the bunkering period. As becomes clear from Figure 8.6 and the previously shown LCOEs, the e-fuel OpEx LCOE is the main contributor to the LCOE, compared to the other components, especially in pathways with a low CapEx LCOE, where no use is made of a CCS system or PEMFC as energy conversion unit.

Pathways that use a CCS system or where the e-fuel is reformed always have a higher OpEx e-fuel LCOE compared to pathways that do not. This increase is caused by the additional fuel required to compensate for the power requirement of the CCS system and the energy loss in the conversion process.

As can be seen in Figure 8.6, the LCOE of the MGO base case also consists of an EU ETS part, which decreases as use is made of a CCS system. From an e-fuel OpEx LCOE perspective, e-hydrogen and e-methanol are the most financially attractive to implement on the Thialf, followed by e-ammonia. Whereas e-diesel and e-LNG do not incentivize switching from MGO to either of the e-fuels.

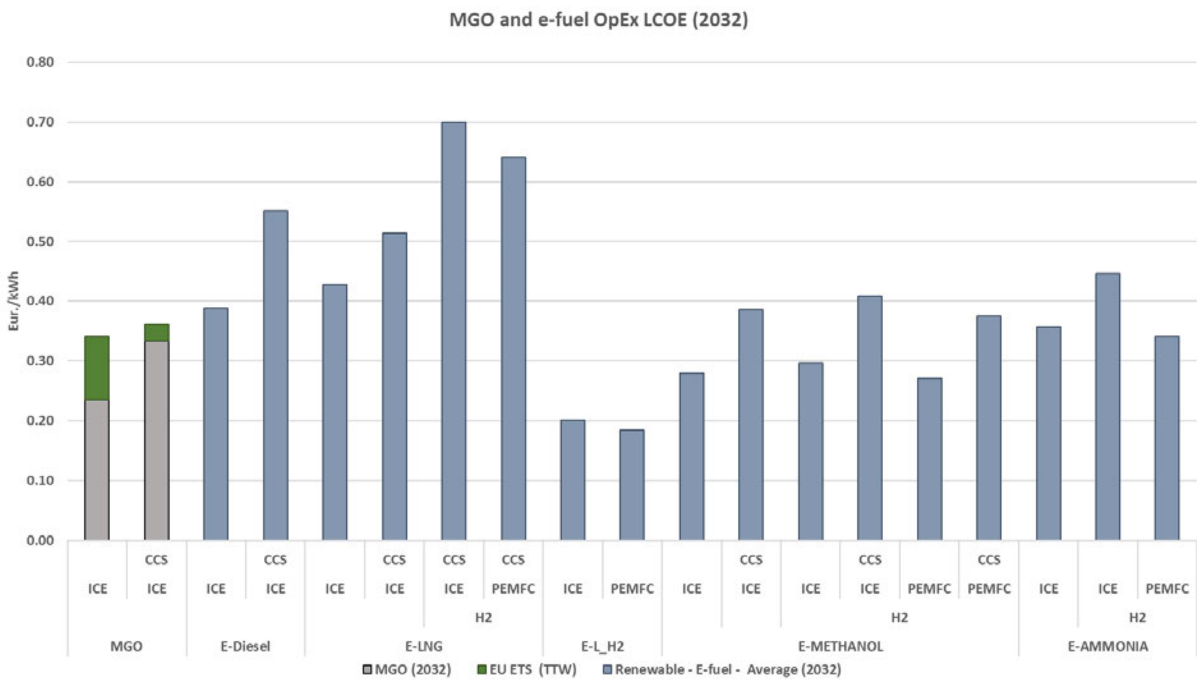

Figure 8.6: OpEx LCOE breakdown of the e-fuels for each pathway on the Thialf.

To obtain the total LCOE for the Thialf, the above-mentioned LCOEs are added for each pathway. The final LCOE is shown in Figure 8.7. Some initial observations from the previous LCOEs and the total LCOE are listed below.

- The LCOE of pathways that make use of a CCS system, a PEMFC or both is always higher compared to pathways that do not make use of these technologies. Thereby worsening the financial attractiveness of a pathway.
- Pathways where the e-fuel is converted to hydrogen always have a higher LCOE, compared to pathways where the e-fuel is not converted. Thereby worsening the financial attractiveness of a pathway.
- Even though no modifications are required to the MGO infrastructure of the Thialf, the e-diesel in an ICE pathway is not the most attractive, based on the LCOE.
- The pathway of e-hydrogen with a DF ICE shows the lowest LCOE followed by the e-methanol DF ICE pathway. the e-hydrogen pathway shows a decrease of -16% compared to the MGO ICE base case and the e-methanol a decrease of -5%.
- The pathway where e-LNG is converted to hydrogen and use is made of a PEMFC as well as a CCS system has the highest LCOE and shows an increase of 233% compared to the MGO ICE base case.
- Pathways which have an LCOE lower than the MGO ICE with CCS pathway, show a financial incentive to be implemented instead of making use of a CCS system to abate emissions.

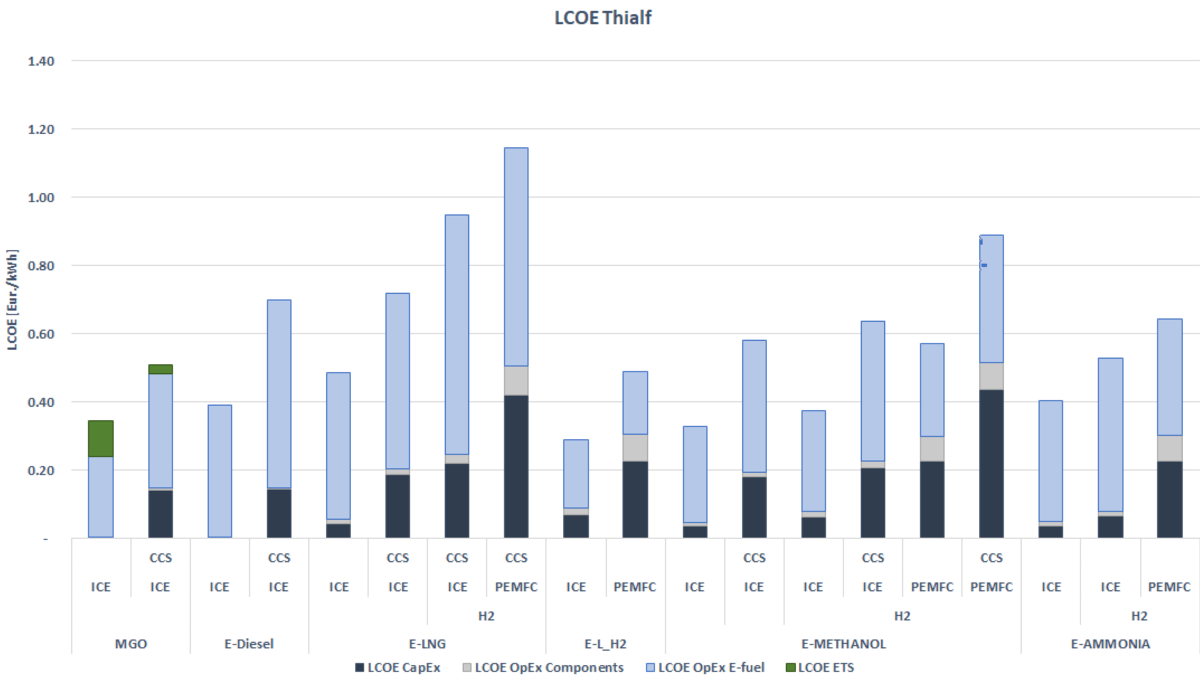

Figure 8.7: Total LCOE for the Thialf

8.4. LCoCA

To determine the LCoCA, the yearly costs and emissions of the MGO base case, corresponding to the retrofitted capacity of 5.4 MW, are used. Each e-fuel pathway's CapEx is annualized by using the CRF, obtained from Equation 2.5, and added to the OpEx to obtain the total yearly costs of each e-fuel pathway. The LCoCA of each pathway is determined by making use of Equation 2.6, where the costs, as well as the CO_2 emissions, which are zero, for each e-fuel pathway, are compared to the costs and emissions related to MGO ICE base case. The LCoCA of each pathway is shown in Figure 8.8. Additionally, the MGO ICE with a CCS system also has an LCoCA, of 415 Eur./mT CO_2, since emissions are abated compared to the MGO ICE base case.

As can be seen, the LCoCA varies significantly for each pathway, and depending on the difference between the cost of the MGO base case and the e-fuel pathway, the LCoCA might show negative values. The closer a positive value of the LCoCA is to zero, the lower the costs to abate one mT of CO_2 and the more financially attractive it is to implement the pathway. A low positive LCoCA indicates that the difference in costs of the e-fuel pathway compared to the MGO pathway is low and that the abated emissions by the e-fuel pathway are large.
A negative LCoCA indicates that either the costs of implementing an e-fuel pathway are lower than the costs of the MGO pathway, or that the emissions related to the e-fuel pathway are higher than MGO pathway. Since a TTW emission factor of zero is adapted for all e-fuels in this study, a negative LCoCA can only be the result of the yearly costs of an e-fuel pathway being lower than the yearly costs of the MGO base case. The larger the negative value, the less it costs to implement the e-fuel pathway and the more attractive it is to implement the pathway. The pathways that showed an LCOE, below that of the MGO ICE base case show a negative LCoCA.
Below some initial observations regarding the LCoCA of the Thialf are listed.

- Since the CapEx is annualized over the lifetime of the pathway, the LCoCA is more dependent on the OpEx of each pathway.
- The LCoCA increases significantly in case use is made of a CCS system, a PEMFC or both. This increase is caused by the high CapEx of these technologies as well as additional required fuel.
- Even though no modifications are required for the e-diesel with an ICE pathway, it does not have the most attractive LCoCA, due to high fuel OpEx costs.
- The pathway where e-hydrogen is utilized in an ICE has the lowest LCoCA of -80 Eur./mT CO_2, followed by the e-methanol with an ICE, with an LCoCA of -24 Eur./mT CO_2.
- The e-LNG to hydrogen pathways, have the highest LCoCA of 1,175 Eur./mT CO_2 and 883 Eur./mT CO_2.
- A PEMFC or CCS system deteriorates the financial incentive to implement an e-fuel, from an LCoCA perspective.

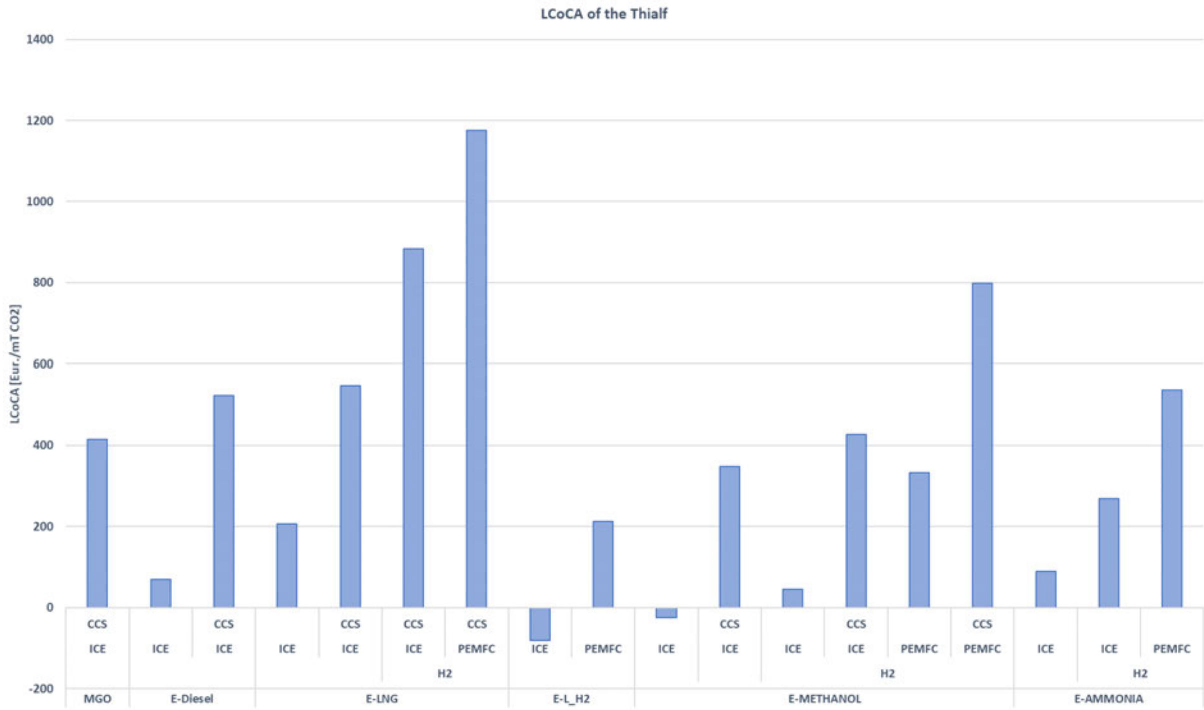

Figure 8.8: LCoCA for the e-fuel pathways on the Thialf

8.5. Health and safety

Several important health and safety as well as environmental aspects of the e-fuels were touched upon in section 3.2.4. The aspects discussed in this section are utilized to rate each e-fuel on a scale from 1 to 10, as was mentioned in section 2.2.1. The e-fuels are rated on their toxicity, physical hazard, reactivity, explosiveness and flammability, and environmental hazard. The ratings per e-fuel are shown in Figure 8.9. To obtain the e-fuel that scores best during the assessment, the average is taken from the ratings of each e-fuel, which are hereafter compared. The e-fuel with the lowest overall rating performs best from health, safety, and environmental perspective. Some initial observations obtained from the health, safety, and environmental assessment of the e-fuels are listed below.

- E-diesel, and thus MGO, score best with an average rating of 4, with only the environmental hazard scoring high at 7.
- E-ammonia scores the worst with an average rating of 6.4, mostly due to its high toxicity and high environmental hazard.
- E-hydrogen second-to-last with an average rating of 5, mostly caused by its high explosiveness and flammability as well as its high physical hazard due to cryogenic burns.
- E-LNG scores has an average rating of 4.8 and performs similarly to e-hydrogen, however, is less reactive.
- E-methanol has an average rating of 4.6, as it only has a medium-high toxicity, reactivity, and flammability.

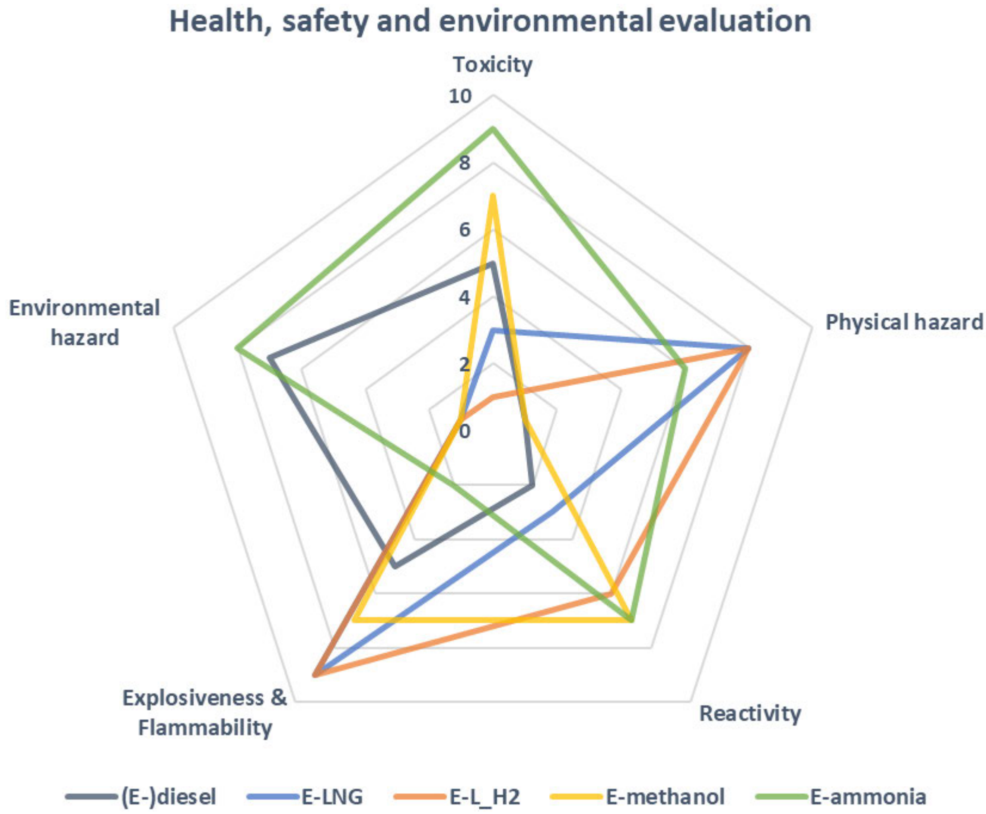

Figure 8.9: Health, safety and environmental assessment of the e-fuels

8.6. Sensitivity analysis

During the sensitivity analysis, certain model input variables are changed to see how the KPIs react to these changes and to determine if the impact of implementing an e-fuel pathway on the Thialf changes. This sensitivity analysis focuses on the CapEx and OpEx of each e-fuel pathway. During the sensitivity analysis, different scenarios for the CapEx are tested, as well as scenarios for the OpEx related to the e-fuels. The OpEx related to the components is disregarded as their impact on the KPIs is minimal compared to the CapEx and OpEx of the e-fuels.
Even though the e-fuel pathway efficiencies, elaborated on in section 3.2.5 contain an error margin, since an average for each step is adopted, they are not included in this sensitivity analysis. Since an average is utilized, the actual efficiency will be close to the value adopted in this research and therefore the effect on the results will be small. All in all, even though KPI results will change with varying efficiencies, the impact of implementing an e-fuel is not likely to be effected and the best and worst performing e-fuels on a KPI will be similar.
Initially, the CapEx sensitivity analysis is discussed in section 8.6.1 and hereafter, the OpEx sensitivity in section 8.6.2.

8.6.1. CapEx sensitivity

The CapEx associated with each modification, which were shown in Chapter 6, were obtained from literature or by talking to fuel cell experts. However, since the CapEx associated with a modification is vessel-specific, and the values currently used give an indication regarding the costs of such a modification, a sensitivity analysis is performed to see how the KPIs react to changes in the CapEx. Additionally, technological developments in the coming years might result in cheaper options to retrofit an ICE or cheaper PEMFCs. By performing a sensitivity analysis on the CapEx, any developments or lack of progress regarding the used technologies is also taken into account.

Since only the LCOE and LCoCA depend on the CapEx, only these KPIs are considered during the sensitivity analysis. Two scenarios are tested, which are listed below, where the CapEx price of each modification is altered with an increase or decrease factor. During this sensitivity analysis, the currently used values for the OpEx remain unchanged.

1. **Scenario 1:** The CapEx of each modifications increases with 20%.
2. **Scenario 2:** The CapEx of each modifications decreases with 20%.

The LCOE results of the CapEx sensitivity analysis are shown in Figure 8.10, the LCoCA results in Figure 8.11 and the numerical values of both are shown in Appendix F. Both the LCOE and the LCoCA are compared with the previously obtained LCOE and LCoCA during the case study, which is indicated with scenario 0.

As shown in Figure 8.10, all LCOEs increased for scenario 1 and decreased for scenario 2. However, the largest increase and decrease of the LCOE occurs with only 0.09 Eur./kWh, which is a small fraction of the total LCOE. The increase or decrease of the CapEx values has the largest impact on the LCOE of the e-methanol to hydrogen pathway that makes use of PEMFC and CCS, where the LCOE varies with approximately 10%.
All in all, the CapEx values' variations have a minimal effect on the LCOE and, thus on the feasibility of implementing an e-fuel pathway.

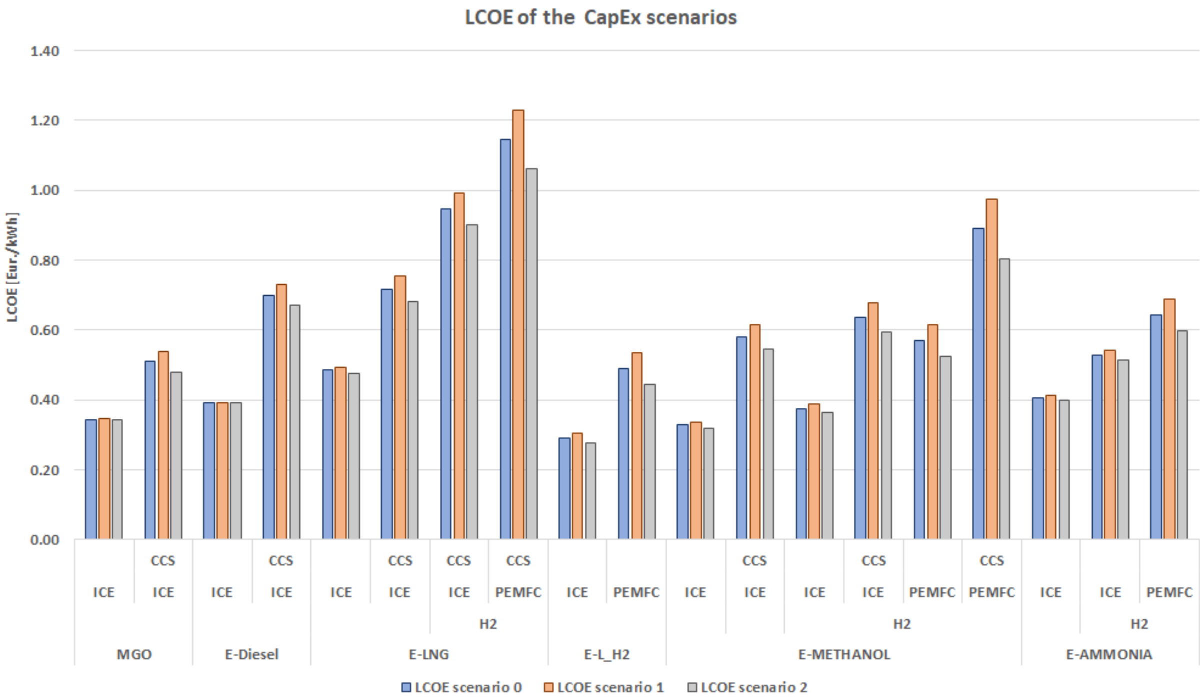

Figure 8.10: LCOE results of the CapEx sensitivity analysis

Similar to the LCOE, all LCoCA values for scenario 1 deteriorate and improve for scenario 2. A decrease in the LCoCA indicates an improvement, and thus that the cost difference between the e-fuel pathway and the MGO base case has decreased. The largest LCoCA increase and decrease, of about 127 Eur./mT CO_2, occurs for the e-methanol to hydrogen pathway that makes use of a PEMFC and CCS.
Changes of the CapEx values can significantly impact the LCoCA, especially for pathways that use a PEMFC or CCS, as these are technologies with a high CapEx. The CapEx changes have the largest impact on the e-methanol pathway that makes use of an ICE, where the LCoCA is increased or decreased with about 44%.

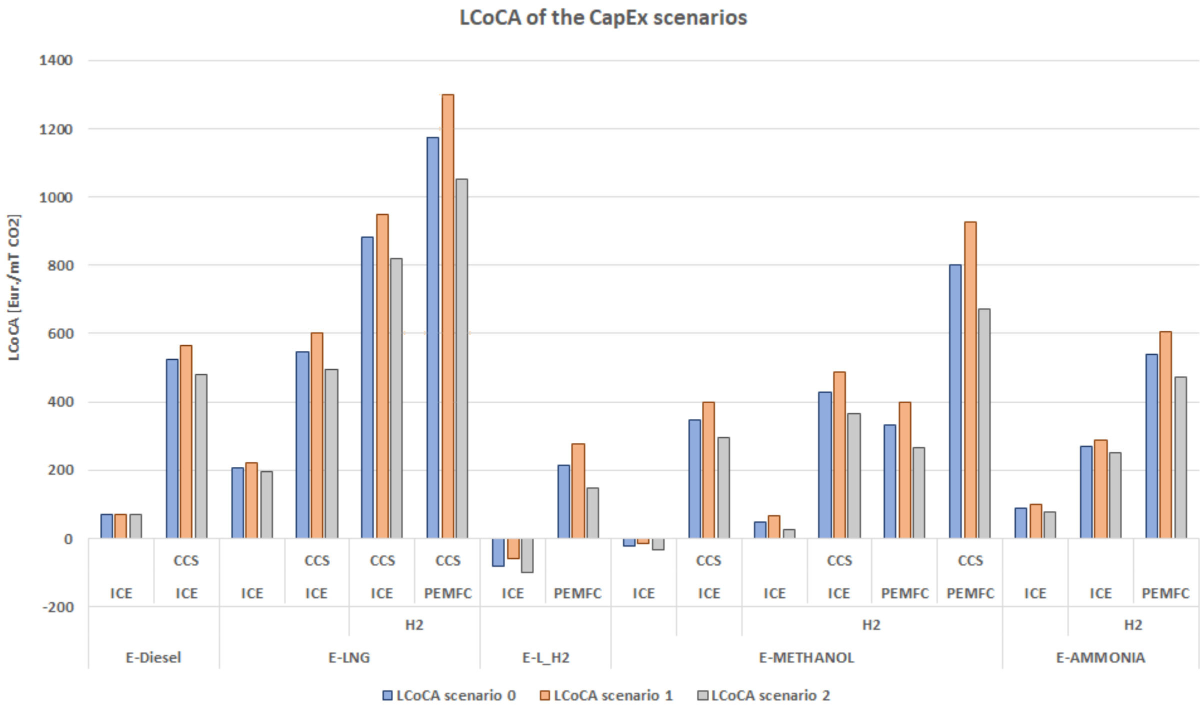

Figure 8.11: LCoCA results of the CapEx sensitivity analysis

8.6.2. OpEx sensitivity

The average e-fuel and EU ETS prices in 2032, currently used in this study, are based on assumptions obtained from literature. Four different scenarios are tested to account for the uncertainty of these values, which are listed below. Table 8.1 shows the prices utilized in the scenarios. The maximum and minimum e-fuel prices are obtained by multiplying the average e-fuel price with an increase or decrease factor of 35%. By doing so the maximum and minimum values, utilized in the scenarios are similar to the minimum and maximum values found in literature. The maximum and minimum of the EU ETS price are obtained by using an increase factor of either 7.5% or 2.5%. By altering the e-fuel and EU ETS prices, the OpEx of each e-fuel pathway will change, thereby the LCOE and LCoCA as well as only these KPIs depend on the OpEx. During this sensitivity analysis, the currently used values for the CapEx remain unchanged.

1. **Scenario 1:** The maximum e-fuel prices in 2032 are utilized, in combination with a growth rate of 7.5% per year for EU ETS.
2. **Scenario 2:** The maximum e-fuel prices in 2032 are utilized, in combination with a growth rate of 2.5% per year for EU ETS.
3. **Scenario 3:** The minimum e-fuel prices in 2032 are utilized, in combination with a growth rate of 2.5% per year for EU ETS.
4. **Scenario 4:** The minimum e-fuel prices in 2032 are utilized, in combination with a growth rate of 7.5% per year for EU ETS.

Table 8.1: E-fuel and EU ETS prices for scenario 1 and 2

2032 price	E-diesel	E-LNG	E-methanol	E-ammonia	E-hydrogen	EU ETS	MGO
Max. price *[Eur/kWh] & [Eur/mT CO_2]* (↑ 35%)	0.209	0.231	0.151	0.192	0.113	192 [1]	0.147
Avg. price *[Eur/kWh] & [Eur./mT CO_2]*	0.155	0.171	0.112	0.142	0.084	155 [2]	0.137
Min. price *[Eur/kWh] & [Eur/mT CO_2]* (↓ 35%)	0.101	0.111	0.073	0.092	0.055	125 [3]	0.128

[1] *EU ETS price with 7.5% growth rate*
[2] *EU ETS price with 5% growth rate*
[3] *EU ETS price with 2.5% growth rate*

The LCOE results of the OpEx sensitivity analysis are shown in Figure 8.12, for the LCoCA in Figure 8.13 and the numerical values are shown in Appendix F. Similar to the CapEx sensitivity, the previously obtained LCOE and LCoCA, during the case study, are indicated with scenario 0.

The values of the LCOE do not depend on the EU ETS price and thereby the LCOEs for scenario 1 and scenario 2 are similar as well as for scenarios 3 and 4. As can be seen, the LCOE worsened for scenarios 1 and 2 and improved for scenarios 3 and 4. The largest increase and decrease, which occurs for the e-LNG to hydrogen pathway that makes use of a DF ICE, has a value of 0.20 Eur./kWh, which is significant compared to the LCOE of scenario 0. As becomes clear from Figure 8.12, variations of the OpEx have a larger impact on the LCOE, compared to variations in the CapEx.
All in all, e-fuel price variations significantly impact the LCOE, as it may vary up to 30%.

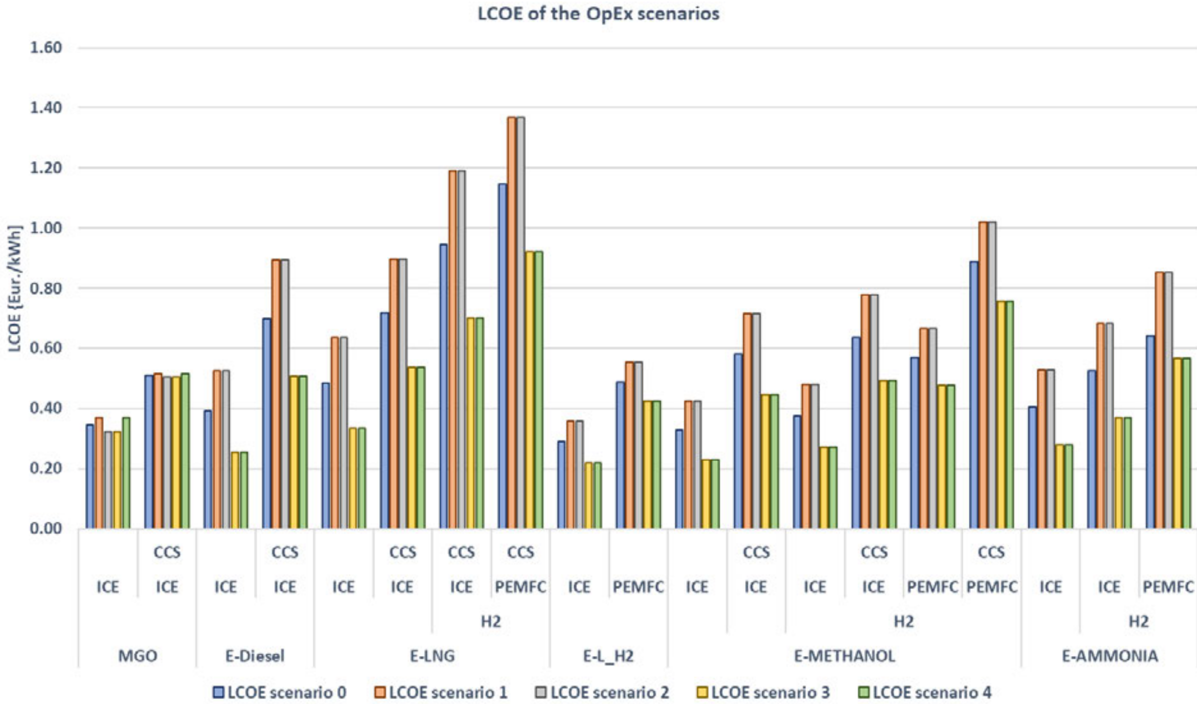

Figure 8.12: LCOE results of the OpEx sensitivity analysis

Values of the LCoCA depend on the e-fuel as well as on the EU ETS price since the costs of each pathway are compared to the costs of the MGO base case, which changes with the EU ETS price. Similar to the LCOE, the LCoCA also worsened for scenarios 1 and 2 and improved for scenarios 3 and 4. As becomes clear from Figure 8.13, scenario 4 is the ideal scenario, as this is where the largest LCoCA improvement occurs. During this scenario, the e-fuel prices are lowest and the MGO base case price is highest. The largest deterioration and improvement of the LCoCA occurs during scenarios 2 and 4 for the E-LNG to hydrogen pathway that makes use of a PEMFC and CCS system. The LCoCA of this e-LNG pathway varies by approximately 40%.
Changes in the OpEx, have an even more significant impact on the LCoCA compared to variations in the CapEx. The LCoCA of e-ammonia is increased by about 350% in case of high e-fuel prices and a low EU ETS price.

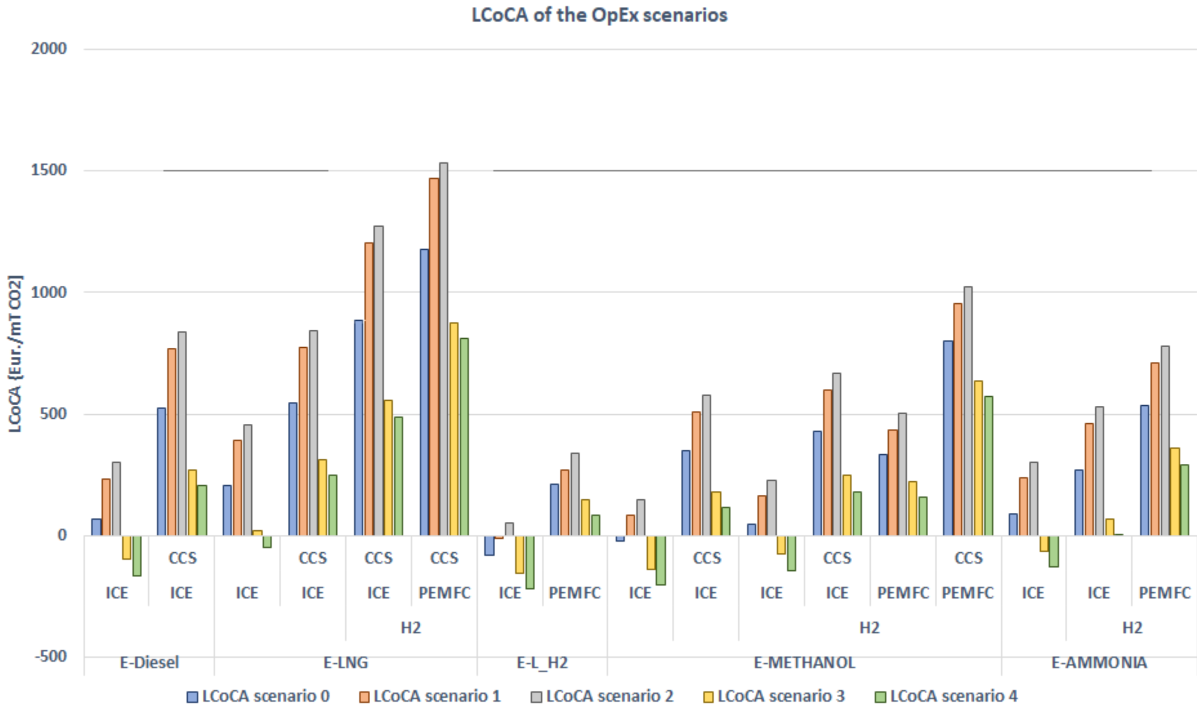

Figure 8.13: LCoCA results of the OpEx sensitivity analysis

All in all, changes in the CapEx have a small effect on the LCOE and LCoCA, and the best and worst-performing e-fuel pathways remain the same. Secondly, the number of pathways that are financially attractive to implement also remained the same. All in all, changes in the CapEx have no effect on the e-fuel pathways that can be disregarded to implement on the Thialf or other large offshore vessels operating on MGO, based on the LCOE and LCoCA.

Additionally, changes in the OpEx have a significant effect on the LCOE and, thus, on the financial attractiveness of a pathway. The e-hydrogen and e-methanol pathways that make use of an ICE are always financially attractive abatement options to implement and, in the low e-fuel price scenarios, also show a financial incentive to be implemented as they are below the MGO ICE base case and thus are able to reduce costs.
Changes in the EU ETS price only affect the MGO pathways, and since the e-fuel pathways are compared to the MGO with CCS pathway, where a percentage of the CO_2 emissions are abated, the effect of the EU ETS price on the pathways that can be disregarded, based on the LCOE, is minimal. Additionally, low e-fuel prices result in additional pathways being financially attractive to implement, especially in the high EU ETS price scenario.

8.7. Validation of Results

Due to the hypothetical nature of this research, the results can not be compared to real-life results, however, validation of the input and the methodology can still be performed. Through an input as well as face validation, performed by sustainability experts within HMC the input values, methodology and hereby also the results are validated. Since the sustainability experts within HMC all focus on various aspects regarding making a large offshore vessel more sustainable, experts with a wide range of expertise were consulted to validate this study. Additionally, since HMC is still investigating the possibility of implementing e-fuels on their vessels and has not identified one e-fuel as optimal, the validation of the results can therefore be executed independently.
The input validation is performed to determine the accuracy of the input values of the model. Since there is no uniform method for this validation, the input values are validated by evaluating the aspect stated below.

- Reliability of the sources.
- The extent of manual modification of the input values from the source to the input value for the model.
- The degree of input significance in relation to the model's output.

Manual manipulation of obtained data from literature, to fit the input value of the model can affect the results of this study. For example, converting the units of measurement of obtained data to fit the desired model input units involves a higher risk of inaccuracy than directly copying data in the correct input units. To mitigate this risk, the simplest method is to repeat the manual operations multiple times to detect and eliminate any potential inaccuracies.
It is important to understand the significance of the input values and the impact that they have on the outcomes of the model. For input variables that have a significant impact on the outcome of the model, a sensitivity analysis was executed to see if changes in these input variables still result in logical outcomes of the model. If that is the case, input values can be partially validated.

The methodology, which includes calculations, intermediate steps, and the model, are face validated by sustainability experts within HMC. Through this face validation, the sustainability experts provide feedback on this study and identify the shortcomings of this study.
Although the input and face validation do not guarantee fully validated input, methodology, and model, it significantly reduces the risks of any inaccuracies in the research. The input, methodology, and model have been successfully validated using the input and face validation method.

8.8. Conclusion of case study

Based on the results from the case study, the impact of each e-fuel pathway on the Thialf and on HMC is obtained. An overview of the impact of each e-fuel pathway is depicted in Table 8.2. The color coding indicates the impact that the e-fuel pathway has on the Thialf and on HMC, compared to the MGO base case. Green indicates the e-fuel performs well and thus has a small, positive, or no impact, followed by yellow, orange, and lastly, red, which indicates the worst-performing e-fuel on the KPI.

All in all, the e-diesel, e-hydrogen, e-methanol, and e-ammonia pathways that only make use of an ICE are the most promising e-fuel pathways to be implemented on the Thialf in approximately 2032.
E-LNG is the least attractive to implement on the Thialf, which is mainly caused by the fact that must be produced from green electricity and CO_2 from renewable sources to be a viable option and by the fact that it shows the highest LCOE.
Even though the e-hydrogen pathways are financially attractive, they pose a storage capacity problem, as about 6% of the ballast tanks must be retrofitted.
Similarly, e-ammonia is also a financially attractive option to implement on the Thialf, and the assumption is that its OpEx will decrease even further in the future. However, its high toxicity requires large additional modifications to the Thialf, which entails additional CapEx for HMC.
E-methanol is also a financially attractive abatement option, however similar to e-LNG, green electricity and CO_2 from renewable sources must be available.
Since e-diesel does not require any modifications to the infrastructure of the Thialf, it is a financially attractive option as it has a low LCOE. However, similar to e-LNG and e-methanol green electricity and CO_2 from renewable sources must be available.

Even though several pathways have a higher potential to be implemented on the Thialf, there is not one optimal pathway that performs well on all KPIs, as each e-fuel pathway has its advantages and challenges. Depending on KPIs that HMC regards as more relevant, a decision could be made on which e-fuel to implement on the Thialf.
The results of the case study indicate that, in case CO_2 for renewable sources is available, e-diesel shows the overall smallest impact in case it is implemented on the Thialf to retrofit 5.4 MW, followed by e-methanol. An important consideration that HMC should take into account is that the results of this case study give a general indication regarding the impact that implementing an e-fuel has. By performing an additional vessel study on the Thialf, regarding the available volumetric storage and health and safety measures, the percentage of the ballast tanks that is available for a retrofit can be obtained as well as the health and safety measures can be further investigated. Hereby, the possibility of implementing e-hydrogen or e-ammonia on the Thialf can be disregarded or not.
Additionally, since assumptions are made regarding the external conditions of each e-fuel, e-fuel market developments should be tracked to get a better understanding of e-fuel availability, pricing, and regulations, which could affect the attractiveness of implementing an e-fuel.

The results of the case study are utilized to form a general conclusion regarding the impact that implementing an e-fuel has on other large offshore vessels, which is discussed in Chapter 9.

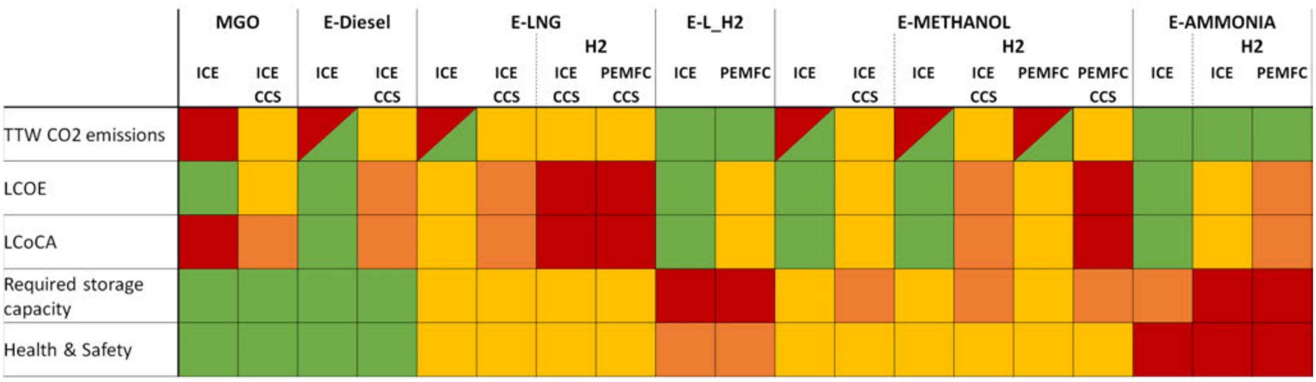

Table 8.2: Concluding overview of the KPIs from the case study, for each pathway

9 Conclusion

Although several CO_2 abatement options are available for the marine sector, not every option will be as attractive as another. Biofuels are such an abatement option, however, the assumption is that they will only function as a transition fuel, as the maritime sector will have to compete with other sectors, resulting in a significant price increase. Since the OpEx dominates the financial incentive of implementing an alternative fuel, biofuels are not expected to form a permanent abatement solution for the marine sector.
CCS systems are another abatement option that is able to significantly reduce emissions from the marine sector. The high CapEx of the CCS system as well as the additional fuel required to comply with the power requirement of the CCS system, result in other abatement options being more financially attractive to implement. In case the efficiency of a CCS system increases and its CapEx decreases in the coming years, it could potentially form a viable abatement option, however, abating 100% of the CO_2 emissions remains a challenging process.
E-fuels are another abatement option that is able to completely abate CO_2 emissions from the marine sector. Below, the conclusions regarding the implementation of an e-fuel on a large offshore vessel are touched upon, which are based on results from the case study performed on the Thialf.

LCOE & LCoCA

Based on the LCOE, certain e-fuel pathways are financially less attractive abatement solutions to implement on large offshore vessels operating on MGO. E-fuel pathways with an LCOE higher than that of the MGO with a CCS pathway can be disregarded, as implementing a CCS system to the currently installed infrastructure, and hereby abating emissions, is financially more attractive than implementing an e-fuel. Additionally, e-fuels with an LCOE below that of the MGO ICE base case indicate that even though additional CapEx is required, there is a financial incentive to implement the pathway, as operating on that e-fuel will reduce costs compared to the MGO ICE base case.
Important to consider is that the LCOEs are based on expected fuel price developments for 2032 and thereby carry some level of uncertainty.
Table 9.1 gives an overview of the pathways with an LCOE below that of the MGO with CCS pathway, additionally, their variation compared to the MGO ICE pathway is depicted as well.
When disregarding the pathways, with an LCOE below that of the MGO with a CCS pathway, it becomes clear that retrofitting the MGO fuelled ICE to a DF ICE compatible with the e-fuel is financially the most attractive pathway for each e-fuel.

Table 9.1: Pathways with an LCOE below the MGO with CCS pathway *(With an expected EU ETS price of 155 Eur /mT CO_2)*

(E-)fuel	**MGO**		**E-diesel**	**E-LNG**	**E-hydrogen**		**E-methanol**		**E-ammonia**
Pathway	ICE	ICE + CCS	ICE	DF ICE	DF ICE	PEMFC	DF ICE	$H_2 \rightarrow$ DF ICE	DF ICE
LCOE *[Eur /kWh]*	0.34	0.51	0.39	0.48	0.29	0.49	0.33	0.37	0.40
LCOE variation	-	+48%	+14%	+41%	-16%	+42%	-5%	+9%	+18%
LCoCA *[Eur./mT CO_2]*	-	415	70	207	-80	212	-24	46	90

Depending on the e-fuel price and the technologies utilized for each pathway, the contribution of the CapEx varies. On average, the CapEx contributes to approximately 17% of the total LCOE of the pathways shown in Table 9.1. This indicates that the OpEx is the main financial driver for vessel owners regarding which e-fuel to implement. Since the LCOE is mainly dominated by the OpEx, low e-fuel prices, as well as high-efficiency pathways, are preferred.

Since this study adopted a zero WTW CO_2 emission factor for each e-fuel, the CO_2 abatement is similar for each e-fuel pathway. Thereby, the results of the LCoCA are similar to the LCOE results, as pathways with an LCOE below that of the MGO ICE base case have a negative LCoCA. A negative LCoCA indicates that there is a financial incentive to implement an e-fuel pathway, compared to the MGO ICE base case, as implementing the e-fuel pathway not only results in an abatement of emissions but also in a reduction of costs.
The LCoCA of the e-fuel pathways from Table 9.1, are compared to the assumed EU ETS price in 2032 to obtain the financial attractiveness of an e-fuel as an abatement option compared to the EU ETS. Even though all pathways from Table 9.1 are financially attractive to implement, only certain pathways are a cheaper option to abate one mT of CO_2 compared to the EU ETS.

When comparing the LCOE of the e-fuels, depicted in Table 9.1, it becomes clear that e-LNG is the least financially attractive e-fuel. Even though e-LNG shows a high production efficiency, a high expected demand results in a slight price decrease and relatively high prices compared to the other e-fuels. Thereby, since other e-fuels are significantly more affordable and thus pose less impact on the vessel owner, e-LNG can be disregarded as an abatement option for a vessel operating on MGO.
The LCOE of e-diesel, shown in Table 9.1, is based on results from the case, and thus does not include any CapEx, as no modifications are required on a vessel operating on MGO. However, e-diesel is expected to show a relatively high price compared to other e-fuels, which is also in line with its low production efficiency. This results in other pathways having a lower LCOE and LCoCA. In the scenario where CapEx is required for the implementation of e-diesel, for example, for a new-built vessel, an average of 17% can be added, which results in an e-diesel LCOE close to that of e-LNG. Therefore, with its low expected price decrease and high LCOE in case the vessel does not operate on MGO, e-diesel can be disregarded as an abatement option.

E-hydrogen

- E-hydrogen is the most financially attractive e-fuel to implement. Its high production efficiency, compared to the other e-fuels, results in a low e-fuel price, a low **LCOE** and a negative **LCoCA**.
- From a **storage capacity** perspective, implementing e-hydrogen poses the largest impact on the vessel. E-hydrogen requires the largest additional volume, which results in the largest percentage of the ballast tanks that must be retrofitted or the highest increase in the bunkering frequency. A retrofitting 0.9 MW with e-hydrogen already results in 1% of the ballast tanks that require a retrofit. The required additional volume depends on the capacity that is made more sustainable and could affect the hydrostatic stability and displacement of the vessel. Depending on the type of vessel, e-hydrogen can be disregarded as an abatement option, as expanding the installed fuel storage tanks or increasing the bunkering frequency might not be feasible. In the case of a SSCV, a large ballast volume is present, of which it might be possible to retrofit a percentage to function as e-hydrogen storage tank. However, in the case of a large offshore cargo vessel, all possible space is reserved for cargo and implementing e-hydrogen is not a likely option.
- E-hydrogen also poses a significant **health and safety** challenge, as it is a highly flammable and physically hazardous fuel that can cause frostbite. Therefore it requires modifications to the vessel to ensure safe fuel handling, which results in additional CapEx for the vessel owner.

E-hydrogen is a financially attractive option, however, it imposes a large storage challenge on the vessel, further research regarding the volumetric storage is required to determine if e-hydrogen can actually be implemented on the vessel. Therefore, the subsequent most financially attractive e-fuel is investigated, which is e-methanol.

E-methanol

- E-methanol shows a moderate production efficiency and a steep expected price decline, which both result in a low **LCOE** and **LCoCA**.
- Even though additional **storage capacity** is required, the percentage of ballast tanks that must be retrofitted or the increase in the bunkering frequency is moderate compared to e-hydrogen and e-ammonia. Thereby the impact on the vessel and for the vessel owner is relatively small compared to other e-fuels.
- E-methanol is a more hazardous e-fuel compared to e-diesel and additional **health and safety** measures are required to ensure safe fuel handling on the vessel. However, e-methanol poses a smaller impact on the vessel and vessel owner as it is less hazardous compared to e-LNG, e-hydrogen and e-ammonia.
- An important consideration is that for e-methanol to be a viable 100% CO_2 emission reduction option, it must be produced from renewable energy and from CO_2 originating from a renewable source. If this is not the case, no zero **WTW CO_2 emission factor** can be adopted, and e-methanol can be disregarded as an abatement option. In case no CO_2 from renewable sources is available, a CCS system could be added to realize a 100% abatement, however, this would result in higher LCOEs and the pathway being disregarded as an abatement option.

From a financial, storage capacity and health and safety perspective, e-methanol is a very attractive e-fuel. However, the availability of renewable energy and CO_2 could withhold the implementation of e-methanol. Therefore the subsequent most financially attractive e-fuel is investigated, which is e-ammonia.

E-ammonia

- E-ammonia shows a higher **LCOE and LCoCA** compared to e-methanol, however as the production of e-ammonia is a more energy-efficient process, the assumption could be made that the e-ammonia price will turn out closer or even lower than the e-methanol price, thereby lowering the LCOE and LCoCA of e-ammonia.
- When implementing e-ammonia on a large offshore vessel, significant additional **storage capacity** is required, which imposes implementation challenges as well as a relatively high impact on the vessel and vessel owner.
- Implementing e-ammonia on a large offshore vessel will have the largest impact on the vessel as well as on the vessel owner. Compared to the other e-fuels, e-ammonia is the most hazardous e-fuel, and therefore, significant **health and safety** measures will have to be taken, with additional required CapEx, to ensure safe fuel handling. The hazard of an e-fuel does not result in the e-fuel being disregarded, it only imposes a safety challenge on the vessel and additional CapEx for the vessel owner. The more hazardous the e-fuel, the larger the number of modifications required to safely handle the e-fuel, and the higher the CapEx.

E-ammonia is expected to become a financially attractive abatement option, that faces no challenges regarding the emission of CO_2. However, its relatively high additional required storage capacity and mainly its high toxicity complicate the implementation of e-ammonia and poses a large impact on the vessel and vessel owner.

By evaluating the results of the case study, a general indication is obtained regarding the impact of an e-fuel on a large offshore vessel. This general indication per e-fuel is shown in Table 9.2. Depending on the large offshore vessel and on KPIs that stakeholders regard as more or less relevant, a decision could be made regarding what e-fuel to implement.
However, it can be concluded that implementing e-diesel on an MGO-fuelled vessel has the smallest impact on the vessel, whereas implementing e-hydrogen has the smallest financial impact on the vessel owner. E-methanol can be seen as median, which has a relatively small financial impact on the vessel owner and a relatively small impact on the vessel compared to the other e-fuels.

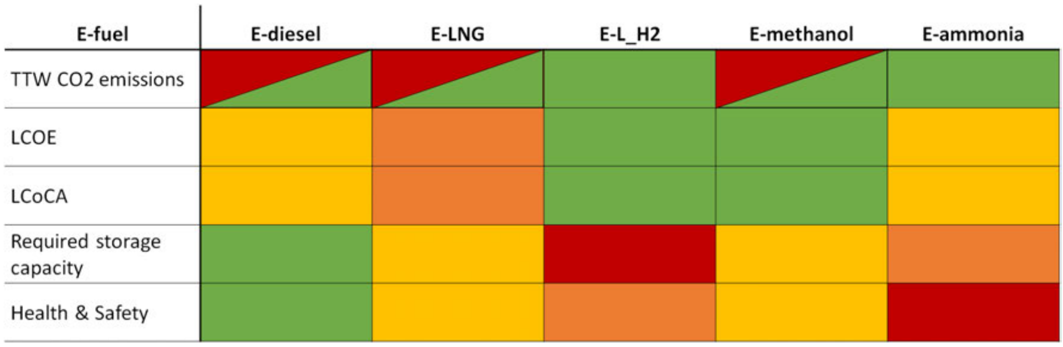

Table 9.2: Concluding overview of the e-fuels and their KPIs

Companies such as HMC, which are active in the marine sector, have their own fleet and are looking into the implementation of an e-fuel on one of their vessels, could make use of the conclusions and methodology of this study as a supportive tool to identify what e-fuel to implement. An important consideration is that the concluding impact of implementing an e-fuel, shown in Table 9.2 is based on the case study performed on the Thialf. The impact on the vessel and on the vessel owner is, to a certain extent, vessel-specific.
Additionally, users of this methodology should take into account that the results give a generic insight regarding the impact that implementing an e-fuel on a large offshore vessel has. To get a better understanding of the impact of implementation, an extensive health and safety, as well as a volumetric storage study, should be performed on the large offshore vessel to determine what percentage of the ballast tanks can be retrofitted without affecting its operations. Through this study, insights are created regarding the limitations of the vessel, and depending on these vessel characteristics, certain e-fuels might be less feasible to implement on the vessel than others.
Since assumptions were made regarding the availability and pricing of each e-fuel, e-fuel market developments should be tracked to ensure up-to-date data is used and to get a better understanding of e-fuel availability, pricing, and regulations, which could affect the attractiveness of implementing an e-fuel.

The results, as well as the methodology of this study, can also be utilized by the academic world as starting point for further research regarding the implementation of e-fuels in the marine sector. The results of this study give a general indication regarding the impact of implementing an e-fuel on a large offshore vessel. By expanding the methodology of this study, with a more extensive technical as well as financial evaluation, more accurate as well as better insights could be obtained regarding the actual impact both on the vessel and for the vessel owner. Additionally, the model and methodology could also be utilized to obtain the impact of implementation on vessels other than large offshore vessels and be used as a supportive tool by the academic world to help further decarbonize the marine sector.
Additional recommendations for future work are given in Chapter 10.

10 Discussion

In this chapter, the methodology and results of this study are discussed, and recommendations for future work are given. The results of this research give an indication regarding the impact that the implementation of the selected e-fuels has on a large offshore vessel and for the vessel owner. The results are based on data from HMC as well as from literature and on several assumptions from literature or self-adopted assumptions. In case the methodology of this research is utilized, up-to-date values should be used to obtain as accurate results as possible.
In this chapter, each phase of the research is reflected on, and several discussion points are stated.

10.1. Model phase

- As this study was performed at HMC, the KPIs that are currently used in this study were set after consulting sustainability experts within HMC regarding aspects that a company with its own fleet and that is active in the maritime sector takes into account when looking into the implementation of an alternative fuel on a large offshore vessel. The set KPIs give a general indication regarding what factors are important to an offshore marine company, however, it is conceivable that other companies or stakeholders prioritize other KPIs than the ones set in this study. Therefore, even though other stakeholders can utilize the methodology of this study, they should consider that this study was performed in the context of HMC.
- An important KPI that is not considered during this study is the flexibility of an e-fuel pathway. Flexibility refers to the ability to customize an e-fuel pathway and hereby taking redundancy into account. Flexibility and redundancy are essential for a company active in the marine sector, as it covers uncertainties caused by assumptions made regarding the implementation of an e-fuel, additionally, their vessels should always be able to operate.
- The time frame set for this study, which was 0-10 years, significantly impacts the final results. The set time frame resulted in several pathways not being considered, as the period before the technologies were able to be implemented on large offshore vessels exceeded ten years. Extending the time frame of this study could result in more pathways being available and perhaps obtaining a pathway that is even more attractive to implement than the pathways currently taken into account in this study.

10.2. Literature phase

- Production and conversion efficiencies of the e-fuels contain an error margin as for this study an average value is utilized, whereas in reality, the value sits within a range as it depends on multiple factors. This error margin is thereby also incorporated into the results. Varying efficiencies have an effect on certain KPI results and should therefore be considered, however, due to the fact that this variation will not be significant, the impact of an e-fuel pathway is not likely to change.
- During the literature phase, much information, and data is gathered from online sources as well as from sources within HMC as input for the technical and financial evaluation and for the model. During this phase, certain assumptions were made or adopted from literature regarding the input values of the model. Thereby, it is important always to use up-to-date data in case the methodology of this study is utilized.
- In the energy conversion pathways of the carbon-containing e-fuels, the assumption was made that CO_2 emissions, originating from the conversion of the e-fuel to hydrogen, are similar to the emissions originating from the combustion of an e-fuel in ICE. However, this might not be the case as emissions might be lower.

10.3. Feasibility assessment phase

- In the technical evaluation, a generic overview created from the vessels of HMC, was used as starting point to determine the modifications required to implement an e-fuel. Even though this does give an indication regarding what modifications are required, the modifications are vessel specific and depend on the installed energy infrastructure of the vessel. Therefore, the identified modifications only give an indication regarding the technical requirements to implement an e-fuel.
- Results of the technical evaluation, and therefore also the outcomes of this study, are strongly related to the set base case of this study. Therefore, depending on what kind of base case is utilized, the required modifications vary for each e-fuel pathway and, thereby, also the costs, resulting in changes in the LCOE and LCoCA.
- The technical evaluation mainly focused on the fuel storage, fuel piping, and energy conversion unit of a large offshore vessel. Modifications to additional components were disregarded as the assumption was made that their impact on the results would likely be insignificant. However, the CapEx and OpEx of a large number of smaller components required for the implementation of an e-fuel could still affect the results of this research.
- Currently, the technical evaluation focused on components required to implement an e-fuel pathway, however, modifications related to maintaining the hydrostatic stability of the vessel, in case the mass of the vessel or the ballast volume changes have a significant impact on the vessel and could result in certain e-fuel pathways being less realistic to implement.
- During the financial evaluation, values for the CapEx were obtained, of which some were based on own-made assumptions or assumptions adopted from literature. These values give an indication regarding the costs related to implementing an e-fuel on a large offshore vessel. However, the implementation of an e-fuel is vessel specific, the actual CapEx might vary from the values obtained during the financial evaluation.
- The e-fuel prices utilized in this study are adopted from online literature and are based on assumptions that incorporate uncertainty in the result. Since these prices play an important role in the impact for the vessel owner, variations of these prices will result in changes in the KPI results as well as in the impact of implementation.

10.4. Validation phase

- To obtain the results of this study MGO was utilized as a base case, to which the KPIs of the e-fuels were compared. Hereby, this study's results depend on the base case's characteristics. Conditional upon what fossil base case is adapted for this study, the impact of certain KPIs might vary.
- In the OpEx sensitivity analysis all e-fuel prices were increased and decreased with the same factor. However, in reality, the price of certain e-fuels will increase or decrease more compared to other e-fuels.
- Since the validation of the input values, methodology, and model is performed by sustainability experts within HMC, and as the context of this study is also performed within HMC, which is also investigating e-fuels as an abatement option, it might be possible that selection bias might occur. This would result in the outcomes of this study not being validated properly.

10.5. Recommendations for future work

In this section, several recommendations for future work related to the implementation of e-fuels on large offshore vessels are presented.

- The model designed during this study is specifically intended for companies with their own fleet of large offshore vessels that are active in the maritime sector. However, The model could also be modified to meet the needs of governments or organizations, such as the IMO, to develop policies regarding e-fuels or make the maritime sector more sustainable. A recommendation is, therefore to look into the KPIs that such organizations value as crucial and to see how the model and methodology of this study could be used to their benefit.
- In this study, the assumption was made that all e-fuels will be available in the coming years. However, in reality, competition is likely to occur within the maritime sector and between other sectors regarding some e-fuels, which could result in higher e-fuel prices or e-fuels not being available. Therefore, including the availability of the e-fuels in the model will lead to more accurate results and is therefore recommended for future work.
- Since an average efficiency is adopted for e-fuel conversion or production steps, certain KPI results contain an error margin. Even though the impact of these KPIs is not likely to change, the results may vary. Therefore, executing a sensitivity analysis could be performed regarding these efficiencies to evaluate if a variation in these values has an actual effect on the impact of implementation or if this variation can be neglected.
- In this research, the technical evaluation was predominantly focused on the fuel storage, energy conversion unit, and piping infrastructure, however, a more extensive technical analysis is recommended as hereby additional technical modifications could be identified. By performing a more extensive technical evaluation, the impact that implementing an e-fuel has on the vessel and for the vessel owner could be determined more accurately and implementation bottlenecks could be easier identified.
- The financial evaluation conducted in the research was mainly based on the obtained data from literature, which in some cases also contains assumptions. However, by performing a more in-depth financial study, for example, in collaboration with manufacturers, more accurate results can be obtained as well as additional costs, such as costs related to retraining of the crew, can be identified.
- This research takes a time frame between 0-10 years into account, and therefore certain e-fuel pathways are not feasible. A recommendation is to extend the time frame, as hereby more viable pathways can be taken into account, which could result in identifying a pathway that is more suitable to implement than the pathways considered currently.
- In the coming years it might be the case that regulations, such as the EU ETS, will also be put in place for other types of GHGs. By adding the emission of other GHGs to the model as KPI, any new regulations could be anticipated and are therefore recommended for future work.
- The potential of an ICE operating on an e-fuel is high, as operating the engine on a higher utilization and with maximum up-time will result in more emission being abated. Looking into the emission being abated by increasing the utilization of the retrofitted engine and still meeting DP3 redundancy requirements is therefore given as a recommendation.
- Since the results of this study depend on the characteristics of the fossil base case, it would be interesting to see how the results of this study will vary in case another fossil base case is utilized instead of MGO.
- Since all of the KPIs depend on the capacity to be retrofitted, a recommendation for future work is to execute a sensitivity analysis regarding the retrofitted capacity to see if it has an effect on the outcomes of this study.
- To ensure that the results are validated independently and without any bias, a validation executed by non-stakeholders regarding making the vessel more sustainable is given as a recommendation.

Bibliography

[1] Kuwait Petroleum Corporation (KPC). *Safet data sheet - Marine Gas oil*. (2012). URL: https://www.kpc.com.kw/Data%5C%20Sheets/Marine%5C%20Gas%5C%20oil.pdf.

[2] H. Ababned and B.H. Hameed. "Electrofuels as emerging new green alternative fuel: A review of recent literature". In: *Elsevier* 254 (2022). DOI: https://doi.org/10.1016/j.enconman.2022.115213.

[3] ABS. *Ammonia as marine fuel*. October 2020. URL: https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ammonia-as-marine-fuel-whitepaper-20188.pdf.

[4] ABS. *LNG as marine fuel*. (July 2022). URL: https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/sustainability-whitepaper-lng-as-marine-fuel.pdf.

[5] ABS. *Methanol as marine fuel*. February 2021. URL: https://safety4sea.com/wp-content/uploads/2021/02/Sustainability-Methanol-as-Marine-Fuel.pdf.

[6] Arcsilea ABS CE-Delft. *Potential of ammonia as fuel in shipping*. September 2022. URL: https://www.emsa.europa.eu/publications/item/4833-potential-of-ammonia-as-fuel-in-shipping.html.

[7] DNV - EMSA (European Maritime Safety Agency). *Study on the use of fuel cells in shipping*. (2016). URL: https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html.

[8] Department of Agriculture. *Physical chemical properties of anhydrous ammonia*. n.d. URL: https://www.mda.state.mn.us/physical-chemical-properties-anhydrous-ammonia (visited on 01/13/2023).

[9] Renewable Hydrogen Alliance. *What are the efficiencies (i.e., energy losses) associated with energy storage and retrieval using competing hydrogen storage methods?* 27 March 2021. URL: https://renewableh2.org/transportation-and-storage/what-are-the-efficiencies-i-e-energy-losses-associated-with-energy-storage-and-retrieval-using-competing-hydrogen-storage-methods/#:~:text=The%5C%20amount%5C%20of%5C%20energy%5C%20used,the%5C%20energy%5C%20in%5C%20the%5C%20hydrogen. (visited on 01/12/2023).

[10] J. Andersson and S Grönkvist. "Large-scale storage of hydrogen." In: *International journal of hydrogen energy* 44.23 (May 2019). DOI: https://doi.org/10.1016/j.ijhydene.2019.03.063.

[11] Audi. *Audi steps up research into synthetic fuels*. 11-08-2017. URL: https://www.audi-mediacenter.com/en/press-releases/audi-steps-up-research-into-synthetic-fuels-9546 (visited on 11/10/2022).

[12] M. Aziz, A.T. Wijayanta, and A.B.D. Nandiyanto. "Ammonia as Effective hydrogen Storage: A Review on Production, Storage and Utilization". In: *MDPI* 13.12 (2020). DOI: https://doi.org/10.3390/en13123062.

[13] P. Balcombe et al. "How to decarbonise international shipping: Options for fuels, technologies and policies". In: *Elsevier* 182 (2019), pp. 72–88. DOI: https://doi.org/10.1016/j.enconman.2018.12.080.

[14] F. Baldi, F. Marechal, and S. Brynolf. "The cost of innovative and sustainable future ship energy systems". In: *ECOS* (2019).

[15] F. Baldi et al. "A Cogeneration System Based on Solid Oxide and Proton Exchange Membrane Fuel Cells With Hybrid Storage for Off-Grid Applications". In: *Frontiers in Energy Research* (2019), pp. 63–73. DOI: 10.3389/fenrg.2018.00139.

[16] S. Bengtsson, K. Andersson, and E. Fridell. “A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels”. In: *SAGE Journals* 225.2 (2011). DOI: https://doi.org/10.1177/1475090211402136.

[17] S. Bezergianni and A. Dimitriadis. “Comparison between different types of renewable diesel”. In: *Elsevier* 21 (2013), pp. 110–116. DOI: https://doi.org/10.1016/j.rser.2012.12.042.

[18] L. van Biert. *Solid oxide fuel cells for ships: System integration concepts with reforming and thermal cycles*. (2020). URL: https://doi.org/10.4233/uuid:dd1f7899-38ee-4c78-a5b0-a6fa92c90f56.

[19] P. Breeze. “The Solid Oxide Fuel Cell. In Fuel Cells”. In: *Elsevier* (2017), pp. 63–73.

[20] T. Brown. *Round-trip Efficiency of Ammonia as a Renewable Energy Transportation Media*. 2017-10-20. URL: https://www.ammoniaenergy.org/articles/round-trip-efficiency-of-ammonia-as-a-renewable-energy-transportation-media/#:~:text=In%5C%20this%5C%20study%5C%2C%5C%20%5C%E2%5C%80%5C%9Cthe%5C%20net,to%5C%201.13%5C%20MWh%5C%2Fton%5C%20ammonia. (visited on 01/13/2023).

[21] N. Brückner et al. “Evaluation of Industrially Applied Heat-Transfer Fluids as Liquid Organic Hydrogen Carrier Systems”. In: *Chemsuschem* 7.1 (2013), pp. 229–235. DOI: https://doi-org.tudelft.idm.oclc.org/10.1002/cssc.201300426.

[22] S. Brynolf et al. “Electrofuels for the transport sector: A review of production costs”. In: *Elsevier* 81.2 (2018), pp. 1887–1905. DOI: https://doi.org/10.1016/j.rser.2017.05.288.

[23] K. Q. Bui, L. P. Perera, and J. Emblemsvag. “Life-cycle cost analysis of an innovative marine dual-fuel engine under uncertainties”. In: *Journal of Cleaner Production* 380 (2022).

[24] Ship Bunker. *Rotterdam Bunker Prices*. (n.d.) URL: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam (visited on 03/15/2023).

[25] A. Buonomano et al. “Hybrid solid oxide fuel cells–gas turbine systems for combined heat and power: A review”. In: *Applied Energy* 156 (2015), pp. 32–85. DOI: https://doi.org/10.1016/j.apenergy.2015.06.027.

[26] Maersk Mc-Kinney Moller Center. *Industry Transition Strategy*. (October 2021). URL: https://www.zerocarbonshipping.com/publications/industry-transition-strategy/.

[27] S. Chakraborty. *Understanding The Design of Liquified Gas Carriers*. 2019. URL: https://www.marineinsight.com/naval-architecture/understanding-design-liquefied-gas-carriers/ (visited on 11/08/2022).

[28] Amrit Chandan et al. “High temperature (HT) polymer electrolyte membrane fuel cells (PEMFC)–A review”. In: *Journal of Power Sources* 231 (2013), pp. 264–278.

[29] Y. CHoi et al. “Design and analysis of liquid hydogen fuel tank for heavy duty truck”. In: *International journal of hydrogen energy* 47.32 (April 2022). DOI: https://doi.org/10.1016/j.ijhydene.2022.02.210.

[30] A. Christodoulou and K. Cullinane. “Potential alternative fuel pathways for compliance with the ‘FuelEU Maritime Initiative’”. In: *Transportation Research Part D: Transport and Environment* 112 (2022), p. 103492. DOI: https://doi.org/10.1016/j.trd.2022.103492.

[31] ClassNK. *Part C ”Guidelines for the safety of ships using ammonia as fuel” Of Guidelines for ships using alternative fuels*. November 2022. URL: https://www.classnk.or.jp/hp/pdf/research/rd/2022/05_e07.pdf.

[32] The International Council on Clean Transport. *Greenhouse gas emissions from global shipping 2013-2015*. (2017). URL: https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf.

[33] International Council on Clean Transport (ICCT). *Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate poicies*. (March 2021). URL: https://theicct.org/sites/default/files/publications/Well-to-wake-co2-mar2021-2.pdf.

[34] The International Council on Clean Transportation (icct). *Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025*. (2017). URL: https://theicct.org/sites/default/files/publications/HFO-Arctic_ICCT_Report_01052017_vF.pdf.

[35] M Turhan Çoban and Y Müh Kd Bnb Cüneyt EZGİ. “Design and analysis of diesel fueled solid oxide fuel cell system onboard surface ship”. In: *Journal of Naval Science and Engineering* 6.1 (2010), pp. 59–78.

[36] Center on Global Energy Policy Columbia SIPA. *Levelized cost of carbon abatement: An improved cost-assessment methodology for a net-zero emissions world*. (2020). URL: https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/LCCA_CGEP-Report_111522.pdf.

[37] CIMAC - International Council on Combustion Engines. *CIMAC White Paper 4 - Importance of a Well-to-Wake Approach*. (2020). URL: https://www.cimac.com/cms/upload/Publication_Press/Strategy_Group_Publications/CIMAC_White_Paper_4-GHG_Strategy_Group-Importance_of_a_Well-to-Wake_Approach.pdf.

[38] European Comission. *EU Emissions Trading System (EU ETS)*. N.d. URL: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en#:~:text=The%5C%20EU%5C%20ETS%5C%20works%5C%20on,A%5C%20capEN&text=is%5C%20set%5C%20on%5C%20the%5C%20total,so%5C%20that%5C%20total%5C%20emissions%5C%20fall (visited on 04/20/2023).

[39] European Commission. *Reducing emissions from the shipping sector*. n.d. URL: https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-shipping-sector_en (visited on 09/13/2022).

[40] European Commission. *Reducing emissions from the shipping sector*. (n.d.) URL: https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en (visited on 03/16/2023).

[41] European Council. *Fit for 55*. (2022). URL: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/ (visited on 09/21/2022).

[42] P.S. Daling and K.R. Sørheim. *Characterization of Low Sulfur Fuel marine Fuel Oils (LSFO)*. (2020). URL: https://www.itopf.org/fileadmin/uploads/itopf/data/Documents/RDaward/Summary_Report_Sintef_Low_sulphur_fuel_oils.pdf.

[43] CE Delft. *FuelEU Maritime and EU ETS*. (February 2022). URL: https://cedelft.eu/wp-content/uploads/sites/2/2022/02/CE_Delft_210396_FuelEU_Maritime_and_EU_ETS_Def_February-2022.pdf.

[44] C. Deniz and B. Zincir. “Environmental and economical assessment of alternative marine fuels”. In: *Journal of Cleaner Production* 113 (2016), pp. 438–449. DOI: https://doi.org/10.1016/j.jclepro.2015.11.089.

[45] Pavlos Dimitriou and Taku Tsujimura. “A review of hydrogen as a compression ignition engine fuel”. In: *International Journal of Hydrogen Energy* 42.38 (2017), pp. 24470–24486.

[46] I. Dincer and C. Zamfirescu. *Advanced Power Generation Systems, Chapter 4 - Hydrogen and Fuel Cell Systems*. Elsevier, 2014. ISBN: 978-0-12-383860-5.

[47] DNV. *EU ETS: Preliminary agreement to include shipping in the EU’s Emission Trading System from 2024*. January 2023. URL: https://www.dnv.com/news/eu-ets-preliminary-agreement-to-include-shipping-in-the-eu-s-emission-trading-system-from-2024-238068 (visited on 04/11/2023).

[48] DNV. *EU ETS: Preliminary agreement to include shipping in the EU’s Emission Trading System from 2024*. January 2023. URL: https://www.dnv.com/news/eu-ets-preliminary-agreement-to-include-shipping-in-the-eu-s-emission-trading-system-from-2024-238068 (visited on 02/22/2022).

[49] DNV. *EU ETS: Preliminary agreement to include shipping in the EU’s Emission Trading System from 2024*. January 2023. URL: https://www.dnv.com/news/eu-ets-preliminary-agreement-to-include-shipping-in-the-eu-s-emission-trading-system-from-2024-238068 (visited on 04/20/2023).

[50] DNV. *Handbook for hydrogen-fuelled vessels*. (2021). URL: https://www.dnv.com/maritime/publications/handbook-for-hydrogen-fuelled-vessels-download.html.

[51] DNV. *Maritime Forecast to 2050*. (2020). URL: https://eto.dnv.com/2021/maritime-forecast-2050/about.

[52] A. Al-Douri et al. "Greenhouse gases emissions in liquified natural gas as a marine fuel: Life cycle analysis and reduction potential". In: *The Canadian journal of Chemical Engineering* 100.6 (2021), pp. 1178–1186. DOI: https://doi-org.tudelft.idm.oclc.org/10.1002/cjce.24268.

[53] Ember. *Carbon price tracker*. (2023). URL: https://ember-climate.org/data/data-tools/carbon-price-viewer/ (visited on 03/16/2023).

[54] FCBI Energy. *Methanol as a marine fuel report*. (2015). URL: https://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf.

[55] U.S. Department of Energy. *Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications*. (2016). URL: https://www.energy.gov/sites/prod/files/2016/07/f33/fcto_battelle_mfg_cost_analysis_pp_chp_fc_systems.pdf.

[56] U.S. Department of Energy. *Potential Roles of Ammonia in a Hydrogen Economy*. (2006). URL: https://www.energy.gov/sites/prod/files/2015/01/f19/fcto_nh3_h2_storage_white_paper_2006.pdf.

[57] Office of Energy Efficiency and Renewable Energy. *Fuel Cell Basics*. n.d. URL: https://www.energy.gov/eere/fuelcells/fuel-cell-basics#:~:text=PEM%5C%20fuel%5C%20cells%5C%20are%5C%20the,liquefied%5C%20natural%5C%20gas%5C%2C%5C%20or%5C%20ethanol (visited on 10/21/2022).

[58] Office of Energy Efficiency and Renewable Energy. *Hydrogen Storage*. n.d. URL: https://www.energy.gov/eere/fuelcells/hydrogen-storage (visited on 11/21/2022).

[59] A. English et al. "methanol". In: *Chemical engineering Science* (2015). DOI: https://doi-org.tudelft.idm.oclc.org/10.1002/0471238961.1305200805140712.a01.pub3.

[60] Eni. *Light fuel oil*. (2017-08-30). URL: https://www.eni.com/en_AT/products-services/heating/light-fuel-oil/light-fuel-oil.shtml (visited on 10/14/2022).

[61] Era - Environmental. *GHS Hazard Classification: Everything You Need to Know*. May 2014. URL: https://www.era-environmental.com/blog/ghs-hazard-classification#:~:text=GHS%5C%20uses%5C%20three%5C%20hazard%5C%20classes,Physical%5C%20Hazards%5C%20and%5C%20Environmental%5C%20Hazards. (visited on 10/14/2022).

[62] Fertilizers Europe. *Guidance for inspection of atmospheric, refrigerated ammonia storage tanks*. (2014). URL: https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Guidance_for_inspection_of_atmospheric__refrigerated_ammonia_storage_tanksVJ_website.pdf.

[63] CO2 emissie factoren. *Lijst emissiefactoren*. nd. URL: https://www.co2emissiefactoren.nl/lijst-emissiefactoren/ (visited on 10/13/2022).

[64] DNV GL. *Rules for classification - Ships - Part 6 Additional class notations - Chapter 2 Propulsion, power generation and auxiliary systems*. (July 2020). URL: https://static1.squarespace.com/static/5f0d42f16639a745affd633e/t/5ff5d082add77853459846ec/1609945229408/DNVGL-RU-SHIP-Pt6Ch2.pdf.

[65] M. Grahn, M. Taljegard, and S. Brynolf. *Electofuels or hydrogen as marine fuel: a cost comparison*. (2021). URL: https://publications.lib.chalmers.se/records/fulltext/254511/local_254511.pdf.

[66] M. Grahn et al. "Review of electrofuel feasibility - cost and environmental impact". In: *Progress in Energy* 4.3 (2022). DOI: 032010.

[67] L. Guczi and A. Erdohelyi. *Catalysis for Alternative Energy Generation*. Springer, 2012. ISBN: 978-1-4614-0343-2.

[68] B. Gurau and E.S. Smotkin. "Methanol crossover in direct methanol fuel cells: a link between power and energy density". In: *Elsevier* 112.2 (2002), pp. 339–352. DOI: https://doi.org/10.1016/S0378-7753(02)00445-7.

[69] G. Hagen. *Hydrogen powered propulsion for an offshore crane vessel A technical and economical evaluation*. Master Thesis, Delft University of Technology. (2021). URL: http://resolver.tudelft.nl/uuid:cc6cf25f-d209-4576-a7f9-51c0df404cab.

[70] R.L. Harrington, Society of Naval Architects, and Marine Engineers (U.S.) *Marine engineering*. Society of Naval Architects and Marine Engineers, 1992.

[71] Heinzmann. *Artemis, Dual-Fuel Solutions*. (2019). URL: https://www.heinzmann.com/en/diesel-engines/dual-fuel-retrofitting (visited on 03/06/2023).

[72] Yannick Hoff. "Operational Characteristics Of A Metal Supported Solid Oxide Fuel Cell Power Generation System On Methanol For Naval Applications". In: (2022).

[73] IEA. *Oil demand by scenario, 2010-2030*. (October 2022). URL: https://www.iea.org/data-and-statistics/charts/oil-demand-by-scenario-2010-2030 (visited on 03/16/2023).

[74] IEA-AMF. *Diesel and gasoline - Composition of gasoline and diesel*. n.d. URL: https://www.iea-amf.org/content/fuel_information/diesel_gasoline#:~:text=Gasoline%5C%20and%5C%20diesel%5C%20fuel%5C%20contain,changes%5C%20somewhat%5C%20depending%5C%20on%5C%20composition. (visited on 11/24/2022).

[75] IMO. *IMO's work to cut GHG emissions from ships*. n.d. URL: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx (visited on 09/13/2022).

[76] IMO. *Section 2 Fuel oil - General requirements*. N.d. URL: https://www.imorules.com/NSR_V2_PT7_CH3_2.html (visited on 04/20/2023).

[77] O. Berkehan Inal, C. Dere, and C. Deniz. "Onboard Hydrogen Storage for Ships: An Overview". In: *Proceedings of the 5th International Hydrogen Technologies Congress (IHTEC-2021)* (May 2021). DOI: https://doi-org.tudelft.idm.oclc.org/10.1177/14750902221145747.

[78] E. Inkeri, T. Tynjala, and H. Karjunen. "Significance of methanation reactor dynamics on the annual efficiency of power-to-gas -system". In: *Renewable Energy* 163 (2021), pp. 1113–1126. DOI: https://doi.org/10.1016/j.renene.2020.09.029.

[79] IRENA. *Navigating the way to a renewable future: Solutions to decarbonise shipping*. (September 2019). URL: https://www.irena.org/publications/2019/Sep/Navigating-the-way-to-a-renewable-future.

[80] IRENA and Ammonia Energy Association. *Innovation Outlook: Renewable Ammonia*. (2022). URL: https://www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia.

[81] IRENA and Methanol Institute. *Innovation Outlook: Renewable Methanol*. (2021). URL: https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol.

[82] A. Iulianelli et al. "Advances on methane steam reforming to produce hydrogen through membrane reactors technology: A review". In: *Catalysis Reviews* 58 (2016), pp. 1–35. DOI: https://doi-org.tudelft.idm.oclc.org/10.1080/01614940.2015.1099882.

[83] Arun KS Iyengar et al. "Performance of a natural gas solid oxide fuel cell system with and without carbon capture". In: *Journal of Energy Resources Technology* 143.4 (2021).

[84] H. Jorschick et al. "Benzyltoluene/dibenzyltoluene-based mixtures as suitable liquid organic hydrogen carrier systems for low temperature applications". In: *Elsevier* 45 (2020), pp. 14897–14906. DOI: https://doi.org/10.1016/j.ijhydene.2020.03.210.

[85] Kyunghwa Kim et al. "A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments". In: *Journal of marine science and engineering* 8.3 (2020), p. 183.

[86] Arno de Klerk. "Transport fuel: Biomass-, coal-, gas-and waste-to-liquids processes". In: *Future energy*. Elsevier, 2020, pp. 199–226.

[87] J. Kokarakis. *Standards and Guidelines for Natural Gas Fuelled Ship Projects*. July 2015. URL: https://www.onthemosway.eu/wp-content/uploads/2015/06/Standards-and-Guidelines-for-Natural-Gas-Fuelled-Ship-Projects%5C%E2%5C%80%5C%99.pdf (visited on 01/26/2023).

[88] Andrei David Korberg et al. “Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships”. In: *Renewable and Sustainable Energy Reviews* 142 (2021), p. 110861.

[89] K. Kouzelis. *Maritime fuels of the future*. Master Thesis, Delft University of Technology. (2021). URL: http://resolver.tudelft.nl/uuid:9d1bb908-c47e-45f9-a607-96ea9251a9fb.

[90] D.F.A. van der Kroft and J.F.J. Pruyn. “A study into the availability, costs and GHG reduciton in drop-in biofuels for shipping under different regimes between 2020 and 2050”. In: *MDPI* 13.17 (2021). DOI: https://doi.org/10.3390/su13179900.

[91] D.N. Kuimov, M.S. Kinkin, and A.D. Lukyanov. “Low-Sulfur fuel and Oil Production”. In: *Materials Science Forum* 870 (2016), pp. 671–676. DOI: https://doi-org.tudelft.idm.oclc.org/10.4028/www.scientific.net/MSF.870.671.

[92] Alfa Laval et al. *Ammonfuel - An industrial view of ammonia as a marine fuel*. August 2020. URL: https://www.topsoe.com/hubfs/DOWNLOADS/DOWNLOADS%5C%20-%5C%20White%5C%20papers/Ammonfuel%5C%20Report%5C%20Version%5C%2009.9%5C%20August%5C%203_update.pdf.

[93] G. Leonzio. “Process analysis of biological Sabatier reaction for bio-methane production”. In: *Elsevier* 209 (April 2016), pp. 490–498. DOI: https://doi.org/10.1016/j.cej.2016.01.068.

[94] Linde. *Safet data sheet - Liquid hydrogen*. (2022). URL: https://www.lindeus.com/-/media/corporate/praxairus/documents/sds/hydrogen/liquid-hydrogen-gas-h2-safety-data-sheet-sds-p4603.pdf?la=en#:~:text=Special%5C%20hazards%5C%20arising%5C%20from%5C%20the%5C%20substance%5C%20or%5C%20mixture&text=Hydrogen%5C%20has%5C%20a%5C%20low%5C%20ignition,Explosion%5C%20hazard%5C%20%5C%3A%5C%20EXTREMELY%5C%20FLAMMABLE%5C%20GAS..

[95] E. Lindstad et al. “Reduction of maritime GHG emissions and the potential role of E-fuels”. In: *Elsevier* 101 (2021). DOI: https://doi.org/10.1016/j.trd.2021.103075.

[96] Air Liquide. *Storing Hydrogen*. n.d. URL: https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored (visited on 11/08/2022).

[97] J. Liu et al. “Recent advance of metal borohydrides for hydrogen storage”. In: *Frontiers* (2022). DOI: https://doi.org/10.3389/fchem.2022.945208.

[98] Environmental Defens Fund Europe ltd. *Electrofuels for shipping*. (2019). URL: https://www.edfeurope.org/news/2019/10/12/electrofuels-shipping#:~:text=Electrofuels%5C%20for%5C%20Shipping%5C%2C%5C%20produced%5C%20by,namely%5C%20ammonia%5C%2C%5C%20hydrogen%5C%20and%5C%20methanol..

[99] DNV GL Maritime. *Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility*. January 2016. URL: https://www.methanol.org/wp-content/uploads/2020/04/IMO-Methanol-Marine-Fuel-21.01.2016.pdf.

[100] T. McKenney. *The role of onboard carbon capture in maritime decarbonization*. September 2022. URL: https://www.zerocarbonshipping.com/publications/the-role-of-onboard-carbon-capture-in-maritime-decarbonization/ (visited on 11/30/2022).

[101] C.J. McKinlay, S.R. Turnock, and D.A. Hudson. “Route to zero emission shipping: Hydrogen, ammonia or methanol?” In: *Elsevier* 46.55 (2021), pp. 28282–28297. DOI: https://doi.org/10.1016/j.ijhydene.2021.06.066.

[102] National Library of Medicine - PubChem. *Methanol*. n.d. URL: https://pubchem-ncbi-nlm-nih-gov.tudelft.idm.oclc.org/compound/Methanol (visited on 11/08/2022).

[103] J.D. Medrano-Garcia, M.A. Charalambous, and G. Guillen-Gosalbez. “Economic and environmental barriers of CO_2-based Fischer-Tropsch electro-diesel”. In: *ACS Sustainable Chemistry Engineering* 10.36 (2022), pp. 11751–11759. DOI: https://doi.org/10.1021/acssuschemeng.2c01983.

[104] Direns Mines. *Internal Combustion Engines*. n.d. URL: https://direns.mines-paristech.fr/Sites/Thopt/en/res/TechnoCHP.pdf (visited on 01/13/2023).

[105] W. Miroslaw. “Potential of porous-media combustion technology as applied to internal combustion engines”. In: *Journal of Thermodynamics* 2010 (2010).

[106] “Chapter 5 - Natural Gas Liquefaction Cycle Enhancements and Optimization”. In: *Handbook of Liquefied Natural Gas*. Ed. by S. Mokhatab et al. Gulf Professional Publishing, 2014, pp. 229–257. ISBN: 978-0-12-404585-9. DOI: https://doi.org/10.1016/B978-0-12-404585-9.00005-2.

[107] S.S. Muir and X. Yao. “Progress in sodium borohydride as a hydrogen storage material: Development of hydrolysis catalysts and reaction systems”. In: *Elsevier* 36 (2011), pp. 5983–5997. DOI: https://doi.org/10.1016/j.ijhydene.2011.02.032.

[108] M. N. Nabi et al. “A comparative study of the number and mass of fine particles emitted with diesel fuel and marine gas oil (MGO)”. In: *Elsevier* 57 (2019), pp. 22–28. DOI: https://doi.org/10.1016/j.atmosenv.2012.04.039.

[109] United Nations. *The Paris Agreement*. (2022). URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (visited on 09/13/2022).

[110] Bloomberg NEF. *Carbon Offset Prices Could Increase Fifty-Fold by 2050*. (January 2022). URL: https://about.bnef.com/blog/carbon-offset-prices-could-increase-fifty-fold-by-2050/ (visited on 03/16/2023).

[111] M. Niermann et al. “Liquid Organic Hydrogen Carrier (LOHC) - Assessment based on chemical and economic properties”. In: *Elsevier* 44 (2019), pp. 6631–6654. DOI: https://doi.org/10.1016/j.ijhydene.2019.01.199.

[112] M. Niermann et al. “Liquid Organic Hydrogen Carriers and alternatives for international transport of renewable hydrogen”. In: *Elsevier* 135 (January 2021). DOI: https://doi.org/10.1016/j.rser.2020.110171.

[113] F. van Nievelt. *Maritime application of sodium borohyrdrie as an energy carrier*. Master Thesis, Delft University of Technology. (2019). URL: http://resolver.tudelft.nl/uuid:58a04edd-3392-4642-b6d0-dfbeee9a89be.

[114] F.M. van Nievelt. *Maritime application of sodium borohydride as an energy carrier*. Master Thesis, Delft University of Technology. (2019). URL: http://resolver.tudelft.nl/uuid:58a04edd-3392-4642-b6d0-dfbeee9a89be.

[115] P. Nikolaidis and A. Poullikkas. “A comparative overview of hydrogen production processes”. In: *Renewable and Sustainable Energy Reviews* 67 (2017), pp. 597–611. DOI: https://doi.org/10.1016/j.rser.2016.09.044.

[116] Pavlos Nikolaidis and Andreas Poullikkas. “A comparative overview of hydrogen production processes”. In: *Renewable and sustainable energy reviews* 67 (2017), pp. 597–611.

[117] I. Nikolic et al. *Guide for good modelling practice in policy support. TUD / TPM*. (2019). URL: 10.4233/uuid:cbe7a9cb-6585-4dd5-a34b-0d3507d4f188.

[118] OECD. *Policies for a Carbon-Neutral Industry in the Netherlands,* (2021). URL: https://doi.org/10.1787/6813bf38-en..

[119] A. Onorati et al. “The role of hydrogen for future internal combustion engines”. In: *International Journal of Engine Research* 4 (2022), pp. 529–540. DOI: 10.1177/14680874221081947.

[120] “Optimization of a 30 kW SOFC combined heat and power system with different cycles and hydrocarbon fuels”. In: *Fuel Cells Bulletin* 2008.5 (2008), pp. 4–5. DOI: https://doi.org/10.1016/j.ijhydene.2021.11.049.

[121] International Maritime Organization. *Fourth IMO GHG Study 2020*. (2020). URL: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%5C%20IMO%5C%20GHG%5C%20Study%5C%202020%5C%20-%5C%20Full%5C%20report%5C%20and%5C%20annexes.pdf.

[122] International Maritime Organization. *IMO 2020 - cutting sulphur oxide emissions*. 2020. URL: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx (visited on 10/11/2022).

[123] International Maritime Organization. *Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2020)*. (2021). URL: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%5C%20pollution/MEPC%5C%2077-6-1%5C%20-%5C%202020%5C%20report%5C%20of%5C%20fuel%5C%20oil%5C%20consumption%5C%20data%5C%20submitted%5C%20to%5C%20the%5C%20IMO%5C%20Ship%5C%20Fuel%5C%20Oil%5C%20Consumption%5C%20Database%5C%20in%5C%20GISIS.pdf.

[124] J.L. Osorio-Tejada, E. Liera-Sastresa, and S. Scarpellini. "LNG: an alternative fuel for road freight transport in Europe". In: *Sustainable Development* 21 (2015), pp. 235–246. DOI: 10.2495/SD150211.

[125] T. Ovaska et al. "Effect of Alternative Liquid Fuels on the Exhaust Particle Size Distributions of a Medium-Speed Diesel Engine". In: *Energies* 12.11 (2019). DOI: https://doi.org/10.3390/en12112050.

[126] GMM consortium partners. *Public Final Report: WP 5 - System Design for Short Sea Shipping*. (2022). URL: https://publications.tno.nl/publication/34637752/GPkj6y/TNO-2021-green.pdf.

[127] E.C. Peeters. *The challenges and opportunities of a hydrogen internal combustion engine*. (2022). URL: http://resolver.tudelft.nl/uuid:63823e24-85e8-47d3-a585-7f5c6ebb74fb.

[128] Ovidiu Popovici. "The study of the efficiency of a direct methanol fuel cell". In: *Journal of Electrical and Electronics Engineering* 7.2 (2014), p. 31.

[129] S.I. Prodanov. *Techno-economic assessment of ammonia as a marine fuel*. Master Thesis, Hamburg School of Business Administration. (December 2021). URL: http://www.spmaritime.eu/wp-content/uploads/2022/07/MBAS_18_MT_4287_compressed-1.pdf.

[130] New York State Energy Research and Development Authority. *Hydrogen Fact Sheet Hydrogen Production - SMR*. (2013). URL: https://www.amiqweb.es/app/download/9343795/6hydrogenproductionsteammethanereforming.pdf.

[131] A. Ritari, J. Huotari, and K Tammi. "Marine vessel powertrain design optimization: Multiperiod modeling considering retrofits and alternative fuels". In: *Engineering for the maritime environment* (2023). DOI: https://doi-org.tudelft.idm.oclc.org/10.1177/14750902221145747.

[132] C.J. Robuck. *MSC Guidelines for Independent Fuel Tanks*. 8 January 2017. URL: https://www.dco.uscg.mil/Portals/9/MSC/PRG/PRG.E1-16.2017.08.01.Independent_Tanks.pdf (visited on 01/26/2023).

[133] Jasper A Ros et al. "Advancements in ship-based carbon capture technology on board of LNG-fuelled ships". In: *International Journal of Greenhouse Gas Control* 114 (2022), p. 103575.

[134] Y. Ryu, Y. Lee, and J. Nam. "Performance and emission characteristics of additives-enhanced heavy fuel oil in large two-stroke marine diesel engine". In: *Elsevier* 182 (October 2016), pp. 850–856. DOI: https://doi.org/10.1016/j.fuel.2016.06.029.

[135] The Engineers Post - M. Saif. *Four stroke diesel cycle engine and its working [explained with P-V and T-S diagram]*. 28 November 2021. URL: https://www.theengineerspost.com/diesel-cycle/ (visited on 01/13/2023).

[136] D.M.F. Santos and C.A.C. Sequeira. "Sodium borohydride as a fuel for the future". In: *Elsevier* 15.8 (2011), pp. 3980–4001. DOI: https://doi.org/10.1016/j.rser.2011.07.018.

[137] J. Schröder et al. *Methanol as Motor Fuel Summary Report*. (2020). URL: https://www.iea-amf.org/app/webroot/files/file/Annex%5C%20Reports/AMF_Annex_56.pdf.

[138] M. Schuler. *Growing Support for Zero-Emission Shipping Target Ahead of Critical IMO Meeting*. March 2023. URL: https://gcaptain.com/growing-support-for-zero-emission-shipping-target-ahead-of-critical-imo-meeting/?subscriber=true&goal=0_f50174ef03-f6110b4a6a-170375778&mc_cid=f6110b4a6a&mc_eid=3c57fb18d9 (visited on 04/19/2023).

[139] Øyvind Sekkesæter. "Evaluation of concepts and systems for marine transportation of hydrogen". PhD thesis. Master Thesis, NTNU, Trondheim, Norwegen, 2019.

[140] Y. Shen et al. “Hydrogen generation from methanol at near-room temperature”. In: *Chemical Science* 8.11 (2017), pp. 7498–7504. DOI: 10.1039/c7sc01778b.

[141] Verifavia shipping. *Emission factors*. n.d. URL: https://www.verifavia-shipping.com/shipping-carbon-emissions-verification/faq-which-emission-factors-shall-be-used-110.php (visited on 10/13/2022).

[142] Sigma-Aldrich. *Safet data sheet - Ammonia*. (2021). URL: https://www.sigmaaldrich.com/NL/en/sds/aldrich/294993.

[143] Sigma-Aldrich. *Safet data sheet - Methanol*. (2021). URL: https://www.sigmaaldrich.com/NL/en/sds/sial/322415.

[144] I. Skov. *Integrated electrofuels and renewable energy systems*. (2015). URL: 10.13140/RG.2.1.4318.5682.

[145] Dr. G.L. Soloveichik. *Metal Borohydrides as Hydrogen Storage Materials*. -. URL: https://www.sigmaaldrich.com/NL/en/technical-documents/technical-article/materials-science-and-engineering/batteries-supercapacitors-and-fuel-cells/metal-borohydrides (visited on 11/03/2022).

[146] MAN Energy Solutions. *Hydrogen in shipping*. (n.d.) URL: https://www.man-es.com/campaigns/download-Q1-2023/Download/hydrogen-in-shipping/faffa612-4edc-4a2a-a5f9-df89c632a431/Future-Fuels-Hydrogen.

[147] MAN Energy Solutions. *ME-GI Gas-ready Ship*. (Augustus 2015). URL: https://mandieselturbo.com/docs/default-source/shopwaredocuments/me-gi-gas-ready7fedf09dc06645f89f38c7c52b2187b1.pdf?sfvrsn=4 (visited on 10/15/2022).

[148] Man Energy Solutions. *Engineering the future two-stroke green ammonia engine*. (2019). URL: https://fathom.world/wp-content/uploads/2020/05/engineeringthefuturetwostrokegreenammoniaengine1589339239488.pdf.

[149] Total Marine Fuels Global Solutions. *Safet data sheet - Liquified natural gas (LNG)*. (2020). URL: https://marinefuels.totalenergies.com/system/files/atoms/files/liquified_natural_gas_lng_089791_france_english_20220926.pdf.

[150] Statista. *Annual fuel consumption by ships worldwide from 2019 to 2020, by fuel type*. (2021-09). URL: https://www-statista-com.tudelft.idm.oclc.org/statistics/1266963/amount-of-fuel-consumed-by-ships-worldwide-by-fuel-type/ (visited on 10/14/2022).

[151] M. Taljegard et al. “Electrofuels - A possibility for shipping in a low carbon future?” In: 2 (2016).

[152] Emigreen - Emission Control Technologies. *Standards and Guidelines for Natural Gas Fuelled Ship Projects*. September 2022. URL: https://www.emigreen.eu/all-one-needs-to-know-regarding-selective-catalytic-reduction/#:~:text=What%5C%20is%5C%20the%5C%20catalyst%5C%20used,32.5%5C%25%5C%20urea%5C%20in%5C%20demineralised%5C%20water. (visited on 02/03/2023).

[153] TNO. *E-Fuels: Towards a more sustainable future for truck transport, shipping and aviation*. (July 2020). URL: https://www.tno.nl/nl/newsroom/2020/09/fuels-cruciaal-verduurzaming-zwaar/.

[154] TNO. *TNO’s zware waterstofverbrandingsmotor wint tweede prijs EARTO Innovation Awards*. (2022-12-10). URL: https://www.tno.nl/nl/newsroom/2022/10/zware-waterstofverbrandingsmotor-earto/ (visited on 11/15/2022).

[155] Engineering Toolbox. *Fossil and Alternative Fuels - Energy Content*. 2008. URL: https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html (visited on 10/13/2022).

[156] Man Diesel & Turbo. *Safety Concept - Marine: Dual-fuel engines*. December 2015.

[157] Bureau Veritas. *Guidelines on Conversion of Ship to LNG as Fuel*. February 2019. URL: https://erules.veristar.com/dy/data/bv/pdf/654-NI_2019-02.pdf.

[158] Bureau Veritas. *What well-to-wake decarbonization means for shipowners*. 2022. URL: https://marine-offshore.bureauveritas.com/what-well-wake-decarbonization-means-shipowners#:~:text=What%5C%20does%5C%20well%5C%2Dto%5C%2Dwake,and%5C%20all%5C%20emissions%5C%20produced%5C%20therein. (visited on 10/13/2022).

[159] V. Viray-Mendoza. *What is MGO?* (2020-10-21). URL: https://maritimereview.ph/what-is-mgo/#:~:text=MGO%5C%20usually%5C%20consists%5C%20of%5C%20a,Intermediate%5C%20Fuel%5C%20Oil%5C%20(IFO1 (visited on 10/15/2022).

[160] O.P.R. van Vliet, A.P.C. Faaij, and W.C. Turkenburg. "Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis". In: *Energy Conversion and Management* 50.4 (2009), pp. 855–876. DOI: https://doi.org/10.1016/j.enconman.2009.01.008.

[161] F. Vogler and G. Würsig. "Fuel cells in maritime applications challenges, chances and experiences". In: *The 4th International Conference on Hydrogen Safety (ICHS)* (2011).

[162] N. de Vries. *Safe and effective application of ammonia as a marine fuel*. Master Thesis, Delft University of Technology. (2019). URL: http://resolver.tudelft.nl/uuid:be8cbe0a-28ec-4bd9-8ad0-648de04649b8.

[163] N. de Vries. *Safe and effective application of ammonia as a marine fuel*. Master Thesis, Delft University of Technology. (2019). URL: http://resolver.tudelft.nl/uuid:be8cbe0a-28ec-4bd9-8ad0-648de04649b8.

[164] Wärtsilä. *Wärtsilä 32 methanol engine and methanolpac*. Product presentation. January 2023.

[165] Wartsila. *Fuel efficiency in gas conversions*. 2013. URL: https://www.wartsila.com/static/studio/assets/content/ss3/bwp-fuel-efficiency-in-gas-conversions.pdf (visited on 01/13/2023).

[166] S. Wu, B. Miao, and S.H. Chan. "Feasibility assessment of a container ship applying ammonia cracker-integrated solid oxide fuel cell technology". In: *Elsevier* 47 (2022), pp. 27166–27176. DOI: https://doi.org/10.1016/j.ijhydene.2022.06.068.

[167] Xchange. *Want to reduce maritime shipping emissions?* (2022). URL: https://www.container-xchange.com/blog/shipping-emissions/ (visited on 09/21/2022).

[168] X. Zhen and Y. Wang. "An overview of methanol as an internal combustion engine fuel". In: *Elsevier* 52 (2015), pp. 477–493. DOI: https://doi.org/10.1016/j.rser.2015.07.083.

[169] Hao Zhong et al. "Sodium borohydride regeneration via direct hydrogen transformation of sodium metaborate tetrahydrate". In: *Journal of Power Sources* 390 (2018), pp. 71–77.

A

Introduction

An overview of the experts consulted for this study, within and outside of HMC is shown in Figure A.1, together with their are of expertise.

Group of experts	Function	Area of expertise
Sustainability experts	Project managers & Sustainability managers & Project engineers	Decarbonizing large offshore construction vessels
Retrofit experts	Technical superintendents & Equipment managers	Equipment and infrastructure of large offshore construction vessels
Cost experts	Sales manager & Chief Commercial Officer	Abatement technologies and their associated CapEx and OpEx
Fuel cell experts	Chief Commercial Officer	Fuel cell technologies, their TRL and their associated CapEx and OpEx

Figure A.1: Experts consulted during this research

B

Fuels

Fuel oils

Heavy Fuel Oil

HFO, also referred to as residual fuel, is currently the most common fuel in the shipping industry [150]. HFO is a very viscous substance that consists of any excess leftovers from an oil refining process. The substance is so viscous, that it needs to be heated to approximately 130 degrees Celcius for it to flow and thus be used. HFO contains several heavy metal impurities and often has a high sulphur (S) content of about 3.5% m/m (mass by mass). During the combustion of HFO, large amounts of air pollutants, such as SO_x, NO_x and climate pollutants, such as CO_2 and N_2O are emitted. Due to its large sulphur content, the exhaust gas will also contain a high sulphur particle level, that will eventually form SO_x [34].
Besides climate and air pollution, HFO also poses a significant risk to the marine environment in the case of a potential spill. Spilled HFO has the tendency to emulsify in seawater, hereby forming large tar chunks and exponentially increasing the spilled volume. Even though these negative environmental effects are well known, HFO still remains one of the preferred marine fuels, due to its low cost, high availability and due to the fact that many large marine engines were designed to be powered by HFO [34]. However, the usage of HFO as fuel has been restricted due to sulphur content regulations set up by the IMO. According to this regulation, vessels operating outside of emission control areas are limited to a sulphur content of 0.5% and vessels within the control areas are even limited to a sulphur content of 0.1% [122]. The alternative, presented by the IMO is the usage of HFO in combination with scrubbers that remove SO_x from exhaust gasses [122].

Light Fuel Oil

LFO is a fuel that is similar to HFO except it went through a hydrogenation process, causing the sulphur content to be below 1% [60]. Therefore, these types of fuels are also referred to as Low sulphur Fuel Oils (LSFO), Very Low sulphur Fuel Oil (VLSFO) if the sulphur content is below 0.5% and Ultra Low sulphur Fuel Oil (ULSFO), if the sulphur content is below 0.1% [42]. All these fuels are derived from the same raw chemicals, and the varying sulphur content is realized by the comprehensiveness of the desulphurization process, where sulphur and sulphur compounds are extracted by making use of catalysts [91].
These low sulphur-containing fuels started to gain more traction in the last few years, mainly because of the limit that the IMO set on the sulphur content in marine fuel. However, only VLSFO and ULSFO are of interest as only they meet the 0.5% sulphur content limitation set by the IMO. The IMO set these regulations to reduce SO_x emissions, as they are harmful to the environment and human health [123]. Once emitted SO_x can cause acid rain, which can poison crops, and forests and acidification of sea waters [122].

E-fuels

Liquid Organic Hydrogen Carriers (LOHC)

As was mentioned before, one of the disadvantages of H_2 as an alternative fuel is its low volumetric energy density, LOHCs could propose a solution to this problem. LOHC is a generic term for several different organic liquids that are able to store hydrogen chemically. The advantages of LOHCs are that they are potentially cheap, easily manageable, transportable and safe. Additionally, LOHCs are able to store hydrogen for a long period of time without any hydrogen losses. The hydrogen storage in a LOHC is based on a reversible hydrogenation and dehydrogenation process of double carbon bonds. During hydrogenation, the double bonds of the LOHC are saturated with hydrogen, this process takes place at an elevated pressure and temperature and is exothermic, meaning energy is released. On the other hand, the hydrogen is released from the LOHC during dehydrogenation, which takes place at an elevated temperature, at atmospheric pressure, and is endothermic. After the dehydrogenation process, the LOHC can be loaded with hydrogen and the hydrogenation process can be gone through again [111].

Because of the fact that hydrogen can be stored in the molecules of a LOHC, the volumetric energy density can be significantly increased. Storing H_2 in a LOHC, highly simplifies the handling of H_2, because of the fact that LOHCs have approximately the same properties as currently used fossil fuels, such as diesels. Hereby, the existing onboard infrastructure could be used, when making use of us LOHCs, however, two storage tanks will be necessary, one for the hydrogenated and one for the dehydrogenated LOHC [111].

As stated before LOHC is a generic term for various different organic liquids, however, there are only a few promising LOHCs that show more advantageous characteristics compared to other LOHCS. These LOHCs are N-ethylcarbazole (NEC), dibenzyltoluene (DBT), toluene (TOL) and methanol (MET) [112]. For this research, only DBT will be considered as LOHC, because of the fact that it is one of the more extensively studied, in recent literature, and because it shows the highest potential to be used as a hydrogen storage medium, according to several published papers, such as [84] [21].

In a paper published by Niermann et al., eight promising LOHCs, including the ones mentioned above, are evaluated, based on important characteristics and on their potential implementation in the mobility, energy-transport and energy-storage sectors [111]. One of the conclusions of this research was that DBT is the most promising LOHC for the energy-transport and energy-storage sector, even though it is not the cheapest option or the option with the highest storage capacity. In another paper, also published by Niermann et al., the techno-economic performance of several LOHCs is analyzed. Herein, dibenzyl-toluene is also mentioned as one of the more viable options for hydrogen delivery and import. However, Niermann et al. also mention that some further research will be necessary before the LOHC can be implemented [112].

DBT is a compound that is industrially used as a heat transfer oil, since 1960, and is available in large quantities at a relatively low price [84]. DBT is a compound with a high TRL, several small as well as large-scale hydrogenation and dehydrogenation plants are operational and several projects, have already been realized. In addition, DBT has a storage capacity of 6.2 wt.-% (weight percentage) and excellent properties regarding the reversibility in the H_2 storage procedure [111]. Other characteristics of DBT will be stated in section 3.2.3.

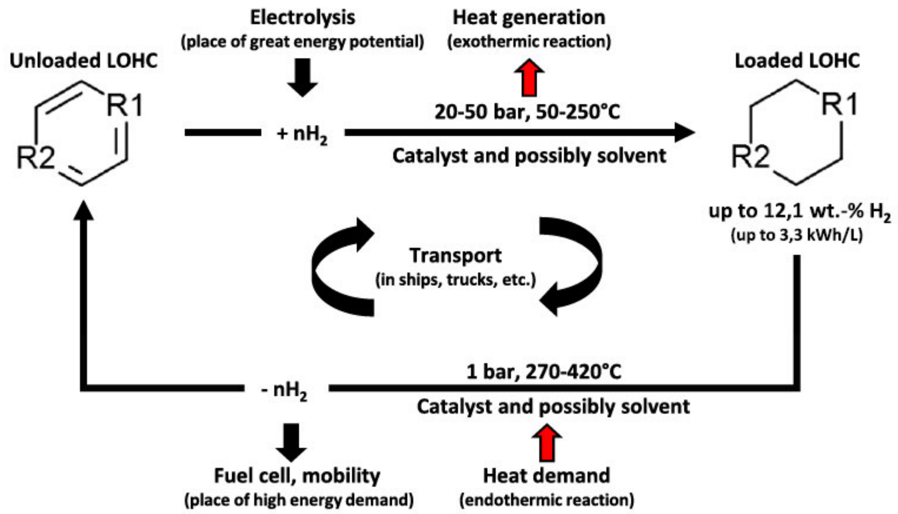

Figure B.1: Schematic overview of hydrogenation and dehydrogenation process of LOHC's [112]

Metal borohydrides

Metal borohydrides ($M(BH_4)_n$), are another category of materials that is able to chemically store hydrogen, just as LOHCs. However, in the case of metal borohydrides, the H_2 is stored in a solid state, where it is combined with several compounds or elements by the metal, ionic or covalent bonds to form the metal borohydrides. Metal borohydrides have the theoretical capacity to store more than 7.5 wt.-% of hydrogen and have therefore become a category of interest [97].

$M(BH_4)_n$ is the general notation for metal borohydrides, where *M* indicates the metal and *n* the valence of the metal, which indicates the maximum amount of bonds the metal is able to form. Examples of metal borohydrides are, lithium borohydride ($LiBH_4$), sodium borohydride ($NaBH_4$) and magnesium borohydride ($Mg(BH_4)_2$).

$NaBH_4$ is a material that is widely researched in literature and globally the most commercially produced metal borohydride [145]. $NaBH_4$ was first discovered in the 1940s and since then much research has been performed and papers have been published regarding different aspects of the material. For instance, the paper published by Muir and Yao [107], reviews the progress regarding all research executed into $NaBH_4$, hereby focusing on $NaBH_4$ hydrolysis, $NaBH_4$ based hydrogen storage systems and cost-effective $NaBH_4$ generation. In addition, in the paper published by Santos and Sequeira [136], the potential of $NaBH_4$ as a fuel is discussed, where the focus is on its properties, synthesis methods, and its current and future outlook as a hydrogen carrier.

Sodium borohydride ($NaBH_4$) is a solid white material that is often available as a powder. $NaBH_4$ has a high hydrogen storage capacity compared to other metal borohydrides, $NaBH_4$ has the ability to store approximately 10.8 wt.-% of hydrogen [107]. The hydrogen can be released in a process where $NaBH_4$ reacts with water, to liberate four hydrogen molecules, at room temperature [136]. The reaction is carried out in a reactor, where dry $NaBH_4$ is added to water and hydrogen is separated. The hydrogen can be used as fuel in an ICE or fuel cell and the $NaBO_2$ can be regenerated to $NaBH_4$ by making use of a sustainable energy source [114]. The hydrogen liberation reaction can be seen in displayed in reaction B.1.

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 \tag{B.1}$$

E-fuel energy conversion

Every e-fuel contains a certain amount of chemical energy which can be converted into mechanical energy, via an energy conversion unit and used to power a vessel. Every e-fuel has several options regarding how the chemical energy, stored in the fuel, can be converted. However, in this study, only these three types of power conversion units are considered, which are an ICE, Solid Oxide Fuel Cell (SOFC) and a Proton Exchange Membrane Fuel Cell (PEMFC). These three are chosen as an ICE is currently used on the vessels of Heerema, and the SOFC and PEMFC are two of the most studied alternative power conversion units for the maritime sector. Several SOFC and PEMFC projects are even already operational, to assess their potential [7]. The SOFC and the PEMFC were also identified as the two of the most promising fuel cell technologies by several studies, such as a study on the manufacturing costs by the U.S. Department of Energy [55], and the fuel cell application study carried out by DNV [7].
In this section, an overview is given of the energy conversion units that are included in this study.

Internal combustion engine (ICE)

High-capacity ICEs that are installed on large offshore vessels, such as the vessels of HMC, operate with an efficiency of approximately 40% [135]. Figure B.2 shows an engine cycle for a compression ignition four-stroke, which refers to the number of strokes the piston makes per engine cycle, ICE [135]. A spark ignition engine is another type of ICE, which operates in a similar manner as the compression ignition, however, a spark is fired that ignites the mixture instead of the increase in pressure which causes ignition of the mixture. The four strokes are shortly elaborated on below.

1. **Suction**, the intake valve is open and as the piston moves down, air or a mixture of air and fuel is sucked into the cylinder. Mixing air with the fuel can be done outside of the cylinder or inside the cylinder [127].
2. **Compression**, the piston moves up the inlet valve is closed and the air-fuel mixture is compressed. Depending on the type of ICE the mixture is ignited by a spark or is self-ignited as the auto-ignition temperature of the fuel is reached due to the increasing pressure [127].
3. **Power**, the combustion, caused by the ignition, causes the piston to move down and move the crankshaft, hereby the chemical energy is converted into mechanical energy [127].
4. **Exhaust**, Once the piston is at the bottom, the exhaust valve is opened and the combusted mixtures us pushed out of the cylinder [127].

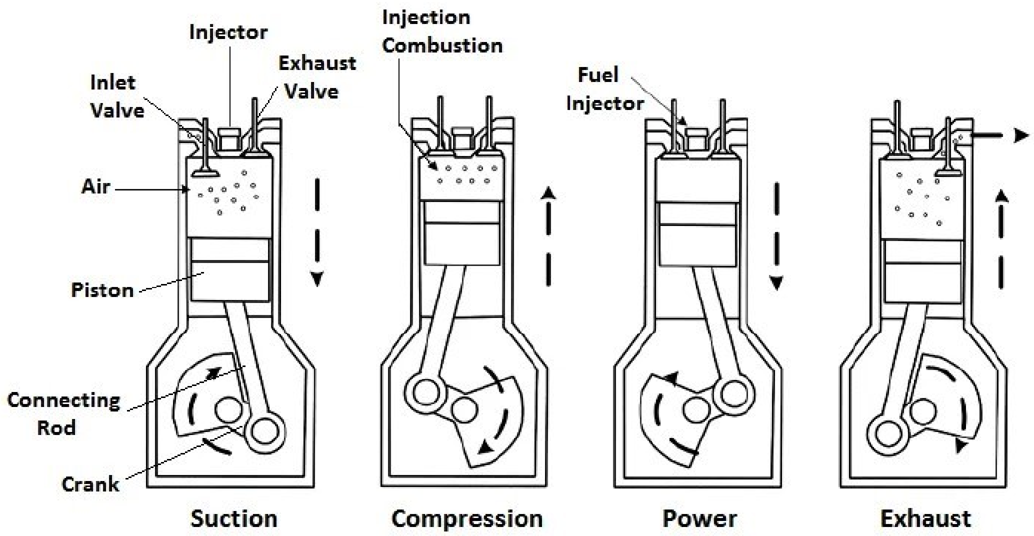

Figure B.2: Graphical representation of the engine cycle of a compression ignition four-stroke engine [135]

Fuel Cell

The SOFC and PEMFC are two types of fuel cells that could be used as power conversion unit on vessels. A fuel cell is an electrochemical cell that is able to convert the chemical energy from a fuel into electricity through electrochemical reactions with oxygen or another oxidizing agent. A difference between a fuel cell and an ICE is that fuel cells directly convert chemical energy into electricity, whereas an ICE converts chemical energy into electricity through mechanical and thermal energy [18]. Additionally, fuel cells have a lower power density $Watt/m^3$ than an ICE [18]. The most common fuel to be used in fuel cells is hydrogen, however, also other fuels could be used in a fuel cell, either directly or by first converting the fuel to hydrogen.
A short description of the two fuel cell types considered in this study is given below and their working principles are shown in Figure B.3.

- **SOFC**
  - The electrolyte consists of a solid ceramic, that only conducts oxygen ions and is an insulator, hereby the SOFC is able to remain stable for a long period of time, thus increasing its lifetime [18].
  - Due to high operating temperatures, SOFCs are able to reform carbon-based fuels, such as natural gas [57].
  - The conductivity of oxygen ions through the electrolyte is extremely low and to achieve reasonable levels operating temperatures will have to be in the range of 500-1000 °C [18].
  - Efficiencies of 60% can be reached [15], however, the dynamics are low, therefore SOFCs are less likely to be utilized for highly fluctuating loads [69].
- **PEMFC**
  - A PEMFC makes use of a hydrated polymer as an electrolyte and an acidic membrane, saturated in water is utilized to conduct charged hydrogen ions through the fuel cell[69].
  - Low temperature, as well as high-temperature PEMFCs, are available [28].
  - They fuel used in the low-temperature PEMFC needs to be of very high purity to avoid contamination of the catalyst [69].
  - High-temperature PEMFC allow for higher fuel impurities [28].
  - In general a PEMFC can not make use of carbon-based fuels, such as natural gas, as their operating temperature is too low [57].
  - To prevent the PEMFC from flooding, which decreases its efficiency, drains need to be installed to flush away excess water [69].
  - PEMFC can reach efficiencies of approximately 50% [18].

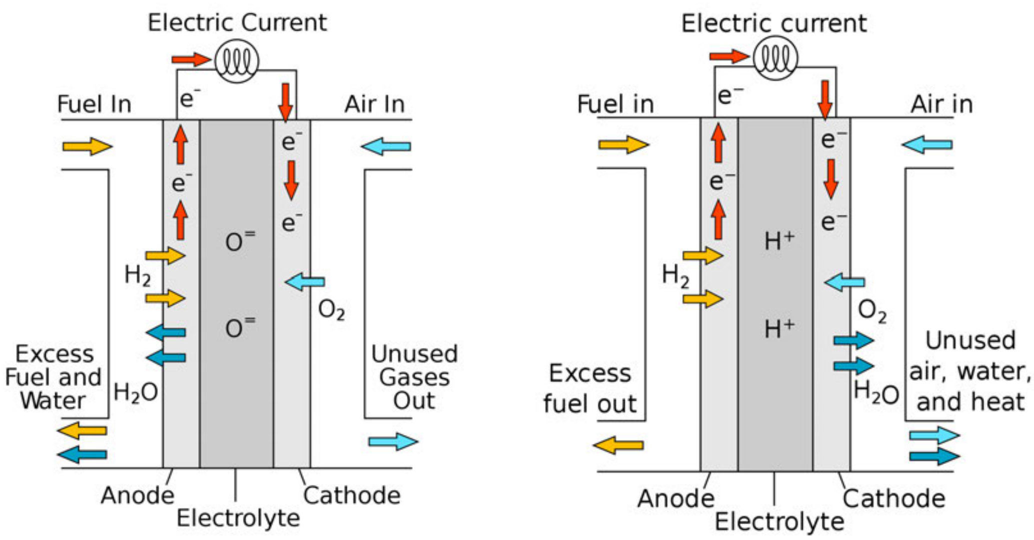

Figure B.3: Graphical representation of the working principles of a SOFC (left) and a PEMFC (right) [19]

C

Vessel Characteristics

Vessel Infrastructure

Fuel storage

- **Bunker tank**
  - MGO is pumped into the bunker tank during a bunkering operation.
  - Multiple bunker tanks are present, which are also used to store MGO for a longer period of time.
  - Size of the bunker tanks depends on the available space, but also on the frequency between bunkering.
- **Settling tank**
  - Before the MGO can be utilized in the engines, it needs to be purified of any contaminants, excess water or residuals. Therefore the MGO passes through several filters before reaching the settling tank.
  - A large offshore vessel often contains two or more settling tanks.
  - In the setting tank any residuals, contaminants, water or other impurities, leftover in the MGO, will settle at the bottom of the tank, since they are heavier than the MGO, and are extracted.
- **Service day tank**
  - To ensure the quality of the MGO, it passes through a filter as well as a purifier, where any last contaminants are extracted, before reaching the service day tanks.
  - The service day tank holds all ready-to-use MGO necessary for immediate use and is the last tank where the MGO is collected before it reaches the engine. The MGO will not go through any more processing steps.
  - Excess fuel that is pumped into these service day tanks, can be pumped back, through an overflow line, to the settling tank, where it is stored temporarily and can re-enter the fuel system.
  - Any clean excess MGO that is pumped to the engine, and will not be combusted, can be pumped back to the service day tank, through the fuel return line.
- **Overflow tank**
  - The overflow tanks are used to store any excess MGO that is pumped into the bunker tanks.
  - The overflow tank should never reach its maximum storage level and to prevent this the tanks contain an alarm system that indicates how full the MGO tanks are.
  - The MGO in these overflow tanks can be pumped back into the fuel system at the same position where the fuel from the bunker tanks enters the fuel system.
- **Sludge tank**
  - Any residuals, water or contaminants which are extracted from the settling tank or from the purifier, as well as drain oil from the engine, are stored in the sludge tank.

Other infrastructure components

Besides the major TTW infrastructure components mentioned in the sections above, there are also other, smaller, components that should be taken into account. Depending on the fuel and its characteristics, some additional components might be necessary or already existing components might need some modification. Most of these additional components are placed after the engine, as they are related to gasses which are emitted after combustion.
Even though there are components that are included in the TTW infrastructure of some vessels operating on a certain fuel, such as a vaporiser or a heater, these are not included in this research as their impact on the KPIs are not big enough. In this section, only additional components that will be of relevance to the end result of this research are taken into account and shortly discussed.

Purifier and filters

As was mentioned before, the fuel that is stored in the service day tanks and that is eventually supplied to the engine, should be purified of any excess water or impurities present in the fuel. In order to ensure the MGO is of the correct purity, the fuel system is equipped with several filters and a purifier, as can be seen in figure 4.2.
The purifier used in the MGO system is in the form of a centrifuge, of which often two or more are placed in an MGO fuel system. The maximum separating efficiency of a centrifuge depends on the fuel type, and its characteristics, and the rated capacity of the centrifuge. Therefore, the centrifuge type may vary depending on the fuel used in the system. By making use of the variation between the specific densities of water, MGO and the impurities in the MGO as well as the centrifugal force, which occurs due to the spinning motion, the water and impurities are separated from the MGO. The excess water, together with the impurities is transferred to the sludge tank and stored [70].
Filters are installed in the fuel system, to protect pumps and other components from large residuals as well as to purify the fuel before it is supplied to the engine. Therefore the filters exist with varying membrane thicknesses and membrane pore sizes. The filters require replacement at a 2000-4000-hour interval, under standard operating conditions [70].

Fuel injector

The MGO is injected into the cylinders of the engine by the fuel injectors, which contain a nozzle, that is controlled electronically, and sprays fuel at high pressure into the combustion chamber. As was mentioned earlier, the booster pump, which is placed before the fuel injector, ensures that the MGO is at a high enough pressure to be pushed through the fuel injector, which then sprays fuel droplets into the cylinder.
The materials used for the fuel injectors are chosen such that they can withstand high stresses and match the durability of the engine. The materials used in the fuel injector and the pressure present depend strongly on the fuel used and its characteristics.

Turbocharger

A turbocharger is used to increase the power output of the engine, by supplying the cylinders with air at a pressure higher than the atmospheric pressure and therefore at a higher density. Due to this density increase, the cylinders contain a greater amount of air mass and can therefore burn a greater amount of fuel [70].
A turbocharger is equipped with a centrifugal compressor and an axial-flow exhaust gas turbine, which are both mounted on a short stiff shaft to form the rotor. All elements of the rotor are built of non-corrosive materials, such as steel or cast iron. The exhaust gas turbine extracts energy from the exhaust gasses of the engine and uses this energy to power the compressor [70]. After the exhaust gas has passed the turbocharger it is passed through a SCR system before being emitted.

SCR system

The selective catalytic reduction (SCR) system is placed after the engine, which can be seen in figure 4.2, as it an after-treatment system for the exhaust gasses. The SCR system is placed as it reduces the NO_x particles in the exhaust gas created by the combustion of MGO. The SCR is often placed on a vessel operating on MGO, or other fuels that emit NO_x, to comply with IMO Tier III regulations, that are set to reduce NO_x emission from the maritime sector. In the SCR system, the NO_x particles are reduced to nitrogen and water molecules, through a chemical process where a nitrogen-based reducing agent is used. A mixture of urea and water is injected into the exhaust gas, where the water evaporates and the urea turns into ammonia. The ammonia bonds with the NO_x and by making use of a converter the NO_x is converted into nitrogen and water vapour [152].

Operational modes

[redacted]

Figure C.1: Yearly average energy consumption of the different operational modes for 2022-2025 for the vessels of HMC

[redacted]

Figure C.2: Daily CO_2 emissions of the vessels of HMC and frequency of occurence

[redacted]

Figure C.3: Yearly average CO_2 emissions of the vessels of HMC from 2022-2025

D

Technical and financial evaluation

Technical evaluation

Other components evaluation

Lastly, additional components, necessary to implement a specific e-fuel should also be considered. These components might be related to safety measures, that have to be taken into account in case an e-fuel is implemented or with the handling of the e-fuel.
In the generic fuel system infrastructure, shown in figure 4.2, several components, besides the energy conversion unit and fuel tanks, are already depicted. During this evaluation, these components are examined whether they should be retrofitted, replaced or can be utilized as is. In case additional components need to be installed, to implement an e-fuel, the extra volume that these components take up should also be considered.

E-hydrogen

Some additional components are required for the usage of e-hydrogen as fuel on a vessel. Several of these components are listed below.

- Open Rack vapouriser
    - The liquid e-hydrogen, needs to be vaporized to a gaseous state and heated up to a temperature which is compatible with the ICE. During evaporation of the liquid e-hydrogen, the pressure and temperature of the fuel will already start to increase [69].
    - The vapouriser makes use of seawater to evaporate the liquid e-hydrogen to a gaseous state [69].
- N_2 purging system
    - The system is used to purge the components of the energy infrastructure and hereby ensure no explosive gas mixture is created [50].
- Selective Catalytic Reduction (SCR) system
    - NO_x emission from e-hydrogen combustion are similar or lower to currently MGO-fuelled engines. Therefore a SCR system to reduce the NO_x emissions [146].

E-diesel

Since e-diesel and MGO have similar characteristics, the same additional components, besides the fuel storage and energy conversion unit, can be utilized. First of all purifiers and filters are used in the infrastructure. The filters are placed to remove any large residuals from the e-diesel and protect the pumps. The purifiers are utilized to further increase the quality of the e-diesel and are in the form of a centrifuge, which separates any impurities from the e-diesel [70].
An SCR system is installed downstream of the engine and is used to reduce the NO_x particles in the exhaust gas through a chemical reaction between urea, water and the exhaust gas [152].

E-LNG

Depending on the energy conversion pathway of e-LNG some additional components are required for the usage of e-LNG as fuel on a vessel. Several of these components are listed below.

- Gas valve unit (GVU)
  - The GVU regulates the gas feed pressure in accordance with the engine's load requirements [156].
  - The GVU performs safety functions such as conducting a leakage test of the automatic shut-off valves before the engine starts operating and inerting the gas line with nitrogen [156].
  - Each engine requires a GVU to control the engine-specific gas pressure, which needs to be installed outside of the engine room at a remote location since the GVU can not be equipped with double-walled pipes [156].
  - The GVU room is equipped with gas-tight walls and contains gas and fire detection sensors and ventilation systems [156].
- N_2 purging system
  - The system is used to purge the components of the energy infrastructure and hereby ensure no explosive gas mixture is created.
- Methane reformer
  - For the pathway where e-LNG functions as a hydrogen carrier a methane reformer must be equipped on the vessel to extract the hydrogen.
- Selective Catalytic Reduction (SCR) system
  - Due to higher combustion temperatures, compared to MGO, significant NO_x emission occurs. An SCR system should be equipped to lower the NO_x emissions [156].

E-methanol

Depending on the energy conversion pathway of e-methanol some additional components are required for the usage of e-methanol as fuel on a vessel. Several of these components are listed below.

- Methanol fuel pump unit
  - The unit is placed before each separate DF engine and outside of the engine room, in the fuel preparation room [164].
  - The pump unit is utilized to boost up the pressure of the e-methanol to the engine load injection pressure, which is approximately 600 bar [164].
- Methanol reformer
  -
  - For the pathway where e-methanol functions as a hydrogen carrier a methanol reformer must be equipped on the vessel to extract the hydrogen.
- N_2 purging system
  - The system is used to purge the components of the energy infrastructure and hereby ensure no explosive gas mixture is created [164].
- Selective Catalytic Reduction (SCR) system
  - NO_x emissions, although significantly lower compared to MGO combustion, are still present during the combustion of e-methanol. Therefore, to comply with regulations set by the IMO, an SCR system is placed downstream of the engine.
  - Due to the lower NO_x, emissions of less urea will be necessary, thereby decreasing the size of the system [164].

E-ammonia

Depending on the energy conversion pathway of e-ammonia some additional components are required for the usage of e-methanol as fuel on a vessel. Several of these components are listed below.

- N_2 purging system
  - The system is used to purge the components of the energy infrastructure and hereby ensure no explosive gas mixture is created [6].
- Ammonia cracker
  - For the pathway where e-ammonia functions as a hydrogen carrier an ammonia cracker must be equipped on the vessel to extract the hydrogen.
- Selective Catalytic Reduction (SCR) system
  - Due to the high combustion temperature and pressure of e-ammonia in an ICE, a significant amount of NO_x is emitted [3].
  - To comply with the regulation set by IMO, an SCR system is necessary downstream of the engine [3].
  - The SCR system is utilized to control the NO_x emissions as well as any ammonia slip that might occur [3].

Financial evaluation

An overview of all prices up to 2050 is shown in Figure D.1 as well as in Figure D.2. The sources and data behind the prices are elaborated on below.

- The current e-diesel price range of 0.075 - 0.248 Eur./kWh is obtained from [22] and used together with the 2050 e-diesel price assumption of DNV [51], to interpolate the e-diesel prices between 2022 and 2050. A similar approach is utilized to obtain the price assumptions of the other e-fuels as well as MGO and EU ETS prices.
- The 2022 price range of e-LNG of 0.109 - 0.283 Eur./kWh is obtained from [22] and the 2050 price range of 0.173 - 0.09 Eur./kWh from [51]. Which are both used to interpolate the e-LNG prices between 2022 and 2050.
- The 2022 price range of e-methanol of 0.137 - 0.271 Eur./kWh is obtained from [81], together with a yearly price reduction of 7%/year, until 2030 and of 1% per year from 2030 up to 2050.
- The 2022 price range of e-ammonia of 0.130 - 0.258 Eur./kWh is obtained from [80], together with a yearly price reduction of 3%/year, which are used to determine the e-ammonia prices.
- The 2022 price range of e-hydrogen of 0.102 - 0.253 Eur./kWh is obtained from [79], together with a yearly price reduction of 7%/year until 2030 and hereafter with approximately 2% per year until 2050.
- The EU ETS pricing is obtained from real-life data and an increasing factor of 5% per year is utilized, obtained from [110].
- The MGO price is obtained from real-life data from [24], and together with the EU ETS forecast the future MGO price assumptions are made.

	[Eur./kWh]	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
E-diesel	Max	0.25	0.25	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.23	0.23	0.22	0.22	0.22
	Min	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09
E-LNG	Max	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.26	0.25	0.25	0.24	0.24	0.24	0.23
	Min	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
E-methanol	Max	0.27	0.25	0.23	0.22	0.20	0.19	0.18	0.16	0.15	0.15	0.15	0.15	0.15	0.14
	Min	0.14	0.13	0.12	0.11	0.10	0.10	0.09	0.08	0.08	0.08	0.08	0.07	0.07	0.07
E-ammonia	Max	0.26	0.25	0.24	0.23	0.23	0.22	0.21	0.21	0.20	0.20	0.19	0.18	0.18	0.17
	Min	0.13	0.13	0.12	0.12	0.12	0.11	0.11	0.11	0.10	0.10	0.10	0.09	0.09	0.09
E-LH2	Max	0.25	0.24	0.22	0.20	0.19	0.17	0.15	0.14	0.12	0.12	0.12	0.11	0.11	0.11
	Min	0.10	0.10	0.09	0.08	0.08	0.07	0.07	0.06	0.05	0.05	0.05	0.05	0.05	0.05
MGO	Max	0.08	0.08	0.08	0.08	0.08	0.09	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13
	Min	0.09	0.09	0.09	0.09	0.09	0.10	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.15

	[Eur./kWh]	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
E-diesel	Max	0.22	0.22	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19
	Min	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10
E-LNG	Max	0.23	0.22	0.22	0.22	0.21	0.21	0.20	0.20	0.20	0.19	0.19	0.18	0.18	0.18	0.17
	Min	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
E-methanol	Max	0.14	0.14	0.14	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.12
	Min	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06
E-ammonia	Max	0.17	0.16	0.16	0.15	0.15	0.14	0.14	0.14	0.13	0.13	0.12	0.12	0.12	0.11	0.11
	Min	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06
E-LH2	Max	0.11	0.11	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.07
	Min	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
MGO	Max	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Min	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16

Figure D.1: Data used for e-fuel and MGO pricing.

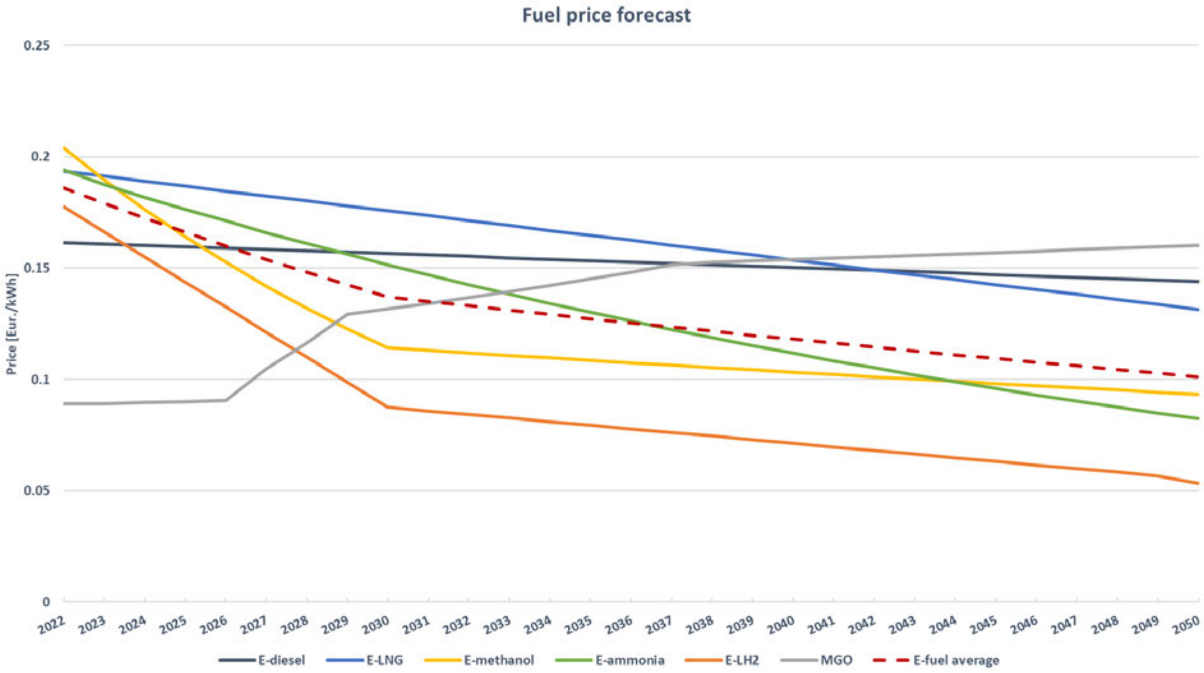

Figure D.2: Fuel price forecast until 2050

E

E-fuel energy infrastructures

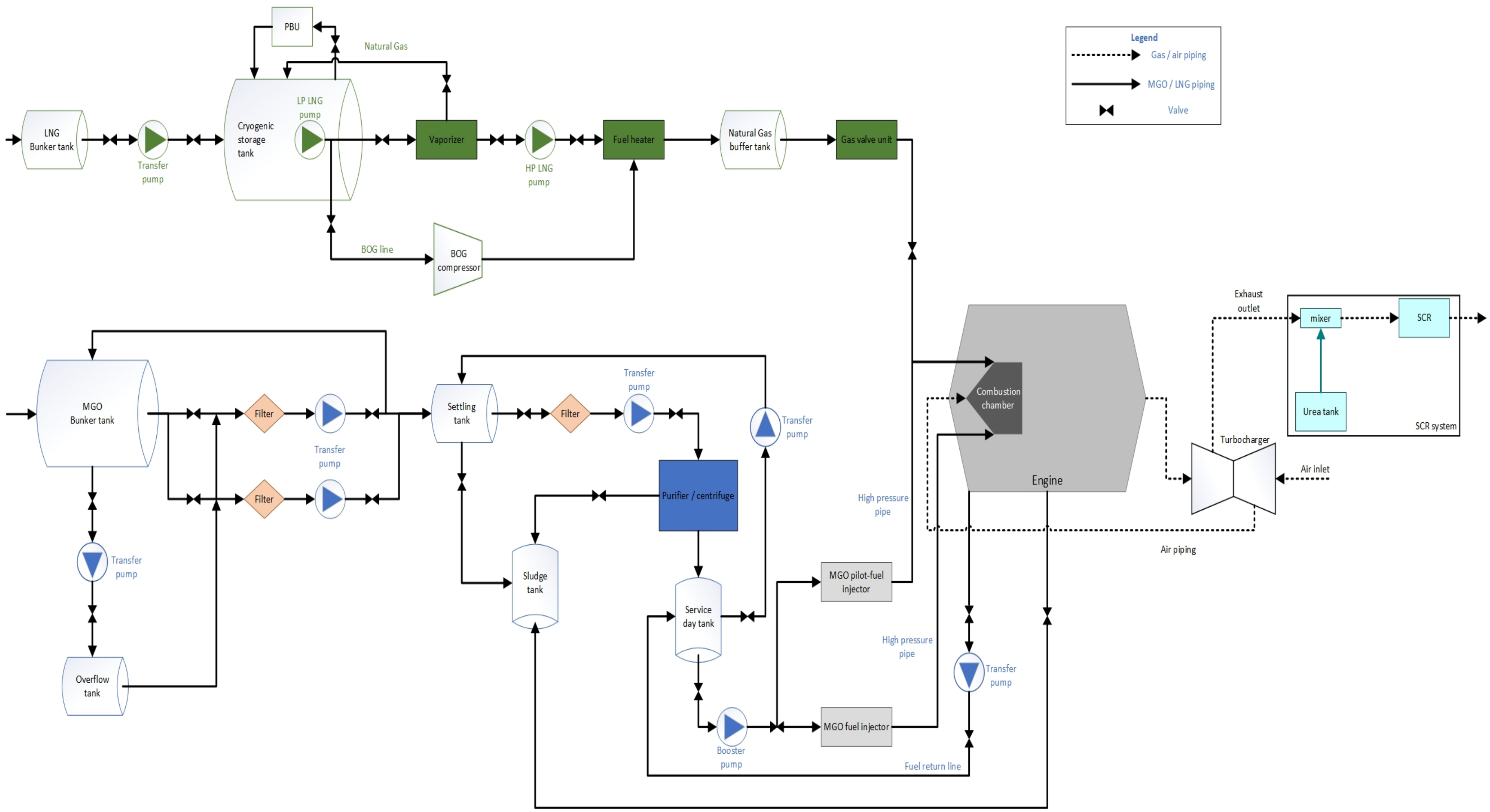

Figure E.1: Energy system of a vessel equipped with a DF ICE fueled by MGO and e-LNG

F

Case study & Results

Case study

[redacted]

Figure F.1: Normal distribution of emissions per power.

Figure F.2: Cumulative distribution of emissions of the Thialf

Sensitivity analysis

CapEx sensitivity

		MGO		E-Diesel		E-LNG				E-L_H2		E-METHANOL						E-AMMONIA		
								H2						H2					H2	
		ICE	ICE CCS	ICE	ICE CCS	ICE	ICE CCS	ICE CCS	PEMFC CCS	ICE	PEMFC	ICE	ICE CCS	ICE	ICE CCS	PEMFC	PEMFC CCS	ICE	ICE	PEMFC
Scenario 0	LCOE scenario 0	0.34	0.51	0.39	0.70	0.48	0.72	0.95	1.15	0.29	0.49	0.33	0.58	0.37	0.64	0.57	0.89	0.40	0.53	0.64
	LCoCA scenario 0			70	522	207	548	883	1175	-80	212	-24	348	46	427	333	799	90	269	537
Scenario 1	LCOE scenario 1	0.34	0.54	0.39	0.73	0.49	0.75	0.99	1.23	0.30	0.53	0.33	0.62	0.39	0.68	0.62	0.98	0.41	0.54	0.69
	LCoCA scenario 1			70	564	220	602	948	1298	-60	278	-13	400	65	488	399	927	101	288	604
Scenario 2	LCOE scenario 2	0.34	0.48	0.39	0.67	0.48	0.68	0.90	1.06	0.27	0.44	0.32	0.54	0.36	0.59	0.53	0.80	0.40	0.51	0.60
	LCoCA scenario 2			69	480	194	493	819	1052	-101	146	-35	295	27	367	267	672	79	250	471

Figure F.3: Results of the LCOE and LCoCA from the CapEx sensitivity analysis

OpEx sensitivity

		MGO		E-Diesel		E-LNG				E-L_H2		E-METHANOL						E-AMMONIA		
								H2						H2					H2	
		ICE	ICE CCS	ICE	ICE CCS	ICE	ICE CCS	ICE CCS	PEMFC CCS	ICE	PEMFC	ICE	ICE CCS	ICE	ICE CCS	PEMFC	PEMFC CCS	ICE	ICE	PEMFC
Scenario 0	LCOE scenario 0	0.34	0.51	0.39	0.70	0.48	0.72	0.95	1.15	0.29	0.49	0.33	0.58	0.37	0.64	0.57	0.89	0.40	0.53	0.64
	LCoCA scenario 0			70	522	207	548	883	1175	-80	212	-24	348	46	427	333	799	90	269	537
Scenario 1	LCOE scenario 1	0.37	0.51	0.53	0.89	0.63	0.90	1.19	1.37	0.36	0.55	0.42	0.72	0.48	0.78	0.67	1.02	0.53	0.68	0.85
	LCoCA scenario 1			232	769	390	775	1206	1467	-14	270	83	509	161	600	435	955	236	461	711
Scenario 2	LCOE scenario 2	0.32	0.50	0.53	0.89	0.63	0.90	1.19	1.37	0.36	0.55	0.42	0.72	0.48	0.78	0.67	1.02	0.53	0.68	0.85
	LCoCA scenario 2			299	835	457	842	1272	1534	53	337	150	576	228	667	502	1021	303	528	777
Scenario 3	LCOE scenario 3	0.32	0.50	0.26	0.51	0.33	0.54	0.70	0.92	0.22	0.42	0.23	0.45	0.27	0.49	0.48	0.76	0.28	0.37	0.57
	LCoCA scenario 3			-99	270	18	314	555	877	-153	148	-137	180	-76	248	224	637	-63	70	358
Scenario 4	LCOE scenario 4	0.37	0.51	0.26	0.51	0.33	0.54	0.70	0.92	0.22	0.42	0.23	0.45	0.27	0.49	0.48	0.76	0.28	0.37	0.57
	LCoCA scenario 4			-166	203	-49	247	488	810	-220	81	-204	113	-142	181	157	571	-130	3	291

Figure F.4: Results of the LCOE and LCoCA from the OpEx sensitivity analysis