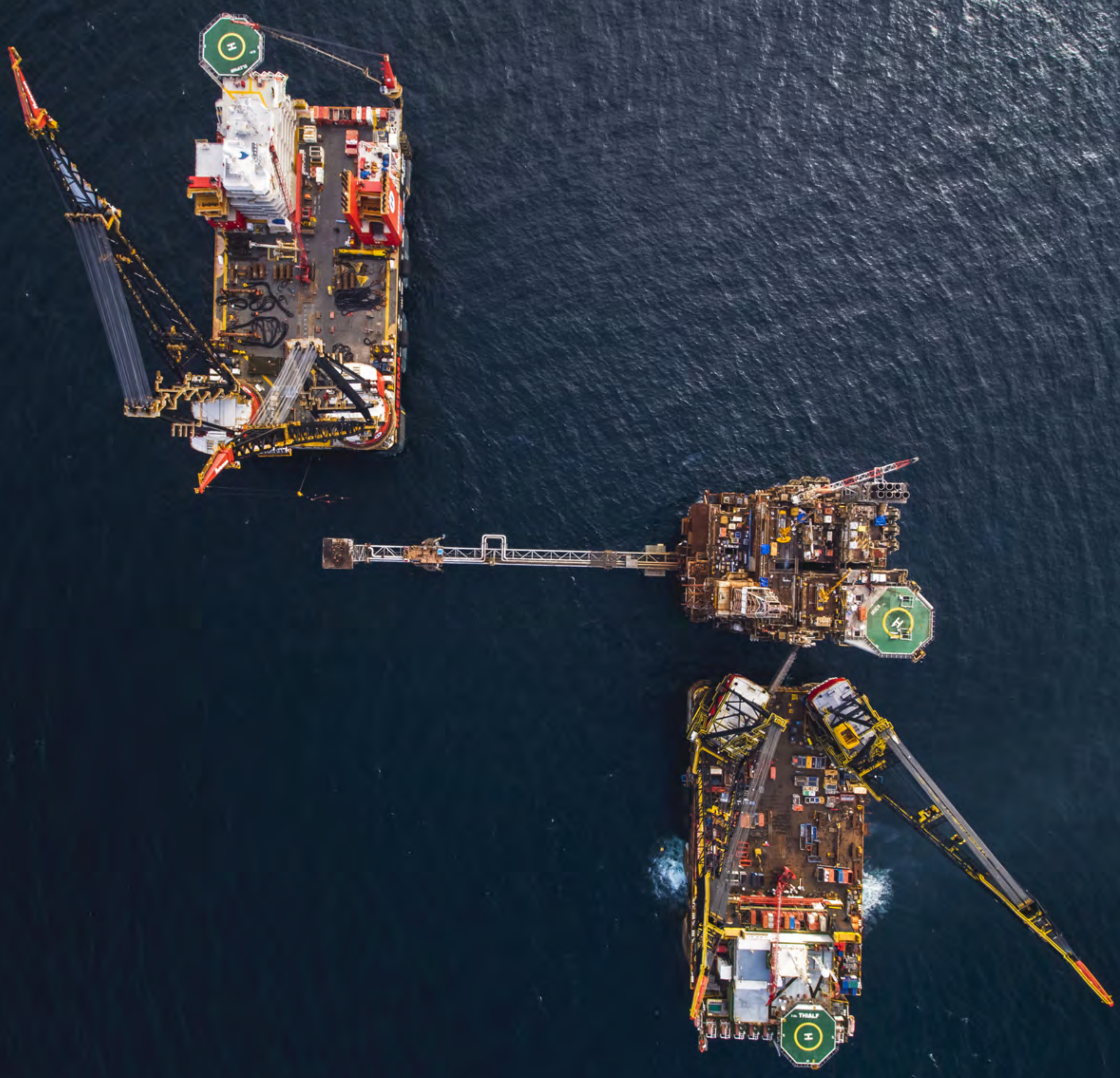
Hydrogen powered propulsion for an offshore crane vessel

A technical and economical evaluation



G.R.C. Hagen

TU Delft

HEEREMA

Hydrogen powered propulsion for an offshore crane vessel

A technical and economical evaluation

by

G.R.C. Hagen

To obtain the degree of Master of Science
At the Delft University of Technology
As part of the master Offshore and Dredging Engineering

Student number:	4324803	
Student email:	gilleshagen@gmail.com	
Student phone:	+31 6 81463510	
Project duration:	August 1, 2020 – June 22, 2021	
Thesis committee:	Prof. dr. ir. A.J.M van Wijk,	TU Delft, Chair
	Ir. K. Visser,	TU Delft, MT&T
	Ir. V. Doedée,	Heerema Marine Contractors

Preface

I started my university studies in Maritime Engineering at TU Delft 8 years ago. For the final project for my bachelor's degree I investigated the applicability of dense hydrogen carriers in shipping. This initiated my interest in hydrogen as an energy carrier. From that moment on, I have always tried to make sustainability the main subject of my education. When I was offered the opportunity to do research on the applicability of hydrogen as an energy source for Heerema, I did not need to think twice. Looking back now at the end of this project, it has been a very educational process for me, both as a student and as a person. I hope that for you as a reader it will be interesting as well.

I would like to thank Professor van Wijk for his insights on the topics of this research.

I would like to thank everyone involved in this project at Heerema Marine Contractors, especially Vincent Doedee, Meike Kolthof and the sustainability department, for their help and support over the past year. Given the Covid-19 pandemic, I was forced to work from home these past 11 months. Without their support and contact via Skype, writing this thesis would have been much harder for me. I would also like to thank John Bierlee for his help in developing the structure of my thesis.

Finally, I would like to thank everyone that supported me throughout my Bachelor's and Masters, and I hope to talk to you all soon and celebrate this significant milestone in my life.

Gilles Hagen

Amsterdam, June 15 2021

Abstract

The International Maritime Organisation (IMO) has set the goal to reduce the total annual greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008. For this reason, shipowners will have to innovate the drive-trains and energy systems of their vessels to reduce harmfull emissions. To achieve this goal, solutions must be found to store large amounts of cleen energy on board of ships and convert the chemical energy in an efficient way with these drive-trains. Hydrogen is considered as a promising solution for this. However, storing hydrogen is complicated and requires much volume. To overcome this barrier, hydrogen can be stored in dense hydrogen carriers (DHCs). This thesis will perform a technical and economical feasibility study of dense hydrogen carriers as a fuel to power a semi-submersible offshore crane vessel.

The Sleipnir, the largest crane ship in the world, is the main subject of this thesis. The objective is to evaluate the technical and economic feasibility of hydrogen based fuels for semi-submersible offshore crane vessels and their impact on the drive-train design. This will be done by designing a new drive-train that can deliver 6.5 MW electricity to power the ship's hotel load.

A literature survey was conducted to obtain the most feasible ways to store hydrogen on the Sleipnir. Liquid hydrogen, ammonia and methanol where identified as these feasible DHCs. They will be evaluated on technical and economic feasibility and health, safety and environmental impact. From health, safety and environmental analysis, liquid hydrogen comes out best. Unlike ammonia and methanol, it is not a toxic substance, minimizing safety risks when handling the fuels. In addition, it emits no CO_2 and, when used in a fuel cell, no NO_x either. Hydrogen does however have a higher flammability risk compared to the other DHCs but with good ventilation systems installed, this risk can be well controlled.

Next, it was determined which power unit is best suited for each of the three DHCs. For the liquid hydrogen, a proton exchange membrane fuel cell was chosen because this configuration emits no harmful emissions and has a high conversion efficiency. Ammonia and methanol can not be directly used in a PEM fuel cell and will therefore be used in an internal combustion engine. Since ammonia has a slow flame speed and bad combustion characteristics, it was decided to combust it in a spark ignite 4 stroke internal combustion engine. In addition, $30\%_{vol}$ hydrogen will be added as pilot fuel to improve combustion in the combustion chamber. Methanol has better combustion characteristics than ammonia and can therefore be burned in a compression ignite 4-stroke internal combustion engine. It still needs to be mixed with hydrogen at a ratio of $10\%_{vol}$ to get a full combustion.

The three configurations that emerged from the literature study as most feasible options have been further investigated. First, a design was made of the drive-train and its components. With this design and the efficiencies of the separate components, a heat & mass balance was made to calculate the on-board efficiency of the options. In addition, the required volume of the fuel tank was calculated. This is the largest part of the entire drive-train and can be limiting in the technical feasibility of the system. The heat and mass balance showed that the H_2-PEMFC has a slightly higher on-board efficiency than the ammonia and methanol drive, 44% compared to 43% respectively. However, the volume of the liquid hydrogen tank must be at least twice that of the ammonia and the methanol tanks in order to store enough energy to comply with the operational profile of the Sleipnir.

After calculating the fuel consumption, an economic evaluation was executed to compare the economics of the three options with each other and with the current system. The levelized cost of electricity was calculated and compared with the current LCOE of 0.150 €/kwh paid by Heerema. Ammonia comes out of this evaluation as the cheapest option with a LCOE of 0.152 €/kwh, Hydrogen has a LCOE of 0.195 €/kwh and Methanol is the most expensive option with a LCOE of 0.209 €/kwh.

Table 1 shows the assessment of the DHCs by evaluation criteria. Supported by these evaluation criteria set up by Heerema, the conclusion can be drawn that, within the boundary conditions of this thesis, an ammonia fueled drive-train with an internal combustion engine as power unit is the most preferred method to power the Sleipnir using a dense hydrogen carrier. This drive-train is the most cost effective solutions and, in addition, it does not require any difficult technical constraints.

Table 1: Rating of the dense hydrogen carriers based on the evaluation criteria

	Liquid hydrogen	Ammonia	Methanol
Workability			
Health, Safety and environmental impact			
Economic viability			

The main discussion points of the study is the influence of the boundary condition that the system must be operational within 5 years. By saying this, options that have the potential to solve major bottlenecks are left out of scope, like the solid oxide fuel cell. If the boundary condition is extended by a few years, new technology might be available, making ammonia-fuel cell and methanol-fuel cell configurations feasible.

List of Figures

List of Tables

Contents

1
Introduction

During the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in 2015, a total of 189 countries signed the agreement with the central aim to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 °Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °Celsius[78]. Even though the maritime industry was not included in this agreement, the International Maritime Organisation (IMO) has set the goal to reduce the total annual greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008. Likewise, the IMO also set emission control regulations on the emission of pollutants like NO_X ans SO_x in so called Emission Controlled Areas (ECA). This, along with national goals set by the government of The Netherlands to decrease CO_2 emissions with 55% compared to the 1990 level, encourages Dutch maritime companies to investigate potential solutions for greenhouse gas reductions by 2030. To meet these goals, it is of interest to consider the compatibility of renewable (hydrogen based) fuels with marine powering systems

1.1. Problem background

Storing green energy is one of the major issues to overcome for all industries, but especially for the maritime industry since grid connections are no option when operating at sea. Generating green energy is done at many locations around the world, some even for the same price as, or cheaper than fossil electricity. However, the problem is getting green energy at the right location and storing it for a longer period. The transportation of electricity through electricity cables can result in high energy losses and is very limited in distance. For this reason extensive research is conducted on the storage of electricity in molecules such as hydrogen. By producing hydrogen the electricity can be stored for a long time. The second advantage of hydrogen is that it can directly be used on shipping vessels for power production. Because of this, hydrogen is considered as a renewable fuel with great potential in the future.

The maritime sector is a major consumer of fossil fuels with roughly 5% of the global demand [32] and because of the high per-kilometre energy intensity and large power needs, an energy dense sustainable fuel is essential. For this reason, it is predicted that within 30 years hydrogen demand for the maritime sector will grow more than any other sector, as shown in figure1.1.

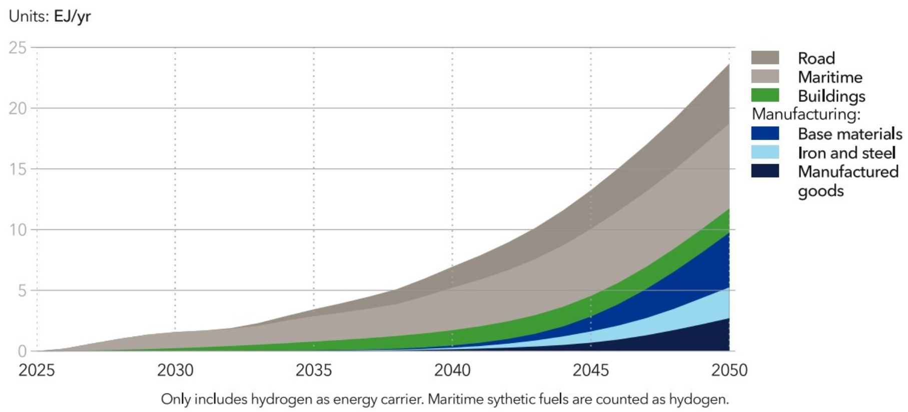


Figure 1.1: World hydrogen demand as predicted by the IEA [32]

1.2. Problem definition

Currently, hydrogen is mostly used in the refining industry for the production of fossil fuels or in the chemical industry for the production of ammonia which can be used as an agricultural fertiliser. Other applications for hydrogen are for the removal of sulfur from fuels during the oil-refining process, see figure 1.2. 85% of all hydrogen used is produced and consumed on-site [32]. This is why long term storage (i.e. several weeks or longer) and transportation of hydrogen has, in the past, not been a big focus for innovation. However, long term storage of large quantities of hydrogen is one of the main requirements for its implementation as renewable fuel in the shipping industry.

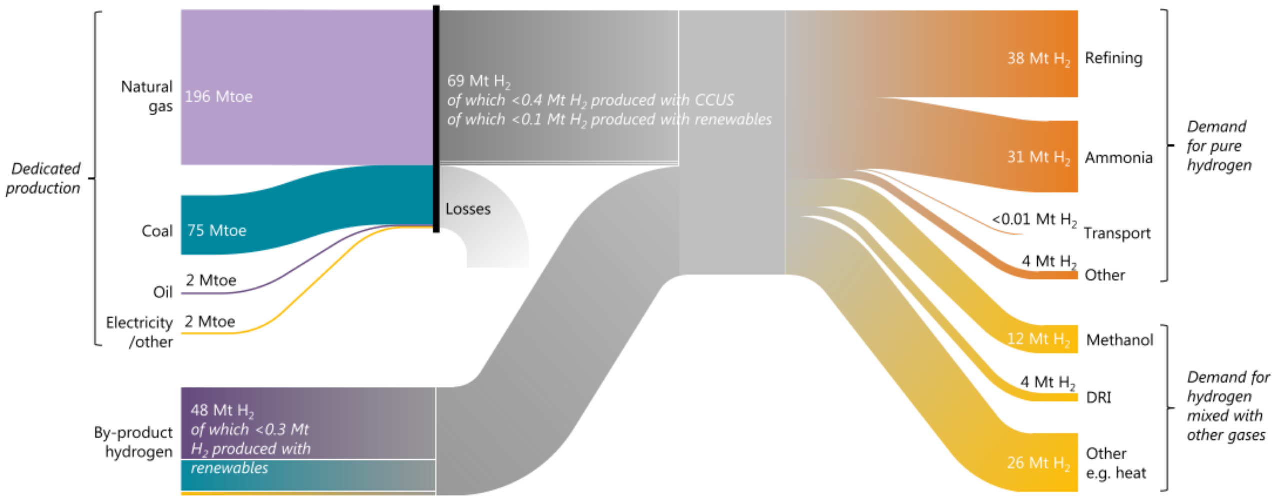


Figure 1.2: Sankey diagram of the hydrogen value chains defined in 2019[32]

Hydrogen is the lightest substance in nature. With a density of only 0.081 kg/m3 at 300 K and 0.1 MPa, it is ten thousand times less dense than water. This results in a volumetric energy density of 2.966 kWh/m^3 under ambient conditions. For comparison, the volumetric energy density of LNG is 6166.7 kWh/m^3. Due to this extremely low energy density, hydrogen stored at ambient conditions will require too much volume to be technically feasible in any industry. For illustration, the fuel tank needs to be approximately 2000 times larger to store the same amount of energy. There are two main methods to increase the volumetric energy density of hydrogen.

The first method is to change the storing conditions of hydrogen. When increasing the storing pressure, the density can significantly increase to respectively 765 kWh/m^3 at 350bar and 1265 kWh/m^3 at 700bar, see figure 1.3. When the temperature of hydrogen is decreased to -253°C, the substance will become liquid with a volumetric energy density of 2364 kWh/m^3. These modifications are already a step in the right direction in terms of increasing energy density, but they also create new problems as these storage conditions are challenging and require major changes to the operating systems and safety regulations.

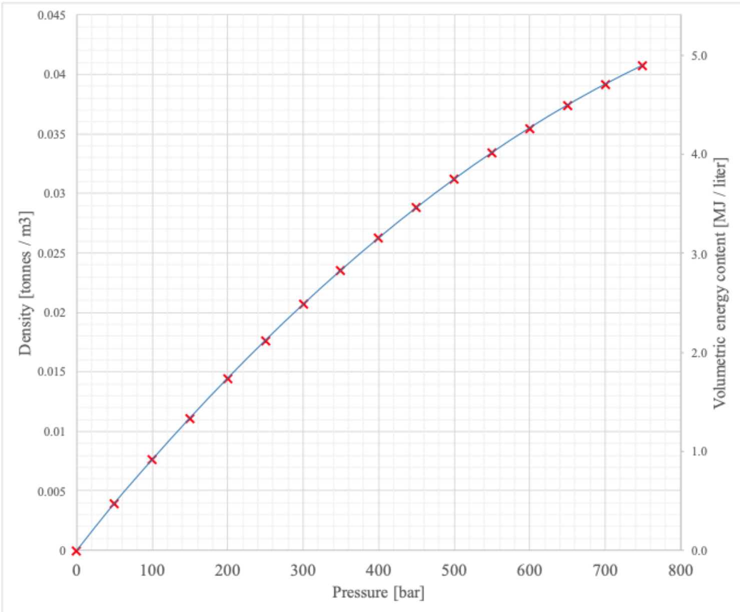


Figure 1.3: The density and volumetric energy content of hydrogen versus pressure [81]

The second method is by chemically bonding the hydrogen to a so called carrier. Because of this chemical bond, the volumetric energy density will increase while maintaining a more convenient storage condition. There are many different chemicals to which hydrogen can be bound. Some are already in an advanced stage of development with pilots in various sectors, others have only been proven at laboratory setting.

Because many of these so-called Dense Hydrogen Carriers (DHCs) are still under development, their applicability in the offshore sector has not yet been much explored. Although the storage conditions of these DHCs are in many cases less complicated than storing pure hydrogen, they will still affect the way energy is stored and generated on board a ship. It is therefore critical to look at the difference in technical and economical impact of these new DHCs on the drive-train and how they compare to the conventional drive-train of an offshore vessel.

1.3. Heerema Marine Contractors

Heerema is one of the world-leading marine contractors that mainly operates in the oil, gas and renewable energy industry. They own a fleet of offshore construction vessels, including the worlds largest and second-largest semi-submersible offshore crane vessels Sleipnir and Thialf. Heerema is the first carbon neutral marine contractor in the world and does so by means of purchasing carbon credits. At the same time, a roadmap has been put in place to fully prevent, reduce and compensate all CO_2 emissions by 2025. A wide scalar of projects is currently being executed to decrease their carbon footprint. A prime example of this is that Sleipnir is mainly sailing on LNG instead of conventional MGO. LNG has a low sulphur content, better hydrogen-to-carbon ratio and emits less NO_x during combustion [45]. All these aspects result in lower greenhouse gas emissions. Heerema acknowledges that hydrogen might play a big roll in the future for powering their vessel. This is why they want to investigate the technical and economical feasibility of DHCs used on their vessels.

In addition to the internal drive of offshore contractors to become more sustainable, Heerema's customers are also becoming increasingly motivated to do so. Companies such as Ørsted and Equinor have set ambitious targets to be CO_2 neutral by 2040 and 2050. Within this ambition, they are demanding the companies within their supply chains to set the same targets. This creates a commercial incentive to look for alternative propulsion systems with renewable fuels.

1.4. International Maritime Organization

The International Maritime Organization (IMO) functions as international regulatory organisation for the maritime industry. They are also responsible for the regulations on marine emission control. These regulations are described in the MARPOL and MARPOL Annex VI documentation that has been drawn up at the International Convention on the prevention of Pollution from Ships in 1973 [33] and ever since have been updated to stay relevant on ship emissions. The annex restricts both the required energy efficiency of vessels and the emissions limitation, including GHG, SO_X and NO_X on global levels and for the specified Emission Controlled Areas (ECAs), see figure 1.4.

Figure 1.4: Current Emission Controlled Areas [10]

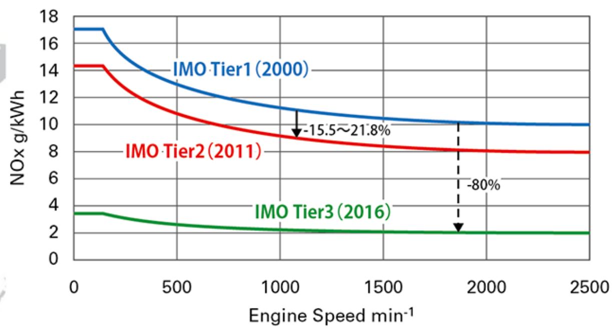


Figure 1.5: IMO TIER system on NO_x emission levels[Diesel]

The IMO defined three levels of NO_X emissions from ships in 2008. These levels relate to ships with a power greater than 130 kW and depend on the engine speed and year of construction of the ship, see figure 1.5. The TIER levels are defined as follows by the IMO[Diesel]:

- TIER I : Apply to engines installed in ships from January 1, 2000 onwards, and affected coastal ships constructed after May 19, 2005.
- TIER II : required a 15% to 22% reduction in NO_X emissions over the first regulations. This amendment entered into force on July 1, 2010 and was applied to engines installed on vessels whose keel-laying date was on or after January 1, 2011.
- TIER III: Apply to any engine in a ship who's keel-laying date is after January 1, 2016 and that operates in the Emission Control Area within 200 nautical miles of North America, Canada and the Caribbean Sea. In addition, after January 1, 2021 this regulation will extend to include the ECAs in the North Sea and the Baltic Sea.

1.5. Research question

In order to execute the technical and economical evaluation of the DHCs as a renewable fuel in the offshore industry, the following research questions are formulated:

1.5.1. Main question

Based on the aforementioned knowledge gap and the scope of this research, the main research question is:

What is the most preferred way from a shipowners perspective to drive a semi-submersible offshore crane vessel while using hydrogen as the energy carrier?

1.5.2. Sub-questions

To support the main research question a number of sub-questions are formulated:

1. What are the current electrical configuration and operational profile of the Sleipnir?
2. How can hydrogen be stored on board of the semi-submersible offshore crane vessel?
3. What technologies are applicable to convert the hydrogen into electrical power?
4. How do the dense hydrogen carriers influence the drive-train design of the semi-submersible offshore crane vessel?
5. What is the most cost effective drive-train configuration?

1.6. Scope of this research

To provide an answer on the main research question that is relevant for Heerema, the following research scope has been determined. This scope sets the boundary conditions regarding the selection of the new drive-trains.

- The new drive-train should be CO_2-neutral and comply with the IMO TIER III regulations.
- The new drive-train should be able to perform the same as the current system regarding the fueling periods and power generation
- The new drive-train should be commercially available within 5 years.
- The new drive-train should have either an internal combustion engine or a fuel cell as power-unit.
- On-board CO_2-capture is not considered. Although internal research within Heerema has shown that CO_2-capture is both technically feasible and potentially economically viable, it is not considered for this research.

- Hydrogen produced from biomass is out of scope since biobased hydrogen has too many (technical) challenges to overcome. In order to cope with the energy demand required by the shipping sector, an area as large as India should be used for biomass agriculture by 2030 and can potentially grow to twice the size of Australia by 2050[42]. Also, the complex processing of biomass into hydrogen means that it is generally a more expensive method to produce low-carbon hydrogen than solar- or wind-based electrolysis[11].
- Hybrid design configuration combining internal combustion engines, fuel cells, batteries or other power units are out of scope.

1.6.1. Key performance indicators

In order to make an informed comparison between the current system and the new options, a list of evaluation criteria must be determined. Based on discussions with Heerema employees, it is determined that the new systems will be evaluated on three different aspects.

- Workability. The new system must not only be technically feasible but must also fit within the ship's current operational profile. Major adjustments to the system are therefore not desirable. This criteria includes the boundary condition that the system must be operational within five years as discussed in section 1.6.
- Health, safety and environmental impact. Risk is inherent to the work Heerema does. That is why health, safety and environmental concerns are at the heart of its culture and operations. Management and control of risk is an integrated part of Heerema's approach to projects. Strict rules and regulations must be adhered to.
- Economic viability of the new drive-train(s). It should be investigated whether the new system is more expensive than the current system and if so, how much more expensive they will be. The influence of a possible CO_2 tax shall also be taken into account.

1.7. Research method

By going through the sub-questions step by step, an answer to the main question will eventually be provided. For each question, different methods will be used to arrive at a substantiated result. The research objective has been defined as follows:

To evaluate the technical and economical feasibility of hydrogen based fuels for semi-submersible offshore crane vessels and their impact on the drive-train design.

This will be done using the methodology shown in figure 1.6. The research will be divided into three phases excluding the case study. An elaboration on the phases is given below.

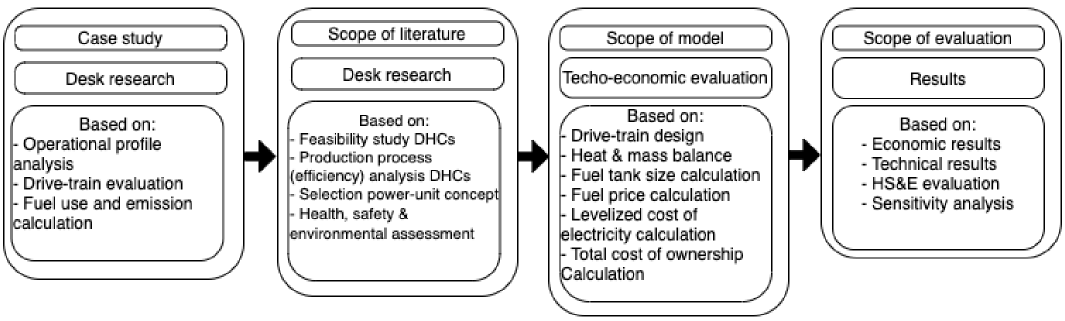


Figure 1.6: Methodology applied in this thesis

Chapter 2: Case study
First, the testcase will be explained. In chapter 2 the operational profile of the semi-submersible offshore crane vessel Sleipnir will be analysed. Also the different operational modes will be elaborated on together with the main energy consumers. The objective of this chapter is to obtain all technical characteristics of the vessel. The used methodology to obtain this information is by desk research using the available documents at Heerema. Furthermore, staff of the Sleipnir has been interviewed.

Chapter 3: Phase 1 - literature study
The first objective is to determine what dense hydrogen carriers are feasible options for the new drive-train. This is done by means of a literature study. The objective is to determine all the required information from the most feasible DHCs to determine their applicability on a semi-submersible offshore crane vessel. The second objective in this phase is to determine what power units are most compatible with the DHCs and what the technical parameters are from these power units.

Chapter 4 & 5: Phase 2 - Drive-train design and modeling
With the DHC-power unit configuration determined in phase one, a detailed technical design can be drafted. With this design, the energy used and efficiencies of the separate components can be determined. This information will be used in a heat & mass balance. After the heat & mass balance, a total efficiency for the system can be determined. These designs will be made by using literature and data provided by the component manufacturers. The designs will then be checked by experts of the industry like Nedstack Fuel Cell Technology B.V. to ensure a adequate design.

An economic analysis of the options will also be carried out at this phase. First, a calculation will be made of the fuel price of the DHCs over the next 30 years. After that, a levelized cost of Electricity (LCOE) and total cost of ownership (TCO) calculation will be done to compare the three options with each other and with the current drive-train. These two methods were chosen because the LCOE is a method used within Heerema and the TCO since it is a very common method for the economic evaluation of alternative fuels that was used by Baldi et al[5] and Bersma et al[9], among others.

Chapter 6: Phase 3 - Techno-economical evaluation
In the final phase of the study, the results of the predetermined options will be presented. An sensitivity analysis will be executed based on the investment cost of the system en the electricity price used for the fuel price. Based on these results, a techno-economic analysis can be made and a substantiated answer can be formulated to the main question of this thesis.

2

Case study

The vessel selected as case study for this thesis is the Sleipnir, worlds largest semi-submersible crane vessel and owned by Heerema Marine Contractors. This chapter provides an introduction on the technical details of the vessel and its dual fuel-electric drive-train and will provide the information required in this thesis for further research. Firstly, the general characteristics will be given in paragraph 2.1. Second, the drive-train of the vessel will be outlined together with further explanation on the fuel storage, power supply and other main components in paragraph 2.2. Paragraph 2.3 will focus on the operational profile of the Sleipnir where the different modes and main electricity consumers will be explained.

Figure 2.1: The Sleipnir during offshore operations

2.1. The semi-submersible offshore crane vessel Sleipnir

The Sleipnir is a heavy lifting vessel designed to execute lifting operations offshore. It has two cranes installed with a combined lifting capacity of 20,000mT and has a length of 220 meters and width of 102 meters. The overall dimensions of the vessel are given in table 2.1. Figure 2.2 provides an indication of the size of the vessel compared to the Technical University Delft. The cranes are mainly used both to install and remove jackets, topsides and wind turbines at open sea. Furthermore, the cranes can be utilized for installation of foundations, moorings and structures in deep-water. The Sleipnir is an on-board power and propulsion system capable of sailing with a cruising speed of 10 knots.

Figure 2.2: The size of Sleipnir compared to the campus of TU Delft

Table 2.1: Overall dimensions Sleipnir

Dimensions Sleipnir	
Length overall	220 m
Beam overall	102 m
Length over Work Deck	180 m
Beam over Work Deck	97.5 m
Depth to Work Deck	49.5 m
Draft range	12-32 m

2.1.1. Dynamic poisoning Classification

At the time of writing, Sleipnir is DP3 (DPAAA) certified by Lloyds. Dynamic Positioning (DP) is a method that uses position reference sensors and autopilot to guarantee that the vessel can stay at the same position without mooring lines when working at see. An accuracy of 30 cm by 30 cm can be achieved, even when working with very heavy machinery and equipment at a close proximity to other (fixed) offshore structures such as drilling rigs or wind turbines. A DP3 classification means that a single failure, including flooding or fire, should not cause the vessel to lose the DP-control systems and position, and potentially drift into another object, causing major safety and property-damage risks. In order to meet strict safety criteria, a high level of redundancy has been incorporated as will be discussed further in this chapter.

2.2. The drive-train of the Sleipnir

In this paragraph the main components of the drive-train for the Sleipnir will be presented. A schematic overview of the drive-train including one engine is given in figure 2.3. A total of twelve engine systems are installed on board resulting in twelve times the drive-train which is represented in figure 2.3.

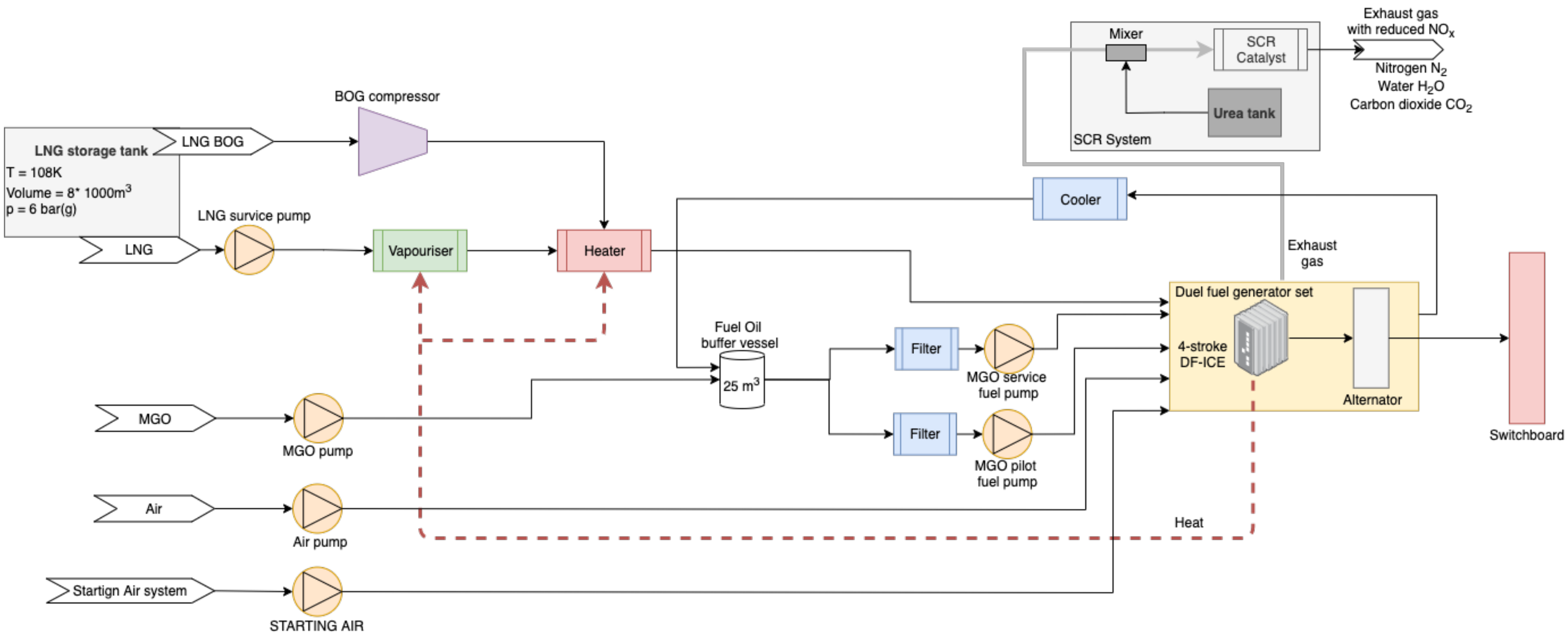


Figure 2.3: Schematic overview of current drive-train Sleipnir

2.2.1. Power production

The Sleipnir is outfitted with twelve identical 4-stroke medium speed turbo-charged dual-fuel generator sets able to produce a combined power of 96MW. The specifications of the generators and engines are as follows:

- 12 x MAN 8L51/60DF, 8000kW each
- 12 x General Electric 9129 kVA, 11kV 60Hz AC synchronous alternator

The power generation of the Sleipnir is diesel-LNG electric, meaning that the internal combustion engines, powered by MGO and LNG, are driving alternators to generate electric power. The electricity is distributed throughout the vessel to power all electric consumers. The efficiency curve is given in figure 2.4, calculated with a Lower heating value for LNG of 13.236 kWh/kg and for MGO 11.948 kWh/kg. The engines can run on either MGO or LNG. When the engines are operating in gas mode (LNG) a small amount of diesel fuel will be injected for ignition of the natural gas. The engines are

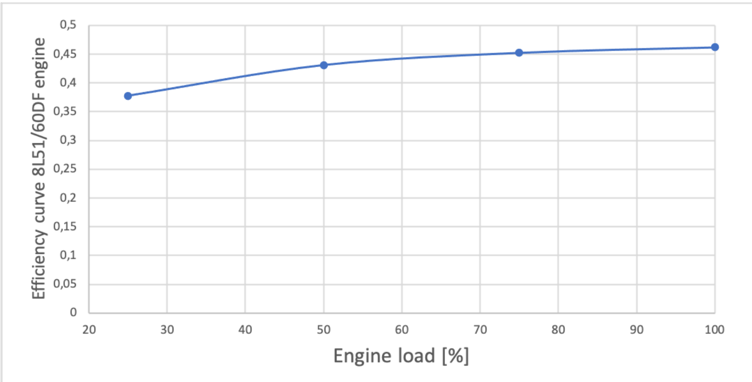


Figure 2.4: Engine efficiency curve for MAN 8L51/60DF when in LNG-mode [Data from open sea test trails]

located in 4 completely separate engine rooms, each with separate fuel systems, auxiliary systems, pumps, heating, cooling, control systems etc. This is done in order to meet the strict requirements for DP3. The redundancy concept dictates that each separate system must be able to fail without causing a chain reaction, making the other systems fail as well. In practice, this means that each single engine room must be able to generate sufficient power to keep the ship in position during work. This implies, the vessel has a high degree of redundancy in the drive-train. This is accomplished in two ways: The first redundancy is the total installed power. The capacity of 96MW, is more than double the power demand in sailing mode (approximately 40MW, see paragraph 2.3). In case of failure of one of the engine rooms this power demand can still be met. The second redundancy concerns a more immediate response during DP operations. To prevent power shortage, electricity must be produced by a minimal number of engines. So, if one engine fails, other engines can still fulfil the power demand so no immediate failure will occur. The Sleipnir requires a minimum of four engines to run on DP3 mode. As can be seen in figure 2.4, the efficiency of the generators is significantly lower when operating in partial load. This results in a lower efficiency when operating under DP classification due to the minimal number of engines that have to be running. So in normal operations the sleipnir has more engines running on half load than required, resulting in a lower total efficiency but with a higher redundancy. In the first quarter of 2020, the Sleipnir consumed a total of 387 TJ [LHV] In this quarter, the engines produced 143 TJ of electricity resulting in a total efficiency of 37% [LHV]. The fuel consumption per day for MGO and LNG is given in figure 2.5. On average in 2020, the Sleipnir has consumed LNG and MGO on a 2:1 ratio.

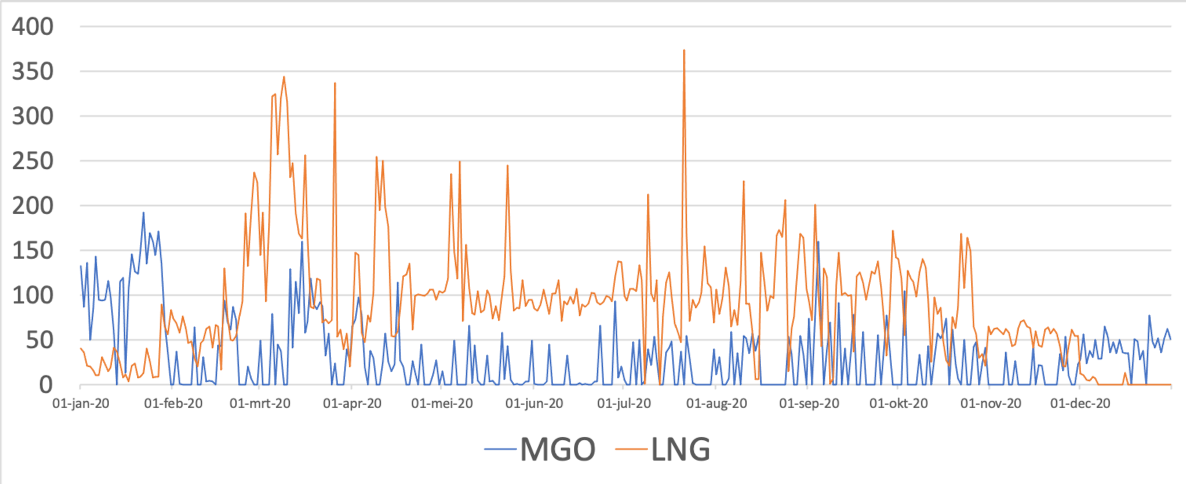


Figure 2.5: Fuel consumed per day in 2020 in m^3

2.2.2. Fuel consumption and storage space

The Sleipnir can use both Marine Gas Oil (MGO) and Natural Gas (NG), produced from stored Liquefied Natural Gas (LNG) to power the dual fuel generators. For this, the vessel is outfitted with eight LNG bunker tanks with a bunker capacity of 1000m^3 each, resulting in 8000m^3 of storage space for LNG. Furthermore, the vessel also has 11136m^3 of storage space for MGO, divided over 5 tanks. Table 2.2 shows the detailed storage capacity of the sleipnir. The 8 LNG-tanks installed on board of the vessel are Type-C single skin cylindrical tanks. These tanks have a volume of 1151 m^3 each have a maximum filling limit of 87%. The tanks store the Natural Gas at a temperature of -165 °C required to keep the fuel liquid.

Table 2.2: Fuel-use in the year 2020

	LNG		**MGO**	
Storage capacity	8 000	m^3	11 136	m^3
	177 600	GJ	407 020	GJ
Fuel use per year	32 255	m^3	11 370	m^3
	812 500	GJ	412 750	GJ
Fuel use per day	88	m^3	31	m^3
	2 250	GJ	1 150	GJ

Using the available data from 2020Q1, the emissions of different pollutants can be calculated. These emissions are given in table 2.3. The engines on board of the vessel delivered a total of 143 TJ of electricity to the electricity grid. Using this, the emission factor per kWh can be calculated using equation 2.1. These factors will later be used to compare the emissions between the current drive-train and the new designs. The Pollutant$_e mitted$ in kg is based on the averaged emission data measured by Heerema.

$$F_{emissions} = \frac{Pollutant_{emitted}}{Electricity_{produced}} \tag{2.1}$$

$F_{emissions}$	$[\frac{kg}{kWh}]$	emission factor per kWh electricity consumed
$Pollutant_{emitted}$	[kg]	Total amount of pollutant emitted in 2020Q1
$Electricity_{produced}$	[kg]	Total amount of electricity consumed in 2020Q1

Table 2.3: Emissions of Sleipnir in the first quarter of 2020

Emissions in 2020Q1	LNG [kg]	MGO [kg]	Total [kg]	Emissions per electricity delivered [kg/kWh]
CO_2	10 866 381	14 859 970	25 726 352	0.6454
CH_4	47 173	232	47 405	0.0012
N_2O	394	834	1 229	0.00003
NO_x	53 011	262 854	315 864	0.0079

2.2.3. Switchboard configuration

Each engine room has its own switchboard from where the produced electricity is distributed throughout the vessel. To fulfil the rules of DP3, the engine rooms can operate fully independent from each other. During normal operations however, three of the four connections are connected, as is illustrated by the dotted lines in figure 2.6.

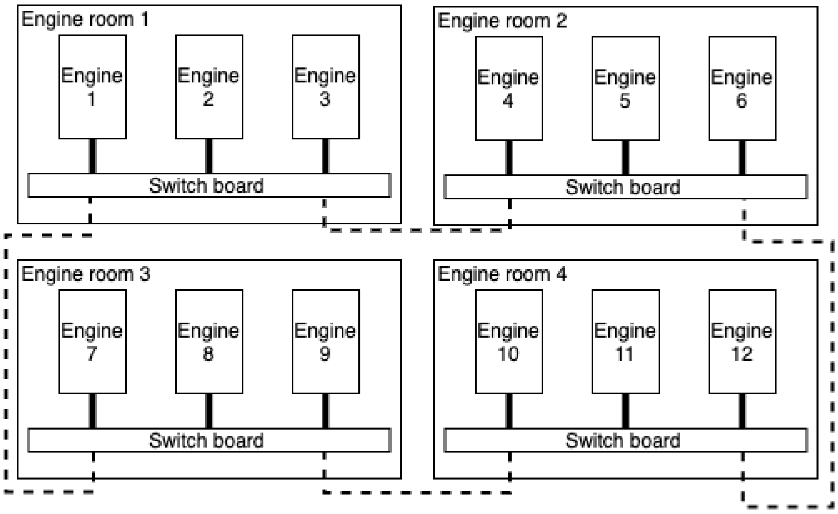


Figure 2.6: Schematic overview of engine room configuration

2.2.4. Other components

Liquefied Natural Gas vaporiser

Since the engine requires gaseous natural gas as fuel, the LNG first needs to be vaporized before consumed by the engine. The vaporiser system consists of three components. First the LNG will go through a LNG vaporizer to heat the fuel approximately 10 °C above vaporization temperature. There are 8 LNG vaporizers, each with a installed power of 890kW and capable of servicing three main engines at 100% maximum cont. rating (MCR) speed. Second, eight fuel gas heater/cooler systems will heat the fuel to a temperature acceptable for the main engines (about 20°C). These heater/cooler systems have a maximum power demand of 110kW each and again capable of servicing three main engines at 100% Maximum continuous rating (MCR) speed. The third component is the Fuel gas buffer vessel. These 10m^3 tanks have the purpose to control the volume of fuel to follow engine load changes.

Boil off gas line

Despite tank insulation designed to limit external heat entering the LNG tanks, even a small amount of heat will cause slight evaporation of the fuel. The gas that results from this is called Boil Off Gas (BOG). To prevent pressure built up in the tanks, this gas has to be vented off out of the tanks. From there, there are two possible routes. The first one, which is most preferred, is to use the BOG in the engines. This results in a lower fuel production from the vaporisers, increasing the overall efficiency. The second option is to reliquefy the natural gas and store it in the tanks. This requires energy and is therefor not the preferred method.

Selective Catalytic Reduction system

A Selective Catalytic reduction system (SCR) is used to reduce the NO$_x$ emissions of the drive-train. This is required to comply with the IMO Tier III regulations as presented in section 1.4. It is positioned at the beginning the the exhaust gas pipeline after the engine. These systems filter NO$_x$ particles from the exhaust gas before it is emitted in to the air. An overview of the SCR system is given in figure 2.7.

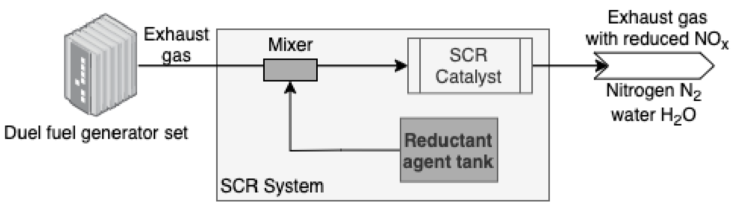


Figure 2.7: Schematic overview of SCR System

In this system a reductant agent is injected and mixed with the exhaust gasses from the combustion engine. This reductant agent will convert NO$_x$ into nitrogen (N$_2$) and water (H$_2O$). Multiple chemicals, like Ammonia or Urea, can be used as reductant agent. Onboard of the Sleipnir, Urea is used. The chemical reactions that take place in the catalyst are given in equations 2.2.

$$
\begin{gathered}
NH_2-CO-NH_2 \rightarrow NH_3+HNCO \\
HNCO+H_2O \rightarrow NH_3+CO_2 \\
4NO+4NH_3+O_2 \rightarrow 4N_2+6H_2O \\
2NO_2+4NH_3+O_2 \rightarrow 3N_2+6H_2O \\
4NO+NO_2+2NH_3 \rightarrow 2N_2+3H_2O
\end{gathered} \tag{2.2}
$$

2.3. The operational profile of the Sleipnir

The Sleipnir has three different operational modes, Idle and R&M, Working and Sailing. Depending on in what mode it is operating in, different configurations can be used regarding the powering system of the vessel. Based on data from the first quarter of 2020 the distribution over time for sailing vs non-sailing is given in figure 2.10.

Operating modes

- Idle and R&M mode(40%): the vessel is carrying out non-critical operations for which its position should be maintained by the DP-system if at open sea or when the vessel is docked in the port or anchored is a safe environment. Only two engine are running. Cranes are being used for routine daily handling of light loads.

- Working mode (39%): While in working mode, the vessel is operating in DP-mode on job-sites. The two main cranes are handling light to heavy loads and are, together with the DP system the main energy demand on the vessel. When in working mode, Sleipnir has a minimum of 6 engines running.

- Sailing mode (21%): the vessel is sailing from one location to the other. The main power consumers are the 8 thrusters. Engine loads are typically 60%-70% of the rated power and more constant compared to the other modes. At least 7 engines are running to produce the required electricity.

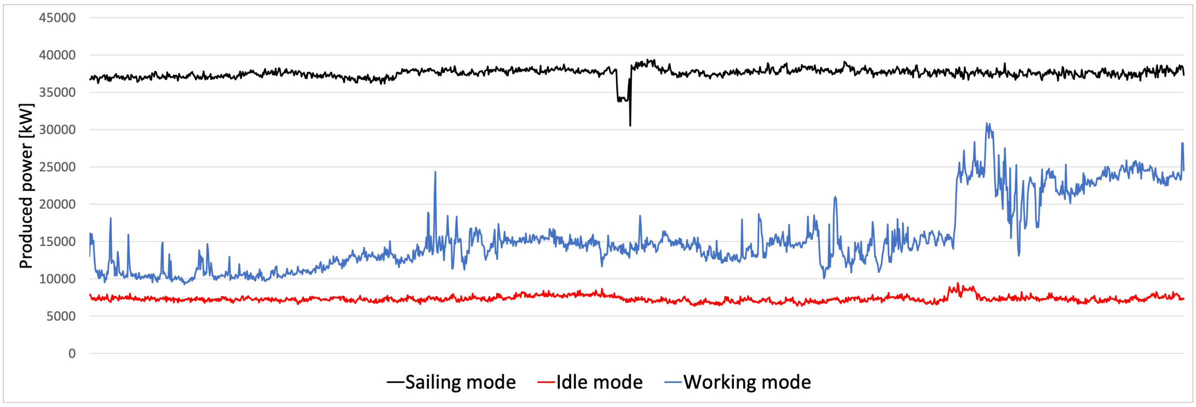


Figure 2.8: Power production per operating mode over 1 day with interval of 1 minute

As can be seen in figure 2.8, the power consumption of the vessel can vary significantly depending on the mode it is in. Figure 2.9 shows the probability for the power requirement. This figure shows that the most occurring power consumption is between 5 and 10 MW with a highest probability between 7 and 8 MW. The probability that the power demand is lower then 6.5MW is 15%. The goal for this thesis is to design a new drive-train that can power the hotel load of the Sleipnir (see section2.4). Even tough the hotel load is not always constant over time. The maximum average is a power demand of 6.5MW. The new designs will have to meet this energy demand within the constraints of the current operational profile and comply with the same regulations. The required storagecapacity and fuel-use to power the hotelload is given in table 2.4

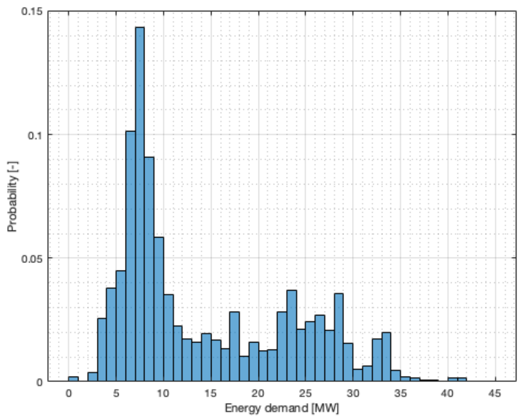


Figure 2.9: The probability of the power demand for the first quarter of 2020

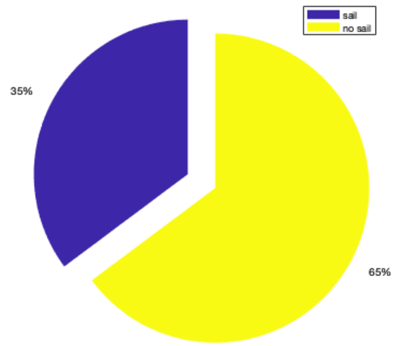


Figure 2.10: The ratio between sailing and not sailing of the Sleipnir for the first quarter of 2020

Table 2.4: Summary of the findings

	Current system	
	LNG	MGO
Total onboard efficiency [% LHV]	35	
Fuel used per year [ton/year]	6 915	3 829
Cargo tank volume required [m^3]	2 570	684
Energy stored in fuel tank [GJ]	52 400	26 200

2.4. Electrical consumers

In order to design a hydrogen powered drive-train for Sleipnir, it is important to be aware of the systems that require electric energy. The largest peaks in power demand are typically caused by the thrusters: the power demand of the thrusters dominates the total power demand of the ship. Furthermore, the power consumption of the crane load can be very irregular. The power consumption can be divided into 4 different groups:

1. hotel load;
2. thrusters;
3. cranes;
4. ballast pumps;

Hotel load

The hotel load is a relatively steady and low power consumer when compared to the other main consumers on board. The hotel load consists of all the electric power that is required for the lights, the heating systems, the laundry, the mess rooms, various hydraulic systems, air compressors and other small consumers on board. The hotel load of the Sleipnir is relatively stable with a maximum average of around 6.5 MW. This can vary depending on temperatures on board (higher air conditioning electricity consumption) or other influences. An overview of a common power demand for the hotel load per operational mode is given in figure 2.11. The irregularity of the hotel load during working mode is due to measuring errors caused by the time steps during measuring and will ordinarily fluctuate vary similarly to the other hotel load graphs.

Figure 2.11: Hotel load per operational mode over 1 day

Thrusters

The Sleipnir is equiped with eight Wartsila thrusters. These are used for propulsion of the vessel and dynamic positioning. Each thruster has a rated power of 5.5 MW. The consumed electric power by all thrusters depends on the type of operation mode the vessel is in. During sailing mode, all thrusters are used for propulsion resulting in a total consumed power of approximately 30MW. When in Idle mode consumed power varies between 0.15MW and 0.30MW since the vessel is not in DP mode or sailing to a next destination. During Work mode the consumption on avarage is approximately 5MW but can increase to 22MW depending on the weather, sea state (waves and current) and the crane operations.

Cranes

There are two electric driven 10 000 mT main cranes on board the Sleipnir. The cranes power demand is very irregular. It can ramp up very quickly to relatively high power levels up to 40MW. Especially slewing (rotating) the crane leads to high peaks in the energy demand of the ship. Commonly the cranes are used for light lifts or operate without any load. Only when initiating a movement, the crane requires a high and short power demand. It requires less power to maintain the movement. The power demand of the cranes can be seen in figure 2.12.

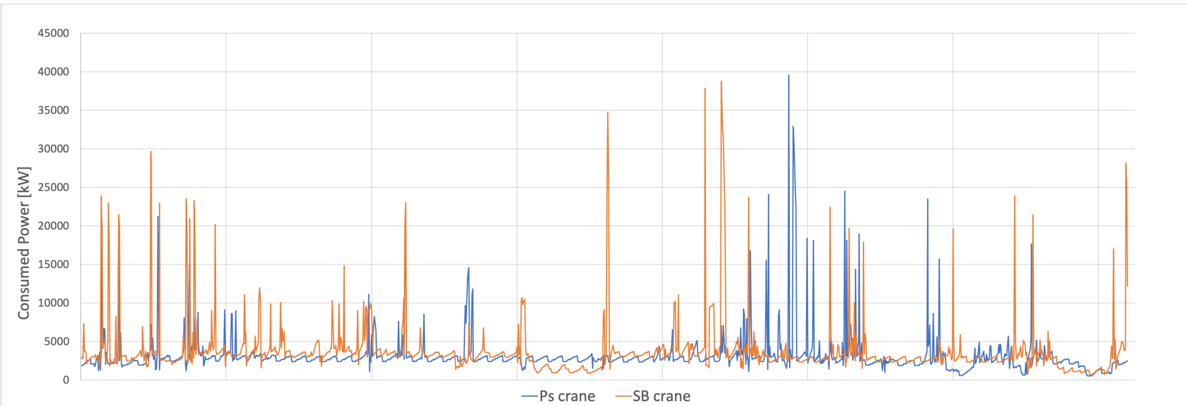


Figure 2.12: Crane energy demand during 1 day in working mode

Ballast pumps

The ballast and anti-heeling pumps play an important role in crane lifting operations. Ballast pumps are used to fill op the ballast tanks of the vessel. The anti-heeling system is used to prevent the ship from heeling over while slewing, by moving ballast water within the ship. The ballast pumps are typically used before the lifting operation and the anti-heeling pumps are used during the operation itself.

3

Concept selection of new drive-trains

This chapter will focus on the different choices to be made when designing the new drive-train for the Sleipnir. The purpose of this chapter is to determine how the hydrogen is produced, the best way to convert the hydrogen into the Dense Hydrogen Carrier (DHC's) and how it is converted into electricity on board of the ship. Figure 3.1 gives an overview of the main choices that have to be made.

1. The first step is to determine how the hydrogen will be produced. This choice is described in section 3.1. The boundary condition for this choice is that, when the hydrogen is produced, there is no CO_2 emission, as discussed in chapter 1.

2. The second step is to further elaborate on the different DHC's. How are they produced, how much energy does is requires to produce them and how do they score in the field of health, safety and environment. These questions are presented in section 3.2.

3. The third step is to determine how the energy stored in the DHC's can be converted into electricity. In this section the two options will be evaluated, an internal combustion engine and a fuel cell system. Within these two different systems, there are also different options:

   - In the case of fuel cell systems, two different systems are considered. The Proton-Exchange Membrane Fuel Cell and the Solid Oxide Fuel Cell. These options are discussed in section 3.3.1
   - With the internal combustion engine, there are two different choices to be made. The first is whether it will be a 2-stroke or 4-stroke engine and the second choice is whether it will be a spark ignition or compression ignition engine. These options are discussed in section 3.3.2

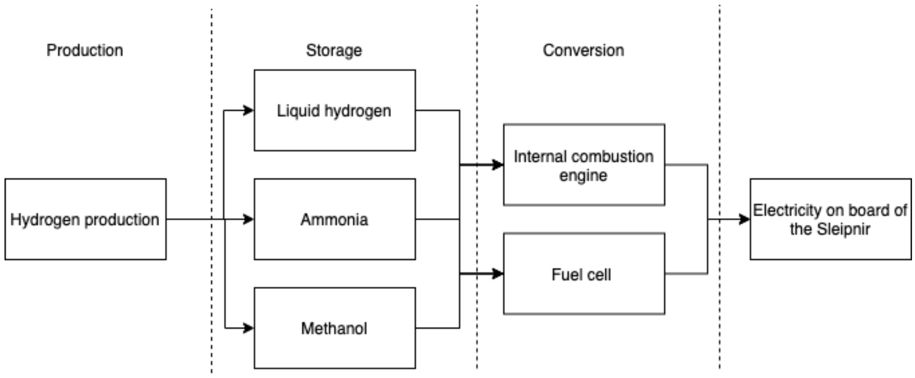


Figure 3.1: The different concept selection steps

3.1. Hydrogen production

Hydrogen can be produced in multiple ways. Three types of hydrogen are looked at in this thesis, depending on the resources and the production process:

1. Grey hydrogen; Grey hydrogen is produced using fossil fuels as a resource. Currently natural gas is primary source being used and is accountable for roughly 75% of all hydrogen produced [32]. The natural gas is used in steam methane reformers (SMR) that convert the natural gas into carbon dioxide and hydrogen. Hydrogen produced via SMR generates 10 kg CO_2 for every 1 kg of H_2. Coal is the second most used source for hydrogen production with a market share of 23%. Hydrogen produced for coal generates 19 kg CO_2 for every 1 kg of H_2. The vast majority of hydrogen produced today is responsible for CO_2 emissions and is therefore not CO_2-neutral. For this reason, hydrogen produced from natural gas, coal or other fossil fuels will not be included in this study.

2. Blue hydrogen; The term blue hydrogen is used for hydrogen production processes where carbon emissions reduction is applied to minimise CO_2 emissions. Carbon capture, utilisation and storage (CCUS) is a process whereby the CO_2 is captured after the hydrogen production. CCUS can be applied to SMR and to the less frequently used Autothermal reforming (ATR) process. CCUS can reduces carbon emissions up to 90% [32]. The first way CCUS can be applied is to separate the CO_2 from the high-pressure synthesis gas stream. This results in a 60% reduction. The second way is to capture CO_2 from the more diluted furnace flue gas. This can result in a 90% reduction but can be up to 2.5 times more expensive than the first method. Since CO_2 is still produced, blue hydrogen is also considered out of scope for this thesis.

3. Green hydrogen; If hydrogen is produced from renewable resources, it is called green hydrogen. During this production process no GHGs are emitted and is therefor the only type of hydrogen production method considered in this thesis. There are different ways to produce hydrogen in a sustainable way, such as electrolysis and hydrogen produced from biomass. This research focuses only on electrolysis, where hydrogen is produced using electricity.

3.1.1. Green hydrogen production

The production of green hydrogen uses renewable electricity like wind or solar power. An electrolyzer uses the electricity to split a water molecule into hydrogen and oxygen atoms. This process is called electrolysis and the reaction is shown in equation 3.1. There are three main technology options for electrolyzers, all with different characteristics.

$$H_2O(+electricity) \rightarrow H_2 + 1/2O_2 \tag{3.1}$$

The first, and most widely used technology is the Alkaline Electrolyzer (AEC). The AEC is the most mature technology and operates at a low temperature (60-80°C). It does not use scarce metals, which makes it a robust and cheap option. At the time of writing, the efficiency of the AEC is averages between 75 and 83% (HHV). However, this is expected to increase to at least 83% or higher in the long term future (HHV) [32].

The second technology is the polymer electrolyte membrane electrolyzer (PEMEC). This technology has a high power density and produces more pure hydrogen than the other electrolyzers. It also operates at low temperatures of 60-80°C. However, the PEMEC is more expensive and complex than the AEC. The lifetime of a PEMEC is also shorter than that of the other two technologies. This results in a lower total production of hydrogen over the lifetime of the electrolyzer and thus a higher total cost of hydrogen.

The third and last technology is the solid oxide electrolyzer Cell (SOEC). This technique has the potential for high electrical efficiency (up to 85%) and relatively low material costs. This high efficiency can be achieved because of the high operating temperature (up to 1000 °C) as much less energy is required to separate water molecules at high temperature [66, 21]. The higher operating temperature results in a faster reaction thus enabling potentially high energy efficiency. However, this technique is the least developed of the three options en currently still the most expensive.

An overview of the characteristics of the three different techniques can be found in table 3.1. For the economic evaluation later in this study, the characteristics of the AEC will be used for the production of the hydrogen. The AEC is the most developed technique of the three different electrilyzers. In addition, the stack lifetime is longer and the CAPEX per kW is lower. These two factors ensure that the price for the produced hydrogen will be lower compared to the PEMEC and the SOEC systems.

Table 3.1: Techno-economic characteristics for different electrolysers [32]

	Alkeline Electrolyser		PEM Electrolyser		Solid Oxide Electrolyser	
	Today	Long term	Today	Long term	Today	Long term
Electrolysis efficiency [% HHV]	75-83	83-95	66-71	79-88	88-96	91+
Stack lifetime [*1000hr]	60-90	100-150	30-90	100-150	10-30	75-100
Load range [%]	10-110		0-160		20-100	
CAPEX [euro/kWe]	500-1400	200-700	1100-1800	200-900	2800-5600	500-1000

3.2. Dense hydrogen carriers

As stated in paragraph 1.2, the main problem with hydrogen is its very low volumetric energy density. To improve this, the gas can be stored as a dense hydrogen carrier. This thesis will look at three different dense hydrogen carriers. These carriers are identified in consultation with Heerema and based on the publications of the International Renewable Energy Agency [36] and International Energy Agency [11]. The first storing method is by liquefying the hydrogen to increase the density. The second and third storing methods increase the volumetric energy density of hydrogen by binding the hydrogen to a carrier, in this case nitrogen and carbon dioxide, to produce ammonia en methanol. Other dense hydrogen carriers are recognised as potential fuels for future shipping but due to their relative low technical readiness level, these options are considered to be out of scope for this thesis since they will not be feasible within 5 years.

3.2.1. Liquefied hydrogen

By lowering the temperature to -253 °C hydrogen becomes liquid. This increases the volumetric energy density by almost 10.000% to 9.98 MJ/l (LHV). This liquefaction process requires a consequential amount of energy. In theory 3900 kWh is required to produce 1 ton of liquefied hydrogen. This is 11.7% energy loss based on the LHV [43]. Realistically, the energy requirement is between 6 and 6.78 kWh/kgH_2, resulting in a loss of approximately 20% based on the LHV [32]. Due to this high energy consumption, the production cost for the process will increase, chapter 5 will further elaborate on this. Table 3.2 gives an overview of the cost parameters for different liquefaction plants.

Table 3.2: Parameters of different hydrogen liquefaction plants. Adapted from Tijdgat [76]

Liquefication plants	IdealHY [71]	Reuß[61]	IEA[32]	Shipping Sunshine [62]
Capacity [LH_2day]	50	50	712	7 070
Annual Operation [hr]	8 000	5 600	NA	8 760
Inlet pressure [bar]	20	30	NA	30
Depreciation period [yrs]	20	20	NA	30
Annual OPEX [%/CAPEX]	4	8	4	3
Losses [%tLH_2]	1.67	1.65	NA	NA
Energy requirement [GJ/tLH_2]	24.3	24.4	22.0	24.3
Electricity price [Euro/MWh]	50	60	16.3	11.8
Investment cost [Meuro]	105	105	1 261	2 755
Liquefication cost [euro/tLH_2]	1 380	1 890	410	120

3.2.2. Ammonia

Ammonia (NH_3) is an inorganic compound composed of a single nitrogen atom bonded to three hydrogen atoms. It is used as a resource for the production of fertilizers, plastics, pharmaceuticals and other chemicals. Because of this, Ammonia is the second largest synthetic product in the world [26] and is produced in a Haber-Bosch reactor developed by Haber and Bosch in the first decade of the 20th century. The reaction process that takes place in this reactor is shown in equation 3.2. Conventional ammonia production uses grey hydrogen produced from natural gas. In order to produce green ammonia, this needs to be substituted for green hydrogen. The reaction takes place at temperatures ranging between 400 and 500 °C and at a pressure ranging between 100 and 250 bar. To promote the reaction, a catalyst based on iron oxide is used [79]. A schematic overview of the

Haber-Bosch process is given in figure 3.2.

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \qquad \Delta H = -92\text{kJ/mol} \tag{3.2}$$

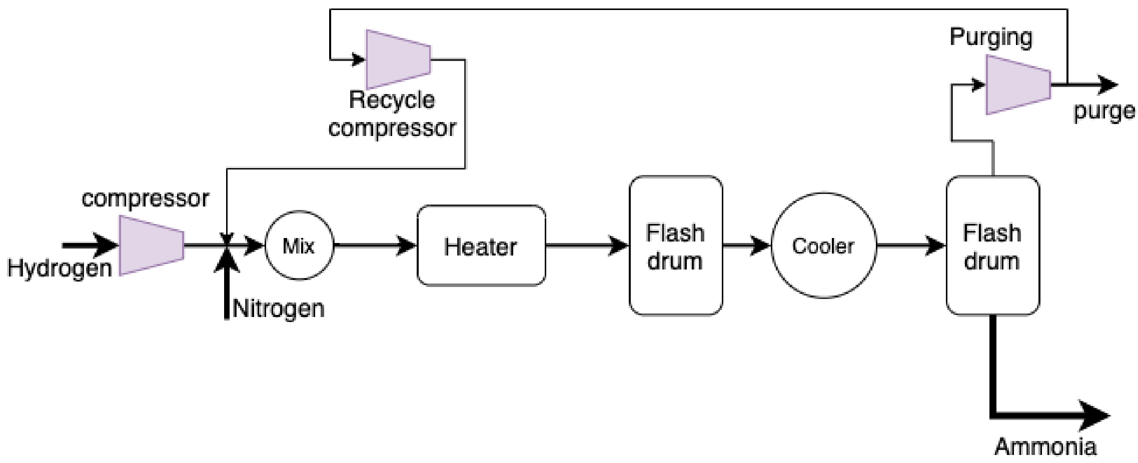


Figure 3.2: Simplified flowsheet of the conventional Haber-Bosch synthesis loop [7]

For the production of 1 ton of ammonia, 0.178 ton of hydrogen and 0.822 ton of nitrogen is required. The nitrogen can be separated from the air using an air separation unit (ASU). The power requirement for this unit is 0.11 kWh/kg N_2 [7] resulting in 0.326 GJ/tNH_3. The hydrogen and nitrogen will be compressed and fed to the Haber-Bosch reactor. The process to convert the input into Ammonia requires 0.64 kWh/kg NH_3[7] resulting in 2.30 GJ/tNH_3 energy consumption [54]. An overview of the energy consumption's is given in table 3.3

Table 3.3: Energy requirements for the production of ammonia [54]

	Mass needed [ton]	Energy required [GJ/t NH3]	Efficiency (HHV) [%]
Green hydrogen	0.178		
Nitrogen	0.822	0.33	
Harber-Bosch reaction		2.30	
Produced Ammonia	1	2.63	88

Ammonia is in a gaseous phase at atmospheric pressure and room temperature, but can be liquefied when the temperature is brought down to -33°C or when pressurized to 10 bar or more. When liquefied, it has a volumetric energy density of 15.6 MJ/l.

3.2.3. Methanol

Methanol (CH_3OH) is a clear and liquid chemical that is water-soluble and biodegradable, comprising of four parts hydrogen, one part oxygen and one-part carbon. Methanol is the simplest member of the organic chemicals alcohols. It is most commonly produced on an industrial scale using natural gas as its feedstock. Methanol is used to create other chemical derivatives that can be used to create materials such as building materials, foams, resins, plastics, paints, polyester and a variety of health and pharmaceutical products. The conventional way for methanol production is from synthesis gas, which can be produced through steam methane reforming (SMR). The production requires a vast amount of fossil fuel and as a byproduct of the process emits a large amount of CO_2. for 1 ton of methanol about 0.6 to 1.5 tons of CO_2 are emitted[8]. This methanol is called grey methanol and is out of scope for this thesis.

Green methanol can also be produced for CO_2 and H_2, as is shown in equation 3.3 and 3.4. The reaction is exothermic and requires high pressure to shift to the right. Another method to produce methanol is by combining CO_2 and H_2, see equation 3.5 [23]. This reaction takes place in a reactor at temperatures around 250-300 °C and pressures of 50-100 bar with a catalyst of $CuO/ZnO/Al_2O_3$.

$$H_2 + CO_2(+heat) \rightleftharpoons CO + H_2O \qquad \Delta H = +41.2\text{kJ/mol} \tag{3.3}$$

$$CO + 2H_2 \rightleftharpoons CH_3OH \qquad \Delta H = -90.7\text{kJ/mol} \tag{3.4}$$

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \qquad \Delta H = -49.5\text{kJ/mol} \tag{3.5}$$

A feasibility study executed by D. Bellotti et. al evaluated the following methanol production case [8]. An simplified plant lay-out is shown in figure 3.3. This installation consumed 0.45 GJ/h for the CO_2 capture from the exhaust gas in this case a combined heat and power biomass plant, 3.7 GJ/h for the electrolyser, 0.11 GJ/h for the methanol reactor and 0.08 GJ was consumed for the compressor, which resulted in a total of 4.125 GJ/h energy consumption. The flow rate was 97 kg/h of methanol which is 97*22.7 (HHV of methanol) = 2202 GJ/hour. The system has an overall efficiency of 81%. Converting the energy requirement from GJ/h to GJ/t Methanol results in the energy requirement for the plant given in table 3.4.

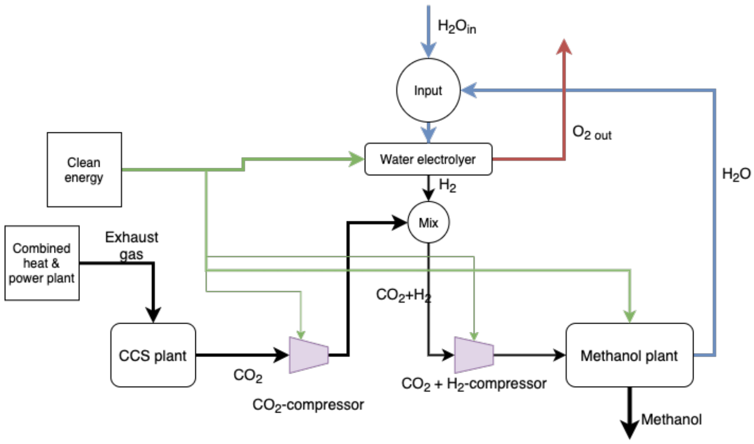


Figure 3.3: Simplified methanol production plant lay-out [8]

Table 3.4: Energy requirements for the production of methanol based on Belloti et al [8]

	Mass needed [ton]	Energy required [GJ/t MeOH]	Efficiency (HHV) [%]
Green hydrogen	0.189		
Capture of CO_2	1.442	4.6	
CO_2 compressor (2 - 30bar)		0.36	
CO_2+H_2 compressor (30-80bar)		0.48	
MeOH reactor		-1.15	
Produced Methanol	1	4.29	81

3.2.4. Health Safety & Environment assessment

Table 3.5 shows a comparison of the three DHCs regarding their health, safety and environmental aspects. They are compared to LNG to indicate the critical elements that characterise the fuels, especially those aspects with regards to safety on board of the vessel. Key parameters in this assessment are toxicity, flammability and (greenhouse gas) emissions.

Table 3.5: List of components properties

	Formula [-]	Density [kg/m3]	$T_{boiling}$ [°C]	$T_{Melting}$ [°C]	Flammability range [%]	$T_{autoignition}$ [°C]	Flash point [°C]
LNG	CH_4	426	-162	-182	5.3 -14	595	Flammable gas
LH_2	H_2	71	-253	-259	4 - 75	500	Flammable gas
NH_3	NH_3	683 (liquid)	-33	-77	15 - 28	630	132
MeOH	CH_3OH	791	65	-98	5.5 - 36.5	454	12

Health effects - toxicity

Based on the Globally Harmonized System of Classification and Labelling of Chemicals, given in table 3.6, the three DHCs are evaluated on their toxicity on humans and nature.

Table 3.6: Hazard assessment of hydrogen carriers based on the Globally Harmonized System of Classification and Labelling of Chemicals

Hazard statement	**Hazard category**	**LH_2**	**MeOH**	**NH_3**	**LNG**
H220 extremely flammable gas	1A	X			X
H221 Flammable gas	2			X	
H225 Highly flammable liquid and vapour	2		X		
H280 contains gas under pressure may explode if heaten				X	
H281 Contains refrigerated gas; may cause cryogenic burn of injury	Refrigerated liquified gas	X			X
H301 Toxic if swallowed	3		X		
H311 Toxic if in contact with skin			X		
H314 Causes severe skin burns and eye damage	1B			X	
H331 Toxic if inhaled	3		X	X	
H370 causes damage to organs			X		
H410 Very toxic to aquatic life with long-lasting effects	1			X	

Liquid hydrogen Liquid hydrogen is a non-toxic material. It can still be harmful when dispersed as gas in an enclosed room. The most important symptoms when someone comes in contact with gaseous hydrogen are eye irritations, sensation of burning, coughing and burns. Gas detection and ventilation systems can prevent these hazards. In addition, contact with the fuel or non-insulated equipment when handling liquid hydrogen installations can cause severe frostbite [24].

Ammonia Ammonia is highly toxic. Exposure to air with high concentrations of ammonia causes burning of the eyes, nose and throat. Ammonia concentrations higher then 5000ppm in the air can lead to death. Extra safety measures are required to minimize the change of an increase in ammonia concentrations. This mostly results in extra ventilation installations and more gas detection units. Ammonia is also harm full to the environment. Uncontrolled spillage of leaking of the DHC in sea can result in long-lasting toxic influence to aquatic life surrounding the ship. Additionally, ammonia is a highly corrosive material, resulting in limitation regarding the materials used for the system, engine and pipelines.

Methanol Methanol is defined as extremely toxic and can cause significant damage to the human body: 1 to 2 ml of methanol per kg body weight is fatal upon ingestion if untreated. Skin or eye contact, as well as inhalation of methanol vapours also result in poisoning of the organs but are of lower concern, as long as it does not persist for hours [80]. Methanol is also a corrosive material.

Safety risks - Flammability

All fuels burn only in a gaseous or vapor state. Hydrogen and ammonia are already gases at atmospheric conditions, whereas methanol is a liquid and must first be converted into a vapor before it will burn [14]. To identify the flammability risk for a fuel, the following two properties are considered: The flammability range and the flashpoint of the fuel.

The flammability of a gas is best explained by means of a flammability diagram. Figure 3.4 shows a Kennedy explosion chart of methane, which is a widely used type of flammability diagram. The range in which ignition can occur depends on the percentage of fuel, oxygen and nitrogen present in the air. Logically, when there is more fuel present, there is a lower percentage of oxygen and nitrogen. Consequently there are 3 limits. The lower limit, point A in the diagram, indicates the minimum amount of fuel that must be present for ignition. The second limit is the upper bound of the fuel percent, point C. When a higher percentage of fuel is present, there is not enough oxygen for combustion. The third limit, point B in the diagram, indicates the minimum percentage of oxygen required for ignition. The ratio of oxygen to fuel determines the flammability range of the fuel. The greater this range, the greater the chance of ignition when the fuel is in the air. Hydrogen gas, with a wide flammability range of 4-75%, has the highest flammability risks of the three DHCs. Methanol also has a relative high flammability range of 5.5-36.5%. The flammability range of Ammonia is relatively low with 15-28%. The Kennedy explosion chart for LNG and the three DHC's are given in figure 3.4-3.7. The orange area in the chart is when the mixture of fuel, oxygen and nitrogen is flammable. When the area is bigger, the explosion hazard is bigger and thus higher safety percussion's need to be taken.

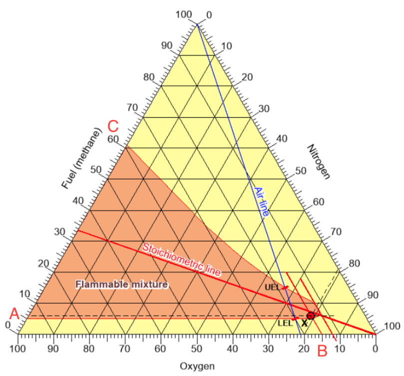


Figure 3.4: Flammability diagram for methane [50]

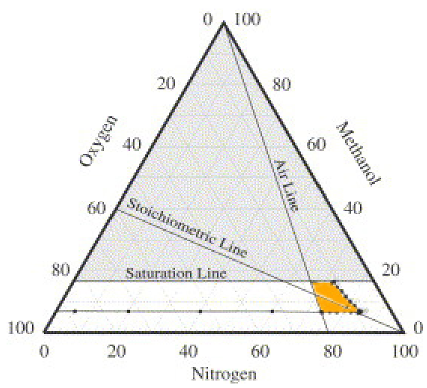


Figure 3.5: Flammability diagram for methanol [13]

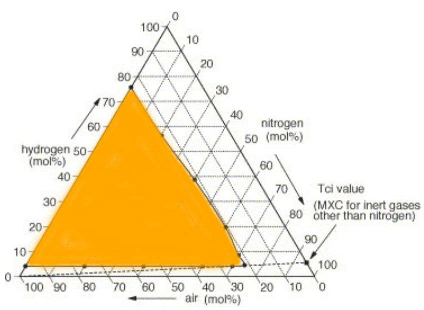


Figure 3.6: Flammability diagram for hydrogen [68]

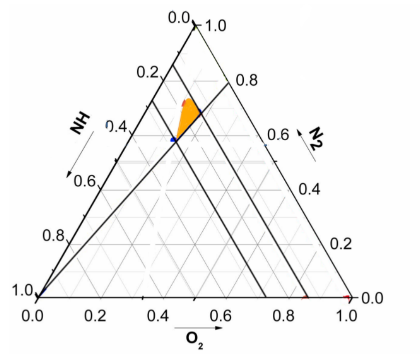


Figure 3.7: Flammability diagram for Ammonia[74]

Safety risks - Flashpoint

Safety on board of ships depends on a large part of the flash point of maritime fuels. The flashpoint is the lowest temperature at which a flame can cause an ignition of the vapour from the fuel in the air. If the temperature of the fuel is below its flashpoint, it cannot produce enough vapors to burn since its evaporation rate is too slow. The lower the flash point, the higher the fire risk of a fuel. During the Maritime Organization in the Safety of Life at Sea (SOLAS) event, The International Organization of Standardization (ISO) has identified a minimal flash point of 60 °C for fuel oils to be of an acceptable level of risks for ship operations. Methanol has a flash point of 12 °C. This is lower than the minimal standard and therefore needs extra safety precaution's, as defined in the ISO code for low flash point and gaseous fuels. In practice, this means extra modifications on the ventilation system, insulation of electrical system, double wall design of all high-pressure methanol fuel components and additional fire detection system are necessary [63, 27]. The flashpoint of Ammonia is 132 °C, so higher then 60 °C and within the limits of the ISO Standards. However, since ammonia is a gas at ambient temperature it has to comply with the same ISO code for low flashpoint and gaseous fuels, just like methanol. Hydrogen is also a gas at atmospheric temperature. It must therefore also comply with the ISO standards for Gases and other low flashpoint fuels.

Environmental risks - CO_2 emissions

The emissions over the lifetime of the DHCs can be divided into two phases: well-to-tank (WTT) and tank-to-propeller (TTP). The WTT phase includes the total emissions from the extraction of raw material to the production and transportation of the fuel. The TTP phase accounts for all emissions that result from use of the DHC on board of the vessel. A schematic overview of this is given in figure 3.8.

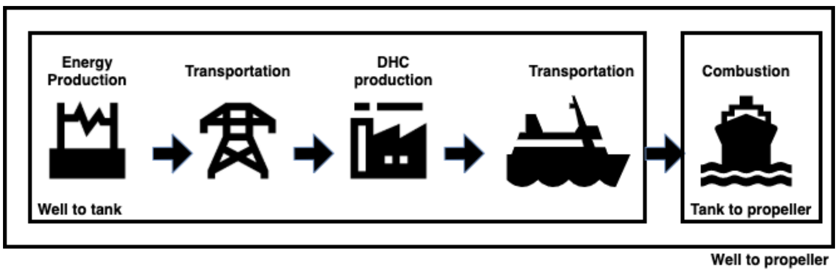


Figure 3.8: Life-cycle of dense hydrogen carriers for well to propeller

All three DHCs have to be carbon-neutral. This means that no CO_2 is emitted over the well to propeller. Hydrogen and ammonia do not contain any carbon molecules. If the production process of these DHCs is also CO_2 neutral by using green electricity and green hydrogen, these DHCs are completely CO_2 free over their lifecycle. Methanol has one carbon molecule and is therefore not by definition a carbon neutral fuel. The source of the CO_2 used for the production is decisive for methanol to become a carbon-neutral fuel. To make CO_2 carbon neutral, the CO_2 must be guarantied by the International Sustainability and Carbon Certification organisation. When the CO_2 is extracted from waste flows from industries using biomass, for example a biogas electricity plant, the production of methanol can be considered carbon-neutral. When methanol is produced with CO_2 captured from fossil fueled industries (called CO_2 for a point source), it is not considered as carbon neutral. First, as discussed in section 3.1, CCUS can only reduce up to 90% of the emitted carbon from these point sources. Second, the production facility where the CO_2 is captured will also claim a share of the CO_2 reduction. This thesis will continue with a allocation of 50% carbon reduction for the production facility and 50% for the methanol. This results that half the CO_2 used for the production of methanol can be considered as carbon-neutral. The different sources for the CO_2 will effect the price of the resource, this will be elaborated on in chapter 5, in this chapter the allocation of the CO_2 will also be discussed regarding a potential carbon tax.

3.2.5. Conclusion

The goal of Section 3.2 was to find different methods to store hydrogen on board of the vessel. A literature study showed that that the three DHCs Liquid hydrogen, ammonia and methanol are developed to be feasible within the scope of this research. There DHCs were included in this study. Table 3.7 gives the properties of the DHCs including the currently used fuel LNG for comparison. Their technical (dis)advantages will be summarised one by one:

1. Energy density: The volumetric energy density of the fuels is very decisive for the volume of the total installation. The volumetric energy density of hydrogen being more than twice as small as that of LNG will result in a fuel tank approximately twice as large to store the same amount of energy[1]. The energy density of ammonia and methanol are somewhat similar to LNG and therefore no major differences in tank volume are expected.

2. Storage temperature: Methanol has a big advantage over the rest when it comes to storage conditions. Being a liquid at ambient temperatures, it does not need complicated insulation systems. LNG and LH_2 do require insulation systems to keep de fuel liquid. This consumes extra energy for insulation and the handling of excessive boil-off gas. Ammonia must also be kept cool to remain a liquid, but due to its relatively moderate storage temperature this will be less complicated than the LH_2 or LNG systems.

3. Production efficiency: ammonia en methanol have a relatively high production efficiency compared to LNG and liquid hydrogen. Even though hydrogen is a resource for the production of ammonia and methanol, the energy requirement for liquification of hydrogen is so substantial that it is more efficient to chemically bond the hydrogen to nitrogen or carbon. An higher efficiency can result in a lower fuel price but this price also depends on the production cost so the influence of the difference in production efficiency on the total cost of the new drive-train will have to be investigated in the economic analysis.

[1] This does not include the differences in the drive-train efficiency

4. Conversion losses: If the ammonia and methanol have to be reformed into hydrogen on board the ship, this will result in an additional loss. Therefore, it is not preferable to convert all ammonia or methanol back into hydrogen. However, this is not necessary for every drive-train configuration and therefore has relatively little influence on the preferability of the different DHCs.

Table 3.7: Properties of the Dense hydrogen carriers [38, 57, 67, 79]

Fuel	**Energy density (LHV) [MJ/kg]**	**Volumetric energy density [MJ/l]**	**Storage pressure [bara]**	**Storage temperature [°C]**	**Production efficiency[a] [% of LHV]**
LNG	47.7	20.8	1-5	-160	n.a.
Liquid H_2	118.8	10	1-5	-253	57
Liquid NH_3	18.8	13	1-17	-34	66
Methanol	19.9	15.8	1	20	51

[a]This is including the production losses of the hydrogen gas

Health, Safety & environmental assessment

Table 3.8 gives an overview of the results found in the HSE assessment. As can be seen, all three DHCs have their advantages and disadvantages. The toxicity of ammonia and methanol have a great influence on the fuel handling on the ship, resulting in more stringent safety measures for the crew and the fueling system. The flammability of hydrogen can lead to a high explosion risk if there are no good ventilation systems that remove potentially leaking gas from enclosed spaces. Also the temperature at which the hydrogen is stored results in extra adjustments to the fuel handling system because of the extra insulation required. Regarding the CO_2 emissions, all three DHCs are considered to be carbon-neutral fuel but methanol still emits CO_2 during combustion (TTP) where as liquid hydrogen and ammonia are completely carbon free.

Table 3.8: Health, Safety & environmental scoring

	Liquid hydrogen	Ammonia	Methanol
Toxicity	+	-	-
Flammability	-	+	=
Flash-point	=	=	-
Emissions	+	=	-

3.3. Selection of the power generation unit

The next step in the drive-train is the conversion of the chemical energy, stored in the DHCs, to electricity. Two methods were considered in this study. The first method is to use a fuel cell where the energy is converted into electricity in a chemical reaction. The second method is by using an internal combustion engine where the energy is first transformed into mechanical energy and then converted into electricity by a generator. An overview of the different options is given in table 3.9. The advantages and disadvantages of the different options will be discussed in this section. Afterwards a choice will be made which power unit will be used by the three DHCs and with that a answer will be formulated for sub-research question 4.

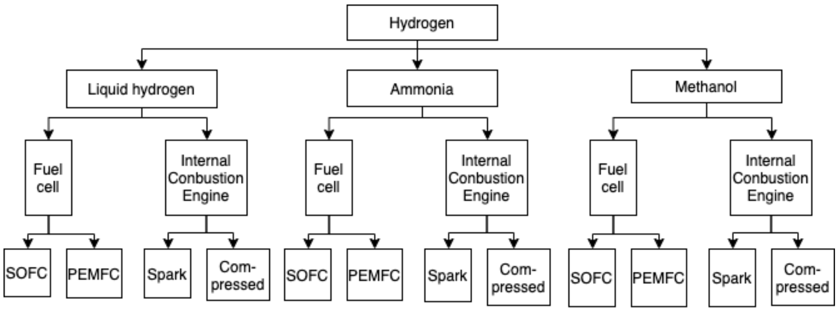


Figure 3.9: All potential drive-train configurations

3.3.1. Fuel cell selection

A fuel cell is defined as an electro-chemical cell that converts the chemical energy from a fuel type into electricity through an electro-chemical reaction with oxygen or another oxidizing agent. Usually a fuel cell uses the oxygen in the air for this reaction. A Fuel cell system is, much like a battery system, fixed to a relatively low maximum power output. In order to increase this output, the fuel cells need to be stacked in serie to increase the voltage. As shown in figure 3.10 fuel cells show a high conversion efficiency compared to ICE, particularly at medium-low load. They are highly modular, making them effective almost regardless of the installed size and redundant for operational failure which is preferred for DP3 mode as discussed in paragraph 2.1.1 [6]. Proton Exchange Membrane fuel cell (PEMFC) and Solid Oxide fuel cells (SOFC) are identified as the most promising technologies by multiple market studies [19] as well as DNV-GL with their fuel cell application study [77].

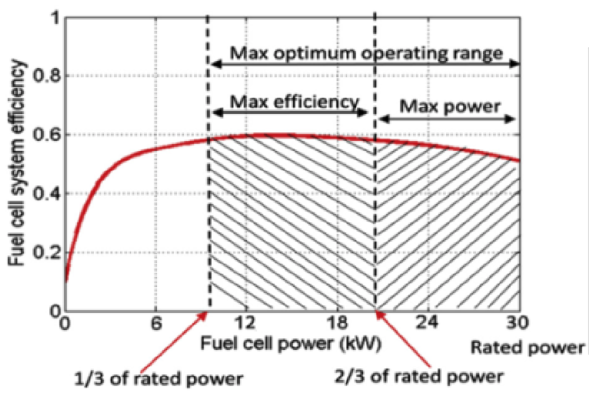


Figure 3.10: Efficiency curve of a typical 30 kW PEM fuel cell (LHV) [85]

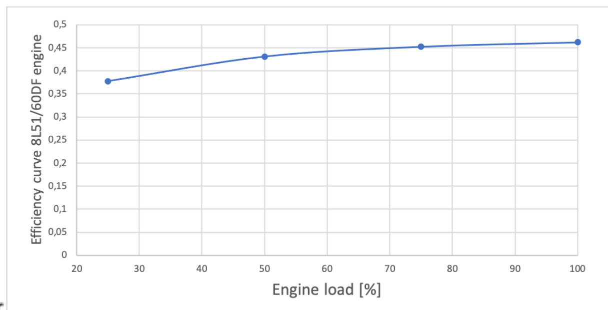


Figure 3.11: Engine efficiency curve for MAN 8L51/60DF when in LNG-mode (LHV)

Proton exchange membrane Fuel cell

The Proton Exchange Membrane fuel cell, or in short PEMFC, is commercially available and applied in multiple sectors like transportation, building industries and maritime and port applications. It has a hydrated polymer as electrolyte instead of the more commonly used liquid option. In the PEM cell an acidic membrane, saturated in water, conducts positively charges hydrogen ions through its structure. A PEMFC operates at a temperature of around 80 °C and have a reaction efficiency of 55 % (LHV). The working principal of a PEMFC is shown in figure 3.12. The total reaction is as follows[12]:

Anode reaction:	$2H_2 -> 4H^+ + 4e^-$
Cathode reaction:	$0_2 + 4H^+ + 4e^- -> 2H_2O$
Total reaction:	$2H_2 + 0_2 -> 2H_2O$

Contamination of the catalysts in a PEMFC is, together with flooding of the cells the main obstacles for the system. To prevent contamination, the hydrogen that fuels the PEMFC needs to have a very high purity level. Depending on the manufacturer, this is 99.5% and higher [52]. Another methode use, to prevent contamination, is purging of the membranes in the cells. This is done within the cell during operation. During purging, contamination particles are blown out of the system. Because of this also a small percentage of hydrogen is lost (0.5%). When flooding occurs in the cells, the surface of the membrane that can react with the hydrogen gets smaller. This way the power output decreases and the efficiency goes down. To prevent flooding of the system, multiple draining systems need to be installed to drain excessive water. Despite these precautions, the efficiency of the PEMFC will decrease by several percent over the lifetime. Due to the constraint on contamination, a PEMFC can only operate with pure hydrogen as a fuel. This means that an Ammonia-PEMFC or a MeOH-PEMFC drive-train require an extra reforming step to crack the hydrogen from the nitrogen and carbon dioxide resulting in extra efficiency losses.

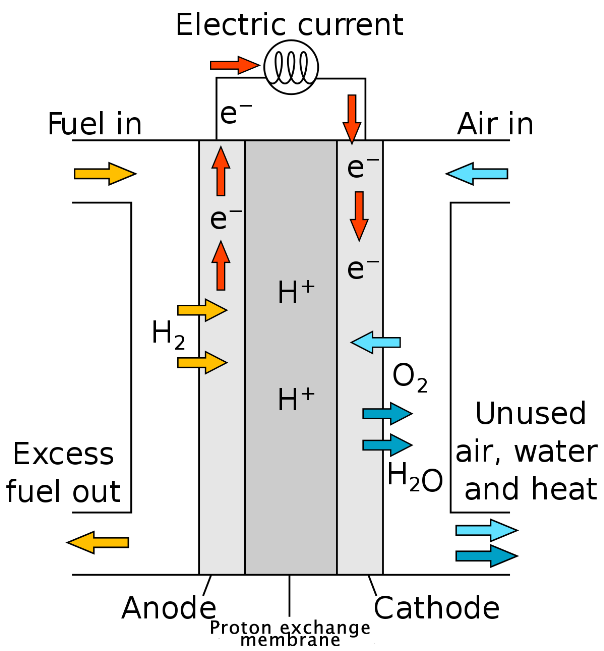


Figure 3.12: Working principal of PEMFC [12]

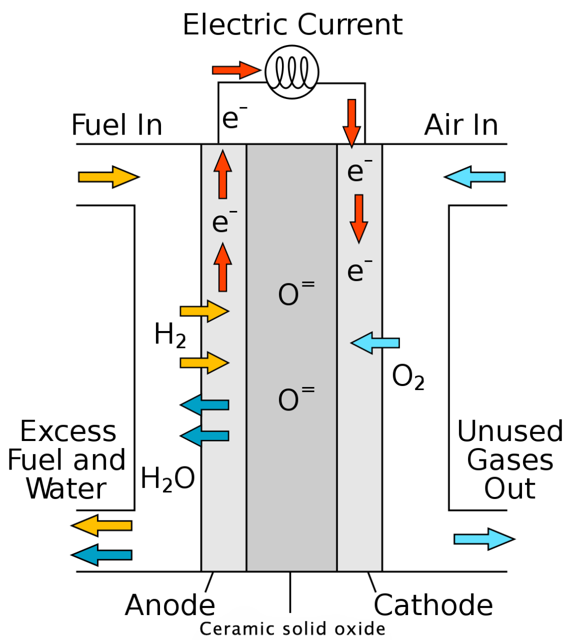


Figure 3.13: Working principal of SOFC [12]

Solid oxide fuel cells

The primary component of a SOFC is a solid ceramic electrolyte. Because solid ceramic is an insulator, it will not conduct electricity. However, it can conduct oxygen ions. Because of this property it is possible to use solid ceramic as a fuel cell electrolyte. The working principal of a SOFC is shown in figure 3.13. The cell reaction is shown below:

Anode reaction:	$2H_2 + 2O^{2-} -> 2H_2O + +4e^-$
Cathode reaction:	$O_2 + 4e^- -> 2O^{2-}$
Total reaction:	$2H_2 + 0_2 -> 2H_2O$

The solid electrolyte of a SOFC gives an advantage over other fuel cells. The electrolyte is expected to remain stable for a very long period of time making the lifetime the longest of any current design. An operational lifetime of 60 000 hours is common for SOFCs and there are even systems that have been running voor over 10 yeas continuously [6].

The SOFC has one major disadvantage. Gaining sufficient oxygen ion conductivity through the ceramic electrolyte is extremely difficult. To achieve a practical production level, the operating temperatures must reach levels between 650-1000 °Celsius. As a result of this high temperature there is also an additional disadvantage. At temperatures higher than 600 °Celsius, internal reformation of hydrocarbon fuels can take place. Efficiencies of 60% can be achieved using an SOFC[12]. SOFCs are characterized by poor dynamic behavior [57]. Consequently, they are expected to handle base loads of thermal and electric energy demand and are not suitable for high fluctuating power demands [6]. Solid oxide fuel cells offer a higher flexibility for fuel possibilities. Various gases and liquids like methanol, LNG, ammonia, hydrogen and more can directly be used in the cells [6].

Currently there are no commercially available SOFC systems available for maritime propulsion. There are projects underway that are investigating this applicability on a small scale. A good example is the AmmoniaDrive test by TU Delft that uses a combination of a SOFC and internal combustion engine to find a solution for zero-emission propulsion for ships[82]. However, this is a hybrid option that has not yet been developed far enough to meet Heerema's requirements.

Sub-conclusion

Table 3.9 gives a summary of the technical characteristics of the two different fuel cells. The PEMFC can only run on pure hydrogen. Ammonia and methanol will first have te be reformed and purified to power a PEMFC. The losses of this reforming process are to big. This is why ammonia and methanol will have a SOFC as power unit. An overview of the remaining drive-train options is shown in figure 3.14.

Table 3.9: Technical characteristics of fuel cells [77, 39, 12, 20, 81]

Power unit	Fuel	Charge carrier	Electric Efficiency LHV [%]	power density [kW/m3]	Start-up time	Operating temperature [°C]	Life time [hour]
PEMFC	H_2	H^+	55	96	<10 secondes	60-80	30,000
SOFC	H_2, NH_3, MeOH	O^{2-}	60	7	>30 minutes	650-750	60,000+

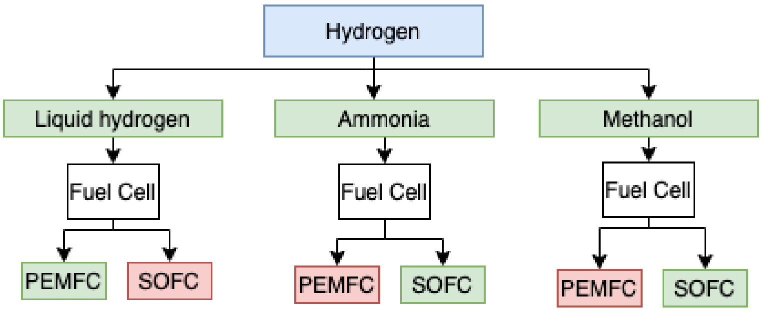


Figure 3.14: Selection of remaining drive-train configuration options

3.3.2. Internal combustion engine

An internal combustion engine (ICEs) burns a fuel together with an oxidizer (commonly air) in a combustion chamber. In this chamber, the expansion of the high-temperature and high-pressure gases produced by the combustion apply a direct force to the pistons of the engine. This force moves the piston over a distance, transforming chemical energy into mechanical energy. The mechanical energy can be used to drive the propeller. However, the drive-train of the Sleipnir is a hydrogen-electric power system meaning all mechanical energy is converted into electricity. For this a generator is required. The efficiency of a generator can be in the range of up to 95%. ICEs are interesting for marine applications due to their high reliability and low costs in terms of investment and operational costs [83]. This paragraph will first elaborate on the fundamental principals that apply to ICEs. Next, the required engine type for each DHC is discussed.

2-stroke and 4-stroke internal combustion engines

An internal combustion engine works in a five steps cycle, the intake, compression, ignition, combustion and exhaust step. In a 2-stroke engine, all five steps of the cycle are completed in only two strokes of the piston so one rotation of the crankshaft). In a 4-stroke engine, the five steps require four strokes of the piston so two rotation of the crankshaft. The 2-stroke engines operate at relatively low rotational speed compared to 4-stroke engines, see figure 3.15. This results in higher engine efficiency, as shown in figure 3.16.

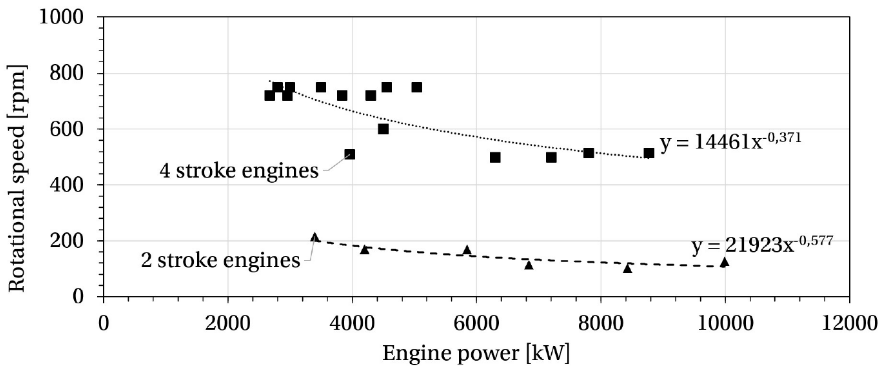


Figure 3.15: Rotational speed of two and four stroke engines [76]

The higher efficiencies that 2-stroke engines can achieve are a great advantage on board of the vessel. Because of a higher efficiency, less fuel is required resulting in lower cost and an increase in operational space on board of the ship. However, the disadvantage of the 2-stroke engine is its low power density as shown in figure 3.17. 2-stroke engines are mostly used in a direct shaft configuration. This is where the engine directly powers the propeller without any gearbox or electrical

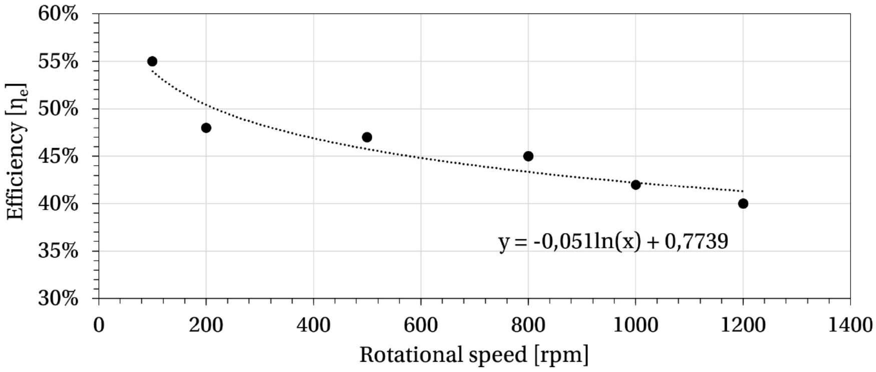


Figure 3.16: Efficiency based on rotational speed [83]

conversions between them. Due to the high rotational speed of the 4-stroke engine, 4-stroke engine drive-train require an gearbox between the engine and propeller to avoid too high propeller speeds resulting in cavitation and propulsion losses [83]. 4-stroke engines are generally used for small power outputs and to generate electricity. Since the Sleipnir has a diesel-electric drive-train configuration, 2-stroke engines will be out of scope for this research.

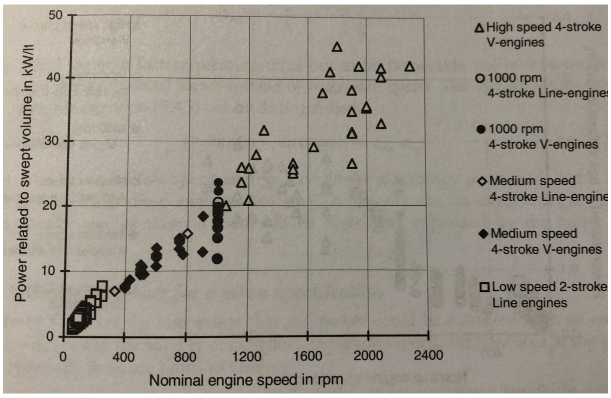


Figure 3.17: Trend between volume specific power for diesel engines and the nominal rotational speed [83]

Spark- compression-ignite engine

The Air-standard cycles are a representation of the ideal cycle that approximate the thermodynamic process of an internal combustion engine[83]. An engine can have different air-standard cycles depending on what kind of fuel it uses. The two most common cycles are the Diesel cycle and the Otto cycle, see figure 3.18 and 3.19. Engines that run on fuels with a very high auto-ignition, usually gasoline, usually run on an Otto cycle. Due to this high auto-ignition, these fuels require a spark to promote ignition, hence the name Spark-ignite (SI) engines. Diesel engines run in a diesel cycle. Ignition of diesel does not require a extra spark but can already occur under high compression resulting in self-ignition. Compression ignite (CI) engines work by compressing air in the combustion chamber, increasing its temperature above the auto-ignition temperature of the fuel, such that injected fuel ignites immediately and burns rapidly. This small explosion causes the gas to expand and forces the piston down, creating mechanical energy [22]. CI-engines usually have a higher efficiency then SI-engines but can be more expensive [83, 51].

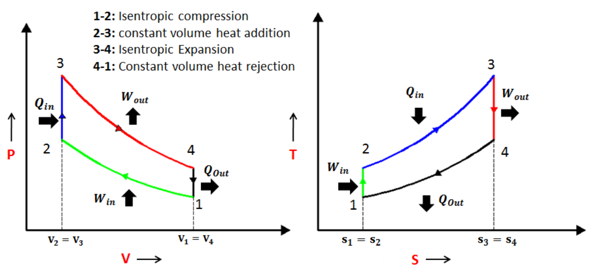


Figure 3.18: Working principal of an Otto cycle [51]

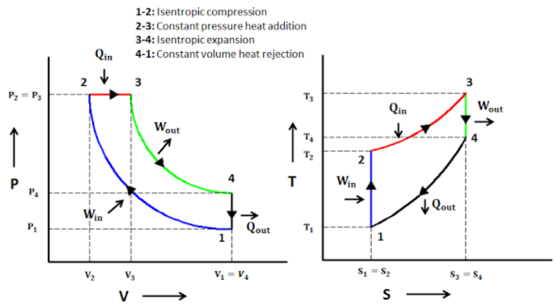


Figure 3.19: Working principal of a Diesel cycle [51]

Fueling option for Internal combustion engines

An ICE can be powered by many different types of single of mixed fuels. Due to the relatively forgiving process in the engines, it has fewer restrictions on the purity of the fuel compared to fuel cells. Because of this, al three DHCs can be used in the combustion engines. Combustion engine fuels are defined by its cetane and octane number. Whereby, the cetane number quantifies the ability to self-ignite, and the octane number quantifies the ability to resist knock. Fuels with a high cetane number are very suitable for CI-engines and fuels with a higher octane number are suitable for Spark Ignition (SI) engines with a higher compression ratio without the occurrence of knock resulting in a higher combustion efficiency [48]. Due to low a cetane and/or octane number, a fuel can have pore combustion behaviour. This means that the fuel is not burning properly and can take place in various ways. With a low octane number, knock can occur in the combustion chamber. In this phenomenon, ignitions take place simultaneously at various places in the chamber, as a result of which the fuel does not burn homogeneously. This results in lower efficiency. The burning rate of a fuel is also a combustion characteristic. A fuel with a slow burning rate takes longer to burn completely in the combustion chamber. This means that the engine has to run at a later speed to ensure complete combustion. Fuels with a slow combustion rate in a high RPM engine will have a lower efficiency because not all of the fuel burns. A pilot fuel can be used to improve the combustion performance of a fuel. By mixing a fuel with very good combustion characteristics with a less good fuel, specific properties can be improved and thus a more complete and homogeneous combustion in the engine can be achieved, resulting in a higher efficiency. This mix can be used in different ratios and will be discussed below per DHC. Equation 3.6 gives the formula needed to calculate the flow rates for different ratios.

$$DER = \frac{\dot{m}_{DHC} \cdot LHV_{DHC}}{\dot{m}_{DHC} \cdot LHV_{DHC} + \dot{m}_{\text{Hydrogen}} \cdot LHV_{\text{Hydrogen}}} \tag{3.6}$$

In this equation:

DER	[-]	DHC energy ratio
$\dot{m}_{DHC}$	[kg/s]	mass flow rate of DHC
LHV_{DHC}	[MJ/kg]	Lower heating value of DHC
$\dot{m}_{hydrogen}$	[kg/s]	mass flow rate of hydrogen
$\text{LHV}_{hydrogen}$	[MJ/kg]	Lower heating value of hydrogen

Hydrogen fueled internal combustion engine

The combustion reaction of hydrogen in an ICE is given in equation 3.7.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat} \tag{3.7}$$

Since air is the oxidiser used in combustion in an engine, NO_X is produced as a by-product.

The ignition range of hydrogen, as discussed in 3.2.4 makes hydrogen favourable for combustion. Due to the low lower limit of 4%, the engine can run on a extremely lean mixture of air/hydrogen. Lean mixtures are more efficient resulting in a lower fuel consumption. This does compromise the volumetric energy density of the engine, which is already low due to the low volumetric energy density of hydrogen. The auto ignition energy of hydrogen is low, 0.02 MJ. This can result in misfiring of the engine. To prevent this, a spark ignite engine is favorable to use when hydrogen is combusted in an ICE.

The burning of hydrogen in internal combustion engines is a process currently being researched by many engine manufacturers. At the time of writing, there are already several dual fuel and single fuel engines available that run on pure hydrogen or on hydrogen with diesel as the pilot fuel. These engines have a relatively low power output of around 500kW and have an electric efficiency of approximately 40%[2-g].

Ammonia fueled internal combustion engine

Ammonia has a high resistance to auto-ignition and very slow combustion kinetics. These characteristics make the combustion of Ammonia in an Compression ignition engine challenging [59]. To increase the performance of ammonia combustion in a SI-engine, a pilot fuel can be used to decrease the auto-ignition temperature, increase the flame speed and increase the flammability limits. Hydrogen is a suitable pilot fuel where a mix of $70\%_{vol.}$ ammonia and $30\%_{vol.}$ hydrogen performs best with respect to efficiency and power [53, 67].

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O + \text{heat} \tag{3.8}$$

A challenge for internal combustion engines running on Ammonia is the possibility of unburned ammonia in the exhaust gas. This may need to be mitigated by an ammonia catch system, like a water curtain. However, if the level of ammonia slip is the same as or lower than the NO_X emissions, this can be mitigated in an SCR system that is installed for the mitigation of NO_X emissions for IMO Tier III regulations.[73].

No ammonia DF engine has yet been commercially available for marine operations, but in experimental set-ups the fumigation technique is commonly used for the injection of ammonia. Furthermore, to enhance the auto-ignition of ammonia, high pressure ratios in the engine are preferred. Wärtsilä is currently researching and developing Ammonia as a fuel for SI and CI engines with field test expected in 2022 from Wärtsilä [30]. MAN claims to have a 2-stroke Ammonia fueled marine engine installed in vessels by 2025 [46].

Methanol fueled internal combustion engine

The combustion reaction of methanol in an ICE is given in equation 3.9.

$$CH_3OH + 3O_2 \rightarrow CO_2 + 3H_2O + \text{heat} \tag{3.9}$$

Methanol presents excellent combustion properties: despite its energy density is less then half of the LNG energy density (20.1 MJ/kg for methanol, 50 MJ/kg for lng) it has a comparable octane number LNG (108 for methanol, 130 for LNG), that allows higher compression ratio and an increase in combustion efficiency [8]. The performance of a engine running on methanol is directly comparably to the engines running on LNG. Both fuels need a pilot fuel to support a satisfying combustion. Since one of the boundary conditions of the new drive-train is that system should have net zero emissions for the Well tot Propeller life-cycle, the methanol combustion engine can not use diesel as a pilot fuel. Another fuel that can be effective to improve the performance of a methanol combustion engine is hydrogen [84]. A 90% methanol and 10% hydrogen blend can be enough for a satisfying combustion in a CI-engine.

Sub-conclusion

The different combustion engine options have been discussed in the section above. All three DHCs can be used in a combustion engine. Due to the low auto ignition energy of hydrogen, a spark ignite engine is the most reliable configuration. Ammonia, because of the narrow ignition range, will be burned together with hydrogen in a Dual fuel Spark Ignite engine. Methanol will be combusted in a Compression Ignite engine with a small volume of hydrogen to get a satisfactory combustion. An overview of the drive-train configurations combining the DHCs and an internal combustion engine is given in figure 3.20.

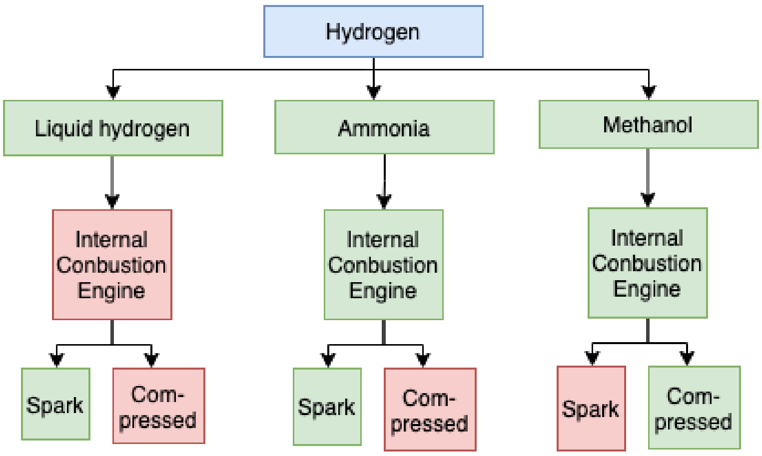


Figure 3.20: Internal combustion engine selection for drive-trains configurations

3.4. Conclusion

In this chapter the different options are discussed for the production of hydrogen, the storage of hydrogen in a dense hydrogen carrier and for the conversion of chemical energy stored in the DHC to electricity. The goal of this chapter is determine the feasible drive-train configurations that can run on DHCs. Three DHCs with the highest potential for use as marine fuel were considered. For each of these DHC, it was then evaluated which fuel cell type and engine type is best compatible. This resulted in a total of six configurations. Since a PEMFC has a higher efficiency than the ICE, and does not produce NO_X during the combustion process, the LH_2-ICE drive-train will no longer be evaluated in this analysis. Although the SOFC has a higher efficiency, it is not included in the study since there are no SOFC units commercially available for maritime propulsion [73]. This results in the final 2 configuration options namely the Ammonia-SI-ICE and Methanol-CI-ICE. The three different configurations are shown in figure 3.21. These three options will be further evaluated in chapter 4 where the drive-train lay-out will be discussed and the heat and mass balance will be calculated.

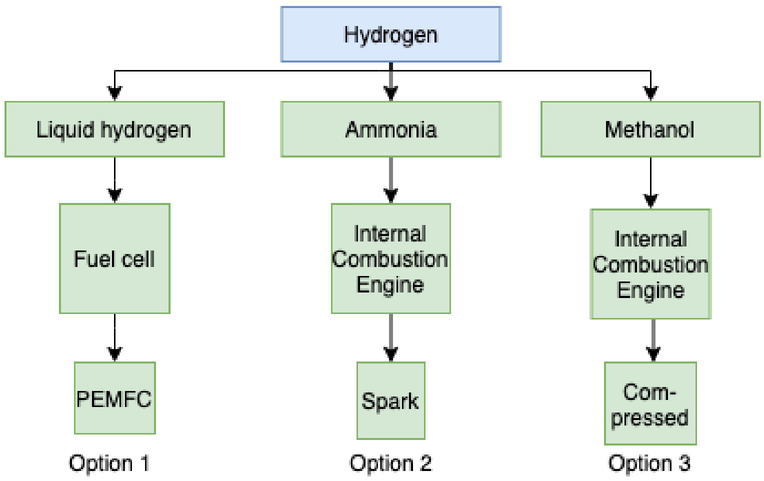


Figure 3.21: Final selection for drive-trains configurations

4 Detailed technical design

This chapter focuses on the further elaboration of the technical designs of the drive-train for the three options defined in the previous chapter. With these designs, an answer will be formulated on sub-question 4: *How do the dense hydrogen carriers influence the drive-train design of the semi-submersible crane vessel?* This chapter is divided into three sections, one for each option. In these sections, first a schematic overview of the drive-train will be given. The main components and specific detailed are discussed. These designs will comply with the classification rules set by the IMO. Second, the heat & mass balance of the three options is calculated and presented. With this calculation, the total efficiency of the systems and the volume of the fuel tanks is calculated. As third and last section in this chapter, a comparison between the findings of the drive-trains is given.

4.1. Liquid hydrogen - proton exchange membrane fuel cell

Option 1 is a drive-train that powers the vessel using liquid hydrogen in an proton exchange membrane fuel cell. This drive-train design is mostly dominated by the regulations for Gas fuelled ship installations and Fuel Cell installations [16]. Figure 4.1 gives a schematic overview of the different components required.

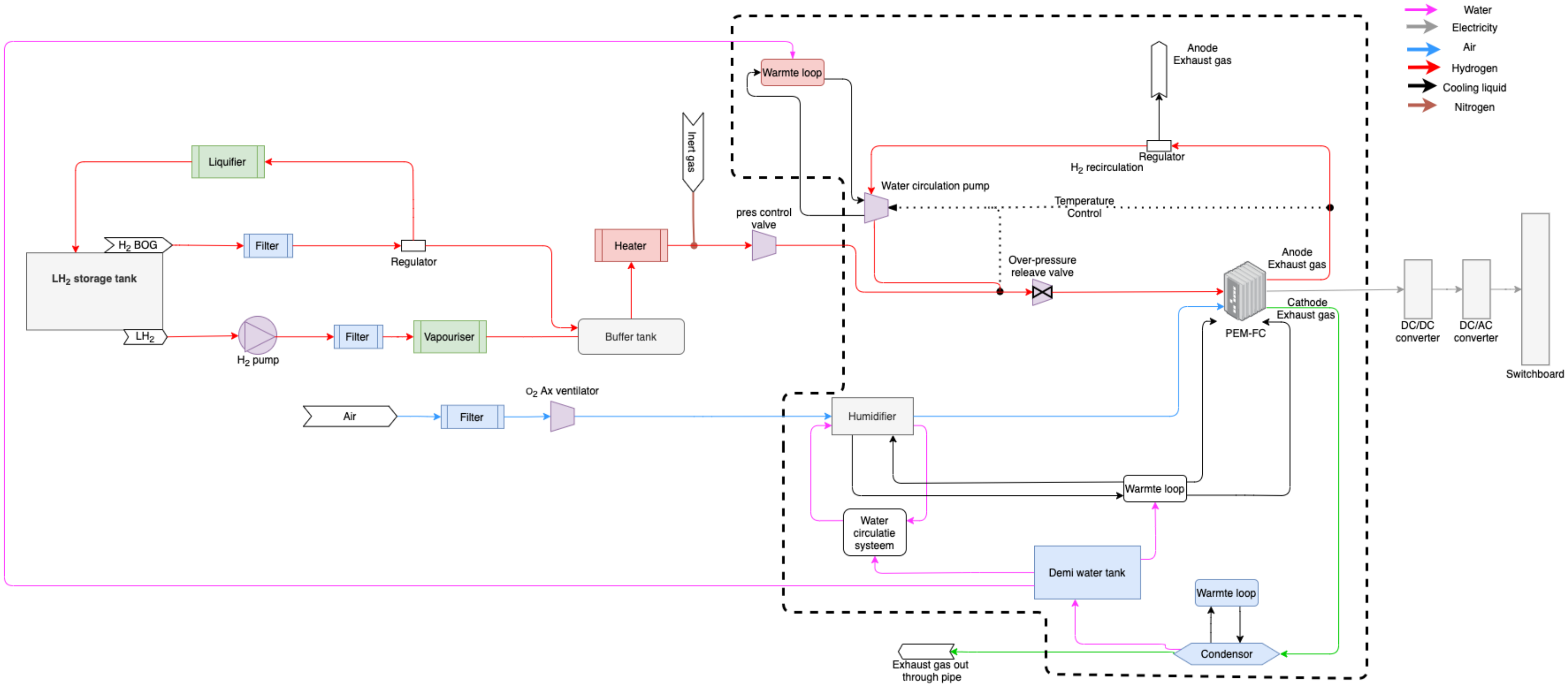


Figure 4.1: Single line diagram for a LH_2-PEMFC system

Fuel cell selection

There are several manufacturers globally that produce proton exchange membrane fuel cells for marine applications, like Ballard Powersystems, NEL Hydrogen and Nedstack Fuel Cell Technology B.V.. Due to an existing relationship between Heerema and Nedstack, it was decided to use their 500kWe maritime purpose fuel cell system for this study. If another PEM system is chosen, the size and components of the system may be different but the performance are expected to remain similar.

The PemGen MT-FCPP-500 fuel cell from Nedstack is a ready-to-use system available in a 20 foot container. All components within the black doted line, see figure 4.1, are installed inside this system. It has a nominal power of 500kWe and a peak power of 626kWe. During normal operations it has a hydrogen demand of 65 kg/MWh resulting in a loss of 1164 kWh. These losses can be divided in operational losses en system losses. The chemical reaction in the stacks has an efficiency of 55%. The electricity needed to operate the fuel cell is approximately 88% of the produced electricity, resulting in a 48% efficiency. An overview of the main specifications can be seen in table 4.1. The System has 60 Nedstack FCS 13-XXL cells installed and the electrical curve for such cells is shown in figure 4.2.

Table 4.1: Specifications of the PemGen fuel cell system [Nedstack]

PemGen MT-FCPP-500 system			Fuel Cell Model	60 x Nedstack FCS 13-XXL	
Dimensions		**Electrical**		**Additional**	
Weight [kg]	15 000	Nominal Power [kWe]	500	Fuel Quality	Grade ≧ 2.5
Length [m]	6.06	Peak Power (BoL) [kWe]	626	H_2 supply pressure [bara]	1.3-7
Width [m]	2.44	Voltage range [VDC]	300-600/600-1200	Balance of plant [years]	20
Height [m]	2.90	Current range [A]	0-200/0-400	Stack refurbishment [*1000h]	24-30 running hours

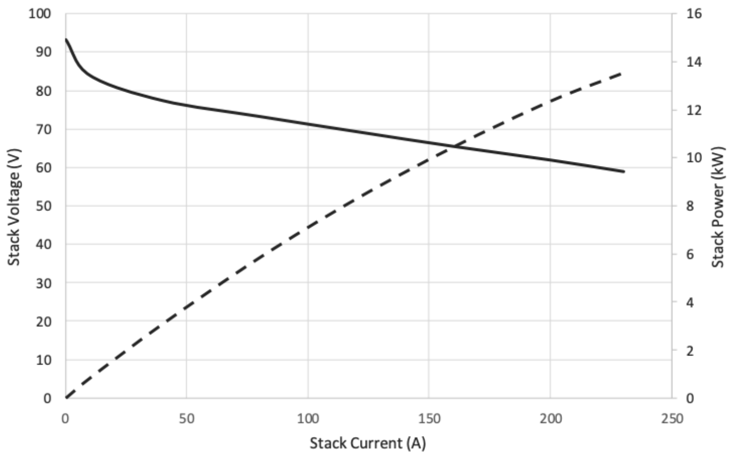


Figure 4.2: Current voltage curve for Nedstack FCS 13-XXL cell [Nedstack]

Storage of liquid hydrogen

Of the three DHCs investigated in this thesis, liquid hydrogen is the most challenging fuel to store, which is due to its extremely low storing temperature.

The conventional way of storing liquid hydrogen is a double wall cylindrical tank with a vacuum in between to reduce heat transfer and minimize BOG production. This vacuum is filled with perlite to increase the insulation. Single wall tanks are not likely to be used since these tanks increase the boil off gas that is produced due to limited insulation. The liquid hydrogen tanks that can be used are similar to the LNG tanks that are currently used. The main difference is the material used as the inner wall of the tank. Since hydrogen molecules are much smaller then methane molecules, there is a bigger change of leaking through the inner wall. To prevent this, the inner wall will need to meet higher standards. 316L Stainless steel (SUS304L) is considered possible material to use for the inner wall due to its low temperature durability [56].

Because of the insulation and double wall, the whole system is expected to have a 20% volume increase. another aspect that must be taken into account when calculating the volume, is that when the hydrogen tanks get emptier, the temperature of (the material of) the tanks will increase. This can cause deformation and stress in the system which can lead to failure. Although this phenomenon is well known, no concrete solution has been found yet. At present, it is minimised by having a minimum amount of hydrogen in the tank. Advice on how much this amount should be varies and lies between 10 and 30%. This thesis will assume 20%[81]. This results in a system volume that must be 1.44 times greater than the amount of hydrogen used.

This configuration consumes 7300m^3 of hydrogen per fueling cycle. At the time of writing, NASA has the largest LH_2 storage tank in the world with a volume of 3800m^3. This is a double-walled system with glass bubble insulation in between. However, this construction requires a stable subgroup to support the volume of hydrogen in the tank and is therefore not a good option on a ship. The material used to reinforce the tanks on board will be made of is most likely a Glass Fiber Reinforced Polymer (GFRP). This material can support an inside tank with a volume of 1000-2000 m^3 depending on the diameter of the tank. For this reason, the 7300 m^3 will be divided into 7 tanks of approximately 1500 m^3 storage capacity.

To minimise the risk of explosions in the fuel tanks containing liquids, the empty space should be filled with an inert gas instead of air. Inert gasses, most likely nitrogen due to low cost, are chemicals that do not undergo any chemical reactions with another material. In this way, the liquid hydrogen cannot react with the other chemicals in the tank so that no hazards or unwanted mixtures can form.

Liquid hydrogen fuel supply line

The liquid hydrogen stored in the storage tank goes through a number of steps before being used in the fuel cell, see figure 4.3. First the LH_2 will be filtered to remove any impurities that may have been in the tank and can influence the performance of the fuel cell. Next the LH_2 will be vaporized to a gaseous state. Due to the evaporation of the hydrogen, a pressure and temperature increase will take place. After the vaporizer the hydrogen will be heated to the required temperature of 63°C by the fuel cell. In this heater it will be mixed with the hydrogen from the BOG. After the heating step, it will go through a pressure control valve. The final step before entering the fuel cell is an over-pressure release valve. In case of an uncontrolled pressure increase, this valve will shut off the hydrogen supply to the fuel cell to prevent damage to the membrane.

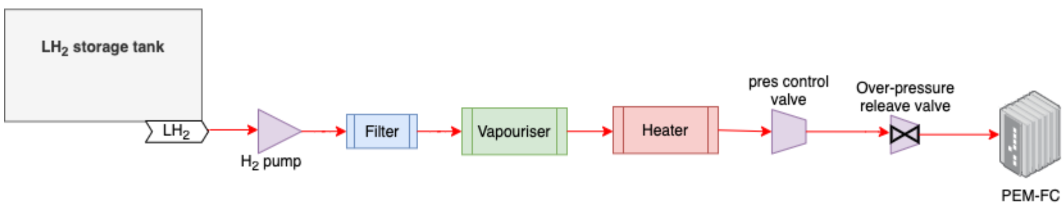


Figure 4.3: Liquid hydrogen fuel supply line

Liquid hydrogen vaporizer Currently, regasification of liquid hydrogen is not a commonly used process. However, the regasification process of LNG is comparable to that of liquid hydrogen [44]. By far the most widely used technology by LNG terminals for regasification of LNG is the Open Rack Vapourisers (ORV) heated by seawater [2]. These systems can run on only using seawater, but when the seawater temperature reaches below 5°C, extra heat is required to operate the ORV. This can be extracted from the power unit.

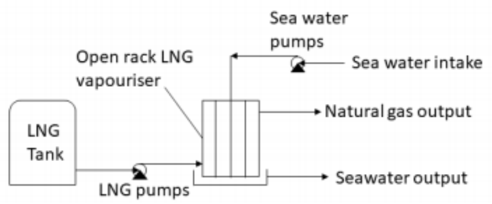


Figure 4.4: Lay-out of a LNG vaporiser

Boil-off gas fuel line

A liquid hydrogen storage tank, just like a LNG storage tank, has to cope with boil-off gas inside the tank. Since the new drive-train will be in constant operation, this BOG can be used to power the Fuel cell, see figure 4.5. This will minimize losses. This flow line has a lower energy consumption than the liquid hydrogen fuel loop since this flow line starts with a gaseous fuel and does not require the pump-vaporizer system. Therefore, this flow line is preferred. By using all the BOG in the fuel cell, the BOG does not need to be re-liquefied, which also required a high energy input. This liquefaction line is however still installed on board of the vessel in case of emergency situations when the fuel cell is shut off and the BOG can not be used in the fuel cell.

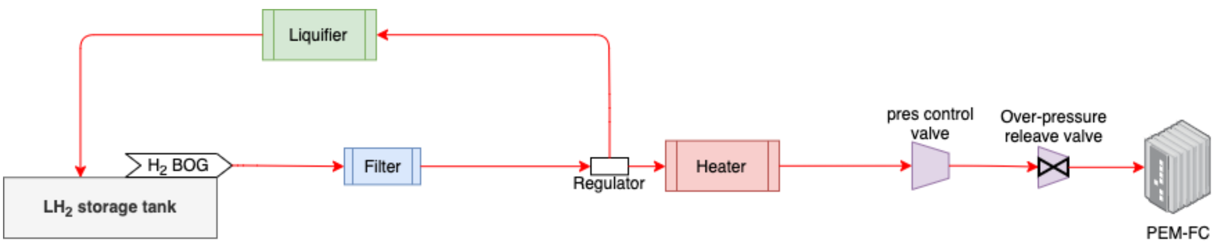


Figure 4.5: Boil-off gas hydrogen supply line

The BOG in a liquid hydrogen tank is estimated to be between 0.3-5% per day [57]. Figure 4.6 gives an overview on how much liquid hydrogen evaporates in the tanks. The BOG rate can be controlled by changing the pressure inside the tank. By lowering the internal pressure, the BOG rate increases. This way, the rate can be controlled to maximise the BOG production and with that limit the required liquid hydrogen. This will increase the overall efficiency of the system.

Air supply line

The oxygen needed at the cathode side of the fuel cell is taken from the air. This air first passes through a filter to remove particulates and other impurities. The oxygen supply of the fuel cell can be supplied under ambient pressure. Due to the pressure drop of a maximum of 0.12 bar in the cell, it is possible that the direction of the air supply is reversed. This is called a back pressure and it is important that there that this will not occur at the cathode exhaust. To prevent this, a fan should be installed after the filter to ensure a constant flow in the correct direction. In addition to regulating

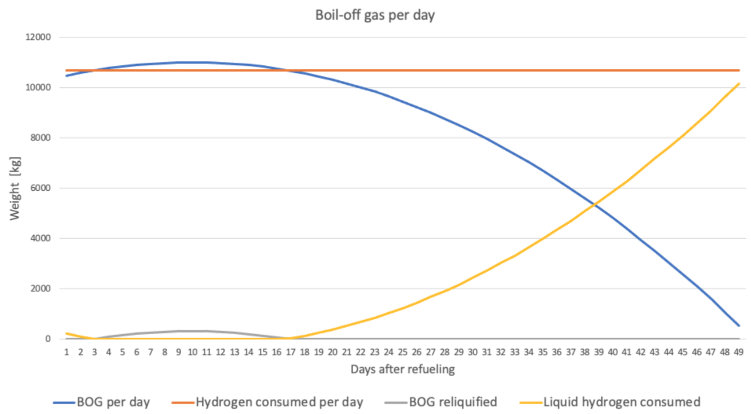


Figure 4.6: Boil-off gas produced per day with 2.5% BOG production.

the pressure, the air must also be brought up to temperature and have the correct humidity. This happens in the humidifier. The warm moist gases from the cathode exhaust are used to bring the new air supply up to the right conditions.

Hydrogen recirculating line

To ensure that enough hydrogen and air reacts to produce electricity, a surplus of hydrogen is injected into the cell. These proportions are shown in table 4.2. Part of the hydrogen does not react in the cell and will leave the cell again via the anode exhaust. Besides the non-reacted hydrogen there is also water vapour in the anode exhaust. About 10% of the water created in the cell passes through the membrane from the cathode to the anode. The third substance in the anode exhaust mix is the 0.5% hydrogen along with any impurities purged from the cell. This anode exhaust mix is heated to 67 °C by the exothermic reaction in the PEMFC.

The anode exhaust mix first passes through a regulator which removes the impurities and purged hydrogen from the mix. The water and hydrogen are then routed back to the hydrogen supply line. By mixing this warm and moist mix with the new fresh hydrogen, the supply for the PEMFC is brought to the right temperature and humidity for a good reaction.

A temperature control system between the three points as shown in figure 4.7 regulates the flow of the hot water and hydrogen mixture to ensure that the temperature and humidity of the anode input is always stable.

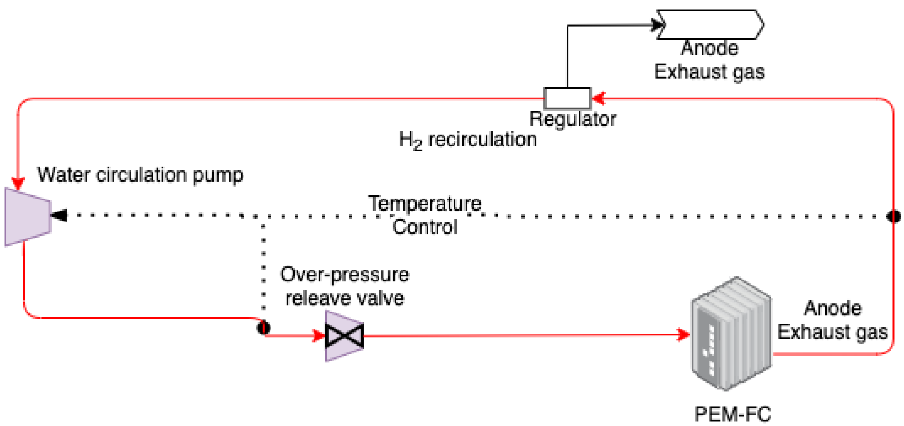


Figure 4.7: Hydrogen recirculating line

Transformer system

A Fuel cell produces an varying direct current (DC) electrical output. DC electricity is mostly used in low voltage applications such as charging batteries and automotive applications. This varying current will undergo two conversion steps before it can be distributed throughout the vessel via the switchboard. The first conversion is a DC/DC transformer. This transformer stabilise the output from the fuel cell. Since Sleipnir is running on a Alternating Current (AC) electrical system, the second step required is a DC/AC power inverter, converting the electricity into an 60Hz frequency.

The typical performance of an electricity transformer is shown in figure 4.9. The figure shows that operating below 20% of the rated power output should be avoided. Since the Hotel load of the Sleipnir has a relatively steady power demand of 6.5 MW. The transformer will not operate in this region. An efficiency of 96% is assumed per transformer in the system. This results in an total efficiency of 92% for the transformer system to convert the electricity output of the fuel cell to a usable AC current in the switchboard [17].

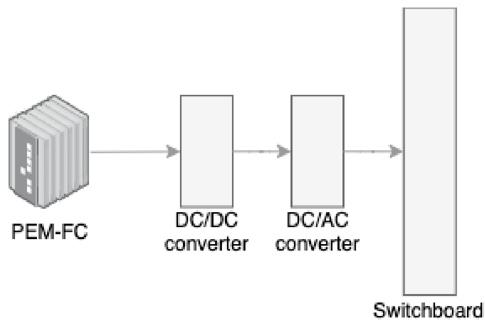


Figure 4.8: Overview of electrical components

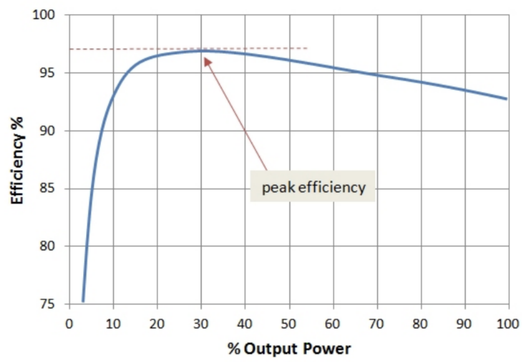


Figure 4.9: Typical efficiency curve for inverters [49]

Nitrogen safety system

The reaction inside the fuel cell is an uncontrolled continuous reaction, as long as there is hydrogen and oxygen inside the cells, there will be a reaction creating electricity and water. For a normal procedure shut-down of the system, the oxygen supply line will be shut off. This way, the hydrogen present in the system will continue reacting with the hydrogen until no oxygen and/or hydrogen is left in the system. This process can take up to 5 minutes. When an emergency shutdown is required, 5 minutes is too long. Therefore an nitrogen safety system is installed. This system can blow all hydrogen present in the pipelines out of the system. With this, not only the oxygen and hydrogen supply are shut off but also all of the hydrogen in the system is removed. This stops the hydrogen oxygen reaction within seconds.

4.1.1. Heat & mass balance

A heat & mass balance is made for the LH_2-PEMFC drive-train. This was conducted together with an engineer from the company NedStack. An overview of the flow rates is given in table 4.2, Table 4.3 displays the mass input and output of the fuel cell.

Table 4.2: Overview of heat and mass balance for LH_2-PEMFC system

	Power out	Power in	Hydrogen out		Hydrogen in		Efficiency
	[kW]	[kW]	[kg/s]	[kW]	[kg/s]	[kW]	[% LHV]
Hydrogen supply line	0	0	0.123	14 660	0.122	14 666	-
Fuel cell system	7 050	0	0.0456	5 410	0.168	19 960	48.5
Transformer system	6 500	7 050	0	-	0	-	92.2
Switchboard	6 500	6 500	0	-	0	-	100

Table 4.3: Chemical reaction in the PEM fuel cell

Input		
New H_2	0.1224	[kg/s]
recirculated H_2	0.0456	[kg/s]
Oxidizer	8.743	[kg/s]
Output		
Mechanical power	7 053	[kW]
Losses	7 489	[kW]
Hydrogen venting	0.0010	[kg/s]
Hydrogen for recirculating	0.0456	[kg/s]
Oxygen	7.94	[kg/s]
Water	1.094	[kg/s]
Fuel cell Efficiency [LHV]	48.5%	

Now that the hydrogen flow rate has been calculated, an assessment can be made of how much hydrogen is needed to design a continuous running system. With the assumption that refueling takes place every 7 weeks, the vessel will consume 62.000 GJ of hydrogen per fueling cycle resulting in an on-board efficiency of 44%. This results in a consumption of 7360 m^3 of LH_2. The fuel storing system for this requirement will have a volume of approximately 10.600 m^3 including the space needed for insulation system and the minimal amount of LH_2 that needs to stay in the tanks. The sankey diagram of the liquid hydrogen powered drive-train is given in figure 4.10.

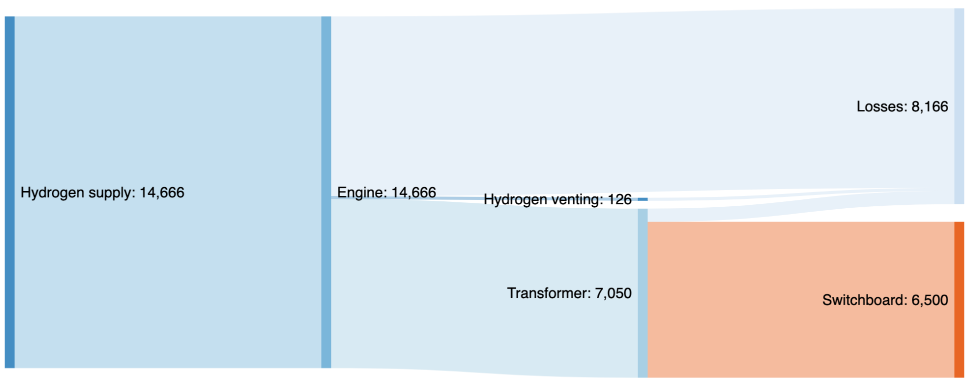


Figure 4.10: Sankey diagram of the liquid hydrogen powered drive-train in kW

4.2. Ammonia - internal combustion engine

Option 2 is a drive-train that powers the vessel using ammonia in a spark-ignite dual fuel internal combustion engine. This drive-train design is mostly dominated by the regulations for Gas fuelled ship installations. [16]. Figure 4.11 gives a schematic overview of the different components required.

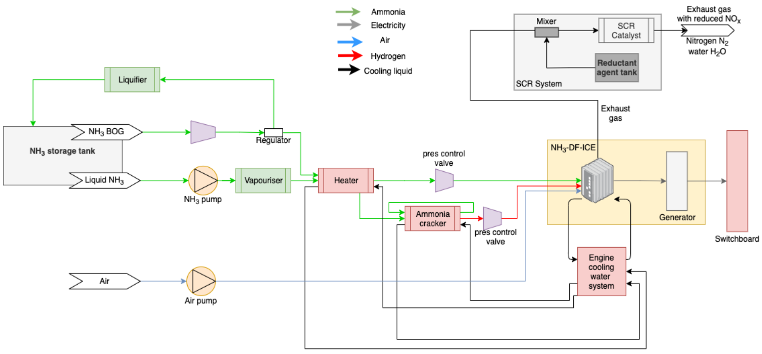


Figure 4.11: Single line diagram for a NH_3-DF-ICE system

Storage of liquid ammonia

On-board storage of ammonia can be done in two ways:

- For quantities up to 50 000 t, ammonia is stored at atmospheric pressure and -33 °C in insulated tanks. At this temperature the ammonia is a liquid resulting in a density of 19 GJ/m^3. Like with LH_2, BOG will also occur for the stored refrigerated ammonia. As with the storage of liquid hydrogen, insulation of the ammonia tank also requires extra space for the double wall and other insulation systems. Because the storage temperature for ammonia is much lower than for liquid hydrogen, a margin of 5% is taken for the double wall. Also, only 5% of the volume needs to remain in the tank at all times to prevent too high temperature fluctuations.
- For smaller quantities of up to 1500 tons, ammonia can be stored under a pressure of 10 bar in stainless steel spheres [41]. At this pressure, the ammonia will liquefy and have the same energy density as Ammonia stored at -33 °C. With this storing method BOG does not occur. However, ammonia is commonly stored at approximately 17 bar to keep it in the liquid phase when the ambient temperature increases.[47]

As calculated in section 4.2.1, a total of 3.421 ton of ammonia need te be stored to comply with the operational profile requirements. Following the DNV-GL rules for classification, at least two storage tanks shall be installed on the vessel to provide enough redundancy in case of failure. In this new drive-train the ammonia will be stored in five 1.100m^3 tanks each able to store approximately 750 tonnes of ammonia.

One other classification rule is the use of a buffer tank for daily operations. This tank will be filled one or two times per day and will power the engine. This way, the engine will not be continually in connection with the main fuel tanks minimizing explosion risks. Again, to provide redundancy, at least two service tanks must be installed, each with a minimal capacity sufficient for 12 hours operation at maximum fuel consumption. Fuel cargo tank can be placed under deck, the daily service tank must be situated on deck and must have a venting system installed for emergency operations.

The DNV-GL rules for classification also has restriction on the locations of the cargo and service tanks. The service tank must be positioned on deck and have a venting system installed so direct venting of fuel gasses can be executed in case of emergency's. The cargo tank can be installed below deck but must be positioned at least 760mm from the hull for inspection access [16].

ammonia supply line

The ammonia supply line is given in figure 4.12. The pressurized ammonia that is in liquid stage stored in the service tank is fist pumped through a vaporised. Next it will be heated before being used in the combustion engine. After the heater, 30%$_{vol}$ of the ammonia will go to the Ammonia cracker for hydrogen reforming. The resulting 70% will directly be injected into the engine. Similar to the storage classification, DNV-GL dictated that for all components in the fuel supply line, enough redundancy must be build in that one single failure does not cause a shut down of the system [16]. Other rules include that all piping should be double walled and that the complete fuel supply system has to be entirely separate from all other piping systems. All piping below deck must not only be double walled but also ventilated. If the ammonia is stored at -33 °C, BOG will occur. This is however at a much lower rate compared to the storage of liquid hydrogen. The BOG rate for ammonia is between 0.05 and 0.1% per day [3]. This gas will be used in the supply line to power the engine. However, in case of emergency situations a liquefier will have to be installed to re-liquefy the BOG when the engines are shut-off.

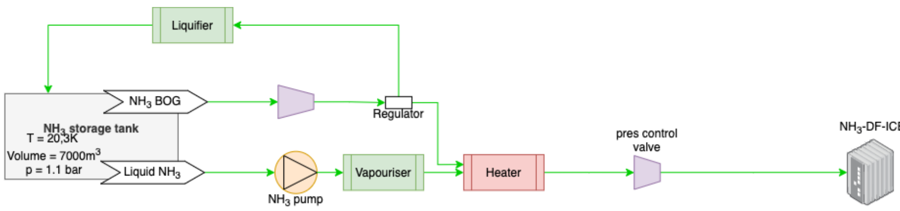


Figure 4.12: Ammonia supply line

Ammonia cracker

The ammonia cracker has been introduced in paragraph 3.3.2. As discussed in chapter 3, the ICE requires an pilot fuel to enhance the combustion characteristics of ammonia. In this case hydrogen, reformed from ammonia, is used as the pilot fuel. For this process an ammonia cracker is installed that will split the ammonia into hydrogen and nitrogen, see equation 4.1.

$$2NH_3 = N_2 + 3H_2 + heat \tag{4.1}$$

This process is an endothermic reaction which means it requires heat input. While ammonia starts to decompose spontaneously at temperatures exceeding 200 °C. Higher temperatures, typically above 650 °C, must be supplied in combination with a catalyst (nickel oxide or iron oxide are commonly used [25]) to achieve high conversion rates [4]. A full hydrogen yield is not required in this drive-train since the hydrogen will be mixed with ammonia in the power-unit. A schematic overview of an ammonia cracker is given in figure 4.13. For this case study a yield of 91% at a temperature of 227°C was derived from figure 4.14 .

Selective catalytic reduction system

To comply with the IMO TIER III regulation, a SCR system needs to be installed located at the exhaust pipeline. This SCR system operates in the same way as the currently installed system on board of the Sleipnir, see paragraph 2.2.4. As reductant agent, multiple chemicals can be used such as urea and ammonia. For this drive-train ammonia is chosen since the ship already has a handling system for this chemical installed. Since there are no existing drive-trains using ammonia as a fuel, the exact amount of NO_x emissions is not yet know and more experiment have to be done to precisely

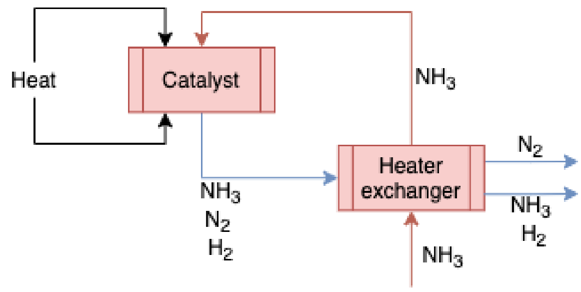


Figure 4.13: Principal of an ammonia cracker

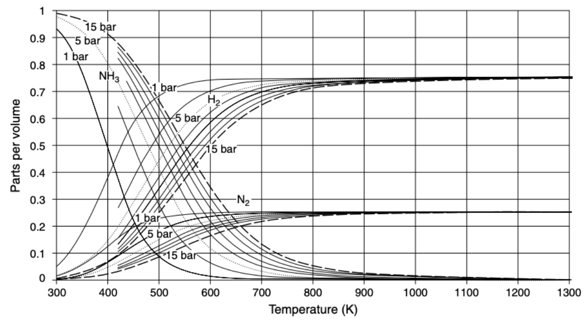


Figure 4.14: Ammonia, hydrogen and nitrogen ratio at different temperatures[25]

determine the reduction of NO_x emissions using a SCR system. It is however assumed, after experimental cases, that the NO_x emissions after the SCR will not be higher than the emissions of MGO [73].

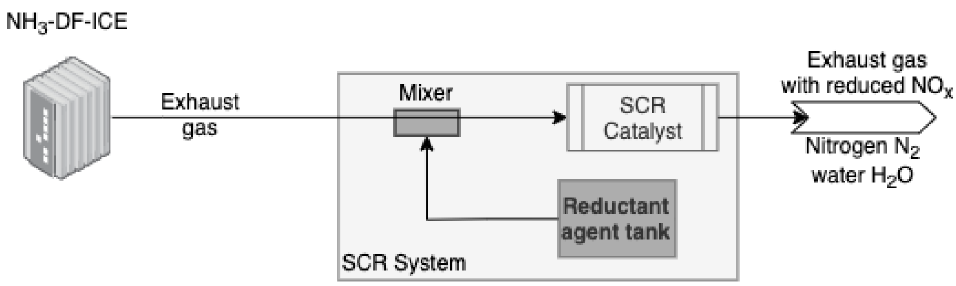


Figure 4.15: Lay-out of the relective catalytic reduction system

Engine cooling system

The internal combustion engine will produce a great amount of heat during the combustion of Ammonia. The exact heat production will be calculated in the heat & mass balance. Fortunately this heat will fully be lost. A part of it, 30% of energy consumption [83] can be converted to reuse-able heat for other systems. A part of this heat will be used in the pre-combustion systems to heat and crack the ammonia. The rest of the usable heat can be used for other purposes but since the ship's current drive-train already produces a surplus of heat, it can be assumed that this heat is lost.

Generator system

To convert the mechanical energy of the combustion engine into electricity, a generator must be placed behind the engine. In this case, because the Sleipnir's electricity grid is alternating current, an alternator must be installed. The alternators that are in the Sleipnir's current system can be used for this. The alternator must provide an 11kV 60Hz alternating current output to be connected to the grid.

4.2.1. Heat & mass balance

A heat & mass balance is made for the NH_3-ICE drive-train. The goal for this calculation is to determine to overall efficiency of the system en the required volume of storage tanks. Due to the conversion losses of the generator (95% efficiency), the engine requires a 6.84MW mechanical energy output. With an efficiency of 45% the engine consumes 15.2MW of fuel. The $70\%_{vol.}$ ammonia and $30\%_{vol.}$ hydrogen mix results in a $96\%_{weight}$ ammonia and $4\%_{weight}$ hydrogen ratio. The mass and energy flows of the engine are given in table 4.4. Assuming that 30% of energy consumption [83] can be converted to reuse-able heat, the vaporizer, heater and ammonia cracker can run on this heat and do not require extra energy input.

Table 4.4: Heat and mass balance Duel fuel combustion engine at 6.5MW power

Input		
NH_3	0.776	[kg/s]
H_2	0.005	[kg/s]
Oxidizer	9.82	[kg/s]
Output		
Mechanical power	6 840	[kW]
Exhaust gas heat available	4 560	[kW]
Losses	3 800	[kW]
Exhaust gas	10 601	[kg/s]
Engine Efficiency [LHV]	45%	[84]

Table 4.5: Heat and mass balance Ammonia reformer

Mass in		
NH_3	0.0317	[kg/s]
Heat in		
Required heat	20.46	[kW]
Heat requirement cracker	106.94	[kW]
Mass out		
H_2	0.005	[kg/s]
NH_3	0.0029	[kg/s]
N_2	0.024	[kg/s]
Reformer Efficiency [LHV]	84%	

Knowing the required ammonia and hydrogen flow, the size of the Ammonia cracker can be calculated. Using the previously determined 91% conversion rate, the cracker requires 0.0317 kg/s ammonia to produce enough hydrogen. The ammonia is first brought up to a temperature of 500 °K. Next it will be cracked, for which it requires a power of 107 kW. The heat and Mass balance is shown in table 4.5. Including the 91% conversion rate and the required heat for the system. The overall efficiency of the ammonia cracker is 84% (LHV). By adding the direct and indirect ammonia flow from the cracker and engine together, the total flow of 0.81 kg of ammonia per second is calculated. This results in a total onboard efficiency of 43%. With the assumption that refueling takes place every 7 weeks, the vessel will consume 64300 GJ of ammonia per fueling cycle. This results in a consumption of 5010 m^3 of NH_3. The fuel storing system for this requirement will have a volume of approximately 5260 m^3 including the space needed for insulation system and the minimal amount of NH_3 that needs to stay in the tanks. The sankey diagram of the ammonia powered drive-train is given in figure 4.16.

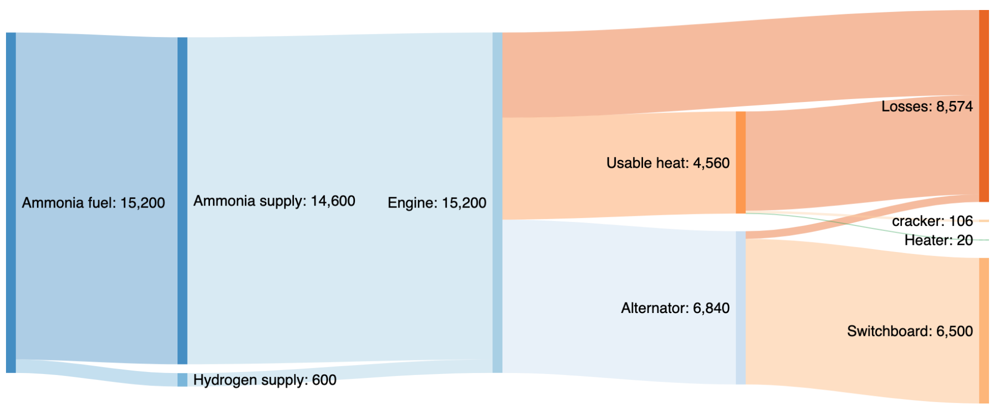


Figure 4.16: Sankey diagram of the Ammonia powered drive-train in kW

4.3. Methanol - internal combustion engine

Option 3 is a drive-train that powers the vessel using methanol in a compression-ignite dual fuel internal combustion engine. This drive-train design is mostly dominated by the IMO regulations for Low-flashpoint liquid fuels 4.17 gives a schematic overview of the different components required.

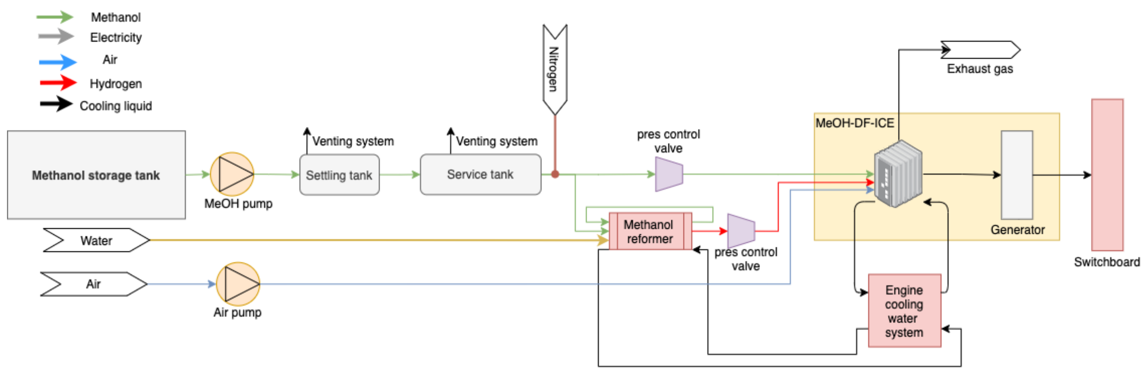


Figure 4.17: Single line diagram for the Methanol fuel drive-train

Storage of methanol

Methanol is liquid at ambient temperatures making the storage installation less complex then the liquid hydrogen and Ammonia. However, when comparing methanol with conventional fuel oils, the configuration is considered more complex due to the corrosive properties of methanol [34]. Methanol can be stored in stainless steel tanks or in cargo tanks made of carbon steel with coatings to protect the carbon steel from corroding. Carbon steel is cheaper but will require a higher operational expenditure since it needs more maintenance. There are no limitations regarding the storage capacity of methanol tanks since the fuel is a liquid at ambient temperatures. Due to the low flash point of the fuel, there are extra restrictions regarding the tanks. These are mostly focused on the extra venting- and gas detection systems to prevent gas build up in the tanks. To prevent impurities from the cargo tank getting in the engine, an extra settling tank is situated before the service tank. This tank is designed to let heavier particles in the fuel settle to the bottom to so they can be removed. The service tank has the same requirements as the ammonia-drive design. Both the settling and service tank will have to placed on deck and should be outfitted with a safety system to limit the change of mechanical damage. The empty space in storage tanks filled with methanol must be filled with an inert gas to prevent the possibility of oxygen burning.

Fuel supply line

Due to the low flash point of methanol, explosion hazard is the most important factor to consider in the design of the fuel supply line. Because of the low temperature at which enough methanol evaporates that an ignition can take place (flash point), additional regulations have been drawn up concerning the fuel handling system so that no methanol vapor can be build up at any unwanted location and cause a fire hazard. These regulations are divided into three parts:

1. The first part is the system from the cargo tank to the daily service tank. All piping in this part can be standard single walled piping.

2. The second part is the system between the fuel service tank and the combustion engine. All piping located below deck shall be double-walled and fitted with a ventilation system. The piping on deck can be standard single-walled piping. All piping should be installed with gas-freeing and an inerting systems. All pre-systems should be entirely separate from all other

piping systems on board and should be placed on the deck whenever possible. Placement of any pre-engine systems in an engine room is forbidden.

3. The third and final part is the engine itself and the post-combustion systems. The engine will be outfitted with additional methanol booster injectors to ensure correct injection of the fuel. The use of methanol in an ICE will also result in additional lubrication precautions. The use of methanol as a fuel generally enhances a cleaner lubricating environment, but results in significantly more engine wear compared to fuel oil. This wear can affect the operation and durability of the engine.

Methanol reformer

Similar to option 2, a part of the methanol needs to be reformed to hydrogen that will be used as a pilot fuel in the engine. The most common way to reform methanol into hydrogen and carbon dioxide is with a methanol steam reformer (MSR) where the methanol will react with water, see equation 4.2.

$$CH_3OH + H_2O = CO_2 + 3H_2 \tag{4.2}$$

A. Iulianelli et al[37] did a review an different studies regarding the reforming of methanol and found that at temperatures at 250°C and higher, conversion rates of 100% can be achieved. However, a by-product of the reforming process is carbon monoxide. This is a toxic material and it is therefore preferable to minimize the formation of this. Operating at lower temperatures of around 200-250°C [60], will minimize the formation of Carbon monoxide. Since a conversion rate of 100% is not required, since the hydrogen will be mixed with methanol after the reforming. This thesis will continue calculating with a conversion efficiency of 90% at a temperature of 225 °C (500 °K), adapted from S. Sá et al[64], see figure 4.19. An overview of the installation is given in figure 4.18.

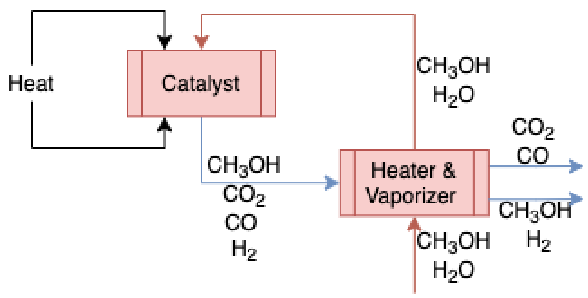


Figure 4.18: Overview of a methanol reformer installation

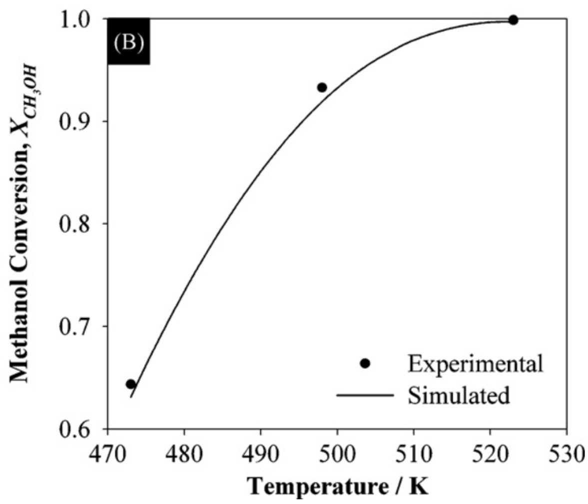


Figure 4.19: Methanol conversion vs reaction temperature for MSR reaction (adapted from S. Sá et al[64]

Other systems

The engine cooling and generator system of this design will be the same as of the Ammonia powered drive-train.

4.3.1. Heat & mass balance methanol

The heat & mass balance for the third option is very similar to that of the ammonia drive-train. The efficiency of the methanol-hydrogen combustion engine is the same at 45% [84]. Resulting in an engine fuel consumes 15.2MW. Methanol requires a $90\%_{vol.}$ to $10\%_{vol.}$ mixing ratio with hydrogen resulting in $99\%_{weight}$ methanol and $1\%_{weight}$ hydrogen to improve the combustion. An overview of the flow rates in the engine is given in table 4.6.

Table 4.6: Heat and mass balance Duel fuel combustion engine at 6.5MW power

Input		
MeOH	0.76	[kg/s]
H_2	0.0015	[kg/s]
Oxidizer	9.84	[kg/s]
Output		
Mechanical power	6 840	[kW]
Exhaust gas heat available	4 560	[kW]
Energy losses	3 800	[kW]
Exhaust gas	10 601	[kg/s]
Engine efficiency [LHV]	45%	[84]

Table 4.7: Heat and mass balance methanol reformer

Mass in		
MeOH	0.009	[kg/s]
H_2O	0.005	[kg/s]
Heat in		
Required heat	4.77	[kW]
Heat requirement cracker	61.17	[kW]
Mass out		
H_2	0.0015	[kg/s]
MeOH	0.001	[kg/s]
CO_2	0.011	[kg/s]
Reformer efficiency [LHV]	81%	

Knowing the required methanol and hydrogen flow, the size of the reformer can be calculated. Using the previously determined 90% conversion efficiency, the reformer requires 0.009 kg/s methanol to produce enough hydrogen. The methanol is first brought up to a temperature of 512 °K. Next it will be cracked, for which it requires a power of 61 kW. The heat and Mass balance is shown in table 4.7. Assuming that 30% of energy consumption [83] is converted to reuse-able heat the heater and methanol reformer can run without requiring extra energy input.

By adding the direct and indirect methanol flow from the cracker and engine together, the total flow of 0.76 kg of methanol per second is calculated. This results in a total efficiency of 43%. With the assumption that refueling takes place every 7 weeks, the vessel will consume 64400 GJ of methanol per fueling cycle. This results in a consumption of 4100 m^3 of methanol. The sankey diagram of the methanol powered drive-train is given in figure 4.20.

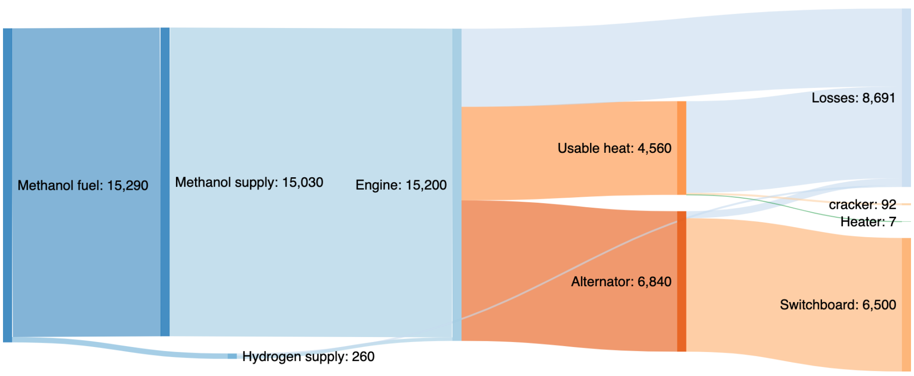


Figure 4.20: Sankey diagram of the methanol powered drive-train in kW

4.4. Conclusion

In this chapter, the new drive-train designs are covered. In addition, a heat & mass balance has been made to calculate the efficiency and fuel flows of the designs. This makes it possible to calculate the volume of the largest component of the system, the fuel cargo tank. Furthermore, the total fuel use per year can be calculated. An overview of the calculations can be found in the table 4.8.

Table 4.8: Summary of the findings

	Option 1 **LH_2-PEM**	**Option 2** **NH_3-ICE**	**Option 3** **MeOH-ICE**
Total onboard efficiency [% LHV]	44	43	43
Fuel used per year [ton/year]	3 285	21 504	20 329
Cargo tank volume required [m^3]	10 600	5 260	4 100
Energy stored in fuel tank [GJ]	62 091	64 318	64 360

Compared to the on-board efficiency of the current system, the three options have a much higher efficiency. Especially the efficiency of option 2 and 3 stand out because they are approximately 10% higher while having a similar power unit to the current system. This can be explained by the operating mode of the engines. As discussed in chapter 2, the Sleipnir must have a minimum number of engines running in order to comply with DP3 classification. Because of this, multiple engines will run on part load and therefore have a lower efficiency. The new systems will only deliver a part of the total energy demand and are designed to meet this demand in the most efficient way. During working mode, e.g. during crane operations, multiple engines are running in order to deliver the required power demand which is higher than 6.5MW. This way it complies with DP3 regulations. A further elaboration on the topic is included in chapter 7.

Even though the difference in efficiency is relatively small between the three options. There is significant difference in the required volume for the storage system. This is mainly because of the difference in density of the different fuels. Liquid hydrogen with an energy density of 9.98 MJ/l requires more than twice as much volume, despite the fact that less kilos of fuel are needed. This difference is further increased by the extra space required for the storage system. Figure 4.21 shows the difference fuel that can be stored in the same area.

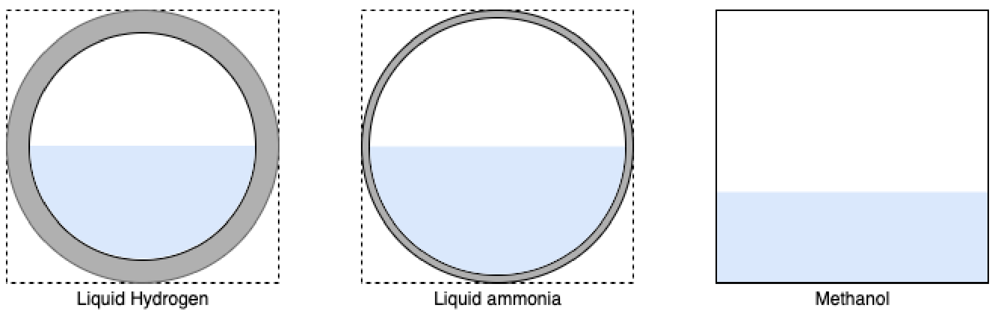


Figure 4.21: Cross section of the different storage systems

After analysing the technical designs, it can be concluded that technically all three options can meet the boundary conditions of the study and supply the required power to the grid. However, due to the differences in volume required to do so, it may be considered impractical to choose option 1. This will be included in the conclusion of this thesis.

5 Economic evaluation

This chapter will focus on the economic evaluation used to answer sub-research question 5: What is the most cost effective configuration?. First the used methods will be explained. Second the investment, operating cost and discount rate will be explained for the different systems. Next, an calculation will be made to determine the purchase price for the DHCs throughout the lifetime of the installation. Fourth, the influence of a CO_2-tax on the business case of the systems will be looked at. Finally, the results of the economic evaluation will be presented together with a sensitivity analysis and conclusion.

5.1. Levelized cost of electricity

In consultation with Heerema, the levelized cost of Electricity (LCOE) method, given in equation 5.1, was chosen as primary evaluation method. The LCOE is a measure of the average net present cost of electricity generation, expressed in €/kWh, for the vessel over its lifetime [40]. This will be applied for the LH_2-PEMFC (option 1), NH_3-ICE (option 2) and MeOH-ICE (option 3) drive-trains. The assumptions and parameters for this analysis are shown in table 5.1. Heerema has a levelized cost of electricty of 0.15 €/kWh as a benchmark for what they are currently paying for the power production on board of the Sleipnir[1].

$$LevelizedCostofElectricity = \frac{\sum_{year=1}^{n} \frac{CAPEX_{year}+OPEX_{year}+Fuelcost_{year}}{(1+r)^{year}}}{\sum_{year=1}^{n} \frac{Electricity_{year}}{(1+r)^{year}}} \tag{5.1}$$

CAPEX	€	The investment cost for the system, see section 5.3.1
OPEX	€	Operational expenditure per year, see section 5.3.2
Fuelcost	€	The money spent on fuel per year, see section 5.4
Electricity	kWh	The electricity delivered to the energy grid in the vessel
r	-	The discount rate used by Heerema, see section 5.3.3
Year	-	The operational year of the drive-train from 1 to 25 years
n	-	Total lifetime of the drive-train (25 years)

[1]The exact price may vary and is confidential

Table 5.1: Ship parameters used in economic evaluation

Parameter	Value	unit
Operating lifetime of the drive-train	25	years
First year the drive-train is operational	2025	
Annual operating weeks	44	weeks
Energy consumed per year [a]	48 048	MWh/year
Benchmark price for electricity used on board	0.15	€/kWh

[a]this is the electricity delivered to the switchboard.

5.2. Total cost of ownership

The second economic analysis used to evaluate the new drive-trains is the total cost of ownership (TCO), see formula 5.2. This method illustrates the total expenditure associated with the three options. This method is commonly used as method to evaluate the cost differences between drive-train designs as discussed in chapter 1.

$$TCO = \sum_{year=1}^{n} (\text{CAPEX}_{year} + \text{OPEX}_{year} + \text{Fuelcost}_{year}) \tag{5.2}$$

TCO	€	Total cost of ownership
CAPEX	€	the investment cost for the system in that year
OPEX	€	operational expenditure per year
Fuelcost	€	The money spent on fuel per year
Year	-	The operational year of the drive-train from 1 to 25 years
n	-	Total lifetime of the drive-train - 25 years

5.3. Input parameters for the evaluation

5.3.1. Capital expenditure

Capital Expenditure (CAPEX) is the investment a company initially makes to buy assets such as vessel or drive-trains. For all options a number of components needs to be purchased. These components are divided into 4 categories:

- Fuel storage: As discussed in chapter 4, there are major differences in the storage conditions for the three DHCs and therefore also in the price. These prices are expressed in €/kWh fuel stored.
- Pre-combustion: As discussed in chapter 3, ammonia and methanol require a pilot fuel to achieve a correct combustion. For this purpose, part of the carrier will be cracked to hydrogen to use as the pilot fuel. In section 4.2.1 and 4.3.1, the power requirements of these systems are calculated.
- Power unit: Two types of power units are used in this study. An internal combustion engine for the ammonia and methanol systems and a proton exchange membrane fuel cell for the liquid hydrogen system. The internal combustion engines will have a lifetime of at least 25 years. For this reason, no additional investments are required during the lifetime of the drive-train but only during the first year. The membrane in the fuel cell does not have a lifetime of 25

years and will therefore need to be replaced three times. The expected lifetime of the fuel cell stacks is currently approximately 40.000 hours (= approximately six operational years) [65]. This lifetime is expected to increase with 25% with every replacement[40]. The prices for the stacks are also expected to decrease of the lifetime op the drive-train. The year the stacks will be replaced and the CAPEX for each stack replacement is given in 5.2.

- post-combustion and additional systems: finally, the costs of the post-combustion and additional systems will be included in the CAPEX and OPEX calculation.

Following Heerema's conditions, the entire installation will be depreciated over 25 years. This means that the components have no residual values. This decision safeguards the most conservative perspective for the LCOE results. An overview of all components and its corresponding prices are given in table 5.3. The list of investments made for each options is given in table 5.4.

Table 5.2: Price estimate for PEM Fuelcell systems [35, 40, 75]

	Year	**CAPEX [€/kW]**	**OPEX [%/CAPEX/year]**
Stack placement	1	700	1
Stack replacement	6	575	1
Stack replacement	13	425	1
Stack replacement	20	325	1

5.3.2. Operational expenditure

The operational expenditure (OPEX) are the costs per year to operate and maintain the components. These costs are determined in a percentage of the initial investment, per year. The percentages used are given in table 5.3. The results of the OPEX calculation is given in table 5.4. The greatest difference in operational expenditure is with the power units. The internal combustion engines have, due to the many moving parts and high operating temperatures, more wear and therefore require more maintenance resulting in a higher OPEX. The OPEX is expected to increase over time due to ageing of the systems resulting in higher maintenance costs. To implement these increasing costs, an increase of the OPEX of 2% per year is assumed and implemented into the LCOE calculation.

Table 5.3: Investment cost analysis of the drive-train systems

	Components	**capex**		Source	**Opex**		Source
Fuel Storage	LH_2 storage tank	0.83	[€/kWh]	[5]	2	[%*capex/y]	[a]
	NH_3 storage tank	0.20	[€/kWh]	[5]	2	[%*capex/y]	[a]
	MeOH storage tank	0.14	[€/kWh]	[5]	2	[%*capex/y]	[a]
Pre-combustion	Ammonia cracker	250	[€/kW]	[5]	1	[%*capex/y]	[40]
	Methanol Reformer	370	[€/kW]	[5]	1	[%*capex/y]	[40]
Power unit	NH_3 DF-ICE	550	[€/kW]	[40]	8	[%*capex/y]	[40]
	MeOH DF-ICE	550	[€/kW]	[40]	8	[%*capex/y]	[40]
	PEM Fuel cell system[2]	800	[€/kW]	[5]	1	[%*capex/y]	[40]
post-combustion and additional systems	Fuel handling system NH_3	57	[€/kW]	[76]	3	[%*capex/y]	[a]
	Fuel handling system MeOH	57	[€/kW]	[76]	3	[%*capex/y]	[a]
	Fuel handling system LH_2	178	[€/kW]	[69]	3	[%*capex/y]	[a]
	SCR system	42	[€/kW]	[40]	3	[%*capex/y]	[40]
	Transformer system	150	[€/kW]	[40]	1	[%*capex/y]	[40]

[a] Own assumption

Table 5.4: CAPEX and OPEX overview per drive-train

Option 1 LH2-PEMFC	CAPEX [*10^3€]	OPEX[a] [*10^3€]	**Option 2 NH3-ICE**	CAPEX [*10^3€]	OPEX[a] [*10^3€]	**Option 3 MeOH-ICE**	CAPEX [*10^3€]	OPEX[a] [*10^3€]
Fuel tank	14 315	286	Fuel tank	2 680	54	Fuel tank	2 503	50
Fuel handeling system	1 157	35	Cracker	27	1	Methanol reformer	23	1
PEMFC system	5 200	52	Fuel handeling system	371	11	Fuel handeling system	371	11
Transformer system	975	10	Generator set	3 575	286	Generator set	3 575	286
PEMFC stack 1	4 550	46	SCR	273	8			
PEMFC stack 6	3 738	37						
PEMFC stack 14	2 763	28						
PEMFC stack 21	2 113	21						
Total	34 810	428	**Total**	6 925	359	**Total**	6 471	348

[a]In the first year

5.3.3. Discount rate

The discount rate is the interest rate used to determine the present value of a future cash flow. This concept uses the time value of money in which money that is currently in possession is worth more than money in possession in the future due to the earning potential [28]. In the time value of money, the discount rate is the interest that can be made on present day money if it is spent on a different investment. This influences the difference between the options with more capital intensive investments compared with the options with more operational intensive expenditures. The discount rate is calculated using two components. The first is the potential earnings that Heerema can make investing present day money in different projects. The second is the interest that has to be payed to an investor or bank that possibly funds part of the capital required. The average between these two values will eventually result in a discount rate. These values are unfortunately confidential and in consultation with Heerema it was decided to calculate with three discount rates, 0%, 5% and 10%.

5.3.4. Cost for CO_2 emissions

The shipping industry will be included in the emission trading system. The exact details of the inclusion of shipping is as of yet unknown, but it can nonetheless be expected that a CO_2 tax for shipping will be implemented in the near future [29]. The rate of this tax is the subject of many discussions but is considered out of scope for this study. However, it is interesting to know at which CO_2 price the new drive-train options will cost as much as the current system on board the ship. Therefore, a corrected LCOE will be calculated that includes the cost of emitting CO_2, see formula 5.4. The total cost of CO_2 per kWh emissions will be described by equation 5.3.

$$\text{emission tax} = \text{CO}_{2emissions} * \text{CO}_{2tax} \tag{5.3}$$

emission tax	[€/kWh]	The CO_2-tax payed per kWh electricity
CO_2 emissions	[kg/kWh]	The amount of CO_2 emitted per kWh electricity
CO_2 tax	[€/kg]	The CO_2 price, vary between 0 [€/ton*CO_2] and 150 [€/ton*CO_2]

$$\text{LCOE}_{corrected} = \text{LCOE} + \text{emission tax} \tag{5.4}$$

$\text{LCOE}_{corrected}$	[€/kWh]	The CO_2 payed per kWh electricity
LCOE	[€/kWh]	The levelized cost of electricity without an CO_2-tax
emission tax	[€/kWh]	The CO_2 payed per kWh electricity

5.4. Fuel price calculation

5.4.1. Production of hydrogen gas

The starting point for this fuel price calculation for the dense hydrogen carriers is electricity. In this research, an electricity price of 4 €/GJ is used, which is the current lowest target price set by the Department of Energy of the United states of America [70]. With this electricity, hydrogen gas will be produced as feedstock for the production of the DHCs. The equation used for the price calculation of hydrogen gas is given in equation 5.5. It was decided not to use the Levelized cost of hydrogen formula because this formula calculates the cost price of hydrogen and does not include differences between cost price and selling price. Equation 5.5 includes the electricity required to produces the hydrogen gas, the electricity price and the process cost which is a factor that includes all other costs that affect the selling price of hydrogen gas. The data used for this equation is given in table 5.5 together with the hydrogen gas price calculated. The price development of hydrogen gas for the next 30 years is given in figure 5.1.

$$H_{2(gas),price} = \text{Electricity}_{required} * \text{Electricity}_{price} + \text{Process cost} \tag{5.5}$$

H_{2price}	[€/t_{H2}]	The price for 1 ton of H_2
$\text{Electricity}_{required}$	[GJ/t_{H2}]	The amount of energy required to produce 1 ton of hydrogen
$\text{Electricity}_{price}$	[€/GJ]	The price for 1 GJ
Process cost	[€/t_{DHC}]	The process costs for the production of 1 ton hydrogen

Table 5.5: Parameters and fuel price for hydrogen gas (energy price = 4 €/GJ) [31]

	2020	**2030**	**2040**	**2050**
Efficiency electrolyzer (HHV) [%]	77	83	86	89
Energy requirement [GJ/ton$_{H2}$]	185.6	172.2	165.0	160.5
Process cost[a] [€/ton$_{H2}$]	1250	725	500	300
Hydrogen gas price [€/ton$_{H2}$]	1 743	1 414	1 160	942
Hydrogen gas price [€/kWh] (LHV)	0.53	0.043	0.035	0.029

[a]Estimated based on [31, 76]

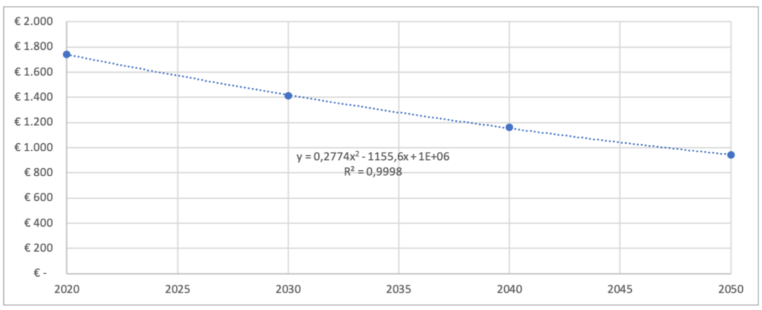


Figure 5.1: Price development of the hydrogen gas from year 2020 until 2050 (electricity price 4 €/GJ)

5.4.2. Production of the dense hydrogen carriers

With this hydrogen gas, three different paths can be taken. The first is to liquefy the green hydrogen by a liquefaction process. The second is to convert the hydrogen to ammonia through a Haber-Bosch reaction and the third is to convert the hydrogen to methanol by reacting it with CO_2 in a methanol reactor. For a detailed explanation on these processes, see chapter 3. Equation 5.6 is used to calculate the fuel price. The feedstock and energy requirements for the three different processes are shown in table 5.6.

$$DHC_{price} = W_{H_2} * H2_{price} + W_{CO_2} * CO2_{price} + \text{Electricity}_{required} * \text{Electricity}_{price} + \text{Process costs} \tag{5.6}$$

DHC_{price}	[€/t_{DHC}]	The fuelprice for 1 ton of DHC
W_{h_2}	[t_{H2}/t_{DHC}]	The amount of H_2 needed to produce 1 ton of DHC
H2_{price}	[€/t_{H2}]	The price for 1 ton of H_2
W_{CO2}	[t_{CO_2}/ton_{DHC}]	The amount of CO_2 needed to produce 1 ton of DHC
$CO2_{price}$	[€/t_{CO_2}]	The price for 1 ton of CO_2
$\text{Electricity}_{required}$	[GJ/t_{DHC}]	The amount of energy required to produce 1 ton of DHC
$\text{Electricity}_{price}$	[€/GJ]	The price for 1 GJ which will vary between 1 €/GJ and 16 €/GJ
Process cost	[€/t_{H2}]	The additional cost to produce 1 ton of DHC

Since many of the technologies used for the production of hydrogen gas and the DHCs are still under development, it is expected that through up-scaling the efficiencies and process costs for the production facilities will decrease in the coming decades. This will clearly influence the DHC price. Because of this, the price will be determined every 10 years, so that the influence of these developments can be taken into account with. The feedstock and process costs used in the calculation are shown in table 5.7. Since the production of ammonia and methanol are already fully developed processes, it is expected that the process costs will not decrease. The process to liquefy hydrogen is however not yet executed at large scale and therefore the process costs will significantly drop when scaled up. The CO_2 price given in table 5.7 is the commodity price for CO_2 captured from a combined heat and power plant.

Table 5.6: Feedstock required for production of 1 ton of DHC as calculated in chapter 3

	feedstock H2 [t\t]	**Feedstock CO2** [t\t]	**Energy requirement** [GJ\t]
Liquid Hydrogen	1	0	24.3
Ammonia	0.14	0	2.63
Methanol	0.189	1.442	4.29

Table 5.7: Estimated feedstock and production cost prices

Feedstock prices [€/ton]	**2020**	**2030**	**2040**	**2050**	**Source**
CO_2 [a]	45	45	45	45	[36, 58]
Process cost [€/ton]					
Liquefaction of hydrogen gas	1042	754	510	310	[36, 72, 76]
ASU+Haber bosch process	105	105	105	105	[36]
Methanol reactor	125	125	125	125	[36, 8]

[a] Estimated CO_2 commodity price based on point source of CO_2 from a biomass fueled combined heat and power plant

Using equation 5.6 and the input from table 5.6 and 5.7 a price development over time can be made for the three DHCs. The production process of ammonia and methanol is already done on a very large scale and can therefore make use of economy of scale. The expectation is that process costs for liquid hydrogen will drop to such an extent that LH_2 will be cheaper than ammonia and methanol around 2040, see figure 5.2. The trend line from these prices will be used for the calculation of the fuel cost per year. The price per ton is given in table 5.8.

Table 5.8: Calculated purchase price for the DHCs (electricity price is 4 €/GJ)

Price DHCs [€/ton]	**2020**	**2030**	**2040**	**2050**
LH_2	2 882	2 265	1 767	1 349
NH_3	359	313	278	247
MeOH	534	472	424	383

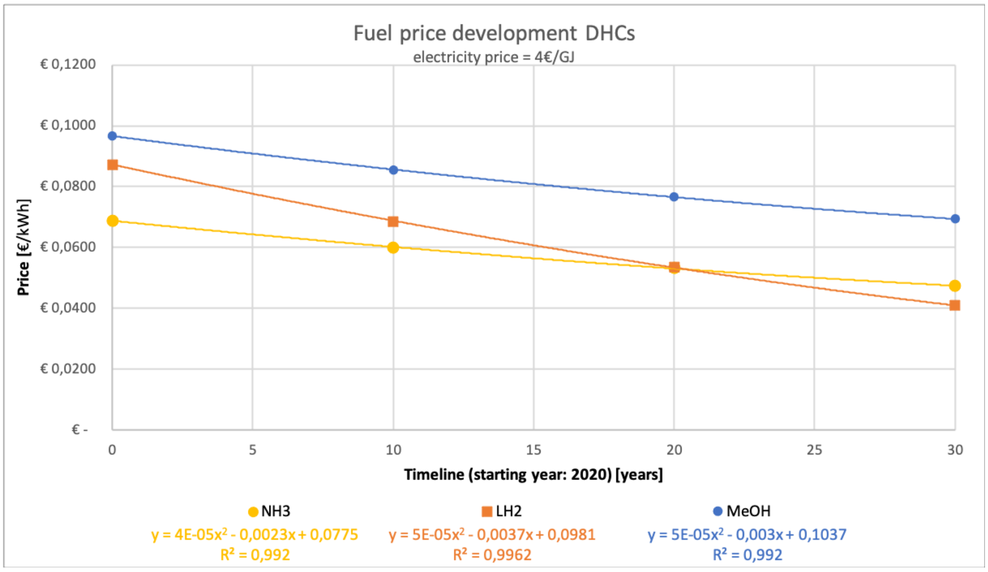


Figure 5.2: Price development of the DHCs from year 2020 until 2050

5.4.3. Fuel cost per year

The fuel cost used in formula 5.1 is calculated with formula 5.7, where $fuel_{price}$ is the price of the fuel per ton, calculated with the trend lines derived from figure 5.2 and the $fuel_{used}$ is the amount of fuel consumed per year for option 1 to 3 as calculated in the heat mass balance (see table 5.9).

$$fuelcost_{year} = fuel_{price} * fuel_{used} \tag{5.7}$$

Fuelcost_{year}	[€]	The money spent on fuel per year
Fuel_{price}	[€/t_{DHC}]	The fuelprice for 1 ton of DHC
Fuel_{used}	[t_{DHC}]	The amount of fuel used per year in ton

Table 5.9: Fuel used per year

	Option 1 LH2-PEM	**Option 2 NH3-ICE**	**Option 3 MeOH-ICE**
Fuel used per year [ton/year]	3 285	21 504	20 329

5.5. Results

In this section, the results of the two evaluation methods will be given. Subsequently, a sensitivity analysis will be carried out to determine which input parameters have the greatest influence on the LCOE.

5.5.1. levelized Cost of Electricity results

In order to make the comparison between the current drive-train and the three alternatives, the levelized Cost of Electricity was calculated for each system. This price indicates how many euros it costs to deliver 1 kWh of electricity to the ship's electricity grid. The benchmark price for electricity on board of Sleipnir is 0.15 €/kWh. The result of the LCOE is given in figure 5.3. The ammonia drive-train, with a LCOE of 0.152 euro/kWh, is the most cost-effective option and only 1.6% more expensive than the current LNG fuel drive-train. The overview of the LCOE is given in appendix A

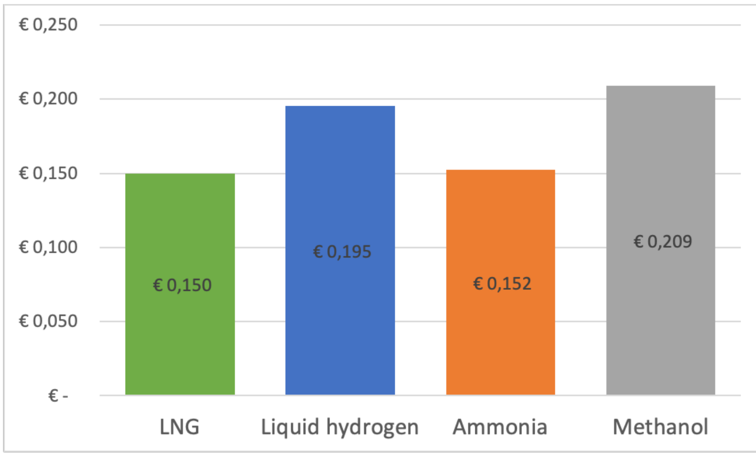


Figure 5.3: Levelized Cost of Electricity for the different drive-trains [€/kWh] (Electricity price = 4€/GJ)

As discussed in section 5.3.4, it is inevitable that in the near future there will be a tax on CO_2 emissions in the maritime industry. The effect of this tax is therefore very important to include in the LCOE evaluation. The current system and methanol both emit CO_2 so their LCOE price will rise as the CO_2 tax rises. The current CO_2 tax for other industries is 50€/ton at the time of writing [18] and is expected to increase over de next 25 years. It is therefore interesting to see at what CO_2-tax, the new drive-train will become equally expensive as the current LNG drive-train. Figure 5.4 shows the LCOE including this 50 €/ton CO_2 tax.

With the current CO_2 tax, the benchmark LCOE price would rise to 0.182 €/kWh. In this situation, option 2 is much cheaper than the current drive-train and option 1 is 7% more expensive. Methanol also emits CO_2 and this increases the LCOE of that system as well. Because methanol emits less CO_2, it will eventually be cheaper than the current system. Figure 5.5 shows the development of the LCOE of the 4 systems depending on different CO_2 taxes. Liquid hydrogen will become cheaper compared to the current system with a CO_2-tax of approximately 75 €/ton. The LCOE for methanol will also rise with higher taxation but will eventually become cheaper the LNG at 150 €/ton. The LCOE corrected for the CO_2 tax is given in figure 5.5.

[2]Price excluding cost for the stack

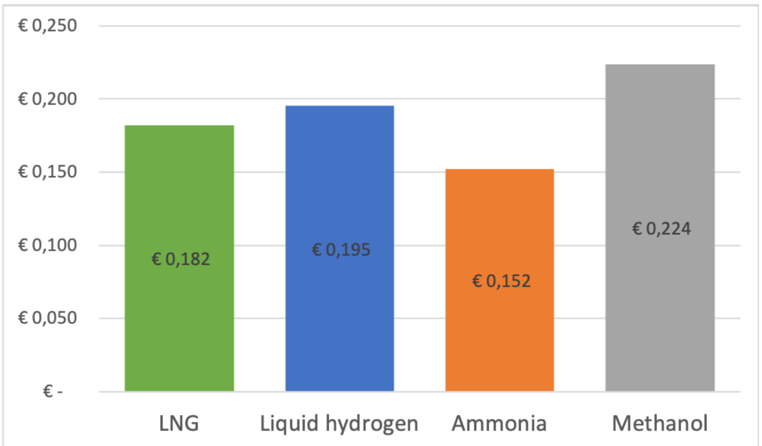


Figure 5.4: Levelized cost of electricity including a 50€/ton CO_2 tax [€/kWh] (Electricity price = 4€/GJ)

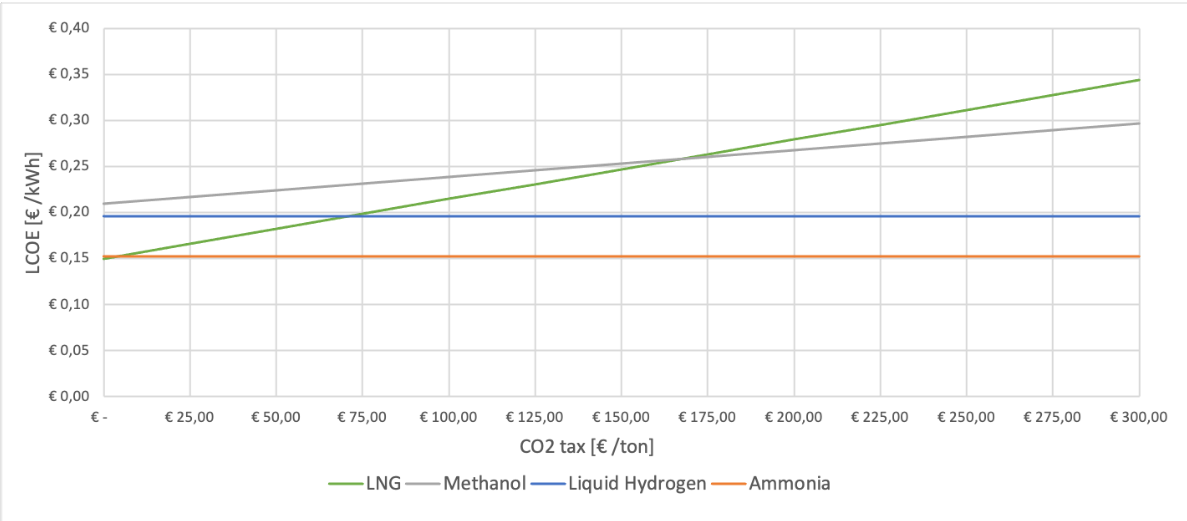


Figure 5.5: LCOE calculated for different CO_2 taxes

5.5.2. Total Cost of Ownership

The second method used is the total cost of ownership calculation. Table 5.10 and figure 5.6 show the results of these three options. From this calculation it can be seen that the fuel costs have the greatest influence on the total cost, varying between 77% for option 1 and 93% for option 3. This is mainly due to the long lifetime of the drive-trains and because the system is continuously running for 44 weeks per year resulting in relatively low downtime. Ammonia is, as expected, the most economic option of the three. Methanol is, due to the high fuel price, more expensive than ammonia, even though the investment and operational expenditure are relatively equal. Hydrogen and ammonia have relatively the same expenditure for fuel but due to the much higher investment cost for the PEM fuel cell and liquid hydrogen storage system, the hydrogen drive-train is more expensive then option 2.

Table 5.10: Total cost of ownership price breakdown

	Hydrogen		**Ammonia**		**Methanol**	
x€1000	Option 1	%	Option 2	%	Option 3	%
CAPEX	€ 34 810	17	€ 6 925	4	€ 6 471	3
OPEX	€ 13 718	6	€ 11 504	7	€ 11 127	4
Fuel cost	€ 158 437	77	€ 155 606	89	€ 223 540	93
Total	€ 207 000		€ 174 036		€ 241 139	

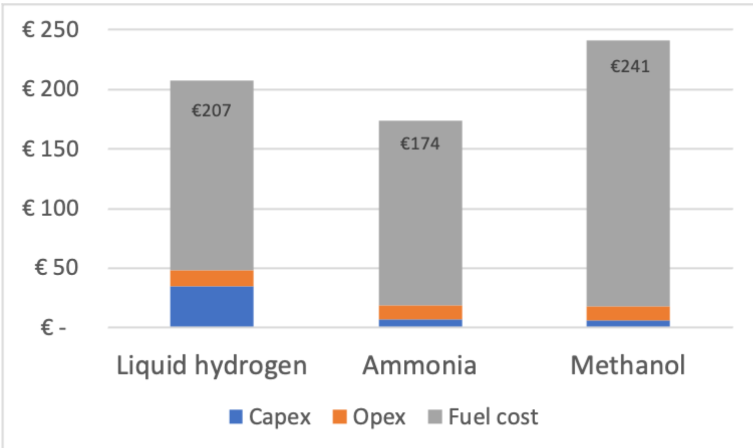


Figure 5.6: Total cost of ownership [x10^6 euro] (electricity price=4€/GJ)

5.5.3. Sensitivity analysis

In addition to the results of the economic analysis, it is interesting to see what effect variations in inputs have on the results of the economic analysis. There are four main input characteristics for the LCOE evaluation that separately will be discussed in this sensitivity analysis. The results given in the tables in this section will be coloured red or green, to indicate whether an option in that situation is cheaper or more expensive than the current system.

CAPEX

As can be seen in table 5.10, there is a big difference in the investment of option 1 compared to options 2 and 3. Due to the higher investment for the hydrogen system, the LCOE of that option ends up being considerably higher than that of the ammonia drive-train. This is also reinforced by the discount rate, which adversely affects higher investments at the outset. To determine the influence of the CAPEX on the LCOE, a new LCOE was calculated that was corrected by a CAPEX reduction of 25, 50, 75 and 100 percent. The results are shown in 5.11. As can be seen, the influence of the CAPEX on the LCOE is minimal.With a 100% reduction, i.e. the system is purchased and installed at no cost, the LCOE will be reduced by 18% for liquid hydrogen and by only 5% for the ammonia and methanol drive-train. A combination of a CO_2-tax of 50€/ton and a reduction of 50% will result in a LH_2 drive-train that has a better business case in comparison with the current drive-train.

Table 5.11: Influence of the CAPEX on the LCOE

Reduction of	Option 1: LH_2 LCOE [€/kWh]	Option 1: LH_2 $LCOE_{CO2-tax}$ [€/kWh]	Option 2: NH_3 LCOE [€/kWh]	Option 2: NH_3 $LCOE_{CO2-tax}$ [€/kWh]	Option 3: MeOH LCOE [€/kWh]	Option 3: MeOH $LCOE_{CO2-tax}$ [€/kWh]
25%	0.184	0.184	0.150	0.150	0.207	0.221
50%	0.173	0.173	0.148	0.148	0.205	0.219
75%	0.162	0.162	0.145	0.145	0.202	0.217
100%	0.151	0.151	0.143	0.143	0.200	0.215

OPEX

Table 5.12 shows the influence of the opex on the LCOE. For all three systems it is a reduction of about 5% on the LCOE when there is a complete reduction of the OPEX. This shows that the influence of the OPEX is minimal on the total business case of the three systems. Only the ammonia drive-train will become cheaper then the current system.

Table 5.12: Influence of the OPEX on the LCOE

Reduction of	Option 1: LH_2 LCOE [€/kWh]	Option 1: LH_2 $LCOE_{CO2-tax}$ [€/kWh]	Option 2: NH_3 LCOE [€/kWh]	Option 2: NH_3 $LCOE_{CO2-tax}$ [€/kWh]	Option 3: MeOH LCOE [€/kWh]	Option 3: MeOH $LCOE_{CO2-tax}$ [€/kWh]
25%	0.193	0.193	0.150	0.150	0.207	0.221
50%	0.190	0.190	0.148	0.148	0.205	0.219
75%	0.187	0.187	0.146	0.146	0.202	0.217
100%	0.185	0.185	0.143	0.143	0.200	0.215

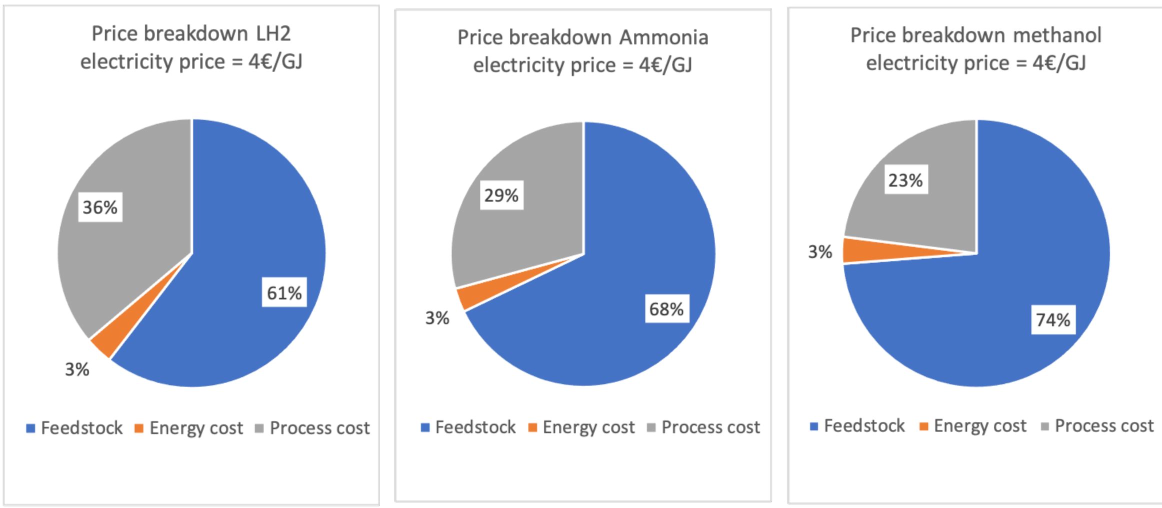
Electricity price

From table 5.10 it can be concluded that the fuel costs have the largest influence on the LCOE and the TCO. It is therefore interesting to see which parameters have the most influence on the development of these fuel costs. The first and most influential parameter is the electricity price. It affects the DHC costs in two ways. First, it has a very strong influence on the cost of producing green hydrogen. Second, it also affects the cost of producing the DHCs from hydrogen. Liquid hydrogen requires 5 to

10 times more electricity for the conversion process compared to ammonia and methanol resulting in higher production cost. In figure 5.7 can be seen that the feedstock has the greatest influence on the price of the fuel. The price of hydrogen gas, which is mostly determined by the electricity price, is thus a very important factor for the final fuel cost for the LCOE. This sensitivity analysis has investigated the difference in LCOE when the electricity price will varies between 1 €/GJ and 16 €/GJ. As can be seen in table 5.13 a variation in electricity price has a greater influence on the LCOE compared to the CAPEX and OPEX. However, at an electricity price of 1 €/GJ, options 1 and 3 are still not cheaper than the current drive-train. This is however the case when there is a CO_2 tax of 50€/ton.

Table 5.13: Influence of different electricity prices and discount rates on the LCOE

Electricity price	Option 1: LH_2 LCOE [€/kWh]	Option 1: LH_2 $LCOE_{CO2-tax}$ [€/kWh]	Option 2: NH_3 LCOE [€/kWh]	Option 2: NH_3 $LCOE_{CO2-tax}$ [€/kWh]	Option 3: MeOH LCOE [€/kWh]	Option 3: MeOH $LCOE_{CO2-tax}$ [€/kWh]
1 €/GJ [0.004 €/GJ]	0.156	0.156	0.117	0.117	0.163	0.178
4 €/GJ [0.014€/GJ]	0.195	0.195	0.152	0.152	0.209	0.224
16 €/GJ [0.058€/GJ]	0.355	0.355	0.294	0.294	0.394	0.408



(a) Liquid hydrogen (b) Ammonia (c) Methanol

Figure 5.7: Price breakdown of the DHCs

Discount rate

The discount rate is used to determine the time value of money. Because the lifetime of 25 years for the drive-train is a long period, the discount rate can therefore have a lot of influence on the final results. The LCOE and LCOE corrected with a 50 €/ton CO_2-tax are calculated with a discount rate of 0%, 5% and 10%.

Table 5.14: Influence of the discount rate on the LCOE

Discount rate	Option 1: LH_2 LCOE [€/kWh]	Option 1: LH_2 $LCOE_{CO2-tax}$ [€/kWh]	Option 2: NH_3 LCOE [€/kWh]	Option 2: NH_3 $LCOE_{CO2-tax}$ [€/kWh]	Option 3: MeOH LCOE [€/kWh]	Option 3: MeOH $LCOE_{CO2-tax}$ [€/kWh]
0%	0.172	0.172	0.145	0.145	0.201	0.215
5%	0.195	0.195	0.152	0.152	0.209	0.224
10%	0.220	0.220	0.160	0.160	0.217	0.232

5.6. Conclusion

This chapter has provided the economic methodology and results to answer sub-question 5 of this thesis. Within the framework of the research, the ammonia-driven drive-train is the most cost-effective configuration and is 1.6% more expensive than the current system. Using the data found in the literature, a fuel price prediction was made for the upcoming 30 years. This prediction shows that ammonia will remain cheaper than liquid hydrogen for the next 20 years. Since the fuel price is the most influential factor for the LCOE en the TCO, option 2 will remain the most cost-effective configuration within the near future.

The fuel price prediction also shows that methanol will stay the most expensive DHCs. Even though the capital investment for this drive-train is cheaper then the other systems, the additional cost of fuel results that this system will be more expensive than option 1 and 2.

The sensitivity analysis shows that the CAPEX and OPEX have minimal influence on the total business case of the systems. Changes in the electricity price have a greater influence but ultimately ensure that only option 2 is cheaper than the current system. The factor that has the biggest influence on reducing the gap between the current system and the new systems is a CO_2 tax. With a tax of 75 €/ton the current business case of option 1 already becomes cheaper than the current system and also methanol becomes eventually cheaper with a tax of 150 €/ton.

6 Conclusion

As elaborated in chapter 1, Heerema recognises the sense of urgency in a hydrogen powered drive-train to power the Sleipnir. With this new system, they want to reduce their carbon footprint while working offshore. The goal of this thesis was to perform a techno-economical analysis on different drive-trains running on hydrogen. In this chapter the conclusions of this analysis are formulated, based on the findings mentioned in this report, answers will be formulated for each sub research question. After this, the main research question will be answered.

6.1. Answers to the sub-research questions

1. **What are the current electrical configuration and operational profile of the Sleipnir?**

   The Sleipnir currently has a Diesel-LNG - electric drive-train for its power generation. In this drive-train a mixture of MGO and LNG is combusted in an internal combustion engine to generate mechanical energy. This energy is then converted into electricity by a dynamo. The system has three different operating profiles varying in a power demand of 8.5 and 38 MW.

   The Sleipnir has, with an installed power of 96MW divided over 12 engines, a significant amount of redundancy build in her drive-train. This is necessary in order to comply with the Dynamic Poisoning Classification that applies to operations at sea.

   It was chosen to design a system that has the power to drive the Sleipnir's hotel load. This system will have to deliver 6.5 MW of power to the grid and must operate 44 week per year. Refueling of the fuel tanks will take place every 7 weeks.

2. **How can hydrogen be stored on board of the semi-submersible crane vessel?**

   There are many ways to store hydrogen on board of a vessel. Due to the increasing demand for sustainable fuels, many new DHCs have been developed. However, most of these are still in the development phase and are not yet feasible within the boundary conditions set for this thesis. A literature analysis showed that liquid hydrogen, ammonia and methanol are currently the most developed DHCs and the most feasible methods to store hydrogen on board a vessel. These DHCs are therefore chosen for further elaboration in this study. The characteristics of these three DHCs can be summarised as follows:

- Liquid hydrogen:
  - Is stored at a temperate -253°C so the storage tanks require a insulation layer resulting in a volume increase of 44% to minimize Boil-off gas.
  - Does not emit any greenhouse gasses in Tank-to-Propeller.
  - With a volumetric energy density of 10 MJ/l when stored at -253°C, it is approximately 50% less dense then LNG and has the lowest density compared to the other DHCs.
  - It is a non-toxic material resulting in a very low health hazard.
  - Has a very wide flammability range resulting in a higher potential flammability risk when leaked in non ventilated enclosed spaces.
- Ammonia:
  - Is stored at a temperate -34°C. To minimize boil-off gas, insulation is installed that results in a volume increase of 10%
  - Does not emit any CO_2 but will require a Selective catalytic reduction system to minimize NO_x emissions to comply with IMO TIER III regulations.
  - It can be liquefied by storing it at -34 °C or at a pressure of 10 bar. Liquid ammonia has a volumetric energy density of 13 MJ/l.
  - It is a toxic material that can be lethal when inhaled and form an environmental hazard when leaked in the ocean.
  - Due to a low flame speed, combustion in high RPM engines can be challenging so ammonia requires a duel fuel mixture with hydrogen.
- Methanol:
  - Is stored as a liquid at ambient temperatures so no insulation systems need to be installed.
  - Because methanol is made from CO_2 and hydrogen, this DHC will always emit CO_2. However, depending on the source of the CO_2, it can still be a CO_2-neutral fuel.
  - Methanol has the largest volumetric energy density of the three DHCs and is liquid under ambient temperatures, making storage the easiest of the three DHCs.
  - It is a highly toxic and corrosive substance.
  - Methanol has the best combustion characteristics of the DHCs and needs only a small volume of hydrogen as pilot fuel in a CI-engine.

3. **What technologies are applicable to convert the hydrogen into electrical power?**

   Within the scope of this study, the internal combustion engine and the fuel cell are investigated as feasible power units for the new drive-trains. Both systems have their advantages and disadvantages. Fuel cells have the advantage that they can convert chemical energy from a fuel into electrical energy without combustion. Consequently, there are no harmful emissions produces as a by-product of the process. Within fuel cells, two types have been studied: the Proton Exchange Membrane fuel cell and the Solid Oxide fuel cell. The SOFC has the advantage of being able to run with high efficiency on different types of fuel. Unfortunately, this power unit is still under development and not yet available for marine use. PEMFC are a very new technique in the maritime industry that is not yet widely used in the maritime industry. Because of this, the systems are still very expensive and there is little experience with them within the industry.

   The internal combustion engines are a power unit widely used in ships. It is a reliable technology that is cheap and low in maintenance. The biggest disadvantage of the engines is that it has GHG, NO_X or other polluting emissions as a by-product of the process, depending on what fuel it runs on.

4. **How do the Dense hydrogen carriers influence the drive-train design of the Semi-submersible crane vessel?**

   There are several aspects that play a role in answering this question. Option 2 and 3 do not differ much from the current LNG system in terms of power unit. All three options have an internal combustion engine that runs on a mix of two fuels to get a good ratio of octane to cetane numbers so that an efficient combustion is achieved. The main difference is that the current system uses MGO as pilot fuel and therefore has higher CO_2 emissions than the new systems that use hydrogen as pilot fuel. The hydrogen-PEMFC option is very different from the current system in terms of drive-train. Using a PEMFC requires a much more complex fuel handling system to generate a good stable electrical output.

   In terms of on-board efficiency, there are also differences between the systems. The heat mass balance calculation shows that the three new options all have an efficiency of around 43%. This is considerably higher than the current system and can be explained because the three new systems run at full load on their designed power output. If the combustion engines of options 2 and 3 are required to run at partial load, the efficiency will decrease to a more similar efficiency as the current system. The fuel cell is less affected by this and will run at similar efficiency at at part load and full load.

   The last and biggest change in the drive-train design is the volume of and type of fuel storage system. The current system runs on LNG which is stored at temperatures of around -160 °C. The storage of LH_2 is very similar to this system, but due to the lower storage temperature of -253 °C, thicker insulation must be used, which takes up more volume, and because hydrogen molecules are much smaller than LNG molecules, different materials must be used to prevent leaks. The storage of ammonia and methanol is much less complicated compared to the current system. Ammonia is stored under a much higher temperature (-34 °C) to liquefy or, if tank volumes do not become too large, can also be stored as a liquid at a pressure of 10-17 bar. This reduces the BOG rate and energy losses through the storage system. Methanol has the most favourable storage conditions of the three DHCs. It is a liquid at ambient temperatures, so it does not require a complicated storage system. Therefore, more methanol can be stored per cubic meter compared to ammonia, LNG and liquid hydrogen.

   In terms of the required volume, there are major differences from the current system. Due to the differences in volumetric energy density, a significant increase in volume is needed to store the required amount of fuel. LH_2 has the biggest difference with a required volume of 10 600 m^3. Ammonia and methanol require 5 260 and 4 100 m^3 respectively. This is still an increase compared to the LNG storage tanks but is considered to be feasible. The size of the LH_2 tanks is so large that it is almost unfeasible to implement on the vessel.

5. **What is the most cost effective configuration?**

   The LCOE and TCO calculations show that the ammonia fueled drive-train is the cheapest configuration. With a LCOE of 0.152 €/kWh, it comes at a similar price compared to the current system and would therefore have minimal impact on the ship's current business case. However, it is particularly interesting to see which factors influence this price the most. Because the system has a long lifetime of 25 years and will run 44 weeks per year continuously, the fuel costs have the greatest influence (77%-93%) on the TCO. Ammonia and methanol are of the most widely produced chemicals in the world, so the production costs of these fuels are expected to decrease little. However, the process of making liquid hydrogen from hydrogen gas has not yet been scaled up to such an extent and is therefore still very expensive. Based on the price developments found in the literature, it can be expected that LH_2 will eventually become cheaper than NH_3. This will happen when the production process is scaled up and economy of scale applies to LH_2.

Another development that could have a major impact on the LCOE is the introduction of a CO_2 tax. This tax will push up the current LCOE and thus reduce the difference with the DHCs. With a CO_2 tax of 75 €/ton, a drive-train running on LH_2 will have the same LCOE as the current system. Methanol will become cheaper than the benchmark price at an CO_2 tax of 150 €/ton.

In conclusion, under the current preconditions for the production of the DHCs and investment cost for the drive-trains, it is cheaper to choose an ammonia-driven system. Liquid hydrogen will become cheaper than ammonia in the future but with the current energy price of 4 €/GJ this tipping point will potentially occur in 20 years time. This difference is still that large that a LH_2 driven system will therefore remain more expensive in the near future.

6.2. Answer to the main research question

The main research question is stated as follows:
What is the most preferred way from a shipowners perspective to drive a semi-submersible offshore crane vessel while using hydrogen as the energy carrier?

To answer the main question of this research, Heerema's three evaluation criteria should be discussed one by one. The first criteria is technical feasibility. Technically, all three systems are able to drive the Sleipnir's hotel load. However, the tank volume for the LH_2 is so large that it is not practical to install such a system to supply only 6.5 MW of electrical power. Even though the Sleipnir has a lot of space, doubling the installed storage volume is not feasible. The ammonia driven system has the same as the hydrogen system that it needs extra space for the system and the extra storage to keep the system cool. However, with the hydrogen system this margin is 1.44x, with ammonia it is only 1.1x. Furthermore, ammonia is more energy dense than hydrogen, which also results in a smaller volume for the storage tank. From a technical point of view, the methanol-based option is the best option. It needs the smallest tank and because it can be stored in square tanks, it is easier to integrate into the ship. In addition, the engine runs on a compression ignite diesel cycle which means that in emergency situations, the engine can still run on MGO when necessary.

The second evaluation criteria is the health, safety and environmental impact of the new drive-trains. The results show that overall hydrogen is scoring the best. It is a non-toxic chemical so there is little or no hazard to work with on board the ship. The wide flammability range does give it a greater risk of explosion than the other DHCs, but with sufficient ventilation this is a well manageable hazard. Hydrogen has the big advantage over the other two options that it has no polluting emissions. Methanol, in any possible configuration, will always emit CO_2 and burning ammonia produces NO_x as a by-product. These emissions can be minimised with a SCR system but will always remain present.

The final evaluation criteria the economic evaluation. The ammonia drive comes out best in the LCOE and TCO analysis. Liquid hydrogen will not become cheaper than Ammonia within the next 20 years and, in combination with the higher CAPEX for the fuel cell power unit, will not become cheaper than the drive-train either. Methanol is already the most expensive option and, assuming that a CO_2 tax will be introduced in the near future, it is not likely that the methanol drive-train will become less expensive.

If compared using the three criteria, the first conclusion is that LH_2 is not the most preferred option because of the huge volume required for the system. Methanol has an advantage because it requires less volume for storage, but storage requirements for LNG are still stricter compared to ammonia. Therefore ammonia can still be considered technically feasible. In addition, the Ammonia option is the cheapest and there is a chance that the Methanol option will be even more expensive due to a CO_2 tax. Therefore, within the established boundary conditions of this thesis, an ammonia-driven internal combustion engine is the most preferred way to drive the Sleipnir from the shipowners perspective.

7
Discussion

This chapter will present a discussion on the methodology, assumptions made in and results of this thesis. The aim of this research is to get an understanding on the influence of dense hydrogen carriers as a fuel on the drive-train design and economics for a semi-submersible offshore crane vessel. The results presented give a good indication on what the most preferred configuration is but nun the less, the influence of the scope and assumptions on these results should be discussed:

7.1. Concept selection of new drive-trains

- In the literature study on the most feasible DHCs, there is the requirement that the DHCs powered systems must be operational within 5 years. This rules out several options that could potentially solve many of the problems of the current DHCs. There are promising developments in the technique of binding hydrogen to salt creating Sodium borohydride among others. These DHCs claim to have better volumetric energy densities and solve issues that arise when using ammonia and methanol regarding toxicity and safety hazards. The process for these new DHCs is that the chemical is completely reformed on board the ship producing pure hydrogen. This eliminates the need for combustion in an ICE so no harmfull emissions are emitted.

- Due to the precondition that the system must be operational within 5 years, the SOFC was not included in the study. However, this fuel cell has operational characteristics that can be promising for the maritime industry. A SOFC can operate with a very high efficiency, as a result of which the volumes of the fuel tanks can be reduced or the fuelling periods can be increased. Next, it can be powered by a more wider range of fuels including methanol and ammonia. An ammonia or methanol - SOFC drive-train will decrease the required fueltank storage making it a more feasible design.

- In the environmental evaluation of the DHCs, only CO_2 emissions were considered. In reality, these DHCs also emit other greenhouse gases that in some cases can be even more harmful to the environment than CO_2. For example, when burning ammonia, N_2O is produced, which is 298 times worse for the environment. Fuel slip due to incomplete combustion in the engines can also be a potential emission hazard.

- In this thesis, the three new drive-train designs are compared with the current system, which runs largely on LNG. However, the applicability of Bio-LNG is not considered. Bio-LNG will be more expensive than regular LNG, but because no retrofit of the drive-train is required, it will remain cheaper than the new systems. Making the comparison between the three new systems and a drive-train running on Bio-LNG is therefore interesting.

- This thesis has stated as preconditions that no net CO_2 should be emitted in the well-to-wheel of the DHCs. Because of this, for example, blue hydrogen has been defined as out of scope. However, this can be a very interesting fuel and feedstock to stimulate the transition to hydrogen. Capturing CO_2 is a technique that is increasingly being used in the transition to a carbon-free industry. With CC(U)S the price of hydrogen may become cheaper, making the business case of the DHCs more comparable to the current system.

- Hybrid configurations of fuel cells and internal combustion engines are a subject of research, among others by the TU Delft with the project AmmoniaDrive. In this project an SOFC is used as a cracker to convert part of the ammonia into hydrogen. With this technique, a higher efficiency can be achieved than just using ammonia in an internal combustion engine. A more elaborate design of this configuration is still needed, but its feasibility could be a good intermediate between the different configurations considered in this research.

7.2. Detailed drive-train design

- The design of the new drive-trains given in this report gives a good first impression of what the system will look like and what the obstacles are in designing the systems. However, it does not include the integration of the system on the ship. Since this thesis investigates a retro fit and the new system has to be placed next to the current system, there is a good chance that this could cause limitations regarding placement of components.

- As discussed in chapter 3, at the time of writing there is no commercially available engine that can run on ammonia. The engine characteristics are therefore based entirely on literature and may differ from the actual performance of these engines, when they are available.

- The new drive-trains are designed as stand-alone systems on the ship. In reality, they will provide the entire energy supply together with the current system. This means that the new power units will also run on part load at some times. This has relatively little impact on the performance of the PEMFC, but it does have an impact on the performance of the combustion engines. As can be seen from the efficiency curve of the current engines, the efficiency drops by about 10% when running on part load. This will have a major impact on the total consumption of the new systems and therefore also on the volume of the fuel tank and on the economics of the system.

- Option 2 and 3 both have a large amount of residual heat that can be used on the ship but is included as a loss in the heat and mass balance. If the new drive trains are designed as part of the overall system, this residual heat could potentially be used and the onboard efficiency of the options would be improved.

- Only the size of the fuel can was calculated to estimated the difference in size of the different systems in comparison with each other and the current drive-train. As the fuel tanks are the largest part of the drive train, it is a good first comparison. However, it does not represent the complete comparison. Since the drive-train components are installed at different locations on board than the fuel tank, this may cause additional restrictions

7.3. Heat & mass balance

- The heat & mass balance is based on a static simulation in which a continuous output of 6.5MW is supplied to the electricity grid. In reality, there will be fluctuations in this power which will affect the efficiency of the power unit and the overall performers of the engine.

- When operating in part load, the efficiency of internal combustion engines can decreases with approximately 10%. This will increase the specific fuel consumption resulting in a higher overall consumption. As seen in the results of chapter 5, the fuel consumption has a major influence of the economics. Changes in this can result in large fluctuations in the LCOE.

- In addition, ammonia and to a lesser extent methanol engines may respond less well to transient fluctuations in the power demand. This will cause the fuel to burn less completely in the combustion chamber. Which will have a major impact on the total consumption of the new systems and therefore also on the volume of the fuel tank and on the economics of the system. This problem will not or to a lesser extent occur with the LH2-PEM system. A PEMFC has a fast response to power fluctuations and this can be made even faster with a battery, if necessary.

- The heat and mass balance does not take into account that the efficiencies of the PEMFC membranes will increase with the changes every 6 years. In addition, possible fluctuations in efficiency as a result of fouling of the membranes has also not been taken into account. Variations in efficiency have an effect on the overall efficiency and therefore on the economics of the system.

7.4. Economic evaluation

- In the economic evaluation, a conservative assumption was made that the system will have no residual values after the 25-year lifetime. As a result, the LCOE and the TCO are higher than they could be in reality.

- The sensitivity analysis shows that a CO_2 tax has the greatest impact on reducing the gap between the current tube business case and that of the new drive-trains. The CO_2 prices at which each system becomes cheaper than the current one are calculated, but no development in the CO_2 price for the next 30 years is included. Assuming that the CO_2 price will rise, this price development will only narrow the gap between the drive-trains.

- The price and energy developments for the production of hydrogen gas and the DHCs have now been taken at 10-year intervals. This is a fairly large time step, so there may be a wider margin of error in the fuel price calculation.

- Despite the fact that the sensitivity analysis shows that differences in CAPEX have minimal influence on the LCOE, a large investment is often a reason not to make certain choices. The prices used in this study for the investment of the systems are largely based on predictions and literature. A further and deeper elaboration of the costs for these components and especially the development of these costs can give a better idea of when it becomes financially feasible to make certain choices regarding de new drive-train designs.

7.5. Recommendation for further work

Based on the above discussion, a number of recommendations have been formulated for further research on this topic.

- By changing the boundary condition of being operational within 5 years, room is created for other DHCs that are less developed but in theory have better characteristics than the DHCs that are currently under investigation. An evaluation in which these DHCs are also included can provide interesting conclusions for a drive-train that does not have to be commercially available within 5 years.
- Carry out a more comprehensive analysis of the emissions from the DHCs to get a better understanding of the reductions achieved by these new drive-trains.
- To get a better idea of the performance of the new systems, it is recommended that a model be developed that can do a dynamic simulation in which the fluctuations in the power demand of the hotel load are included. With that model it can be checked whether the new systems can react fast enough to the variations in power demand.
- Carry out a more comprehensive economic evaluation calculating the return on investment. In this evaluation, a more realistic implementation of a CO_2-tax can also be done in order to develop a more comprehensive business case.
- This study focused on the feasibility of DHC as a fuel on crane vessels. Therefore, it did not include hybrid configurations within its scope. However, this could be a large part of the solution. By adding batteries to the drive-train, transients in the power demand can be better accommodated and the engines run at higher efficiency. Further research into such designs is therefore necessary.
- The recommendation is given to calculate the volume, footprint and weight of the entire new drive-trains and to determine the placement of these systems on board the ship. In this way, the influence of the new systems on the current operational profile can be better determined.

Bibliography

[2-g] 2-g. Hydrogen CHP - 2G.

[2] Agarwal, R., Rainey, T. J., Ashrafur Rahman, S. M., Steinberg, T., Perrons, R. K., and Brown, R. J. (2017). LNG regasification terminals: The role of geography and meteorology on technology choices. *Energies*, 10(12).

[3] Al-Breiki, M. and Bicer, Y. (2020). Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon. *Energy Reports*, 6:1897–1909.

[4] Andersson, J. and Grönkvist, S. (2019). Large-scale storage of hydrogen.

[5] Baldi, F., Brynolf, S., and Maréchal, F. (2019). The cost of innovative and sustainable future ship energy systems. *ECOS 2019 - Proceedings of the 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, (July):239–250.

[6] Baldi, F., Moret, S., Tammi, K., and Maréchal, F. (2020). The role of solid oxide fuel cells in future ship energy systems. *Energy*, 194.

[7] Bañares-Alcántara, R., Dericks III, G., Fiaschetti, M., Philipp Grünewald, Lopez, J. M., Tsang, E., Yang, A., Ye, L., and Zhao, S. (2015). Analysis of Islanded Ammonia-based Energy Storage Systems. (October):1–150.

[8] Bellotti, D., Rivarolo, M., Magistri, L., and Massardo, A. F. (2017). Feasibility study of methanol production plant from hydrogen and captured carbon dioxide. *Journal of CO2 Utilization*, 21:132–138.

[9] Bergsma, J., Hart, P. t., Pruyn, J., and Verbeek, R. (2019). Final Report : Assessment of alternative fuels for seagoing vessels using Heavy Fuel Oil. pages 1–39.

[10] Bø, T. I. (2016). *Scenario- and Optimization-Based Control of Marine Electric Power Systems*. PhD thesis.

[11] Bourne, S. (2012). The future of fuel: The future of hydrogen. *Fuel Cells Bulletin*, 2012(1):12–15.

[12] Breeze, P. (2017). The Solid Oxide Fuel Cell. In *Fuel Cells*, pages 63–73. Elsevier.

[13] Brooks, M. R. and Crowl, D. A. (2007). Flammability envelopes for methanol, ethanol, acetonitrile and toluene. *Journal of Loss Prevention in the Process Industries*, 20(2):144–150.

[14] College of the Desert (2001). Hydrogen Fuel Cell Engines - Module 2: Hydrogen use. Technical report.

[Diesel] Diesel, D. Daihatsu Diesel for environmental regulations.

[16] DNV GL AS (2018). Rules for Classification of Ships Pt .6 Ch. 2. (January 2018):237.

[17] Edelmoser, K. and Himmelstoss, F. (2005). High Efficiency DC-to-AC Power Inverter with Special DC Interface. *AUTOMATIKA: časopis za automatiku, mjerenje, elektroniku, računarstvo i komunikacije*, 46(3-4):143–148.

[18] Ember (2021). Carbon Price Viewer - Ember.

[19] Energy, U. D. o. (2016). Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications. 98(4):681–684.

[20] Ferreira-Aparicio, P. and Chaparro, A. M. T. A. T. T. (2018). Portable hydrogen energy systems : fuel cells and storage fundamentals and applications LK - https://tudelft.on.worldcat.org/oclc/1047959810.

[21] Gigler, J. and Weeda, M. (2018). Outlines of a Hydrogen Roadmap. Technical report.

[22] Gillingham, K. (2007). Hydrogen Internal Combustion Engine Vehicles : A Prudent Intermediate Step or a Step in the Wrong Direction ? (January).

[23] Graaf, G. H., Stamhuis, E. J., and Beenackers, A. A. (1988). Kinetics of low-pressure methanol synthesis. *Chemical Engineering Science*, 43(12):3185–3195.

[24] Gupta, R. E. (2008). *Hydrogen Fuel: Production, Transport, and Storage (1st ed.).* CRC Press.

[25] Hacker, V. and Kordesch, K. (2010). Ammonia crackers. In *Handbook of Fuel Cells*, volume 3, pages 121–127.

[26] Hagen, A. (2007). Use of alternative fuels in solid oxide fuel cells. *Fuel*, 2(2H2):H2.

[27] Harmsen, J., Nesterova, N., Bekdemir, C., and Van Kranenburg, K. (2020). Green Maritime Methanol WP2 Initiation and Benchmark analysis.

[28] Hayes, A. (2021). Discount Rate Definition.

[29] Hellinic shipping news (2021). Shipping sector weighs impact of EU ETS | Hellenic Shipping News Worldwide.

[30] Holmlund-Sund, M. (2020). Flexibility key to enabling shipping's transition to future fuels.

[31] IEA (2019a). IEA G20 Hydrogen report: Assumptions. pages 1–14.

[32] IEA (2019b). The Future of Hydrogen. Technical Report June.

[33] IMO (1973). International Convention for the Prevention of Pollution from Ships. Technical report.

[34] IMO (2016). Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility International Maritime Organization (IMO).

[35] IRENA (2018). Hydrogen From Renewable Power: Technology outlook for the energy transition. Technical Report September.

[36] IRENA, I. R. E. A. (2019). *Hydrogen : a Renewable Energy Perspective - Report prepared for the 2nd Hydrogen Energy Ministerial Meeting in Tokyo, Japan.* Number September.

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

[38] Jackson, C., Davenne, T., Makhloufi, C., Wilkinson, I., Fothergill, K., Greenwood, S., and Kezibri, N. (2020). Ammonia to green hydrogen project. *Feasibility study*, 33(0):1–70.

[39] Jayakumar, A. (2018). An assessment on polymer electrolyte membrane fuel cell stack components. *Applied Physical Chemistry with Multidisciplinary Approaches*, 3:23–49.

[40] Kim, K., Roh, G., Kim, W., and Chun, K. (2020). A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments. *Journal of Marine Science and Engineering*, 8(3).

[41] Klerke, A., Christensen, C. H., Nørskov, J. K., and Vegge, T. (2008). Ammonia for hydrogen storage: Challenges and opportunities. *Journal of Materials Chemistry*, 18(20):2304–2310.

[42] Köhler, J. (2020). Zero carbon propulsion in shipping - scenarios for the development of hydrogen and wind technologies with the MATISSE-SHIP model. *International Shipbuilding Progress*, 67:79–95.

[43] Krasae-in, S., Stang, J. H., and Neksa, P. (2010). Development of large-scale hydrogen liquefaction processes from 1898 to 2009. *International journal of hydrogen energy*, 35(10):4524–4533.

[44] Laouir, A. (2019). Performance analysis of open-loop cycles for LH2 regasification. *International Journal of Hydrogen Energy*, 44(39):22425–22436.

[45] Lindstad, E. and Rialland, A. (2020). LNG and cruise ships, an easy way to Fulfil regulations—versus the need for reducing GHG emissions. *Sustainability*, 12(5):2080.

[46] Lindstrand, N. (2020). Two-stroke ammonia engine.

[47] MAN Energy Solutions (2019). Engineering the future two-stroke green-ammonia engine: Fuelling the future by natural power. Technical report.

[48] Maritime Knowledge Centre, TNO, and TU Delft (2018). Methanol as an alternative fuel for vessels. pages 1–24.

[49] Mark Fedkin (2016). Efficiency of Inverters | EME 812: Utility Solar Power and Concentration.

[50] Matei, A., Drăgoescu, R., Ianc, N., Chiuzan, E., and Rădoi, F. (2020). Use of explosibility diagrams in potentially explosive atmospheres. *MATEC Web of Conferences*, 305:00087.

[51] Mechanical Booster (2017). Diesel Cycle – Process with P-V and T-S Diagram - Mechanical Booster.

[52] Miyaoka, H., Miyaoka, H., Ichikawa, T., Ichikawa, T., and Kojima, Y. (2018). Highly purified hydrogen production from ammonia for PEM fuel cell. *International Journal of Hydrogen Energy*, 43(31):14486–14492.

[53] Mørch, C. S., Bjerre, A., Gøttrup, M. P., Sorenson, S. C., and Schramm, J. (2011). Ammonia/hydrogen mixtures in an SI-engine: Engine performance and analysis of a proposed fuel system. *Fuel*, 90(2):854–864.

[54] Morgan, E. R. (2013). Techno-economic feasibility study of ammonia plants powered by offshore wind.

[Nedstack] Nedstack. MT-FCPP-500. Technical report.

[56] Nguyen, L. T. H., Hwang, J.-S., Kim, M.-S., Kim, J.-H., Kim, S.-K., and Lee, J.-M. (2019). Charpy impact properties of hydrogen-exposed 316L stainless steel at ambient and cryogenic temperatures. *Metals*, 9(6):625.

[57] Niermann, M., Beckendorff, A., Kaltschmitt, M., and Bonhoff, K. (2019). Liquid Organic Hydrogen Carrier (LOHC) – Assessment based on chemical and economic properties. *International Journal of Hydrogen Energy*, 44(13):6631–6654.

[58] Peeters, S., Hart, A., Schlatmann, S., Medema, D., Smits, J., and Tuinbouw, P. (2013). CO 2 uit biomassa Quick scan (update) Juni 2013 Uitgevoerd door: In opdracht van. Technical report.

[59] Pochet, M., Jeanmart, H., and Contino, F. (2020). A 22:1 Compression Ratio Ammonia-Hydrogen HCCI Engine: Combustion, Load, and Emission Performances. *Frontiers in Mechanical Engineering*, 6.

[60] Reuse, P., Renken, A., Haas-Santo, K., Görke, O., and Schubert, K. (2004). Hydrogen production for fuel cell application in an autothermal micro-channel reactor. *Chemical Engineering Journal*, 101(1-3):133–141.

[61] Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., and Stolten, D. (2017). Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Applied energy*, 200:290–302.

[62] Roobeek, R. E. (2020). Shipping Sunshine A techno-economic analysis of a dedicated green hydrogen supply chain from the Port of Sohar to the Port of Rotterdam.

[63] Rozendaal, J. (2021). *Methanol Hybrid Offshore Working Vessels: A technical, environmental and economic assessment.* PhD thesis, Delft University of Technology.

[64] Sá, S., Silva, H., Sousa, J. M., and Mendes, A. (2009). Hydrogen production by methanol steam reforming in a membrane reactor: Palladium vs carbon molecular sieve membranes. *Journal of Membrane Science*, 339(1-2):160–170.

[65] Saito, N. (2018). The economic analysis of commercial ships with hydrogen fuel cell through case studies. *World Maritime University Dissertations*, 618.

[66] Schiller, G., Ansar, A., Lang, M., and Patz, O. (2009). High temperature water electrolysis using metal supported solid oxide electrolyser cells (SOEC). *Journal of Applied Electrochemistry*, 39(2):293–301.

[67] Schramm, J., Klüssmann, J. N., Ekknud, L. R., and Ivarsson, A. (2020). Ammonia Application in IC Engines. *Advanced Motor Fuels Technology Collaboration Programme*.

[68] Schröder, V. and Molnarne, M. (2005). Flammability of gas mixtures: Part 1: Fire potential. *Journal of Hazardous Materials*, 121(1-3):37–44.

[69] Sekkesaeter, (2019). Evaluation of Concepts and Systems for Marine Transportation of Hydrogen. (June):1–191.

[70] Solar Energy Technologies Office (2018). SunShot 2030 | Department of Energy.

[71] Stolzenburg, K. and Mubbala, R. (2013a). Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen. *Hydrogen and Fuel Cells in the Nordic Countries, November 1, 2013*, (278177).

[72] Stolzenburg, K. and Mubbala, R. (2013b). Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen. *Hydrogen and Fuel Cells in the Nordic Countries, November 1, 2013*, (278177).

[73] Technology, G. (2020). Ammonia_ship_fuel_2020-11_web. pages 1–28.

[74] Thanh-Binh, N., Dubois, J.-L., and Kaliaguine, S. (2016). 2016, 520, 7-12, Applied Catalysis A General-SI.

[75] Thomas, D. (2018). Cost Reduction Potential For Electrolyser Technology. *Hydrogenics: Mississauga, ON, Canada*.

[76] Tijdgat, J. (2020). Shipping renewable hydrogen carriers. Technical report, Technical university of Delft.

[77] Tronstad, T., Høgmoen, H., Haugom, G. P., and Langfeldt, L. (2017). Study on the use of fuel cells in shipping. Study commissioned by European Maritime Safety Agency (EMSA). *Dnv-Gl*.

[78] UNFCC (2015). Adoption of the Paris Agreement. Technical Report December.

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

[80] Verhelst, S. and Wallner, T. (2009). Hydrogen-fueled internal combustion engines. *Progress in energy and combustion science*, 35(6):490–527.

[81] Volger, C. (2019). *Alternative fuels on board of carbon-neutral cruise vessels: The selection, implementation and design impact of alternative fuels on board of carbon-neutral cruise vessels*. PhD thesis.

[82] Vos, D., Version, D., and Vos, D. (2020). AMMONIADRIVE : A SOLUTION FOR ZERO-EMISSION SHIPPING ?!

[83] Woud, H. K. and Stapersma, D. (2015). *Design of Propulsion and Electric Power Generation Systems*. IMarEST, Institute of Marine Engineering, Science and Technology,.

[84] Zhen, X. and Wang, Y. (2015). An overview of methanol as an internal combustion engine fuel. *Renewable and Sustainable Energy Reviews*, 52(December):477–493.

[85] Zhou, D., Al-Durra, A., Gao, F., Ravey, A., Matraji, I., and Godoy Simões, M. (2017). Online energy management strategy of fuel cell hybrid electric vehicles based on data fusion approach. *Journal of Power Sources*, 366:278–291.

A

Levelized cost of electricity

Table A.1: Levelized cost of electricity for a H_2-PEMFC system

Year	X1000€	**CAPEX**	**OPEX**	**Fuel**	**Energy deliverd [MWh]**		
2025	1	€ 26.197	€ 428	€ 8.419	48048	€ 33.376	45.760
2026	2	€ -	€ 437	€ 8.221	48048	€ 7.853	43.581
2027	3	€ -	€ 446	€ 8.026	48048	€ 7.318	41.506
2028	4	€ -	€ 454	€ 7.834	48048	€ 6.819	39.529
2029	5	€ -	€ 464	€ 7.645	48048	€ 6.353	37.647
2030	6	€ 3.738	€ 473	€ 7.460	48048	€ 8.708	35.854
2031	7	€ -	€ 482	€ 7.278	48048	€ 5.515	34.147
2032	8	€ -	€ 492	€ 7.099	48048	€ 5.138	32.521
2033	9	€ -	€ 502	€ 6.923	48048	€ 4.786	30.972
2034	10	€ -	€ 512	€ 6.751	48048	€ 4.459	29.497
2035	11	€ -	€ 522	€ 6.582	48048	€ 4.154	28.093
2036	12	€ -	€ 532	€ 6.416	48048	€ 3.869	26.755
2037	13	€ 2.763	€ 543	€ 6.254	48048	€ 5.070	25.481
2038	14	€ -	€ 554	€ 6.095	48048	€ 3.358	24.268
2039	15	€ -	€ 565	€ 5.939	48048	€ 3.128	23.112
2040	16	€ -	€ 576	€ 5.786	48048	€ 2.915	22.011
2041	17	€ -	€ 588	€ 5.637	48048	€ 2.716	20.963
2042	18	€ -	€ 600	€ 5.491	48048	€ 2.531	19.965
2043	19	€ -	€ 612	€ 5.348	48048	€ 2.358	19.014
2044	20	€ 2.113	€ 624	€ 5.208	48048	€ 2.994	18.109
2045	21	€ -	€ 636	€ 5.072	48048	€ 2.049	17.246
2046	22	€ -	€ 649	€ 4.939	48048	€ 1.910	16.425
2047	23	€ -	€ 662	€ 4.809	48048	€ 1.781	15.643
2048	24	€ -	€ 675	€ 4.682	48048	€ 1.661	14.898
2049	25	€ -	€ 689	€ 4.559	48048	€ 1.550	14.189
						€ 132.370	677.186
	€ 207.000	€ 34.810	€ 13.718	€ 158.473			
		16,8%	6,6%	76,6%	LCOE	€ 195,47	Euro/MWh
						€ 0,195	**Euro/kWh**

Table A.2: Levelized cost of electricity for a NH_3-ICE system

Year	**X1000€**	**CAPEX**	**OPEX**	**Fuel**	**Energy deliverd [MWh]**		
2025	1	€ 6.925	€ 359	€ 7.220	48048	€ 13.814	45.760
2026	2	€ -	€ 366	€ 7.125	48048	€ 6.794	43.581
2027	3	€ -	€ 374	€ 7.030	48048	€ 6.396	41.506
2028	4	€ -	€ 381	€ 6.938	48048	€ 6.021	39.529
2029	5	€ -	€ 389	€ 6.847	48048	€ 5.670	37.647
2030	6	€ -	€ 397	€ 6.758	48048	€ 5.339	35.854
2031	7	€ -	€ 404	€ 6.671	48048	€ 5.028	34.147
2032	8	€ -	€ 413	€ 6.585	48048	€ 4.736	32.521
2033	9	€ -	€ 421	€ 6.501	48048	€ 4.462	30.972
2034	10	€ -	€ 429	€ 6.418	48048	€ 4.204	29.497
2035	11	€ -	€ 438	€ 6.337	48048	€ 3.961	28.093
2036	12	€ -	€ 447	€ 6.258	48048	€ 3.734	26.755
2037	13	€ -	€ 456	€ 6.181	48048	€ 3.519	25.481
2038	14	€ -	€ 465	€ 6.105	48048	€ 3.318	24.268
2039	15	€ -	€ 474	€ 6.031	48048	€ 3.129	23.112
2040	16	€ -	€ 483	€ 5.959	48048	€ 2.951	22.011
2041	17	€ -	€ 493	€ 5.888	48048	€ 2.784	20.963
2042	18	€ -	€ 503	€ 5.819	48048	€ 2.627	19.965
2043	19	€ -	€ 513	€ 5.751	48048	€ 2.479	19.014
2044	20	€ -	€ 523	€ 5.685	48048	€ 2.340	18.109
2045	21	€ -	€ 534	€ 5.621	48048	€ 2.209	17.246
2046	22	€ -	€ 544	€ 5.559	48048	€ 2.086	16.425
2047	23	€ -	€ 555	€ 5.498	48048	€ 1.971	15.643
2048	24	€ -	€ 566	€ 5.439	48048	€ 1.862	14.898
2049	25	€ -	€ 578	€ 5.382	48048	€ 1.760	14.189
						€ 103.195	677.186
	€ 174.036	€ 6.925	€ 11.504	€ 155.606			
		4,0%	6,6%	89,4%	LCOE	€ 152,39	Euro/MWh
						€ 0,152	**euro/kWh**

Table A.3: Levelized cost of electricity for a MeOH-ICE system

	X1000€	**CAPEX**	**OPEX**	**Fuel**	**Energy deliverd**		
2025	1	€ 6.471	€ 347	€ 10.213	48048	€ 16.220	45.760
2026	2	€ -	€ 354	€ 10.090	48048	€ 9.474	43.581
2027	3	€ -	€ 361	€ 9.970	48048	€ 8.925	41.506
2028	4	€ -	€ 369	€ 9.852	48048	€ 8.409	39.529
2029	5	€ -	€ 376	€ 9.736	48048	€ 7.923	37.647
2030	6	€ -	€ 384	€ 9.623	48048	€ 7.467	35.854
2031	7	€ -	€ 391	€ 9.511	48048	€ 7.037	34.147
2032	8	€ -	€ 399	€ 9.402	48048	€ 6.634	32.521
2033	9	€ -	€ 407	€ 9.294	48048	€ 6.254	30.972
2034	10	€ -	€ 415	€ 9.189	48048	€ 5.896	29.497
2035	11	€ -	€ 423	€ 9.086	48048	€ 5.560	28.093
2036	12	€ -	€ 432	€ 8.985	48048	€ 5.244	26.755
2037	13	€ -	€ 441	€ 8.886	48048	€ 4.946	25.481
2038	14	€ -	€ 449	€ 8.790	48048	€ 4.666	24.268
2039	15	€ -	€ 458	€ 8.695	48048	€ 4.403	23.112
2040	16	€ -	€ 468	€ 8.603	48048	€ 4.155	22.011
2041	17	€ -	€ 477	€ 8.512	48048	€ 3.922	20.963
2042	18	€ -	€ 486	€ 8.424	48048	€ 3.702	19.965
2043	19	€ -	€ 496	€ 8.338	48048	€ 3.496	19.014
2044	20	€ -	€ 506	€ 8.254	48048	€ 3.302	18.109
2045	21	€ -	€ 516	€ 8.172	48048	€ 3.119	17.246
2046	22	€ -	€ 527	€ 8.093	48048	€ 2.946	16.425
2047	23	€ -	€ 537	€ 8.015	48048	€ 2.784	15.643
2048	24	€ -	€ 548	€ 7.940	48048	€ 2.632	14.898
2049	25	€ -	€ 559	€ 7.867	48048	€ 2.488	14.189
						€ 141.604	677.186
	€ 241.139	€ 6.471	€ 11.127	€ 223.540			
		2,7%	4,6%	92,7%	LCOE	€ 209,11	Euro/MWh
						€ 0,209	**euro/kWh**