Master thesis
Master Sustainable Energy Technology
Heerema Marine Contractors

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October 2022

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Development of a roadmap to a net-zero fleet

A technical and financial evaluation

by

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To obtain the degree of Master of Science
At the Delft University of Technology
As part of the master Sustainable Energy Technology

Student number:	4605837
Project duration:	Feb 1, 2022 – Oct 1, 2022
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PREFACE

When I started my studies in mechanical engineering at the Technical University of Delft 5 years ago, I discovered that I wanted to make a change and do something to make the world more sustainable with new technologies. During my bachelor's, I always tried to make sustainability the main subject of my education, and this is why my bachelor's thesis was on the photoelectrochemical reduction of CO2. I started my master's in Sustainable Energy Technology, where I broadened my vision and knowledge by learning in-depth about solar energy, wind energy and storage technologies, including hydrogen technologies. My main interest is the bridge between financial and sustainability research, which is why Heerema's thesis subject perfectly suited my interests: developing a roadmap to make their fleet more sustainable and evaluating this process on technical and financial criteria.

I would like to thank all the employees within the Heerema Sustainability Department and my fellow thesis students for the great time and inspiring conversations. A special thanks to Hedzer Keulen, who inspired me with his view on sustainability and insights into the marine sector.

Moreover, I would like to thank professor van Wijk, my daily supervisor, who taught me a lot about the hydrogen technologies and who was always available for questions and feedback.

I learned a lot during the writing of this thesis as a student and as a person, I enjoyed the journey, and I am happy to finish my university career with this thesis. I hope every reader can educate him/her self during the reading of the thesis.

Jesse Cornelis Juncker
Amsterdam, September 15, 2022

ABSTRACT

The maritime sector plays an important role in energy transition because offshore vessels are used for building offshore renewables but also have high emissions. The European Union (EU) has determined that from 2025 the maritime sector must pay per ton of CO_2 emission. Heerema Marine Contractors (HMC) is an essential player in the maritime sector and plans to have reduced its emissions by 50% by 2025. This thesis aims to build a model in which different emission-abating options can be compared on financial and technical aspects to determine the best roadmap to achieve sustainability.

To do this properly, literature research is done on emissions-abating fuels and technologies/processes applicable to offshore crane vessels. Five sub-questions are answered to find an answer to the main research question:

What will be the future energy configuration of the Heerema fleet and the most technical and financial feasible roadmap to meet the sustainability goals look like?

- What are an offshore crane vessel's main operational energy-consuming modes?
- Which fuel switches and blends are technically and financially feasible, and what are the key characteristics of these fuels?
- What are the key characteristics of the ship-based emission-abating technologies like batteries and carbon capture and storage?
- What are the current vessel-specific levelized cost of Energy (LCOE) and levelized cost of carbon abatement (LCoCA) of the fuel switches and technologies, and how are they expected to develop over time?
- Which emission-abating future scenarios are technically and financially feasible, and how will these sustainable roadmaps look?

With the evaluation of the answers to these sub-questions, the importance of using hydrotreated vegetable oil (HVO) is shown until e-fuels are available. From 2026 e-fuels are assumed to be wide available for usage on board the three vessels, the Sleipnir, Aegir and Thialf the vessels within the scope. The financial evaluation of the e-fuels is in favour of ammonia. The technical evaluation is based on the limited available storage volume favour for methanol.

These findings result in a roadmap using batteries on board the vessels together with HVO as fuel and when available installing designated ammonia or methanol tanks, and using ammonia or methanol as a 100% fuel blend in the internal combustion engines of the three vessels.

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HMC	–	Heerema Marine Contractor
GHG	–	Green House Gasses
IMO	–	International Maritime Organization
ETS	-	Emission Trading System
MGO	-	Maritime Gas Oil
COE	-	Cost of Energy
LCOE	-	Levelized cost of energy
LCoCA	-	Levelized Cost of Carbon Abatement
LNG	-	Liquid Natural Gas
HVO	-	Hydrotreated Vegetable Oil
FAME	-	Fatty-acid Methyl Esther
GTL	-	Gas-to-Liquid
TNO	-	Toegepaste-Natuurwetenschappelijk Onderzoek
CRF	-	Capital Recovery Factor
CAPEX	-	Capital Expenditures
OPEX	-	Operational Expenditures
HHV	-	Higher Heating Value
CAGR	-	Compound Annual Growth Rate
DP	-	Dynamic Positioning
AGS	-	Advanced Generator Supervisor
DG	-	Diesel Generator
CO	-	Carbon Oxide
NO	-	Nitrogen Oxide
Li-ion	-	Lithium-ion
CCS	-	Carbon Capture and Storage
Vol%	-	Volumetric percentage
mT	-	metric Tonnes
BaU	-	Business as Usual

1. Introduction

The maritime sector contributes to the global problem of climate change. The maritime sector is essential within the energy transition because of its role in building offshore wind parks. However, the shipping industry is responsible for the emission of 940 million tons of CO_2 annually, 2.5 % of the emissions worldwide [18]. Heerema Marine Contractors (HMC) plays a part in this sector with its largest crane vessels in the world.

Within the sustainability team of HMC, there is a significant focus on different aspects of sustainability, prevention, reduction and compensation. With an annual emission amount of around [redacted] metric tons of CO_2. These emissions are part of the greenhouse gasses (GHG), which block the outgoing heat radiation and cause the oceans' PH levels to decrease (become more acidic). The International Maritime Organization (IMO) requires an emission abatement of at least 50% in 2050 compared to 2008 and 40% in 2030 [47], and this goal is set for every organization.

1.1 Problem background

Emission abatement is a challenge for the maritime sector. With the regulation of the IMO described above, every maritime company will have to become more sustainable. The European Union (EU) are introducing new actions to give industries more incentive to become more sustainable. Non-financial incentives by regulations on obligated emission reduction in the Paris Agreement [47] and the introduction of the fit for 55 impose reductions of 50% and 55%, respectively, for the maritime sector. The EU also introduces a financial incentive for the maritime sector by adding the sector to the Emission Trading System (ETS), in which the industry has to pay the price per ton of carbon emission.

The maritime sector is expected to be added to the ETS from 2026 onwards [47]. With this introduction, HMC will have to pay [redacted] yearly for its emissions with the current carbon prices. Within HMC, the sustainability department established a roadmap to meet the sustainability goals of the EU and the IMO. The ambition of HMC is to abate all its emissions by 2030 shown in Figure 1.

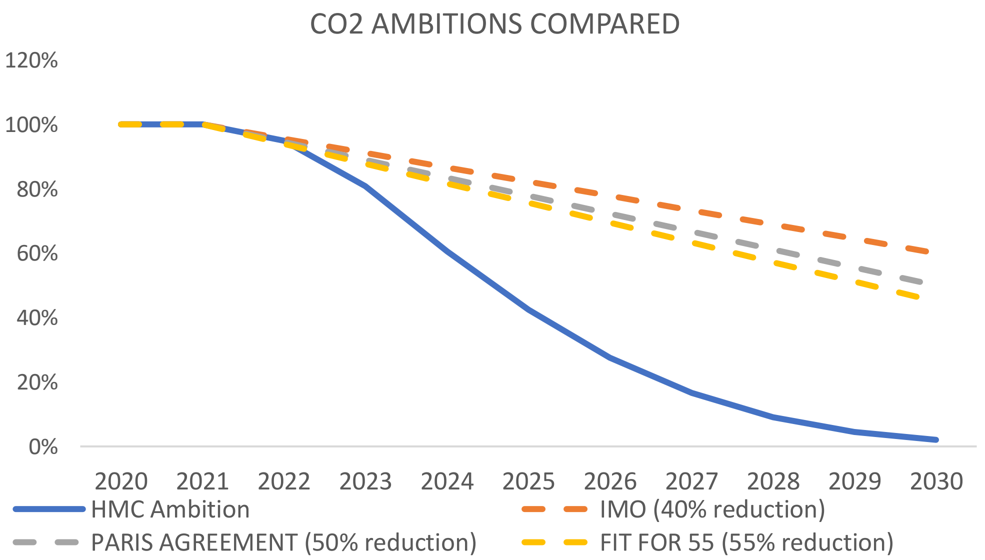

Figure 1 Comparison of different regulations from IMO and EU

The department is working on different projects to make this ambition happen, for example, installing shore power on two vessels of HMC, the Sleipnir and the Thialf. Implementing bio-fuels and e-fuels is under investigation. All the vessels are operational using Maritime Gas Oil (MGO), an emission-intensive fuel. Within this thesis, the ambition of HMC is investigated based together with the influence of fuels and technological adjustments on the emission profile of offshore crane vessels.

1.2 Heerema Marine Contractors

Heerema Marine Contractors is a Dutch company based in Leiden. HMC is one of the world-leading marine contractor companies, and HMC is specialised in operations in the oil/gas and renewable energy sectors. Heerema is the owner of the largest semi-submersible crane vessel in the world called the Sleipnir; the fleet currently consists of the Sleipnir, Thialf, Aegir, and Balder and two tug vessels.

The sustainability department constructed a roadmap based on the IMO and EU objectives, and this roadmap is an emission reduction prediction for 2030. Within the department, the following emission-abating options are considered: fuel switches, battery installation, and a ship-based carbon capture and storage system. Heerema believes in implementing biofuels and hydrogen-carrying fuels within the roadmap.

1.3 Research questions

This research aims to develop a generic model that calculates different sustainable configurations for offshore crane vessels. The model examines different sustainable options based on financial and technical criteria applied to generic inputs.

Main research question: *What will be the future energy configuration of the Heerema fleet and the most technical and financial feasible roadmap to meet the sustainability goals look like?*

Different sub-questions are examined to answer the main research question. The first three questions are answered by examining external and internal HMC documentation. This information is used as data for the generic model and can be considered the literature review of this thesis. These first three questions are used to collect generic information on the operations of the vessels and the characteristics of the emission-abating options.

- **Sub-question 1:** What are an offshore crane vessel's main operational energy-consuming modes?

- **Sub-question 2:** Which fuel switches and blends are technically and financially feasible, and what are the key characteristics of these fuels?

- **Sub-question 3:** What are the key characteristics of the ship-based emission-abating technologies like batteries and carbon capture and storage?

With sub-questions 4 and 5, the decision criteria will be described and calculated. Using various assumptions, the model uses these criteria to evaluate different sustainable adjustments on their financial and technical feasibility.

- **Sub-question 4:** What are the current vessel-specific levelized cost of energy (LCOE) and levelized cost of carbon abatement (LCoCA) of the fuel switches and technologies, and how are they expected to develop over time?

- **Sub-question 5:** Which emission-abating future scenarios are technically and financially feasible, and how will these sustainable roadmaps look?

1.4 Methodology

Within this section, the methodology is described for answering the different sub-questions mentioned above. The final result of this thesis is a generic model that can operate on different assumptions to show the technical and financial influence of emission-abating fuels and technologies on board a vessel. Different feasible scenarios are tested with the model, and the outcomes are analysed.

Sub-question 1: *What are an offshore crane vessel's main operational energy-consuming modes?*

In collaboration with employees of HMC, a description of the different vessels of HMC is constructed. A distinction is made between the different operational modes of the vessels. This distinction is made by using engine data, the power output and the frequency of an operational mode. These numbers are all extracted and used as input for the model. For example, 2500 kW to 3500 kW output is linked to operational modes of a vessel; idle, port or anchorage.

Sub-question 2: *Which fuel switches and blends are technically and financially feasible, and what are the key characteristics of these fuels?*

Within this sub-question, several fuels will be examined. A distinction is made between chemical energy carriers (for example, fuels and molecules) and electrical energy carriers (for example, batteries and electrons). Fuels are distinguished in *current fuels* (MGO, LNG), *drop-in fuels* (HVO, FAME, GTL) and future energy carriers (hydrogen, methanol, and ammonia).

A well-to-wake analysis is done for the different fuels, which is an analysis starting at the fuel production up to the consumption (use) of the fuel. With this, all emissions during a fuel's production process are considered. The energy content, storage and conversion of the energy carriers are discussed. For drop-in fuels, the applicability and tests on the vessels are discussed, and for future energy carriers, the possibility of blending the fuels is discussed.

Sub-question 3: *What are the key characteristics of the ship-based emission-abating technologies like batteries and carbon capture and storage?*

Within this sub-question, the implementation of two different batteries is examined and discussed, as well as the implementation of carbon capture storage systems.

The two types of batteries are lithium-ion and redox flow batteries, which are within this thesis's scope. General information is gathered based on literature. Moreover, various subcontractors provided detailed quotations on implementing batteries on board the vessels.

A collaboration between Toegepaste-Natuurwetenschappelijk Onderzoek (TNO) and HMC is ongoing to implement a carbon capture and storage system. This collaboration provides relevant data on financial and technical aspects for the discussion on the process on board within this thesis.

Sub-question 4: *What are the current vessel-specific levelized cost of energy (LCOE) and levelized cost of carbon abatement (LCoCA) of the fuel switches and technologies, and how are they expected to develop over time?*

Within this sub-question, the emission reduction of the emission abating fuels and technologies are compared with the current situation on board the vessels. This is done according to the schematic overview in Figure 2.

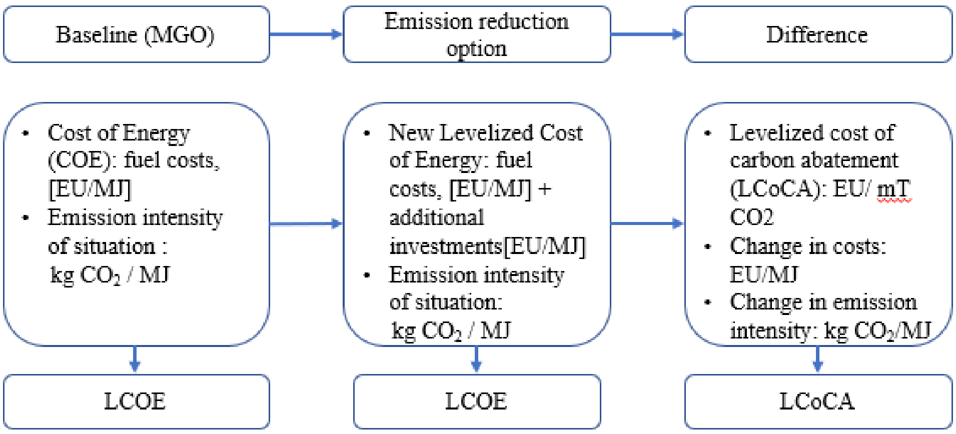

Figure 2 Schematic overview of the methodology, showing the baseline and the decision criteria.

The levelized cost of energy (LCOE) is calculated by combining the answers from literature research from sub-question 1 to 3 and the financial insights into fuel costs and technologies collected by research and interviewing fuel brokers.

The LCOE is calculated yearly, meaning the capital expenditures must be annualised. This is done by introducing the capital recovery factor (CRF) that is calculated using:

$$CRF = \frac{r}{(1-(1+r)^{T_{depreciation}}} = [\%]$$

Equation 1 Capital recovery factor

$$LCOE\ (t) = \frac{Fuelcost_{year} + OPEX + (CRF * CAPEX)}{Energy_{year}} = [\frac{€}{MJ}]$$

Equation 2 Levelized cost of Energy

- $Fuelcost_{year}$: Price paid per year for fuels [Euros]
- OPEX: Operational expenditures (OPEX) and maintenance costs over a year. For batteries, this is maintenance costs and for CCS this

is the transport of CO_2, for fuel this is the maintenance of the fuel tanks. [€]

- CAPEX: Capital expenditures (CAPEX) investment costs are annualised. For technologies, this is the investment and installation costs. For fuels, this is the installation cost for new storage tanks. [€]
- $T_{depreciation}$: the lifetime of the vessel or lifetime of the investment, the number of years for depreciation [years]
- r: discount rate [%]
- $Energy_{year}$: Energy required annual [MJ]

The LCOE is calculated with a capital expenditure that is annualised and added to the annual fuel costs, which is the amount of annual energy required (MJ) multiplied by the price per MJ and the annual emission costs. The sum of all the annual expenditures is divided by the annual energy consumption, which gives the LCOE.

The second decision criteria is the emission intensity expressed in $\left[\frac{kg\ \text{CO2}}{MJ}\right]$ used to quantify the emission reduction potential for all options, the emission intensity is calculated by:

$$Emission\ intensity\ \left[\frac{kg\ \text{CO2}}{MJ}\right] = \frac{Annual\ carbon\ emissions\ \ [kg]}{M_{fuel}\ [kg] * HHV\ \left[\frac{MJ}{kg}\right]}$$

Equation 3 Emission intensity calculation

- $Annual\ carbon\ emissions\ [kg]$: CO_2 emissions.
- $M_{fuel}\ [kg]$: the amount of kg of fuel used in a year.
- $HHV\ \left[\frac{MJ}{kg}\right]$: Higher Heating Value(HHV) is the energy content in the amount MJ per kg of fuel.

This value compares the emission profiles when switching to a new fuel or installing a new technology.

Figure 2 shows that MGO is used as the baseline. The costs for the emission reduction options are determined by calculating the difference between the LCOE's and the change in emission intensity. This differences gives the levelized costs for carbon abatement (LCoCA) per option.

$$LCoCA(t) = \frac{\Delta LCOE(t)}{\Delta Emission\ intensity} = [\frac{€}{kg\ \text{CO2}}]$$

Equation 4 Levelized cost of carbon abatement of fuel switches

- ΔLCOE (t): Difference in cost of energy for an option compared to the baseline.
- $\Delta Emission\ intensity$: Change in emission intensity for an option compared to the baseline.

The LCoCA represents the additional cost of producing the same amount of energy while abating a ton of CO_2 compared with the baseline of MGO. The LCoCA is compared between all the different options.

To give an estimation of the availability of fuels in different areas worldwide, the current market size and the market's growth using a compound annual growth rate (CAGR) from the literature will be used.

$$Availability\ [liter] = \frac{Current\ market\ size\ [€] * (1 + CAGR[\%])^{year}}{Fuel_{cost}[\frac{€}{l}]}$$

Equation 5 Availability quantification

- $Current\ market\ size$ [€]: Market size of a fuel.
- $CAGR$[%]: Compound Annual Growth Rate, expected percentage of annual market size increase.
- $Year$: Number of years from baseline, 2020.
- $Fuel_{cost}[\frac{€}{l}]$ = Fuel price

This formula gives a prediction based on assumptions for the quantification of the volume of a fuel available at a certain moment in a certain area.

Sub-question 5: *Which emission-abating future scenarios are technically and financially feasible, and how will these sustainable roadmaps look?*

The baseline for the roadmap design is the anticipated emissions based on scheduled (future) projects. Based on the available literature, calculations and assumptions, the model for the roadmap is constructed. The different emission reduction options within the model are compared based on the outputs: the LCOE, the emission intensity and the annual expenditures. These outputs are combined with an expectation of the availability of fuels and technologies. Different scenarios are constructed based on the availability of fuels and technologies and are used to validate the model using the vessels of HMC. Hereafter the outcomes are analysed on technical and financial criteria to select the most feasible roadmap for each vessel.

Main research question: *What will the future energy configuration of the Heerema fleet and the most technical and financial feasible roadmap to meet the sustainability goals look like?*

The model's outcomes evaluate the different sustainable options on technical and financial aspects. The technical feasibility of storing the different fuel volumes on board and the health and safety risks are discussed. Hereafter the different financial criteria are compared with the roadmap's profits, losses, and cost savings per year. Based on the technical and financial evaluation, a selection of different fuels and technologies is made.

1.5 Scope of this thesis

A few preconditions were set on which inputs for the model are based. The three largest vessels of HMC in this thesis will be discussed in the scope of this thesis. Firstly, the Aegir, Sleipnir, and Thialf because these three cover 70% of the emissions of HMC. Secondly, as a prerequisite for this research, the drivetrain of the vessel should not be changed significantly, as it will change the outcome of this research.

Fuels should be converted into electricity in the current internal combustion engines using the same specific fuel consumption per engine efficiency. The fuels examined in the scope of this thesis are MGO, Liquefied Natural Gas (LNG), Hydrotreated vegetable oil (HVO), Gas-to-Liquid (GtL), Fatty-acid Methyl Esther (FAME), green hydrogen, green methanol and green ammonia.

The installation of a new tank is inside the scope of this research. For hydrogen-carrying fuels, fuel blending is investigated. On hydrogen-carrying fuels, the assumption is made that these fuels are widely available and expected to be used as 100% fuel blends.

For the installation of batteries, two types of batteries are examined for the Aegir, Sleipnir and Thialf. The lithium-ion battery and, hereafter, the redox flow battery will be examined.

2. THE FLEET OF HEEREMA MARINE CONTRACTORS

This chapter gives insights into the vessels: Aegir, Sleipnir and Thialf. This chapter gives an idea of what kind of work the vessels do and what energy configuration is currently used on board. This literature review on the vessels will answer **sub-question 1:** What are an offshore crane vessel's main operational energy-consuming modes?

2.1 Fleet introduction

The operational fleet of Heerema Marine Contractors consists of different vessels. These vessels are examined based on their general characteristics, power generation, primary electrical consumers, and energy profiles/operational modes. This information will clarify the most common operational modes and the average power consumption.

The main focus concerning the power supply during offshore operations is reliability. During offshore construction, the vessel typically uses its dynamic positioning (DP) system to remain in place, regardless of waves, currents and wind. Therefore, a loss of power can result in a loss of position. Furthermore, it will interrupt offshore construction work, as the power supply to other machineries, such as the cranes and ballast pumps, will be interrupted.

For this reason, redundancy measures are taken to ensure a reliable power supply. The vessels operate in different modes during offshore construction to ensure a continuous power supply. Within the lifetime of the vessels, they operate in different locations and environments and have different operational tasks. Below, the different operational modes are discussed:

- **DP2, Mild weather:** The vessel's dynamic positioning system remains positioned. This mode accounts for the failure of a single component and is most frequently used. Engine loads are typically low (<50%). To account for redundancy, at least one extra engine is running. Using the Advanced Generator Supervisor (AGS) system, the vessel can operate in DP2 mode with all switchboards connected (closed-bus configuration). The cranes usually handle relative light loads for work preparations, supplies, people transfer, etcetera.

- **DP2, Medium weather:** The vessel operates in stronger winds and currents and requires more power than in mild weather.

- **DP3:** The vessel uses its most redundant dynamic positioning configuration. All the switchboards have to be able to operate entirely independent. During DP3, there is an extra backup engine, so it has at least two backup engines available. This independency of the engine rooms is necessary as a single point of failure needs to be prevented.

- **Idle, Port, Anchorage:** The vessel is carrying out operations for which the DP system is not required. This mode typically operates when the vessel is moored in port or anchored. Only one engine is running to provide the necessary power for the daily use of small electrical consumers, such as air conditioning, lighting, etcetera. Cranes are being used for the routine daily handling of light loads.

- **Transit, high speed**: The vessel is in transit and travels at high speed, implying a high power demand.

- **Transit, eco speed:** The vessel is in transit and travels at an economical speed, implying the power is used economically.

The engines are separated into different engine rooms. The engine rooms are connected to switchboards that divide the energy over the designated electrical components. The different electrical components are discussed below. These electrical consumers are similar on board all the three vessels and are active or inactive during the operational modes, which is further discussed in Chapter 2.5.

- **The Hotel load:** The hotel load is relatively constant and relatively low compared to the power generation capacity. The hotel load comprises the electric power required for the lights, heating systems, laundry, mess rooms, hydraulic systems, air compressors, etcetera. This (hotel/base) load is always required on board each vessel.

- **Thruster load:** The thrusters' load is caused by propeller units driven by large electro motors. These thrusters are used for sailing the vessel to the following offshore installation location or keeping the vessel at the envisaged position as part of the dynamic positioning system. The electric power consumed by all the thrusters depends on the type of operation and the environmental conditions. The total consumed power typically varies gradually in time but can change significantly. Protection systems limit the thruster power consumption to prevent the potential overloading of the diesel generators. The highest peaks in power demand are caused by the thruster loads rather than the crane loads.

- **Crane load:** The crane or cranes are electrically driven by electro-motors. The cranes' power consumption is very irregular, and the power consumption can ramp up very quickly to relatively high power levels. Especially slewing (rotating) the crane can lead to high peaks in energy consumption. Most of the time, the crane or cranes are operated for relatively light lift (or empty crane) operations. The power demand is then very ‘spiky’. Relatively high and short power demand is required for initiating the crane movement due to its inertia.

- **Ballast and anti-heeling pumps:** The ballast and anti-heeling pumps play an essential role in lifting operations. Ballast pumps are used to lift heavy objects, and the anti-heeling system is used to prevent the ship from heeling over while slewing.

On every vessel, engine data is generated every couple of seconds for all the different engines on board and is stored on-shore. The engine data will be examined per vessel and compared between vessels in Chapter 0 based on power output and frequency of occurrence.

2.2 Dimensional information on vessels

The vessels discussed in this thesis operate worldwide, building offshore wind parks and oil/gas platforms. In

Table 1, the generic dimensions of the vessels are shown:

Table 1 Dimensions of the vessels

Dimension	Aegir	Sleipnir	Thialf
Length [m]	211	220	201.6
Width [m]	46.0	102	88.4
Operational draft [m]	9 – 11	12-35	11.9 - 31. 6
Transit draft [m]	8	12	12.5
Lifting capacity [mt]	5000	20000	14200
Year launched	2012	2019	1985

2.3 Current power plant configuration

Currently, maritime gas oil (MGO) is used on each vessel. Generators convert this fuel into electricity for all electrical components within the different engine rooms. The internal combustion engine moves the generator.

As discussed above, different generator configurations are used for electrical consumers; an overview is shown in Table 2. These different configurations are used because of the different power demands for different operational modes. For example, when operating in DP3, additional capacity is used as standby resulting in extra emissions. There is always a higher amount of power available than used for redundancy reasons.

Table 2 Power plant configuration of the vessels

Vessels	Aegir	Sleipnir	Thialf
Total engine power installed [kW]	48000	96000	58400
Generator power [kW]	7710	7710	6x4600 4x4300 2x5800
Number of engine rooms and switchboards [#]	2	4	5

All engines are designed for running on MGO except for the engines on the Sleipnir. These engines are dual-fuel engines and can operate on MGO and LNG. These two fuels cannot be stored within the same tank, so separate tanks are used on board the vessel. In Chapter 3, the different possible fuel switches and fuel blends will be discussed. The fuel storage on board is different for all three vessels; see Table 3, this is an important criteria because the storage volume on board of the vessels is limited.

Table 3 Fuel storage on board the vessels

Vessels	**Aegir MGO**	**Sleipnir MGO**	**Sleipnir LNG**	**Thialf MGO**
The total volume of tanks [m3]	6414	3180	11941	8500
The pressure of tanks [bar]	ambient	ambient	7 bar	ambient
The temperature of tanks [degrees]	ambient	ambient	-160	ambient

All the engine room configurations are shown in Appendix 12.2. Below, the configuration for the Aegir shows that not all switchboards are active for all operational modes in Figure 3. The power consumption, the frequency of occurrence and the energy demand per operational mode are quantified in the next paragraph.

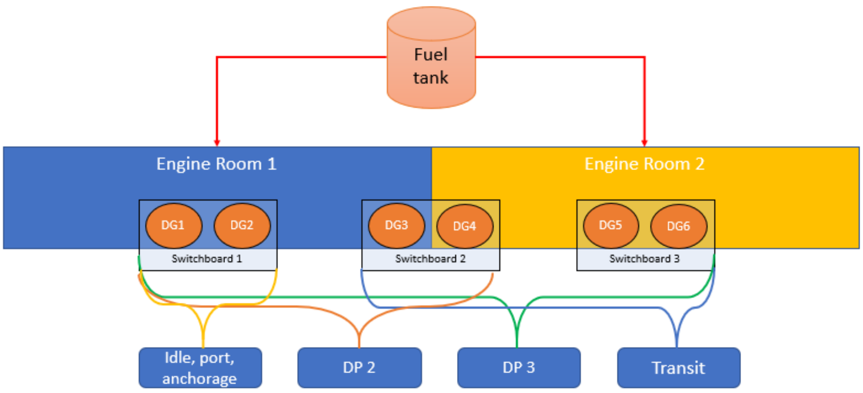

Figure 3 Schematic overview of power generation on the Aegir with engine rooms, diesel generators (DG), switchboards, and operational modes.

2.4 Operational modes

From the engines of every vessel, data has been collected over the vessel's lifetime. Kongsberg is a company that collects data from the engines on board the vessels for HMC (KIMMS-data). With sensors and meters, the power output and fuel consumption are measured. For this thesis, a data collection with a scan rate of one second for the past three years is examined in Appendix 12.1. This data is processed and summarized using a python script to group the data in different operational modes based on power output. Based on knowledge of the different electrical consumers on board the vessels, estimations are made on the frequency of the occurrence of the different operational modes given in Table 4.

Table 4 Frequency of occurrence of different operational modes of the vessels

Frequency of Occurrence [%]	Aegir	Sleipnir	Thialf
DP3	20%	39%	2%
DP 2, mild weather	15%	0%	37%
DP 2, medium weather	5%	0%	8%
Idle, port, anchorage	40%	40%	21%
transit, high speed	15%	15%	24%
transit, eco speed	5%	6%	8%

Table 5 Average power consumption of different modes of the vessels

Power consumption [kW]	Aegir	Sleipnir	Thialf
DP3	7000	8500	7000
DP 2, mild weather	4500	12500	10000
DP 2, medium weather	7000	4500	4000
Idle, port, anchorage	3100	24500	28000
transit, high speed	15800	20500	20000
transit, eco speed	12000	8500	7000

With these frequencies and the accompanied average power consumption per mode, the energy demand of the vessels can be calculated, see Table 6. As shown in Table 5, the installed power is much higher than the average power consumption due to the back-up power. The amount of daily energy used for all the vessels is shown in Table 6.

Table 6 daily fuel consumption of different operational modes for the vessels

Daily energy consumption [10^3*MJ/day]	Aegir	Sleipnir	Thialf
DP3	604.8	1380.6	736.0
DP 2, mild weather	475.2	887.5	473.1
DP 2, medium weather	604.8	1380.6	736.0
Idle, port, anchorage	267.8	611.4	326.0
transit, high speed	1365.1	3116.1	2989.4
transit, eco speed	1036.8	2366.7	1192.3

The pie charts below in Figure 4, Figure 5, and Figure 6 summarise the information above and show the frequency of occurrence and the power profile of the separate vessels.

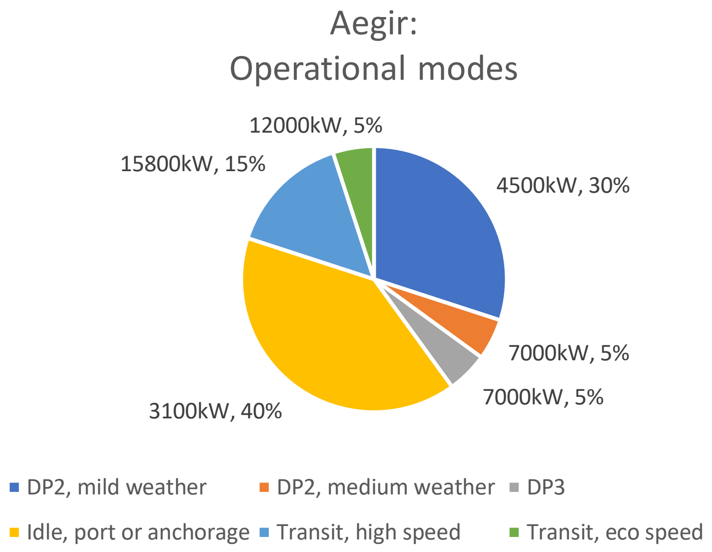

Figure 4 Pie chart of the frequency of occurrence combined with the power consumption for the Aegir

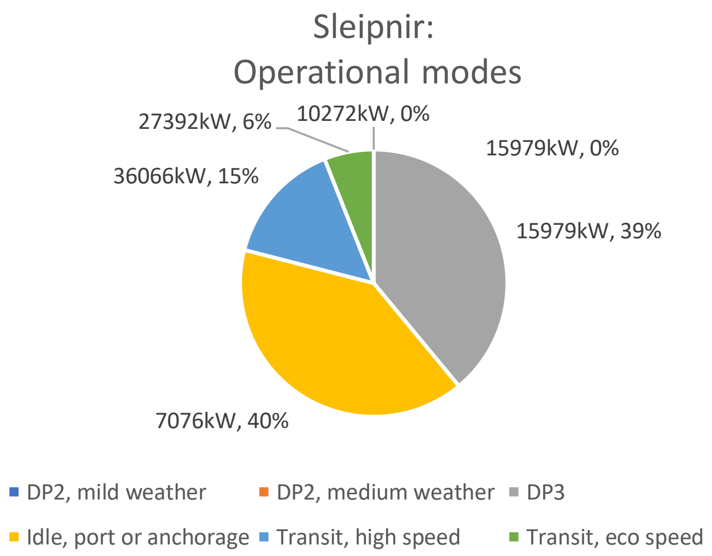

Figure 5 Pie chart of the frequency of occurrence combined with the power consumption for the Sleipnir

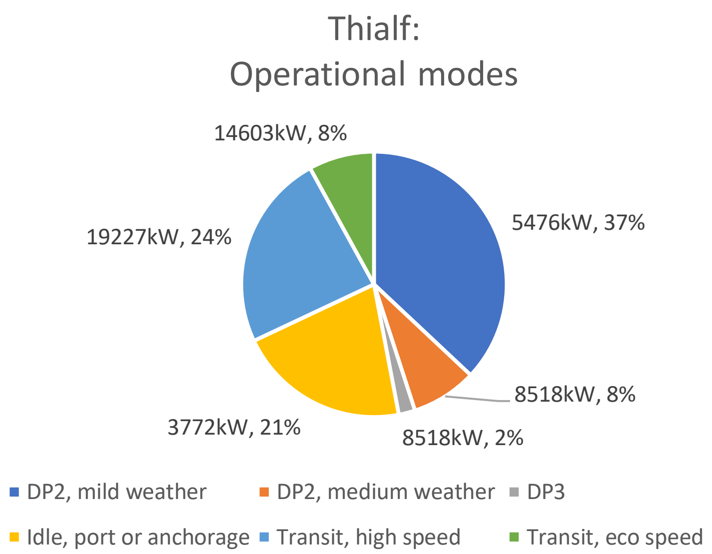

Figure 6 Pie chart of the frequency of occurrence combined with the power consumption for the Thialf

2.5 Main electrical consumers

During the operational modes, different energy consumers can be distinguished. As described above, the hotel, thruster, crane, and pump loads are online/offline for the operational modes, and this is shown in Table 7.

Table 7 Electrical consumers online/offline during operational mode

Active loads	Hotel	Thruster	Crane	Pump loads	Handling cranes
DP3	√	√	√	√	√
DP 2, mild weather	√	√	√	√	√
DP 2, medium weather	√	√	√	√	√
Idle, port, anchorage	√	X	X	√	√
transit, high speed	√	√	X	X	√
transit, eco speed	√	√	X	X	√

The hotel load is always present because it is the load caused by the power usage of household electrical consumers on board. Thrusters are active to ensure the vessels' movement during transit or work to guarantee dynamic positioning at the exact location. Small cranes are used during all-day events to transport and carry small objects.

For most electrical consumers, a surplus of power is installed on top of what is commonly used. This surplus makes it possible to have peaks in the power consumption of the vessels. For example, the graph shown in Figure 8 shows the thruster power and the power generated.

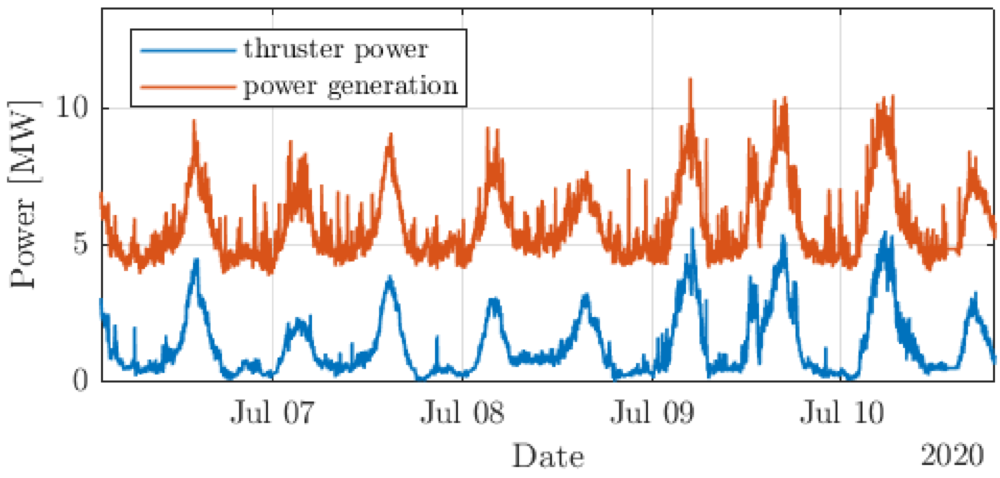

Figure 7 Aegir power production shows the thruster load consumed.

Below in Figure 8, a more irregular load consumption of the Aegir is shown with different energy consumers marked. These two graphs are plotted with data from Kongsberg of the Aegir using a python script from HMC.

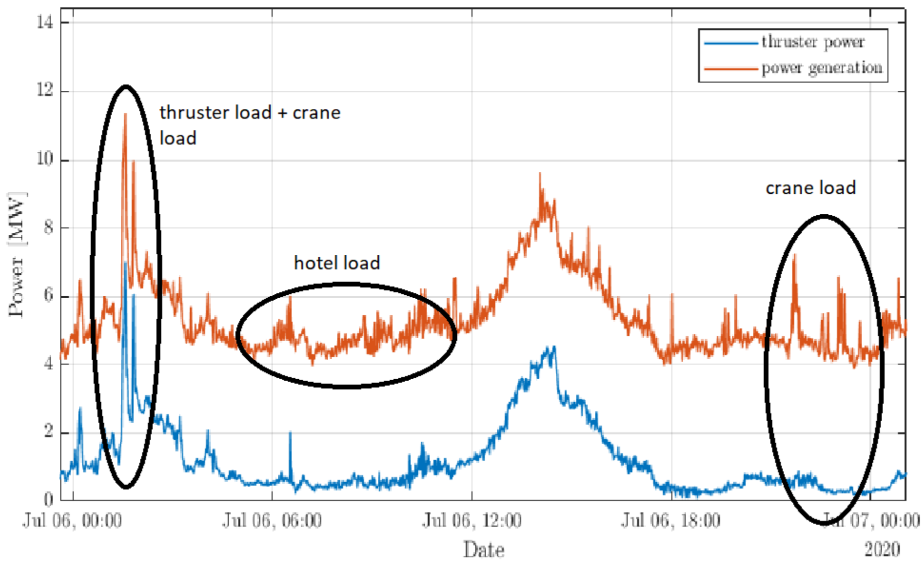

Figure 8 Aegir power generation shows the thruster power and the crane and hotel load.

3 CURRENT AND FUTURE FUEL CHARACTERISTICS

In this chapter, insights into the fuels: MGO, LNG, HVO, GTL, FAME, green hydrogen, green methanol and green ammonia are given. This chapter gives an idea of which fuel characteristics are essential. This literature review on the fuels will answer **sub-question 2:** Which fuel switches and blends are technically and financially feasible, and what are the key characteristics of these fuels?

3.1 Technical fuel evaluation criteria

Most of the energy on board the vessels is stored as MGO, an emission-intensive fuel that is widely available. The price of MGO is relatively low compared to bio-diesels. As this fuel is currently the most used, it will be used as a baseline in this thesis.

Within this thesis, there is a distinction between the fuels that can be used and are available for the maritime sector, the so-called drop-in fuels, and the fuels that still need further research. A fuel is called a drop-in fuel when it can be stored in the currently available tanks and generate electricity in the existing drive trains. The fuels that require more research are the e-fuels. These e-fuels can be used as fuel blends and need designated tanks for storage.

Decision criteria are used to evaluate the different fuels, of which safety and energy density are the most important decision criteria. Without safety and a high enough energy density, a fuel is not scheduled to be used and therefore lies outside the scope of this research.
A high enough volumetric energy density is critical because of the limited maximum volume available for storage on board. Safety is a criteria because the lowest chance of toxicity and explosion hazards for the crew is essential.

A fuel with a lower emission profile is required to get a more sustainable energy system on board the vessels. Within the emissions, a distinction is made between well-to-tank and tank-to-wake emissions. The well-to-wake emissions are the emissions that cover the entire emissions profile, the emissions from the production of the fuel to the chimney of the vessel. The only emissions considered for tank-to-wake emissions are during the fuel conversion into electricity on board. This difference is visualised in Figure 9 below.

Note that whenever HMC enters the ETS expected as of 2026, the company only has to pay for its tank-to-wake emissions because the fuel producer already pays for the well-to-tank emissions. In this chapter, numbers are given for well-to-tank emissions, while these numbers depend on the production process, so these could differ for different processes. The well-to-wake emissions are given during the fuel evaluation because the entire footprint interests HMC. HMC uses CO_2-emission factors for all the fuels available, which give a number of emissions per kg of fuel.

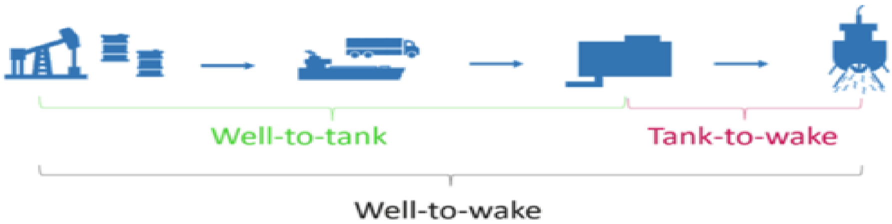

Figure 9 Visualisation of the difference between well-to-tank and tank-to-wake

One of the prerequisites for this research, the drive train, is assumed not to be changed, it is an expensive operation and influences the outcome of this research, so it is left outside the scope of this research. Furthermore, the current price and technology readiness levels of fuels and technologies are included in the research, being critical parameters.

During the selection of the fuels, the fuels are examined on the criteria given above, safety, energy density and their emission profile. The entire production profile is analysed for every fuel to guarantee that a fuel is suitable for the vessels. Below in Figure 10, the entire well-to-wake conversion of the fuels is shown, and the percentages shown are the efficiencies of different conversions.

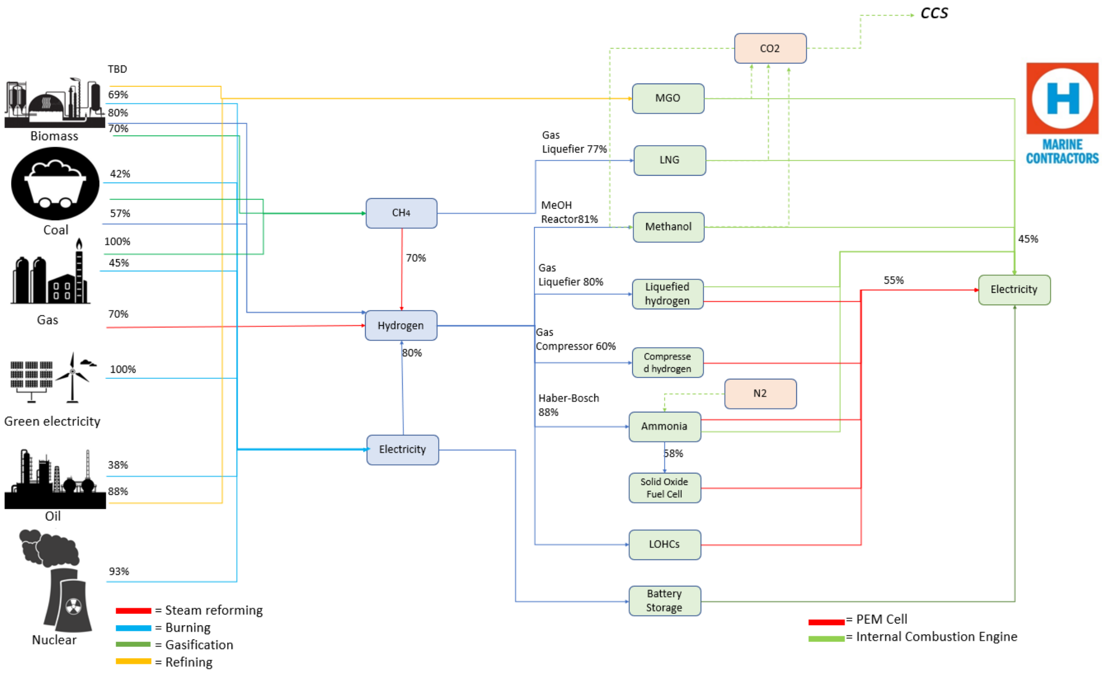

Figure 10 Fuel analysis on production processes of potential fuels

During this analysis, the well-to-wake emissions are calculated for every fuel. Within this thesis, the fuels considered are MGO, liquified natural gas (LNG), Hydrotreated Vegetable Oil (HVO), Gas to Liquid (GTL), Fatty-acid Methyl Esther (FAME), green hydrogen, green methanol, and green ammonia. MGO is used as a baseline. Below in Figure 11, the emissions per MJ are given for well-to-tank and the tank-to-wake analysis. The darker colour shows the emissions on board, and the light colour the emissions during production. For methanol, one of the e-fuels, the emissions during production are negative and result in net-zero emissions by adding the tank-to-wake emissions during conversion.

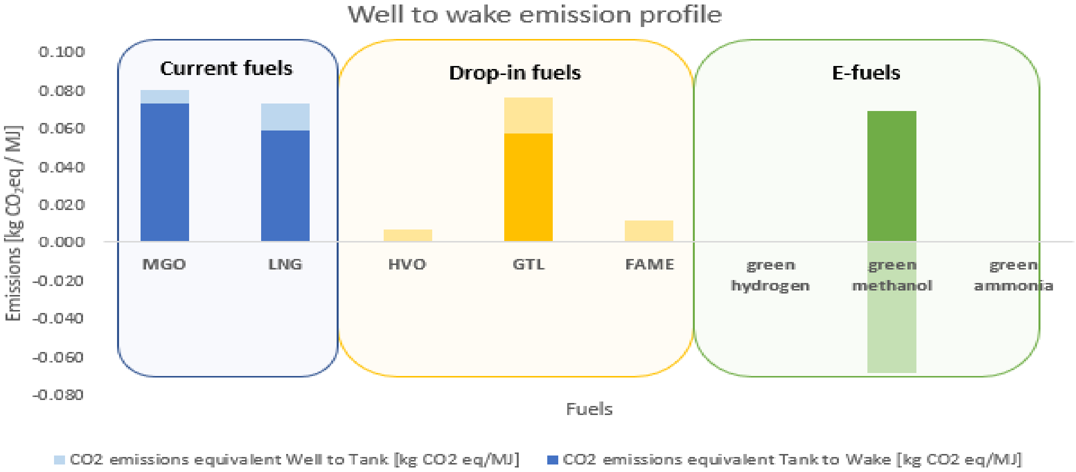

Figure 11 Well-to-wake emission profiles for different fuels.

3.2 Current fleet energy carriers

Maritime gas oil (MGO) and Liquefied Natural Gas (LNG)

Maritime gas oil is a marine fuel that is a type of diesel. This MGO is the most commonly used fuel in the maritime sector. MGO is currently used at the Aegir, Sleipnir, and Thialf. Its characteristics are used as a baseline for comparing the below-described fuels. LNG is a marine fuel used on the Sleipnir. The Sleipnir has dual-fuel engines which can handle MGO as well as LNG.

Production of fuels

MGO is a mixture of gas and heavy fuel oil, with a higher concentration of gas oil than fuel oil [2]. The fuel is produced under the ISO 8217 standards, and this ISO number is accepted by the engine manufacturers and insured. The production is by cracking heavy long hydrocarbon chains. This production process has well-to-tank emissions of 0.33 kg CO_2 equivalent for every kg MGO is [1]; below in Table 8, the emissions are also given per MJ.

LNG is liquefied methane gas by reducing the temperature and increasing the pressure. This liquefying is done with a liquefier efficiency of 89%, in which the gas is compressed and cooled [3]. The well-to-tank emissions during the production process of a kg LNG are 0.70 kg CO_2 equivalent [1]; below in Table 8, the emissions are also given per MJ.

Main characteristics

MGO and LNG are commonly used since the fuels have a high energy density and are widely available [1]. Due to the emission profile of these fossil-based fuels, both the well-to-tank emissions are considered as significant from a sustainable point of view as the tank-to-wake emissions by HMC.

Table 8 Main characteristics of the current fuels

Fuels	Unit	MGO	LNG	References
Energy density	[MJ/kg]	42.7	50.06	[1]
Well-to-wake emissions	[kg CO_2eq / kg fuel]	3.44	3.64	[1]
Tank-to-wake emissions	[kg CO_2eq / kg fuel]	3.11	2.95	[1]
Well-to-wake emissions	[kg CO_2eq / MJ]	0.91	0.81	[1]
Tank-to-wake emissions	[kg CO_2eq / MJ]	0.08	0.07	[1]

HMC installed dual-fuel engines on the newest vessel because LNG has lower emissions in kg CO_2 per MJ than MGO, as seen in Table 8 above. The emissions in kg CO_2 per kg of fuel are higher for LNG than for MGO, but considering the energy content, it reduces the emissions.

During LNG conversion, methane slip occurs, which means 2% of the methane is leaked into the atmosphere without being burned in the drive train, which is 84 times more harmful than carbon dioxide [3]. So methane slip should be minimised by storing the LNG under energy-intensive conditions.

Storage

All the vessels have MGO tanks on board, and only the Sleipnir has LNG-qualified tanks. The difference between the two fuel tanks is the storage temperature and the pressure. MGO has to be stored under ambient pressure and temperatures, whereas LNG has to be stored under 7 bar and -160 degrees Celsius [1].

Conversion

The conversion of the MGO and LNG to electricity is done by internal combustion engines. These engines are different for the three vessels, and the generic information is given in Table 9.

Table 9 Overview of the engines of different vessels

Vessel	**Aegir**	**Sleipnir**	**Thialf**
Engine manufacturer	Hyundai	MAN	MAN
Designed fuel	MGO	MGO / LNG	MGO
Rated power	8000 kW	8000 kW	4500/4900/5500 kW

The efficiencies of the conversions depend on the fuel used and the load demand of the vessel. Every specific load of the engine has a new specific fuel consumption, so for every mode, there is a new specific fuel consumption. For the Thialf, this curve is shown below in Figure 12.

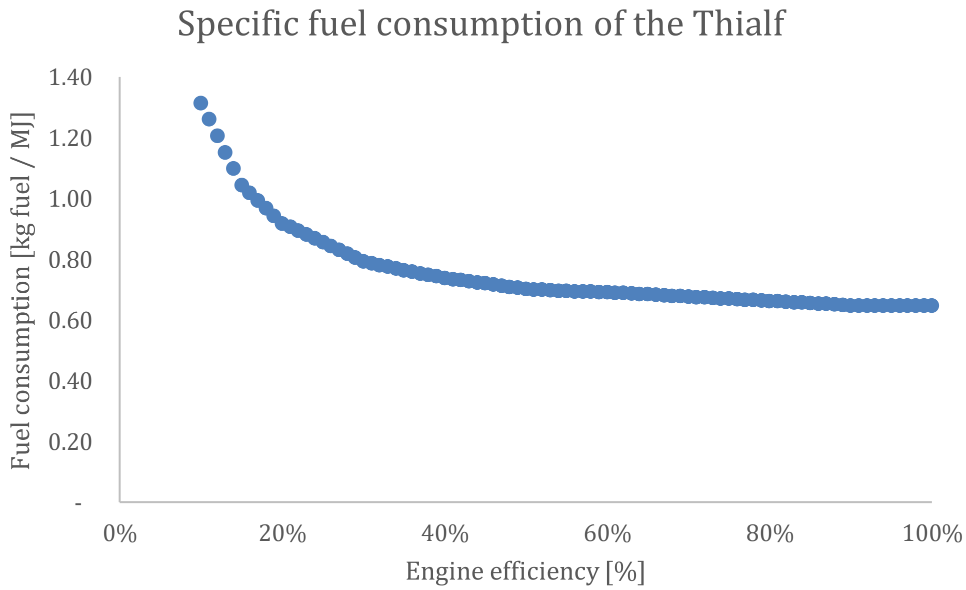

Figure 12 Specific fuel consumption of the Thialf curve, plotted against the engine efficiency

3.3 Drop-in fuels

Drop-in fuels are potential fuels to be used within the current drive train of the vessels. The three fuels examined are HVO, FAME, and GTL, which are comparable fuels to diesel and are currently tested for their applicability for HMC.

Production of fuels.

Hydrotreated vegetable oil (HVO) is a biofuel called renewable diesel. This fuel is made by mixing vegetable oils with hydrogen using a catalyst which results in higher fuel efficiency. This mixing results in a lower chance of oxidation because during the treatment oxygen is removed from the fuel, which leads to lower CO_2 emissions [4]. This production process of a kg HVO is 0.28 kg CO_2 equivalent [1]. Of all fuels suitable for use in diesel engines, HVO delivers the exhaust gasses with the lowest toxic chemical content [14].

Fatty-acid Methyl Esther (FAME) is a fuel comparable with HVO. The fuel is processed vegetable oil. Within the process of producing FAME, the vegetable oil is mixed with methanol, which gives it a lower viscosity. FAME is already used for road transport. The well-to-tank emissions of a kg FAME are 0.41 kg CO_2 equivalent [1].

Gas to Liquid (GTL) is a fuel made from methane. This fuel is made by converting methane into naphtha, which is made into diesel by Fischer-Tropsch synthesis. Fischer-Tropsch synthesis is a process in which hydrocarbons are added and split into the required chains. The well-to-tank emissions of a kg GTL are 0.80 kg CO_2 equivalent [1].

Main characteristics

HVO, FAME, and GTL have passed the experimental phase and can therefore be considered 'drop-in fuels'. The fuels are potential fuel switches since they have a high energy density and comparable storage characteristics to MGO. The downside is that the fuels are not widely available, but some fuel brokers offer the fuels. Because of the significantly lower overall emissions, the fuels are within the scope of this thesis to examine their applicability for the vessels of HMC.

Table 10 Main characteristics of the drop in fuels

Fuels	Unit	HVO	FAME	GTL	References
Energy density	[MJ/kg]	44	37.5	43.0	[1]
Well-to-wake emissions	[kg CO_2eq / kg fuel]	0.31	0.45	3.27	[1]
Tank-to-wake emissions	[kg CO_2eq / kg fuel]	0.04	0.04	2.47	[1]
Well-to-wake emissions	[kg CO_2eq / MJ]	0.007	0.012	0.08	[1]
Tank-to-wake emissions	[kg CO_2eq / MJ]	0.001	0.001	0.06	[1]

As Table 10 above shows, lower emissions occur for the drop-in fuels during the production and the usage (burning) of the fuels than for MGO. HVO was tested and qualified for the Thialf in winter 2021. Note that the tug vessels are currently undergoing tests with HVO.

A durability test by HMC rejected FAME because micro-organisms in the tank could damage the drive train. A unique filter needs to be applied to the vessels before using FAME.

GTL is qualified on board the vessels; currently, the on-deck machinery operates on GTL on board the Thialf.

Storage

All three drop-in fuels can be stored under ambient pressure and temperatures [1]. Only the Thialf has one tank currently storing GTL, and the other vessels do not use drop-in fuels yet.

Conversion

Below in Table 11, an overview of the current situation for the feasibility tests is given; these tests are engine and durability tests. HVO is ready to be used on board the Aegir and Thialf. FAME is rejected on the Aegir, and no further tests are planned on the Sleipnir and Thialf. GTL is qualified on board the three vessels but is currently only used on the Thialf.

Table 11 Overview of the tests on board the vessels

Fuels	test	Aegir	Sleipnir	Thialf
HVO	Durability test	Qualified	Not tested	Qualified
	Engine test	Qualified	Not tested	Qualified
FAME	Durability test	Disqualified	Not tested	Not tested
	Engine test	Qualified	Not tested	Not tested
GTL	Durability test	Qualified	Qualified	Qualified
	Engine test	Qualified	Qualified	Qualified

3.4 E-fuels

E-fuels are potential fuels to be used on board vessels. No significant changes have been made to the vessels' drive-train within this thesis's scope. For the e-fuels that are all hydrogen carriers, fuel blends are examined to be applicable in the current drive train. This chapter examines hydrogen, methanol and ammonia as e-fuels. These fuels are examined in their production processes, main characteristics, storage, safety, and conversion in the form of fuel blending.

Production of fuels.

Hydrogen is a zero-emission fuel that is within the scope of this thesis produced by making use of green electricity. Green electricity is electricity produced by a renewable energy source and without emissions. The reaction in Equation 6 uses green electricity to split water into hydrogen and oxygen, which is done in an electrolyser that captures the hydrogen gas.

$$H_2O + electricity \rightarrow H_2 + \frac{1}{2}\, O_2$$

Equation 6 Electrolysis reaction

After the H_2 is captured, it can be liquefied or compressed; this is done by applying pressure and low temperatures. This liquefaction process is energy-intensive; 21.6 – 28.8 MJ per kg of liquefied hydrogen is used [5].

Green methanol is a fuel that can be produced from green hydrogen and captured carbon dioxide. This reaction takes a number of steps and is energy intensive. First, carbon dioxide must be captured from the air, giving a negative well-to-tank emission profile of -1.37 kg CO_2 per kg methanol. This process costs 0.9 MJ per kg CO_2 [6]. Hereafter the carbon dioxide should be pressurised and should react with hydrogen. This process is called CO_2 hydrogenation with the following reaction [7].

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Equation 7 Green methanol production reaction

This reaction takes place in a methanol reactor and requires 4.32 MJ per kg of methanol [7].

Green Ammonia is a chemical that can be used as a fuel and produced with the Haber-Bosch reaction. Within this process, nitrogen from the air and green hydrogen react together to ammonia (NH_3). Nitrogen can be captured from the air, which requires 0.33 MJ per kg NH_3. To form NH_3, the captured N_2 is mixed with hydrogen following:

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

Equation 8 Green ammonia production reaction

The Haber-Bosch reaction requires 2.3 MJ per kg NH_3, so an amount of 2.63 MJ per kg NH_3 is required [8].

Main characteristics

Liquid hydrogen, methanol, and ammonia have not been tested on board the vessels because the current drive train is not designed for these hydrogen-carrying fuels. The reason for converting hydrogen into methanol or ammonia is to get a higher energy density per volume, which can be stored under less energy-requiring conditions. Adjustments in the drive-train are considered to be too high investments, and consequently the e-fuels are used to blend into the current fuels [9].

The e-fuels, hydrogen and ammonia are emission-free, and the fuels have no well-to-wake or tank-to-wake emissions. In contrast, methanol emits 1.37 kg CO_2 per kg of fuel, which is captured during the production process and therefore considered emission neutral. Currently, the availability of e-fuels is increasing, but they are not widely available.

Table 12 Main characteristics of the e-fuels

Fuels	Unit	Liquid hydrogen	Methanol	Ammonia	References
Energy density	[MJ/kg]	118.8	19.9	18.8	[1]
Energy density	[MJ/m^3]	0.010	0.016	0.013	[1]
Well-to-wake emissions	[kg CO_2eq / kg fuel]	0	-1.37	0	[1]
Tank-to-wake emissions	[kg CO_2eq / kg fuel]	0	1.37	0	[1]
Well-to-wake emissions	[kg CO_2eq / MJ]	0	-0.07	0	[1]
Tank-to-wake emissions	[kg CO_2eq / MJ]	0	0.07	0	[1]
Energy required to produce	[MJ/kg fuel]	24.4	28.7	27.0	[1]

Storage

Hydrogen is converted into methanol and ammonia because of the difficulties of storing hydrogen. Hydrogen is a very flammable compound when exposed to an oxidizer because hydrogen has low ignition energy of 0.02 MJ [44]. Hydrogen is difficult to store because it can escape through metals; when leaked into a non-ventilated space, hydrogen can cause explosion hazards. The hydrogen is required to be cooled down to -253 degrees or converted into methanol and ammonia. The storage characteristics of methanol and ammonia are closer to the characteristics of MGO.

Table 13 Storage characteristics of future fuels

Fuels	Unit	Liquid hydrogen	Methanol	Ammonia	MGO	Ref
Energy density	[MJ/kg]	118.8	19.9	18.8	42.7	[1]
Storage pressure	[bar]	1-5	1	1-17	1	[1]
Storage temperature	[degrees]	-253	20	-34	20	[1]

What can be seen in Table 13 is that methanol could be stored in comparable storage tanks as MGO because of the same storage conditions [1]. In order to store liquid hydrogen and ammonia, new fuel tanks are required because the storage characteristics differ from MGO [1].

Conversion

This section describes the blending of e-fuels into the current fuel MGO. A fuel cell is the most common way to convert hydrogen into electricity. Within the scope of this research, there are no significant changes to the drive train, and the fuels should be converted as fuel blends in an internal combustion engine. Research is ongoing into blending percentages of e-fuels into diesel, and companies are offering engine conversion sets. Within this section, volumetric blending percentages of the e-fuels are given from the literature; these percentages are used as adjustable variables in the model that can be changed.

The addition of hydrogen decreases the power output of a diesel combustion engine for different loads [9]. So blending more hydrogen into diesel gives a lower power output. Due to the high flammability of hydrogen, it ignites too quickly, reducing the combustion duration [10]. When hydrogen addition exceeds 15%, the diesel engine exhibits severe knock, reducing the power output. This reduction is why a maximal hydrogen blending of 15% of the volume is advised [10]. Different engine conversion sets are currently under development, which are expected to give higher hydrogen blending percentages. Hydrogen should be inserted through the air input, resulting in a 15-20% lower power output and a 15-20% emission reduction.

Adding methanol to diesel can be done because methanol has poor auto-ignition properties. Because methanol has a lower volumetric energy density than diesel, the input speed of the fuel into the engine should increase. The energy density of diesel blends with methanol is given in Table 14 [11], in which M5 means a 5% fuel blend with methanol.

Table 14 Fuel blending methanol [12]

Fuels	**Unit**	**D**	**M5**	**M10**	**M15**	**M20**	**M25**	**M30**
Diesel	[Mass%]	100	95	90	85	80	75	70
Methanol	[Mass%]	0	5	10	15	20	25	30
Energy content	[MJ/kg]	42.58	40.36	38.36	36.55	34.9	33.34	32.01

The addition of methanol increases the fuel mass in the premixing period. As well as, methanol accelerates the blend's combustion time, leading to increased cylinder pressure and decreased cylinder temperature [12]. The oxygen concentration is higher in methanol, leading to complete combustion, shorter combustion, and lower CO and NO emissions [12]. This gives a maximal 10% fuel blend because it will keep as high as possible gravimetric energy density and the lowest exhaust temperature, and the improvement in power output is 70% [13].

Adding ammonia into a diesel engine is possible; ammonia should be added as vapour into the engine intake port, together with diesel. This blend results in a loss in power because of the lower energy content of ammonia. Ammonia has a lower combustion temperature than diesel. A maximum energy replacement of 20% was measured during tests [30]. CO_2 emissions were reduced for the same engine torque output as the amount of ammonia was increased [30].

Table 15 Summary of volumetric blending percentages from literature [9,10,11,12].

Fuels	**Unit**	**Hydrogen**	**Methanol**	**Ammonia**
Blending percentage	[Vol%]	15	10	20

4 Technical adjustments for emission reduction

In this chapter, insights into the technical emission reduction adjustments are given that are within the scope of this thesis. This chapter is used to give an idea of the influence of battery systems on board the vessels and the influence of installing a carbon capture and storage process on board the Sleipnir. This literature review on the technical adjustments will answer: **sub-question 3:** What are the key characteristics of the ship-based emission-abating technologies like batteries and carbon capture and storage?

4.1 Technical battery evaluation criteria

Most of the energy on board the vessels is stored in MGO, as discussed in Chapter 0. During DP2 and DP3 operations, additional capacity for redundancy is required. Figure 13 shows the power consumption with the blue line, with the green and red lines showing the available engine capacity on the left y-axis. On the right y-axis, the amount of engines online is shown. During DP modes, the extra engine is online for backup power. During these peaks in available capacity, a battery can be used.

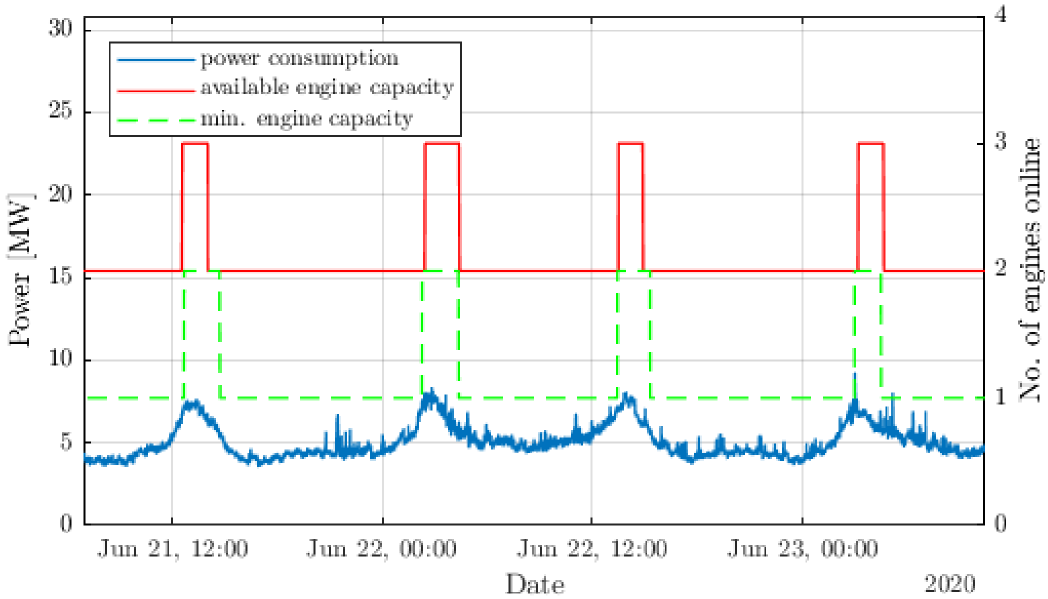

Figure 13 the number of engines online with the available and used power.

Batteries can fulfil two tasks on board:

1. Peak shaving of the load demand, this peak shaving has the advantage of fewer operational hours for the engines and generators, which results in fewer emissions.
2. Spinning reserve; in Figure 13, increased required power shows an increase in available power online. During DP2 and DP3, one (or more) engine(s) could be switched off.

Within the scope of this research, two different batteries are examined for the Aegir, Sleipnir and Thialf. First, the lithium-ion battery will be described, and hereafter the more experimental redox flow battery. The technical potential is described in this chapter, while in Chapter 6, the quantification of battery size and costs are given for the different vessels.

4.2 General battery information

Li-ion battery

The lithium-ion battery is a commonly used battery at the moment. It works on the principle of ionization of lithium atoms. During discharge, the ions are separated from their electrons in the anode due to electrical charge. The ions move through the semi-permeable membrane in the cathode direction because the negatively charged electrons attract the positively charged ions. At the cathode, the ions recombine with the electrons and lose the charge.

Different materials can be used; the most common, also shown in Figure 14, is a lithium cobalt oxide cathode and an anode of graphite [16]. Li-ion batteries have higher energy densities than other battery types, typically 0.36-0.95 MJ/kg or 0.9-2.4 MJ/L [16].

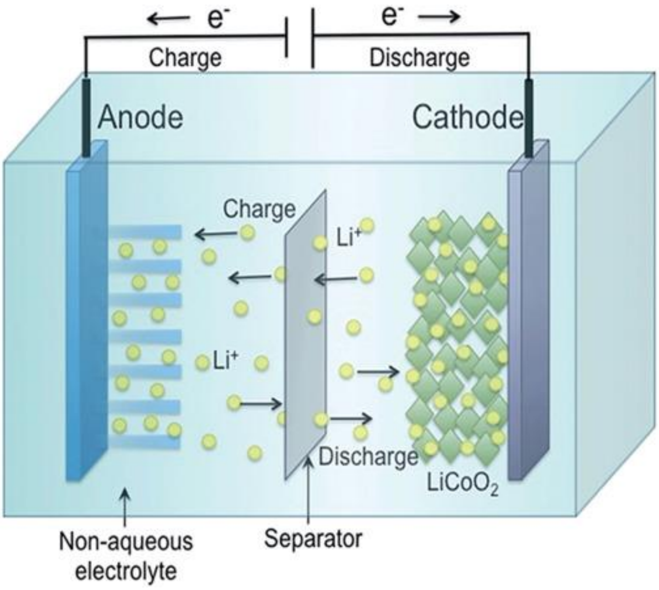

Figure 14 Schematic overview of the working of a Li-ion battery

Redox flow battery

A redox flow battery works as an electrochemical cell. Within this system, two different chemicals are solved in liquids as catholyte and anolyte, comparable with the Li-ion battery. Within this battery type, the liquid is pumped through the cell, which can be seen in Figure 15.

The two cells are separated by a membrane permeable for the types of ions that travel between the electrodes. The electrodes function as the surface at which the oxidation and reduction reactions occur.

For this type of battery, different catholytes and anolytes can be used. The catholyte determines the potential over the electrodes and the anolyte used. A current flows due to the current collectors. The battery can charge and discharge, and typically, it has an energy density of 0.05-0.09 MJ/litre, depending on the chemical composition [45].

The advantage of a redox flow battery is that the tanks are easily changed or filled with new chemicals. So changing or adjusting the battery is done by refilling the tanks.

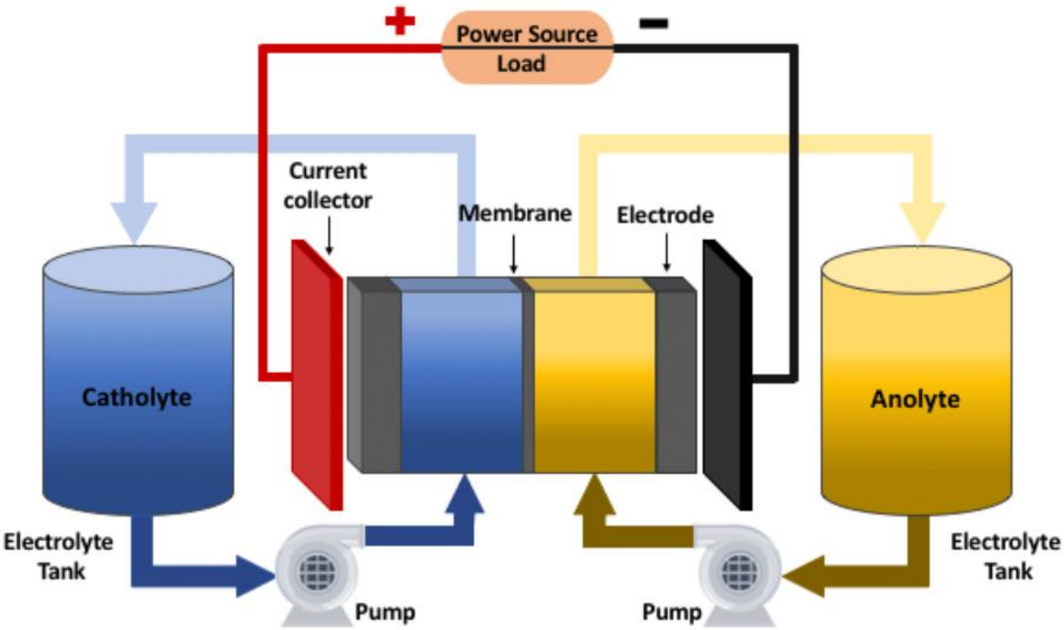

Figure 15 Schematic overview of redox flow battery

Applicability of the batteries on board

Turning off an extra engine during dynamic positioning saves fuel, engine hours, and emissions. Turning off the backup engine saves fuel because the online engine will run on a higher utilization ratio (part load). The higher utilization ratio gives a lower specific fuel consumption (kg fuel / MJ) that saves fuel and emissions.

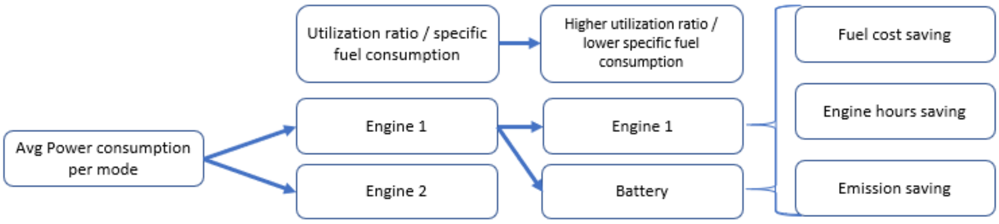

Figure 16 Applicability of a battery explained.

The average power available per operational mode of the vessel is given within Chapter 0. An engine seldom runs on full load and commonly runs on a utilization rate between 20% and 80%; every utilization rate has its specific fuel consumption. The utilization rate and specific fuel consumption are calculated from the engine data collected by Kongsberg.

During DP2/DP3, an engine could be turned off such that the remainder of the engines run on higher utilization rates and will give enough power output for the average power consumption of that mode. During DP, applying a battery will save approx. 10% of the energy consumption, so when the vessel is 40% of its time in DP, the battery will save 4% of the vessel's fuel use and 4% for its emissions.

Energy content

As explained in the introduction of this section, the battery can provide two functions. Based on the DP redundancy requirement, the battery must be able to provide the entire function of an engine for approx. 15-30 minutes. This time is due to the run-up time of the engines. All the engines have a maximum power output of around 7700 kW. The battery energy content is required to be 1925-3850 kWh or 6930-13860 MJ.

Currently, batteries are under development and commonly have a C-rate of 1 [32]. The C-rate is the unit used to measure the speed at which a battery is fully charged or discharged [46]. A battery with a C-rate of 1 will provide a load of 7700 kW for an hour and therefore needs 7700 kWh of energy content. A battery system should be installed with a higher than necessary energy content (7700 kWh instead of 3850 kWh) as used on board.

Placing the batteries on board

Lithium-ion batteries on board the vessels should be containerized. There are two main reasons for this: firstly, this is done for safety, to control fire and toxicity. Secondly, a containerized battery can easily be replaced by a new one. The feeding tanks have to be easily reachable for the redox flow battery to refill the electrolyte.

Conclusion batteries

The batteries on board need to be connected to the switchboards. On the Aegir, all the switchboards are connected, this is not the case for the Sleipnir and Thialf. On Sleipnir and Thialf, implementing a battery system is an extra challenge.

An internal switch in the battery can be used to switch the battery to different switchboards. A discussion is ongoing between the industry and HMC about implementing the batteries on the Sleipnir and Thialf. The aim is to install a battery before 2024, considering all the necessary safety measures.

Both of the types of batteries can deliver high power. Regarding safety and a longer lifetime, the redox flow battery should be used. This battery is also favourable because of the safe installation, no harmful emissions and no use of scarce materials.
The lithium-ion battery should be used when space and cost are more important criteria. This is because the lithium-ion battery has a higher volumetric energy density, 0.9 - 2.4 MJ/L, compared to redox flow, 0.05 - 0.09 MJ/L and a more advanced production method, making the battery cheaper than the redox flow battery.

Since the installation of lithium-ion batteries on maritime vessels is a more developed process, and the prices of installation are lower, together with the higher volumetric energy density, the implementation of the lithium-ion battery on board the vessels should be considered.

The saved emissions for placing a lithium ion battery on board of the three vessels is calculated within the model, this outcome is shown below in Table 16.

Table 16 Annual emissions savings by the installation of one battery per vessel

Vessels	**Aegir**	**Sleipnir**	**Thialf**
Emissions saved with one battery [mT]	1933.5	1852.3	2159.5
Percentage of total emissions [%]	4.0	1.7	2.9

4.3 Carbon Capture Storage

Carbon capture is a process of filtering carbon dioxide from gasses. This is a common process in the chemical sector, but new onboard vessels. The CO_2 is captured, purified, pressurized, and transported to shore. This subchapter explains the carbon dioxide capture process, and the storage process is explained hereafter. This storage is difficult for the marine sector due to the additional volume and weight requirements. TNO is doing research into this process on board the Sleipnir, this is because it is applicable when LNG is the operational fuel. This chapter is descriptive of the research of TNO. This research is expected to be ready in 2026, and the technology should be implemented on board in 2028.

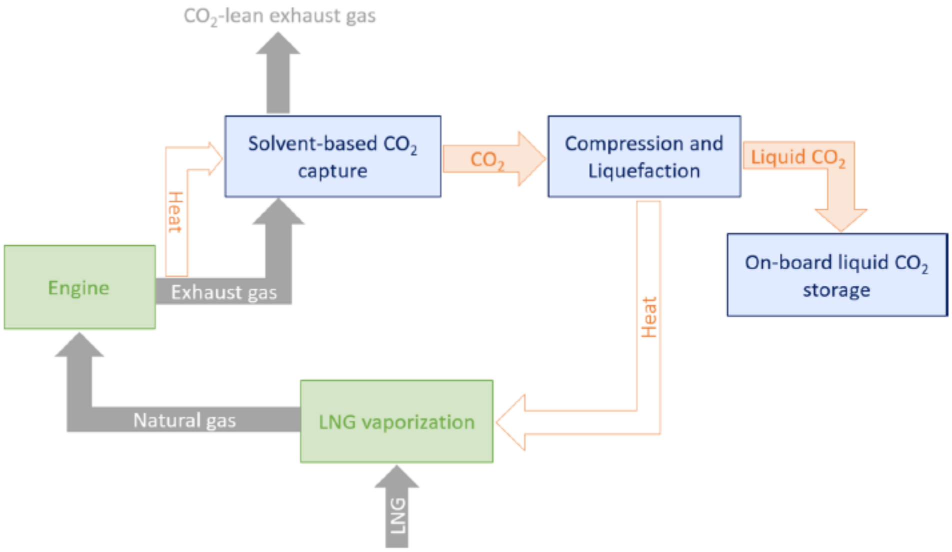

Figure 17 Schematic overview of CCS [33]

Carbon capture process

By burning fuel in engines, greenhouse gases are emitted, like NOx, SOx, and CO_2. There are multiple ways to reduce these emissions, and one of them is carbon capture. This carbon dioxide filtering after combustion is the so-called post-combustion capture process. The gas from the engines comes through a tank filled with a solvent. This can be seen in Figure 17, and the CO_2 – lean exhaust gasses leave through the chimney.

The CO_2-rich solvent is collected at the bottom and pre-heated in a heat exchanger. In the desorption column, the solvent is boiled to a specific temperature, releasing CO_2 from the solvent; this is shown in Figure 17, the orange arrow where only CO_2 leaves.

The CO_2, which is in gas form at the top of the desorber, is then cooled, which condenses the water, leaving us with 99% pure liquid CO_2. This gas is then cooled further and compressed, resulting in a stream of liquid, cold CO_2 at the system's exit. CO_2 should be stored at a pressure of 5 bar and at -50 °C, having a density of 1178 kg/m^3 [33]. This cooling process is done by making use of the cooled LNG.

Carbon storage process

If CCS is used on a cargo ship that sails from port A to port B, the captured CO_2 should be stored on board and offloaded if it enters a port. Many cargo ships operate on the same routes between ports for extended periods, and the amount of onboard storage required could be calculated.

The ongoing research of TNO is described in this chapter and is applied to the Sleipnir. The amount of CO_2 storage required on the Sleipnir is different than for a cargo vessel, and the operational profile of the Sleipnir is more complex than that of a cargo vessel. An offshore crane vessel like Sleipnir makes as few port calls as possible, requiring offshore offloading and transporting CO_2.

When the Sleipnir operates in dynamic positioning mode, it produces 150 mT liquefied CO2 / day, which means 127 m3/day. When the vessel sails from A to B, the vessel would need about 280 m3 of storage space daily, which would mean six to eight 20 ft containers per day.

Two different CO_2 storage methods are examined. Firstly, containerised storage is done because, from an operational point of view, filling up containers and coupling/decoupling them six to eight times a day would fill up the deck. While further down the supply chain, containerised storage may be advantageous, especially considering that one can load a container directly onto a truck, train or inland barge. Secondly, fixed tanks could be an option onboard for the storage of CO_2.

The first option means that the deck area should be reserved when those containers are stored on the deck. For the Sleipnir, 127-280 m^3 a day is required. Considering an available deck space of Sleipnir being 20mx25m gives an area of 500m^2, the storage available on deck would, when considering two containers on top (6 meters) of each other, be 3000m^3. This volume would be filled within 15 days.

The second option for onboard storage is to store the product in fixed tanks which have to be built in. These tanks could fit into empty spaces below the deck of the vessel, and these could also be storage tanks on top of the deck. When the below-deck storage space is used, it should be close to the engine rooms for easier logistics with the transport of the CO_2 on board. Since the vessels seldom go to a port, a way to transport the CO_2 away offshore is required, introducing the following section: Carbon transport.

Carbon transport

Depending on the previously selected type of onboard storage, there are two options for offshore transportation. When the CO_2 is stored in containers, an offshore supply vessel is required to lift the containers onto this ship.

When the CO_2 is stored in fixed tanks, it must be unloaded into a liquid gas carrier. This type of ship is similar to an LNG bunkering vessel used to refuel the Sleipnir. The operations of refuelling liquid natural gas and offloading liquid CO_2 are comparable. In both cases, the vessel is handling liquified gas. So this would be applicable for the Sleipnir to transport the CO_2 away from the vessel.

When the vessel enters a port, the liquefied CO_2 will have to be unloaded, and the CO_2 will enter the onshore transportation phase. Here the options are also related to the first decision of onboard storage. Containers can be loaded onto trucks, trains or inland barges to transport the containers to the end customer. If the CO_2 will arrive in a liquid gas carrier, it makes more sense to transfer it as a gas through a pipeline network. After which, the carbon can be sold to industries or can be stored underground.

Conclusion Carbon Capture and Storage

The research into CCS on board the Sleipnir is ongoing. For the Aegir and Thialf, the installation of the capture system is not scheduled. Because of the significant investments, the payback period exceeds the lifetime of these two vessels, together with the fact that LNG should be the operational fuel. The research of TNO into ship-based CCS is expected to finish in 2026, with the implementation of CCS on the Sleipnir expected in 2028. For the storage of CO_2, option one for storing CO_2 in containers is considered most feasible due to the easier logistics of transporting the CO_2 away from the vessel than installing a fixed CO_2 designated tank. When e-fuels are implemented on the Sleipnir, CCS will be unnecessary because the emissions will already be abated.

The lifetime of the installation is estimated to be 30 years. The installation will save 90% of all the emissions this is shown for the Sleipnir in Table 17.

Table 17 Emissions saved annually after installation of CCS

Vessels	Sleipnir
Emissions saved with CCS [mT]	69884
Percentage of total emissions [%]	90%

5 Company emission reduction ambition

In this chapter, insights into the emission reduction ambition of HMC are given, this is done to give an idea of the importance of this study. A proposal is made on a new relative emission intensity ambition instead of the current absolute ambition. The emissions of the company are given together with the emissions that should be abated.

5.1 Sustainable goal definition

The maritime sector is essential within the energy transition because of its large contribution to building offshore renewable energy production plants. HMC plays a part in this sector with its largest crane vessels in the world. However, the maritime industry is also responsible for 940 million tons of CO_2 annually, which is 2.5 % of the emissions worldwide [18]. With an annual emission amount of around [redacted], the sustainability team of HMC focuses on different aspects of sustainability, prevention, reduction and compensation. The goal is to emit almost no GHG from 2030 onwards.

5.2 The Heerema ambition

HMC feels the need to be a pioneer in sustainable shipping. HMC has been carbon neutral since 2020 by compensating its emissions with offsets, with a current price of approx. [redacted]. In Figure 18, the company's emission reduction ambition is depicted.

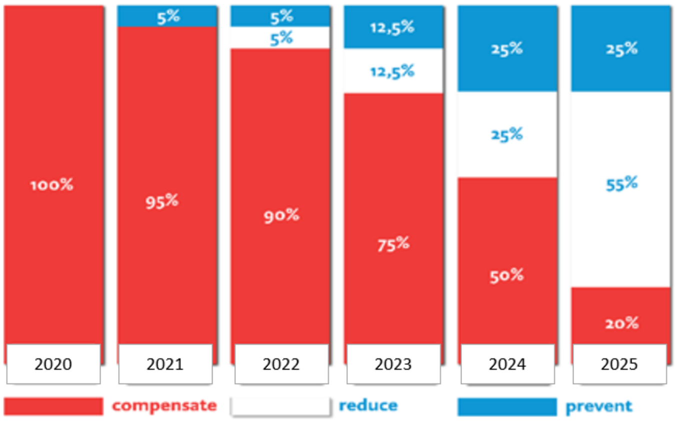

Figure 18 Emission reduction ambition Heerema Marine Contractors

Above in Figure 18, the current emission reduction roadmap toward a sustainable fleet of HMC is shown. HMC is following this roadmap and wants to abate more emissions than the IMO and EU regulations mandate. HMC reduces emissions by using the described emissions abating options in Chapter 3 and Chapter 0. Moreover, it prevents emissions by working more efficient, for example, by updating power software. There are two different ways of calculating the emissions that should be abated:

1. Setting the yearly CO_2 emissions of 2020 as a baseline. (right now)
2. Setting a specific value for the kg CO_2 emissions per MJ as a baseline (proposed)

Option 1 implies that fewer emissions will be emitted when there is less work, reducing overall emissions. This reduction is a good ambition, but HMC is a company that strives for as much work as possible, so it wants to use as much energy as possible, which is the reason why option two is proposed. For option two, a new baseline is proposed with the exact percentages based on a specific emission $\left[\frac{kg\ CO2}{MJ}\right]$. The emission intensity is calculated with the yearly carbon emissions divided by the yearly required energy, see equation 2:

$$Emission\ intensity\ \left[\frac{kg\ CO2}{MJ}\right] = \frac{Annual\ carbon\ emissions\ \ [kg]}{M_{fuel}\ [kg] * HHV\ \left[\frac{MJ}{kg}\right]}$$

Equation 2 Emission intensity calculation

- $Annual\ carbon\ emissions\ [kg]$: CO_2 emissions.
- $M_{fuel}\ [kg]$: the amount of kg of fuel used in a year.
- $HHV\ \left[\frac{MJ}{kg}\right]$: Higher Heating Value(HHV) is the energy content in the amount MJ per kg of fuel.

Figure 19 shows the emission baseline from 2020, depicted as a straight red line at a specific emission intensity. The emission ambition is shown in the decreasing grey line, which is the percentage mandated by the current emission reduction ambition of HMC.

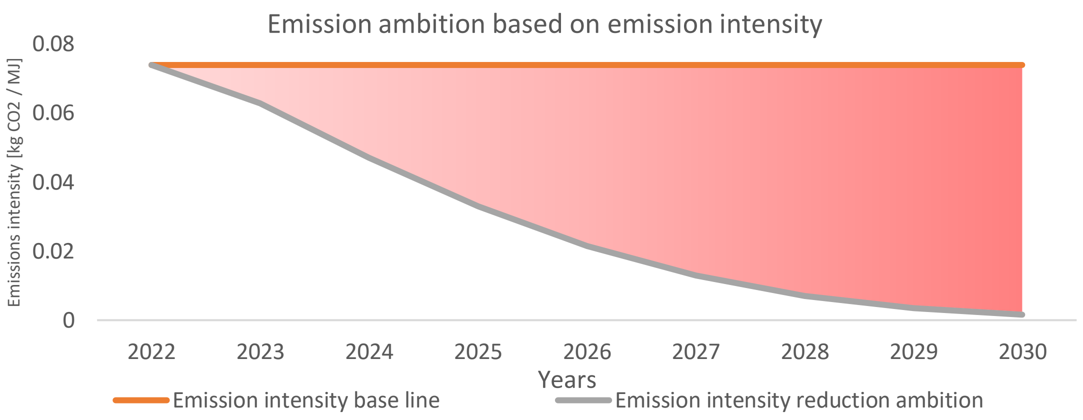

Figure 19 Carbon emission intensity $\left[\frac{kg\ CO2}{MJ}\right]$ for the new baseline proposal

5.2.1 Forecasted energy use based on portfolio

Within HMC, all future projects are scheduled up to three years in advance. For every job, a specific time window is scheduled, and the operational mode is estimated. All operational modes were summed for the following three years, and an estimation of the scheduled fuel consumption is shown below per vessel in Figure 20.

[redacted]

Figure 20 Scheduled work with fuel consumption per year [CONFIDENTIAL]

If solely MGO will be used, it can be seen that the scheduled fuel consumption is going in the opposite direction of the emission abatement goals. The fuel consumption converted into emissions scheduled with the density of the current emission is shown in Figure 21 below.

[redacted]

Figure 21 Emissions for scheduled work together plotted with the emission abatement ambition of Heerema Marine Contractors [HMC DATA]

So to follow the emission ambition, HMC should annually abate an increasing amount of emissions; see Figure 22 below.

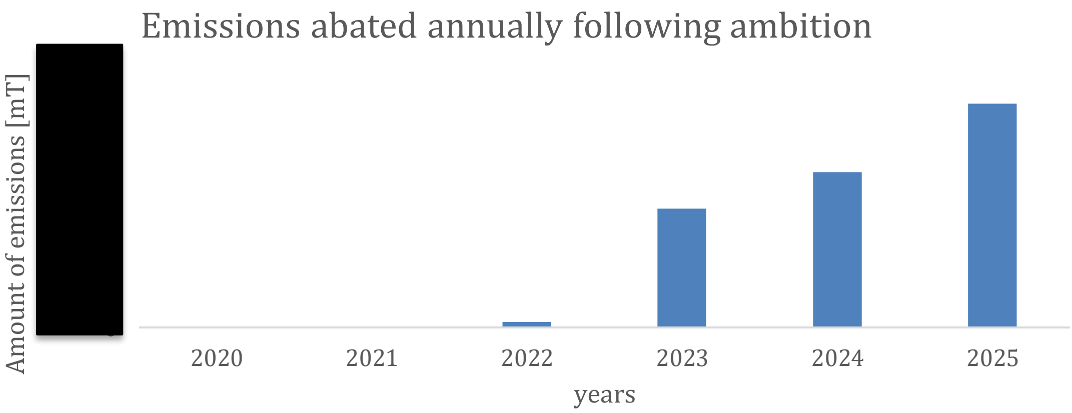

Figure 22 Emissions that should be abated when following the emission abatement ambition of Heerema

6 DECISION CRITERIA FOR A SUSTAINABLE ROADMAP

In this chapter, the different decision criteria are calculated. These criteria are the levelized costs of energy, the emission intensity, the levelized costs of carbon abatement and the availability. These decision criteria are used as inputs for the model and are described in this chapter. This chapter gives the method for calculating these criteria, and the outcomes are analysed in Chapter 8.

These criteria are used as input for the model described in Chapter 7, the prices are expected to change over time, because the numbers in this chapter are based on literature combined with fuel prices. The expected development based on assumptions is given per decision criteria.

This chapter answers **sub-question 4:** What are the current vessel-specific levelized cost of energy (LCOE) and levelized cost of carbon Abatement (LCoCA) of the fuel switches and technologies, and how are they expected to develop over time?

6.1 Decision criteria

To achieve the emission reduction ambition described in Chapter 5, the options for emission reduction given in Chapters 3 & 0 are examined and compared in this chapter. For every emission reduction option, the following vessel-specific decision criteria are calculated:

1. The levelized cost of energy
2. The emission intensity
3. The levelized costs of carbon abatement.

These values are used because they will give financial insights into the emission reduction options. All the options are compared with the current situation's baseline, schematically shown in Figure 2 below, as described in the methodology.

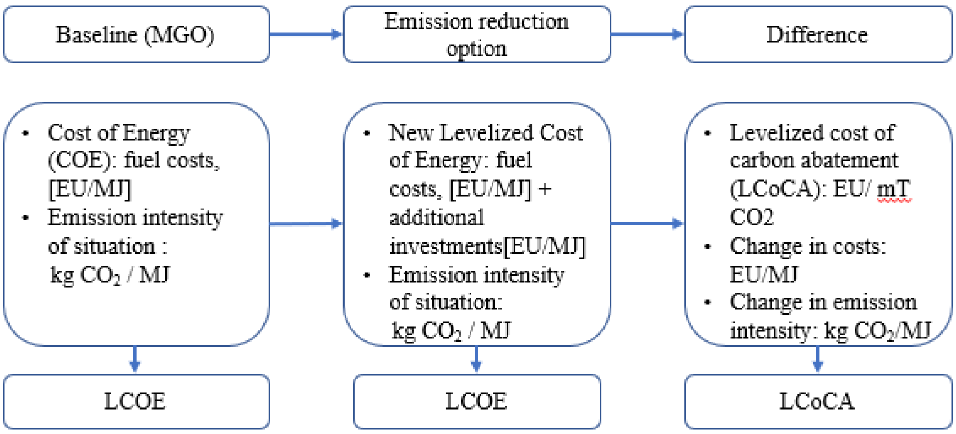

Figure 2 Schematic overview of the methodology

After the calculations shown in Figure 2, an availability analysis is done based on growth expectations for fuel markets. Hereafter, a budget estimation is given, in which a vessel-specific budget is calculated.

6.1.1 The Levelized cost of energy

Levelized cost of energy for fuels

The levelized cost of energy for fuels is the cost of producing one MJ. These fuel costs are considered to develop over time. The LCOE gives financial insights into the different sustainable options throughout the roadmap. The current cost of energy of the vessels (using MGO) is used as a baseline.

Because green methanol and ammonia are produced from green hydrogen, the prices of the e-fuels are linked to the energy required during production. The required production energy is given in Table 12 and is 18% higher for methanol and 11% for ammonia compared to hydrogen. This is why the methanol and ammonia prices are 18 and 11% higher compared to hydrogen. The prices used for the calculation are based on current data from HMC and prices from the literature, shown in Table 18. Within the model, different price scenarios are discussed and analysed.

Table 18 Cost of energy prices [$\frac{€}{MJ}$] 2022 [HMC DATA, 34]

	MGO	LNG	HVO	GTL	FAME	Hydrogen	Methanol	Ammonia
COE [$\frac{€}{MJ}$]	€0.026	0.040	0.057	0.035	0.040	0.034	0.040	0.037

For the current fuels and the drop-in fuels, no additional investments are required; as for these fuels, only the fuel costs (€/MJ) are considered. For e-fuels, additional investments are required because new storage tanks are needed.

These investments are annualised over the vessel's lifetime with the interest rate considered. This is done using the capital recovery factor (CRF) shown in Equation 1. The investment's interest rate of HMC (r in Eq. 1) is confidential, and within this thesis, 4% is assumed.

With Equation 2, the levelized costs of energy are calculated for the different emission-reducing options, which allows the comparison of the annual expenditures throughout the roadmap.

$$CRF = \frac{r}{(1-(1+r)^{T_{depreciation}}} = [\%]$$

Equation 1 Capital recovery factor

$$LCOE = \frac{Fuelcost_{year} + OPEX + (CRF * CAPEX)}{Energy_{year}} = [\frac{€}{MJ}]$$

Equation 2 Levelized Cost of Energy

For e-fuels, designated storage tanks are required, and the specific investment cost of the tanks for hydrogen, methanol and ammonia are estimated to be: 0.23, 0.04, and 0.04 €/MJ, respectively [37]. The total investment depends on the energy required to be stored on board the vessels. The required energy is estimated by calculating the energy content of the tanks between two bunkering periods.

$$Volume\ storage\ tank\ (MJ) = Vol_{\%} * Bunkering_{period} * Average_{fuel\ consumption\ MGO} * HHV$$

Equation 9 required volume for designated e-fuel tanks

- $Vol_{\%}$ [%]= $blending\ percentage$ of e-fuel.
- Bunkering period [days] = amount of days between two refuelling periods.
- $Average\ fuel\ consumption\ MGO\ \left[\frac{mT}{day}\right]$ = Amount of fuel used per day.
- $HHV\ [\frac{MJ}{mT}]$ = Higher heating value, the energy content of a fuel per ton.

The volumetric-blending percentages for hydrogen, methanol and ammonia are 15, 10, and 20%, respectively. Blending percentages up to 100% are required to meet the sustainability ambition, which is why for calculating the volumes of the designated tanks, 100% fuel blends are assumed. Below, Table 19 shows the total investment costs for designated e-fuel tanks in millions of euros.

Table 19 Investment costs for designated fuel tanks when a blending percentage of 100% is used, given in million euros.

Aegir			Sleipnir			Thialf		
Hydrogen	**Methanol**	**Ammonia**	**Hydrogen**	**Methanol**	**Ammonia**	**Hydrogen**	**Methanol**	**Ammonia**
€27.46	€4.78	€5.97	€53.61	€9.32	€11.65	€ 35.03	€6.09	€7.61

The prices from Table 18 are plotted, excluding the capital expenditures for the designated e-fuel tanks in Figure 23. What can be seen is that all costs have additional costs compared to MGO, which is used as a baseline.

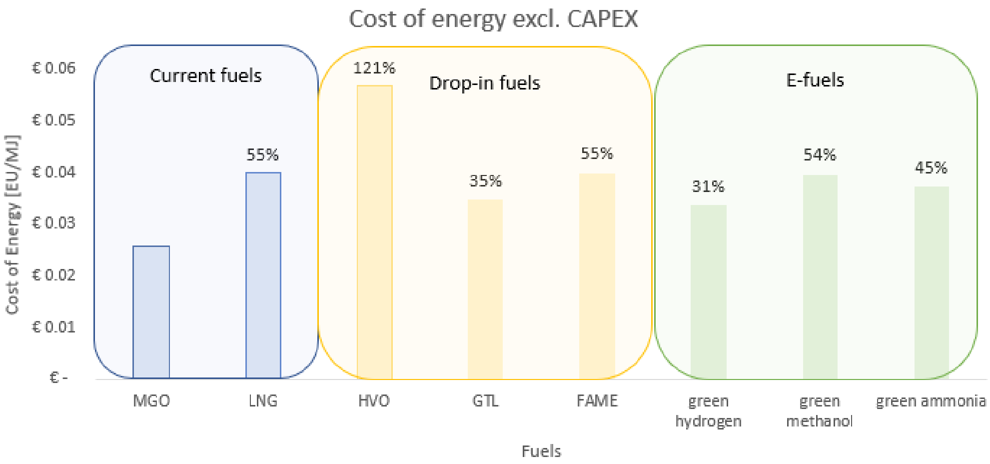

Figure 23 Levelized cost of energy with additional percentage for every fuel, only fuel costs taken into account

As described above, the capital and operational expenditures of the designated e-fuel tanks are required to take into account. Below in

Fuel	Hydrogen	Methanol	Ammonia	Reference
CAPEX storage [€/MJ]	0.23	0.04	0.04	[37]
OPEX storage [%*CAPEX/year]	2	2	2	[37]

Table 20, the numbers are given again for the CAPEX and OPEX.

Table 20 CAPEX and OPEX of e-fuels on board

Fuel	Hydrogen	Methanol	Ammonia	Reference
CAPEX storage [€/MJ]	0.23	0.04	0.04	[37]
OPEX storage [%*CAPEX/year]	2	2	2	[37]

Below in Figure 24, the levelized costs of energy are calculated, including the annualised CAPEX and the OPEX. The levelized cost of energy increases due to capital expenditures for the e-fuels, resulting in ammonia with the lowest LCOE of the e-fuels.

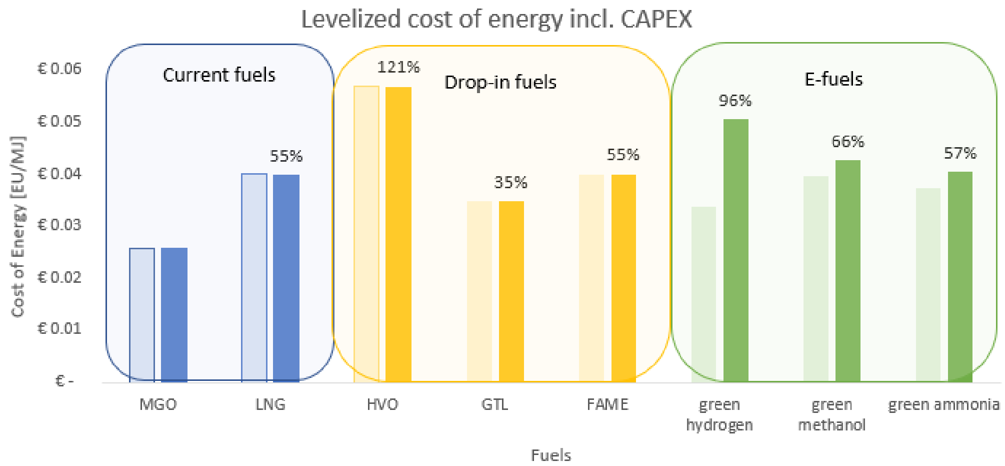

Figure 24 Levelized cost of energy, including additional investments for designated fuel tanks. Taking into consideration e-fuel blending percentages of 100%.

The time development of the LCOE is calculated using a fixed annual percentage by which the fuel prices develop. An assumption is made that both current fuels (MGO and LNG) increase annually by 3%. For the emission-abating fuels, the drop-in and e-fuels, an assumption is made that all the fuel prices decrease annually by 3%. Within this price development per fuel, the ETS price is calculated, so with the emission intensity in kg CO_2 /MJ of fuel, the ETS price of $0.10\,\frac{€}{kg}$ CO_2 is added from 2026. This development is shown in Figure 25. From 2026 the emission penalty is added, which shows an increase in price for the current fuels and the drop-in fuels.

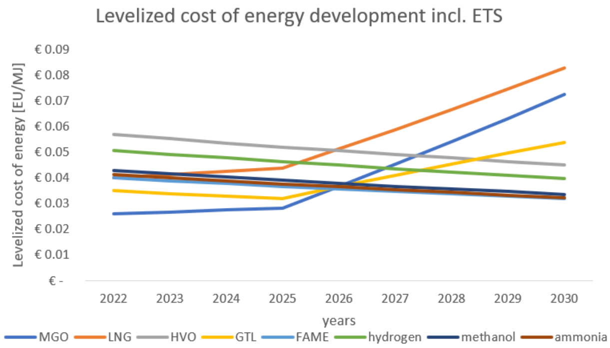

Figure 25 LCOE price development for different fuels including ETS

Levelized cost of energy for technical adjustments

For the implementation of emission-abating technical adjustments, a levelized cost of energy is calculated. This calculation is done by comparing the annual levelized costs of the vessels with and without the technical adjustments. Using a battery saves costs, because the vessels use less fuel, have fewer engine hours and emit less carbon dioxide. These three savings contribute to a reduction of the levelized cost of energy.

- Engine hours: 30 €/hr
- Current MGO price: 1100 €/mT
- Current Carbon price: 100 €/mT

For CCS, a levelized cost of energy is calculated using the CAPEX and OPEX given in Table 21. The CCS process is expected to reduce emission costs by 90% and is only applied to the Sleipnir. The CAPEX and OPEX are expected to stay constant throughout the roadmap.

Table 21 CAPEX and OPEX of CCS and batteries

Fuel	CCS	Battery	Reference
CAPEX [$M€$]	50	1.8	[TNO, Huisman]
OPEX [$M€$]	1.8	0	[TNO, Huisman]

This CAPEX is annualised for calculating the LCOE with a depreciation time equal to the vessel's lifetime. Below in Figure 26, shows the LCOE of the fuels and the technical adjustments below.

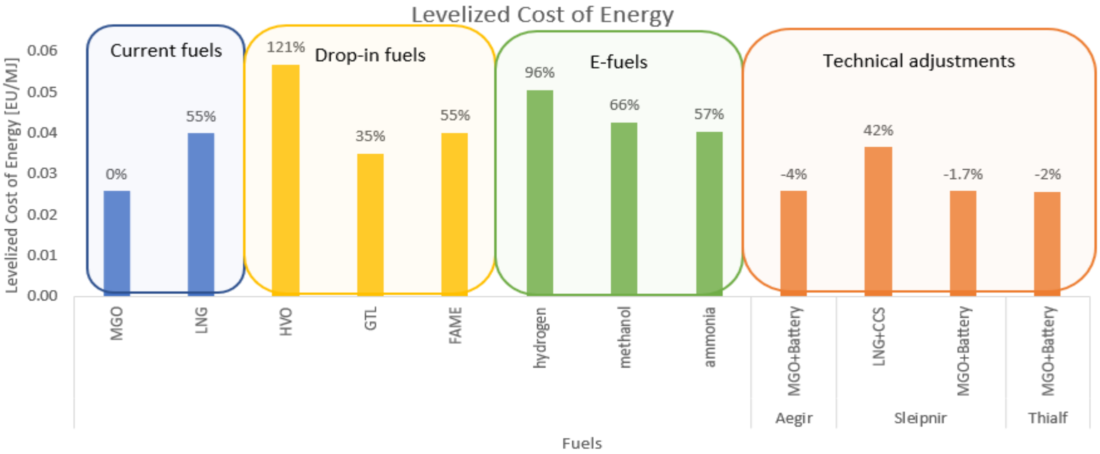

Figure 26 Levelized costs of energy of the emission abating technical adjustments

6.1.2 Emission intensity

The emission intensity is expressed in $\left[\frac{kg\ CO_2}{MJ}\right]$. The emission intensity of a fuel is constant over time because it is calculated by the constant emission coefficient and the energy content of the fuel from the literature. The emission intensity is calculated because it makes it possible to get insights into the emission reduction per sustainable option, the values given in this subchapter are used as inputs for the model.

Below, the equation for the emission intensity is shown in Equation 3. The annual carbon emissions are taken into account in kg, together with the annual used weight of fuel and the higher heating value. So for all the emission-abating options, the emission intensity is calculated.

$$Emission\ intensity\ \left[\frac{kg\ CO_2}{MJ}\right] = \frac{Annual\ carbon\ emissions\ \ [kg]}{M_{fuel}\ [kg] * HHV\ \left[\frac{MJ}{kg}\right]}$$

Equation 3 Emission intensity calculation

Tank-to-wake emissions are considered because the ETS will penalise this amount. After all, the responsibility for the well-to-tank emissions is allocated to the fuel producers.

Green methanol is assumed net-zero because, at the production, the same amount of CO_2 is captured as is emitted during conversion. In Chapter 3, the values are given for the emission intensity of the fuels. For the technical adjustments, the reduction in emissions is explained in Chapter 0. Figure 27, shows the emission intensities with the emission reduction percentage per MJ for all the emission-abating options.

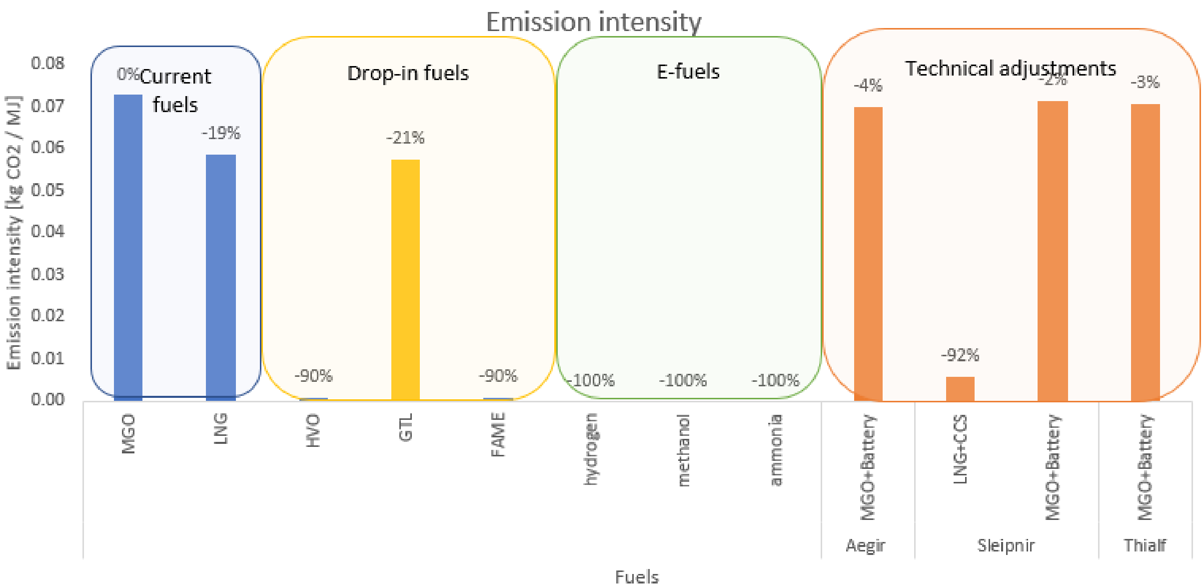

Figure 27 Emission intensity of selected fuels and technical adjustments

Below in Table 22, the emission intensities are given for each emission-abating option, together with the reduction percentages. These values are used as inputs for the model.

Table 22 Emission intensity values for the emission-abating options

Fuel	**MGO**	**LNG**	**HVO**	**GTL**	**FAME**	**Hydrogen**	**Methanol**	**Ammonia**
Emission intensity $[\frac{kg\ CO2}{MJ}]$	0.073	0.059	0.001	0.057	0.001	0.000	0.000	0.000
Emission intensity reduction [%]	0%	-19%	-90%	-21%	-90%	-100%	-100%	-100%

Aegir	**Sleipnir**		**Thialf**
MGO+Battery	**LNG+CCS**	**MGO+Battery**	**MGO+Battery**
0.070	0.006	0.072	0.071
-4%	-92%	-2%	-3%

6.1.3 Levelized costs of carbon abatement

The levelized cost of carbon abatement is expressed in $[\frac{€}{mt\ CO2}]$. The LCoCA is calculated within this section, for this calculation, the values from Chapter 6.1.1 and Chapter 0 are used. The LCoCA is used to gain insights into the costs of every emission-abating option discussed and makes it possible to compare the options to the MGO baseline.

This LCoCA is price-dependent because of the dependency of the LCOE on the fuel price. Below, equation 4 is shown for the calculation of the LCoCA. The change in the levelized cost of energy and the change in emission intensity compared to the MGO baseline is used for this calculation.

$$LCoCA\ [\frac{€}{mt\ CO2}] = \frac{\Delta LCOE}{\Delta Emission\ Intensity}$$

Equation 4 Levelized cost of Carbon Abatement of fuel switches

For the calculation of the LCoCA, MGO is used as a baseline. For the $\Delta LCOE$, the change in levelized cost of energy (including annualised CAPEX) between MGO and a new fuel is calculated. For $\Delta Emissions$, the change in emission intensity is calculated by the change in emission intensity of MGO compared to the new fuel.

For batteries and the installation of a carbon capture storage system, a levelized cost of carbon abatement is calculated. This calculation is done by making use of the same Equation 4. The $\Delta LCOE$ is equal to the investment cost annualised and the operational savings. Below Figure 28, shows the LCoCA values for the different fuels and technologies.

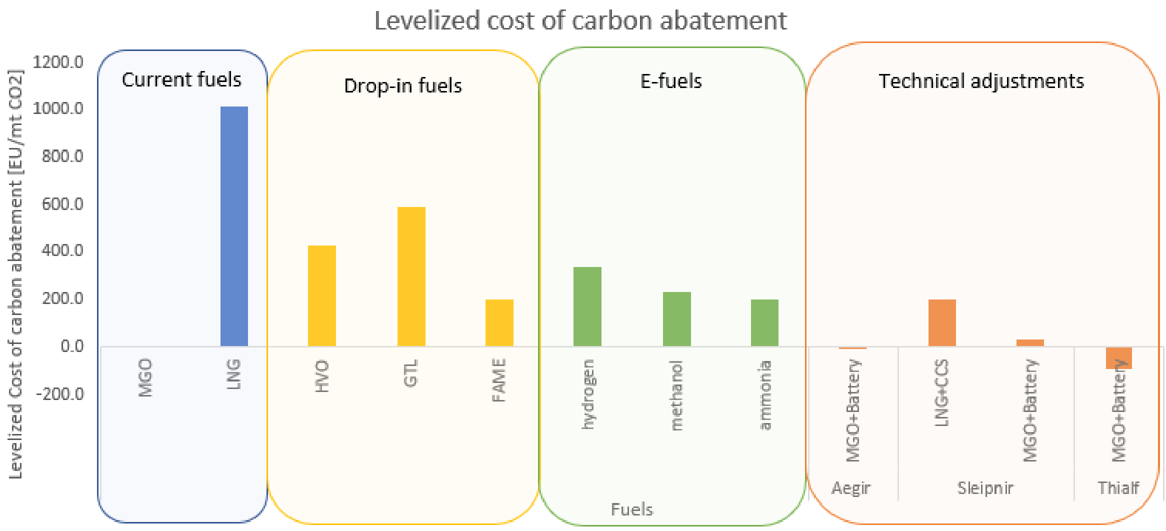

Figure 28 Levelized cost of carbon abatement of the selected fuels.

Below in Table 23, the values of the LCoCA are shown, these values are used in the model described in Chapter 7.

Table 23 levelized cost of carbon abatement considering prices given in previous sections.

	Vessels independent							
	MGO	LNG	HVO	GTL	FAME	hydrogen	methanol	ammonia
LcoCA $[\frac{€}{mt\ CO2eq}]$	-	1013.3	431.5	593.6	198.0	341.0	232.2	199.9

Aegir	Sleipnir		Thialf
MGO+Battery	LNG+CCS	MGO+Battery	MGO+Battery
-7.82	204.02	34.25	-93.10

Using equation 4 and the prices given in previous chapters, the LCoCA of the batteries on board the different vessels is calculated. The values are vessel specific because the implementation of the battery depends on the vessel's operational profile, and those are unique per vessel. The prices for the Aegir and Thialf are negative, which means that the battery installation implementation will earn the company money. These prices are negative since the battery saves costs compared to the initial investment.

The LCoCA for installation of a carbon capture installation is calculated by making use of an estimation provided by TNO. The capital expenditure of the installation is assumed to be 50 million euros with annual operational costs of 1.8 million euros. The lifetime of the CCS installation is estimated to be 30 years.

6.1.4 Availability

The availability of the described fuels is considered within this section. For fuels, the availability means the physical availability of drop-in fuels: HVO, FAME, GTL, and the e-fuels hydrogen, methanol, and ammonia. This section is based on assumptions and predictions from the literature.

The predictions in availability for the future are based on three different variables:

- The historic fuel prices are used to predict future fuel prices during the roadmap, calculated using a trendline.
- The compound annual growth rate (CAGR) is the expected growth rate of the specific fuel market per year from the literature.
- The current market size of the specific fuel market, from literature.

$$Availability\ [litre] = \frac{Current\ market\ size\ [Euros] * (1 + CAGR)^{year}\ [\%]}{Fuel_{cost}\,[\frac{euros}{litre}]}$$

Equation 5 Availability quantification

These three variables are all uncertain to a certain level, and the price prediction is an estimation. The current market size and the CAGR value are values from the literature. These uncertainties are why the model created is generic and can be adjusted for different price scenarios.

The availability varies worldwide; this distribution also changes with a CAGR value. With the vessels of HMC working most of the time in Asia, Europe or Latin America, these areas are examined. These numbers below in Table 24 are used to scale to a specific area when only global availability is known.

Table 24 CAGR of biofuels in areas and market share of different areas worldwide

Fuel	Asia	Europe	Latin America	References
CAGR biofuels [2020-2030]	5.5%	4.0%	4.4%	[39]
Market share [2020]	29%	20%	21%	[38]

Drop-in fuels

Drop-in fuels are assigned to the biofuel market. The European Union’s biofuel market increased to above 15 billion litres in 2019 [19]. These biofuels are primarily produced in western Europe. Below in Figure 29, the global market size is given for biofuels. What can be seen is that there is an overall increase in market size for the different areas. This graph is based on the global market size prediction and the market share data from Table 25.

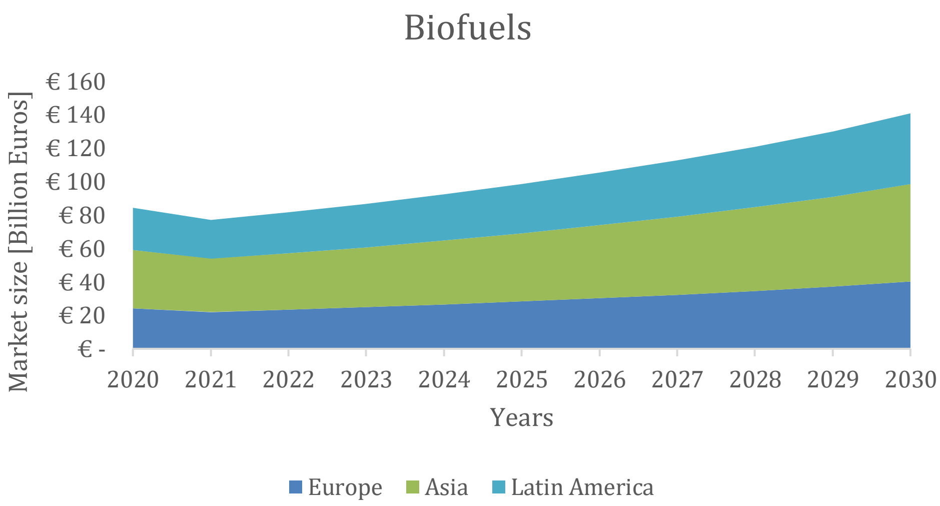

Figure 29 Market size prediction for different areas of the biofuel market.

HVO FAME and GTL are only percentages of the biofuel market. Every fuel within the market has its CAGR for 2020-2030.

Table 25 CAGR and Market size of different drop-in fuels

Fuel	**HVO**	**FAME**	**GTL**	**References**
CAGR [2020-2030]	3.1%	5%	3.7%	[31,40,26]
Market size 2020 [Billion Euros]	5.2	4.9	4.1	[42,43,26]
Price [€/Liter]	[redacted]	[redacted]	[redacted]	[DATA HMC]

Government policies mainly cause this increase in market size. It can be seen that first, Europe will start to increase its production, which is the incentive for Asia to push their production further than Europe. Some governments are not pushing toward biofuels. In Figure 30, the market size development is calculated.

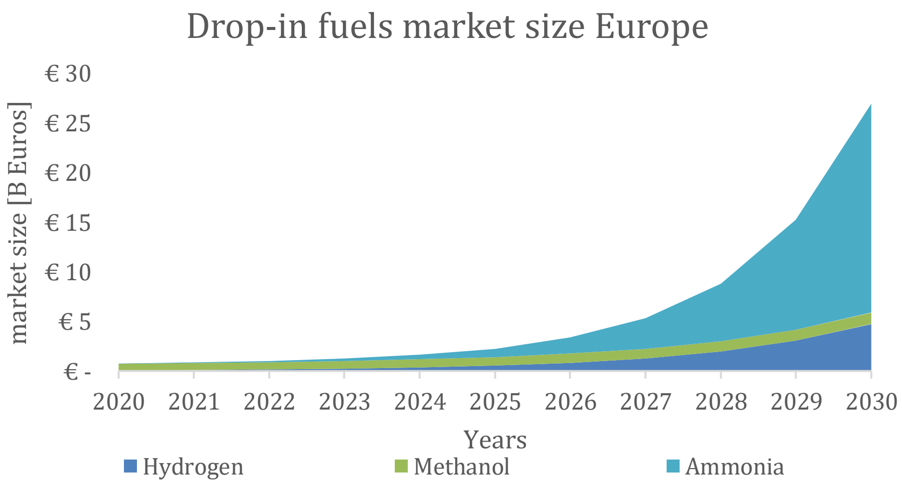

Figure 30 Drop in fuels market size development based on data from Table 25

The figures for the other areas worldwide are given in Appendix 12.4. With the price development of the fuels (estimated at -3% per year), an estimation is made using Equation 10.

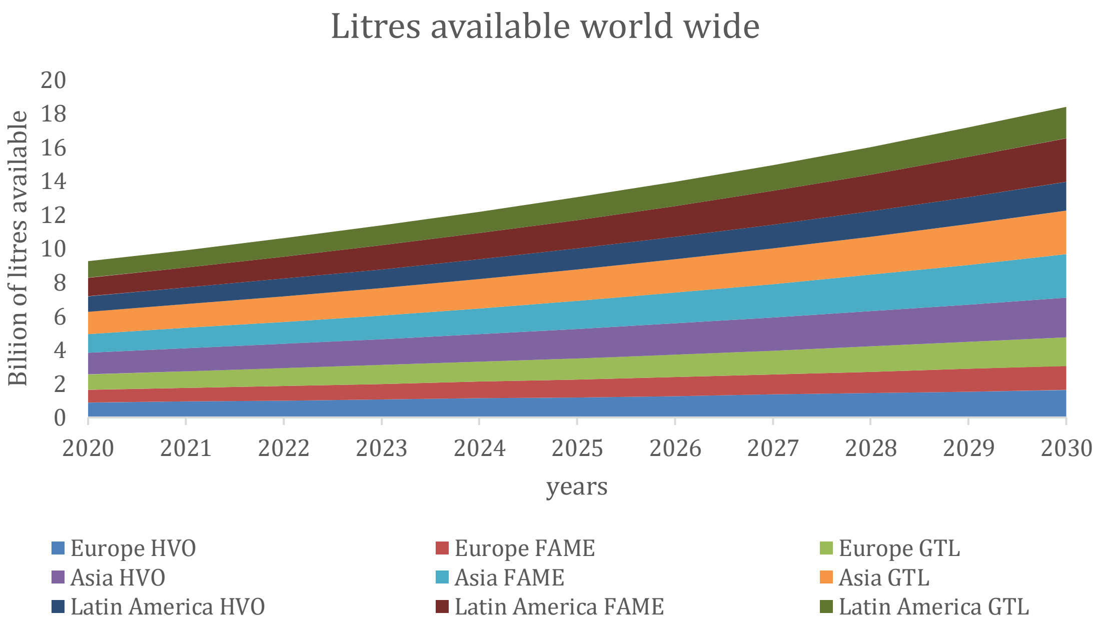

Figure 31 billion litres of biofuels available in different continents

E-fuels

For e-fuels, an estimation is made for the availability using the same method as for the drop-in fuels. The markets for e-fuels are increasing in size quickly, but currently, the markets are still small compared to the biofuel markets. For the scope of this research, it is assumed that there is enough green hydrogen in the market. While in this section, an estimation of the availability of the different e-fuels is given. Because this market is developing, the market size will significantly increase. This increase can be seen in Figure 32 below.

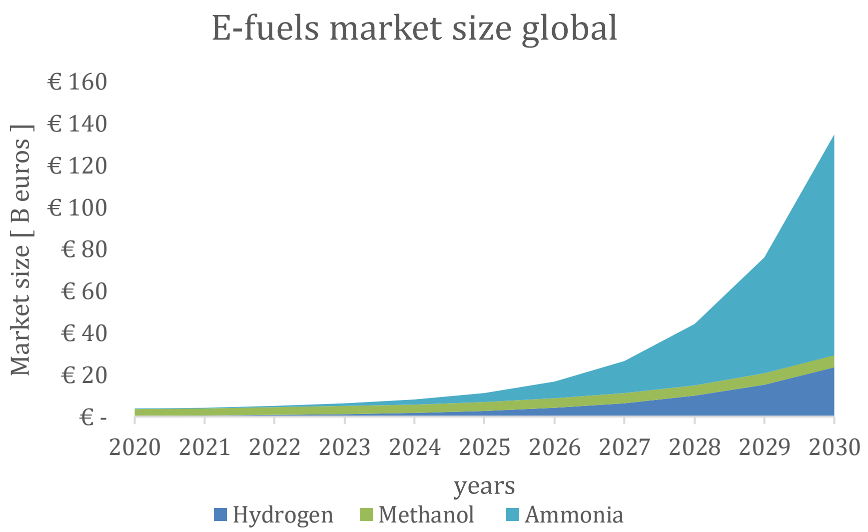

Figure 32 E-fuels development of global market size

The e-fuel markets are small and have the same distribution as drop-in fuels. Below in Table 26, the CAGR, market size and fuel prices are given.

Table 26 Summary of the used values for CAGR, market size and fuel prices

Fuel	**Green hydrogen**	**Green methanol**	**Green Ammonia**	**References**
CAGR [2020-2030]	54.7%	5.8%	90.2%	[24,28,27]
Market size 2020 [Billion Euros]	0.3	3.3	0.17	[24,28,27]
Price [€/Liter]	0.04	0.51	0.02	[34]

Because of significant investments in e-fuel production in Europe, one can see that ammonia has the largest market in Europe, followed by the hydrogen market.

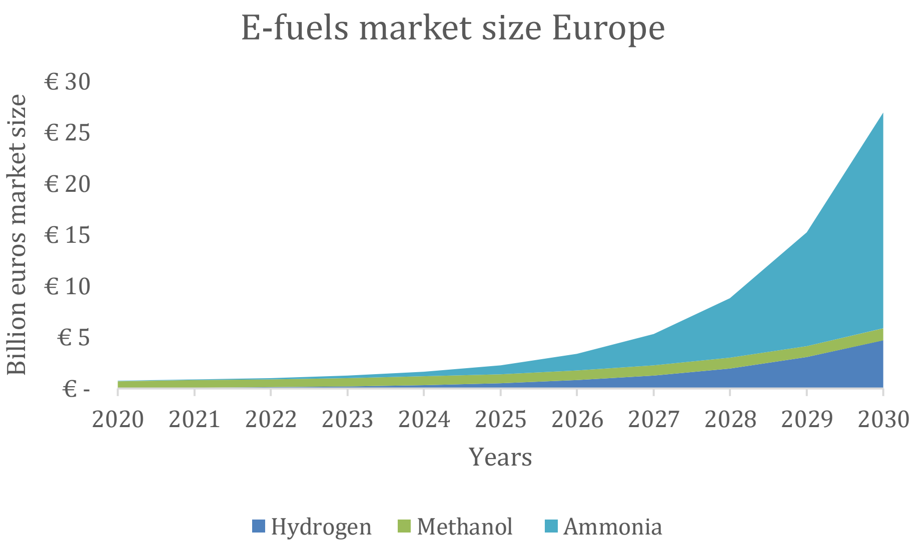

Figure 33 Development of the market size for different e-fuels

With the availability per region of the world, the litres of e-fuels available are estimated and predicted together with the price development. Above, the market size is shown in Figure 33, and below, the litres are shown in Figure 34.

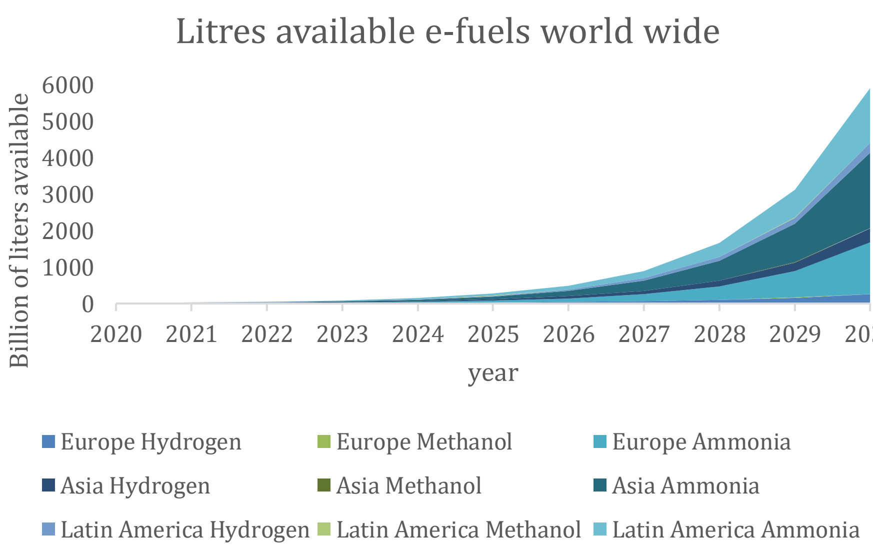

Figure 34 Litres available worldwide for e-fuels

6.1.5 Carbon tax

This section describes the emission trading system (ETS) and its influence on the maritime sector. The European ETS is designed for companies to pay for their emissions and give financial incentives to become more sustainable. The ETS started in 2005 for heavy industries such as metal, glass, lime, cement, and chemicals.

Free allowances were introduced to support the industries. These allowances are free carbon certificates for one ton of carbon given by governments. At the start, companies got 100% of their emissions by free allowances.

With this ETS, there are two ways of providing incentives for companies to make sustainable investments:

- Free allowances are reduced annually, so industries have to pay for a higher percentage of their emissions.
- The prices for carbon certificates have increased a lot since the start.

New heavy industries are added to the ETS every year and start paying for the companies' emissions. When an industry enters the ETS, it gets only a tiny percentage of its emissions as free allowances and has to pay for the rest.

The maritime sector will also be added to the ETS following the European Union's green deal. From 1 January 2023, cargo vessels are required to pay for their emissions, and the offshore work vessels are expected to be added to the ETS from 1 January 2026 onwards [green deal, EU].

Currently, the carbon certificate prices at the ETS are around 100 €/mT CO_2. HMC is carbon neutral by buying offsets priced at [redacted]. However, the carbon certificate price is expected to continue rising. With the current price, HMC would have to pay 20 times more when switching from offsets to certificates from 2026 onwards. This implementation of the ETS gives HMC, asides from the pioneering motivation, an financial motivation to become more sustainable, as shown in Figure 35.

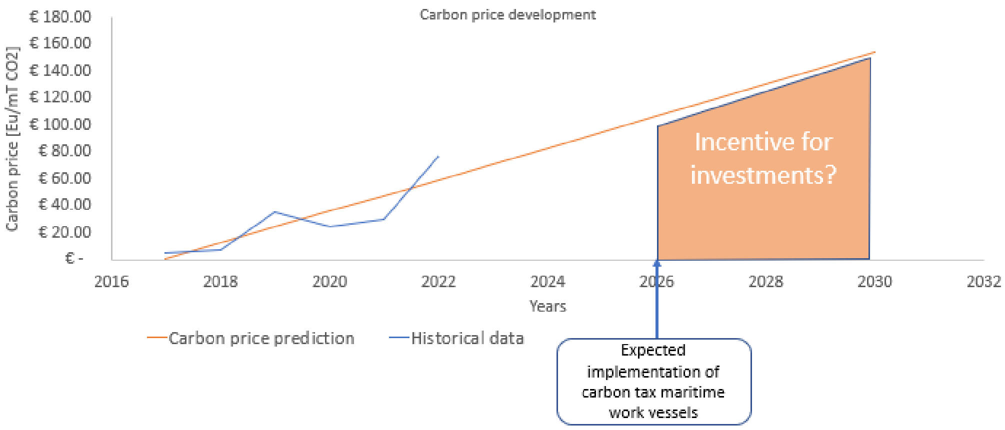

Figure 35 Carbon price development, including an incentive for investments.

Two future price scenarios for the carbon tax and offset prices are used within this thesis, shown in Figure 36 and Figure 37:

- Trendline scenario: The trendline of the historical carbon prices and the offset prices is estimated and extrapolated until 2030.
- Business as Usual (BaU): prices stay the same as current prices, for offsets: [redacted] and for the ETS 100 €/mT CO_2.

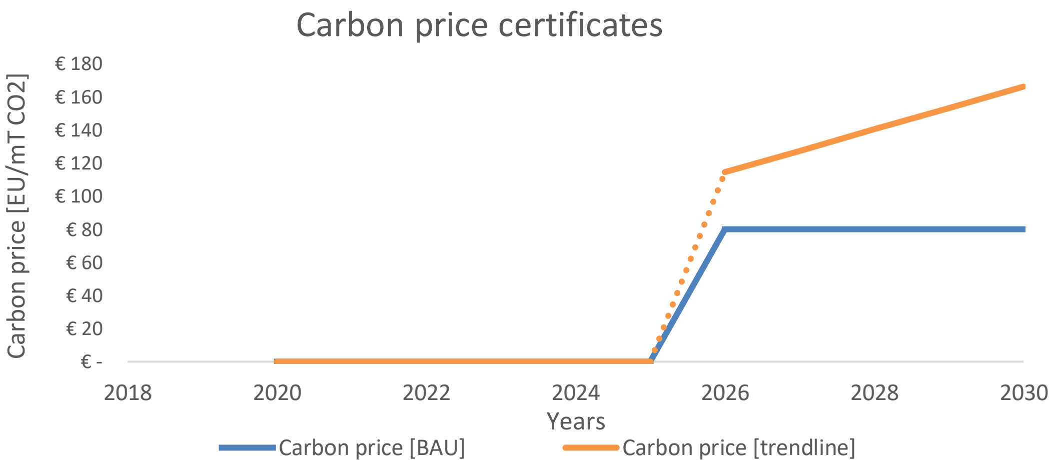

Figure 36 Development of carbon certificate price

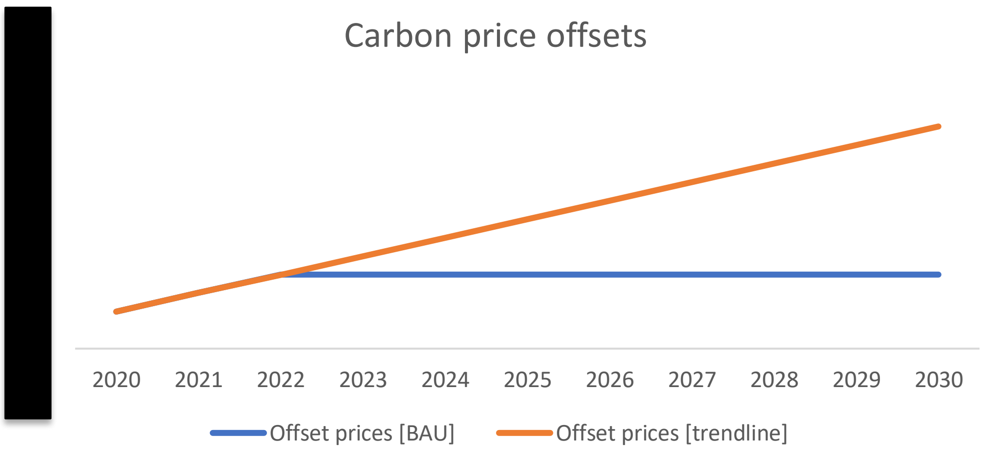

Figure 37 Development of carbon offset price

Budget

As described above, there are different scenarios for the carbon tax with its price development over time. HMC wants to invest in the best solution for its fleet, with the best technical feasible solution and the best financial interest. The orange box in Figure 35 resembles the amount of money HMC may have to pay, providing a budget for the coming years to invest in sustainable solutions on board the vessels. Below is an indication of the amount HMC would pay for the emissions when added to the ETS. For every vessel, the cumulative amount paid for carbon from 2022-2030 is shown below in Figure 38.

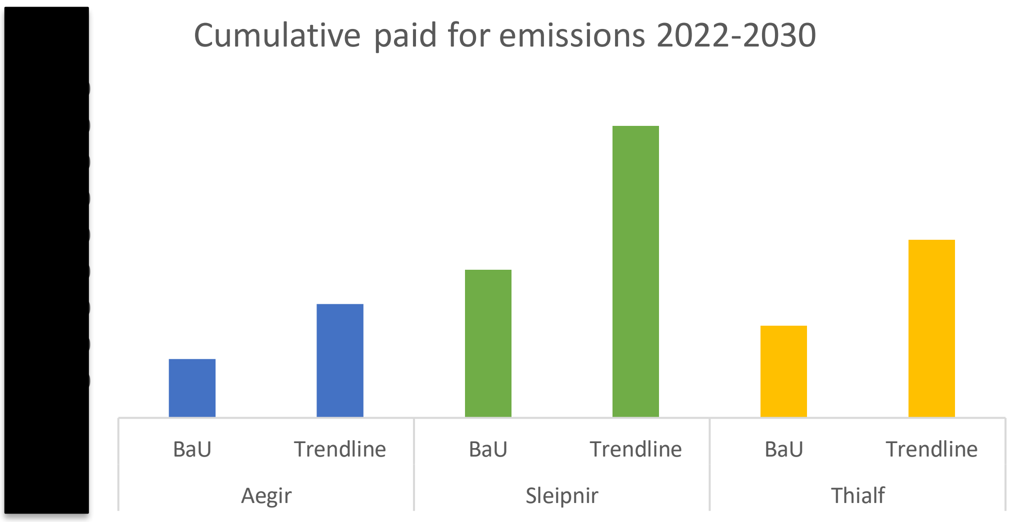

Figure 38 Cumulative paid for emission during 2022-2030 for the trendline and business-as-usual scenarios.

7 THE MODEL

In this chapter, the model constructed will be described. The model is constructed to examine the technical and financial feasibility of the emission-abating options. All the emission-abating decision criteria are calculated, including the price developments over time in Chapter 6 and used as inputs. The prices and price developments are partly based on assumptions and used as variable inputs for the model. This chapter describes the model first, after which the decision criteria and inputs are evaluated. Hereafter the model will be verified and validated.

This chapter will give insights into the following:
- What exactly is modelled?
- How is this modelled?
- What are the inputs?
- What are the outputs?

7.1 Description of the model

A generic model is constructed in excel to examine the technical and financial feasibility of the emission-abating options that are given in Chapter 3 and Chapter 0. This model simplifies the decision-making for maritime companies about which emission-abating options should be considered for offshore crane vessels. The model is constructed in excel and is a linear model, and the model uses the data described in the previous chapters.

1. The input data consists primarily of generic fuel and technology characteristics and price predictions. Next to this input data, vessel-specific characteristics are required, as visualised in blue in Figure 39 below.

2. The model is used for different vessels to visualise the scheduled emission intensity up to 2030 and show the influence of the emission-abating options. The generic input data is processed into the LCOE, the emission intensity and the LCoCA. The vessel-specific input data is processed to give insight into the energy profile of a vessel, the battery savings, the savings due to the installation of CCS and the emission prediction throughout the roadmap. The processed inputs are shown in orange below in Figure 39.

3. The model outputs are LCOE developments, scheduled emission intensity for the different emission-abating options, the required investment costs, and the annual expenditures. These values are visualised in green in Figure 39.

The analysis of the outputs is described in Chapter 8. This chapter analyses the effect of changes in the inputs with different sensitivity analyses. The modelling blocks are shown in Figure 39, and screenshots of the model are shown in Appendix 12.4 The model.

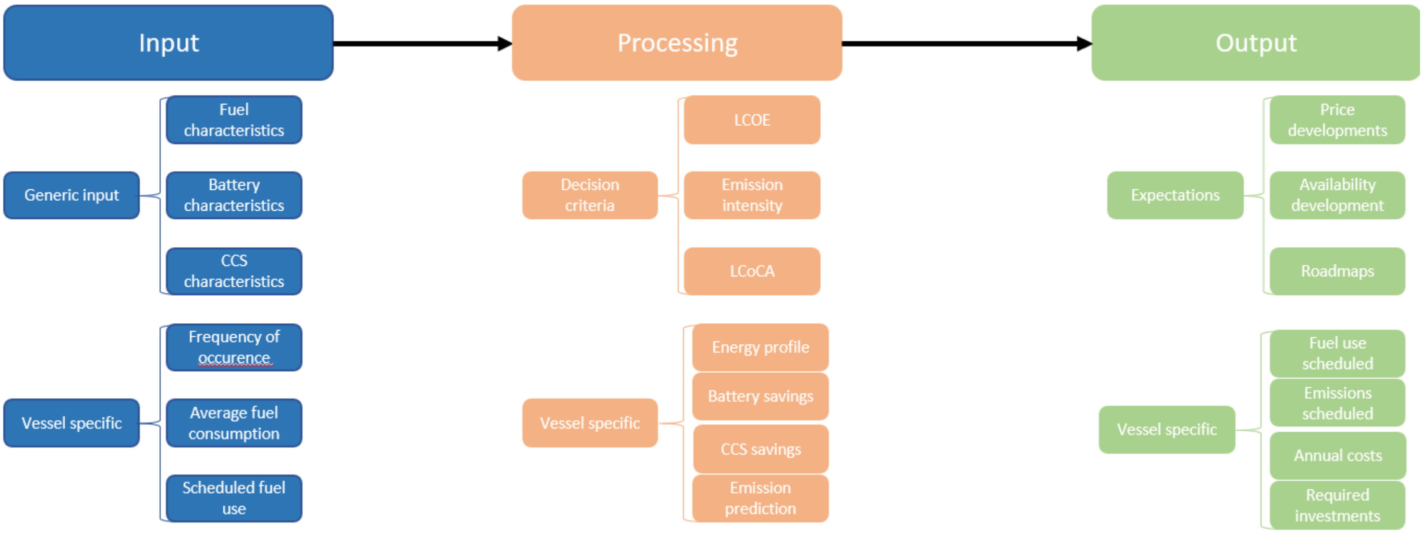

Figure 39 Building blocks of the model

To make sure the model is generic, the inputs required are:

- Frequency of occurrence per operational mode
- Average fuel consumption of a specific operational mode
- Scheduled fuel consumption per operational mode

The model calculates the following outcomes:

- Levelized cost of Energy development over time, based on implementation moments
- Fuel requirements during the roadmap
- A visualisation of the influence of different emission-abating options on the emission intensity
- An (annualised) expenditures overview, the fuel expenses, and the capital expenditures can be annualised or given as initial values.

The decision criteria and the input data are evaluated and verified to ensure the input data is correct. This evaluation is done by applying a sensitivity analysis on price developments and verifying calculations. After the model is verified, it will be validated by applying changes in data and calculating the outcomes for different emission-abating options.

7.2 Evaluation of the decision criteria

Within this section, the decision criteria in Chapter 6.1 are evaluated. The influence of price developments will be examined, and a sensitivity analysis will be executed.

Fuel prices develop over time and the price for MGO and LNG is assumed to increase (+3% annually). For the drop-in and e-fuels, a price decrease is expected worldwide due to regulations and subsidies, and this is an assumption based on European objectives (-3% annually).

For simplicity, the increase and decrease of fuel prices are assumed constant over the years, which is a constant percentage annually. This chapter first evaluates the five decision criteria, and hereafter the input data is evaluated.

Levelized Cost of Energy

The levelized cost of energy is calculated in Chapter 6.1.1 for all the emission-abating options. What can be seen below in Table 27, is that all the fuels and technical adjustments have additional costs with the current prices. The installation of batteries reduces the LCOE for every vessel.

Table 27 Levelized cost of energy for the fuels and technical adjustments with the additional percentage of costs.

	MGO	LNG	HVO	GTL	FAME	hydrogen	methanol	ammonia
LCOE [$\frac{€}{MJ}$]	0.026	0.040	0.057	0.035	0.040	0.051	0.043	0.041
Additional costs [%]	0%	55%	121%	35%	55%	96%	66%	59%

	Aegir	Sleipnir		Thialf
	MGO+Battery	LNG+CCS	MGO+Battery	MGO+Battery
LCOE [€/MJ]	0.026	0.037	0.026	0.026
Additional costs [%]	-4%	42%	-1.7%	-2%

The effect of implementing of the ETS is shown below in Figure 40. The change in LCOE after implementing the ETS is shown for every fuel. The costs of energy are in the left column, the levelized cost of energy, so including CAPEX is the middle column, and the right column is the LCOE, including CAPEX and ETS. The difference between the LCOE of MGO, including ETS, is the smallest for the e-fuels.

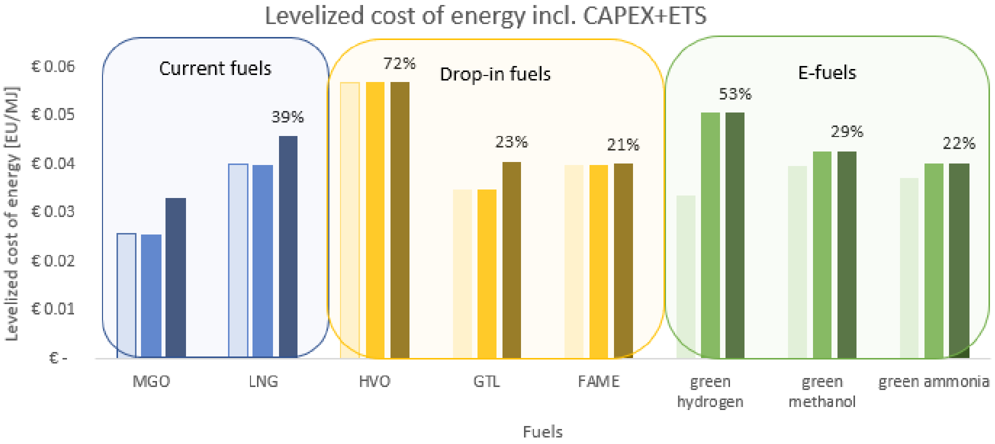

Figure 40 The levelized cost of energy including the ETS prices.

To analyse the effect of the changes of the ETS price, a sensitivity analysis is done to see the effect of the price increase. Below in Figure 41, the influence of different ETS prices is shown. ETS prices of 300Eu/mT CO_2, 200 EU/mt CO_2 and 100EU/mt CO_2 are used from the left to the right column. When the ETS price is equal to or above one of the LCoCA values for the emission-abating options, it is financially more attractive to make the switch. An ETS price of 300 EU/mT CO_2 gives a reduction of the LCOE when a switch to FAME(-15%), methanol(-10%) or ammonia(-15%) is implemented.

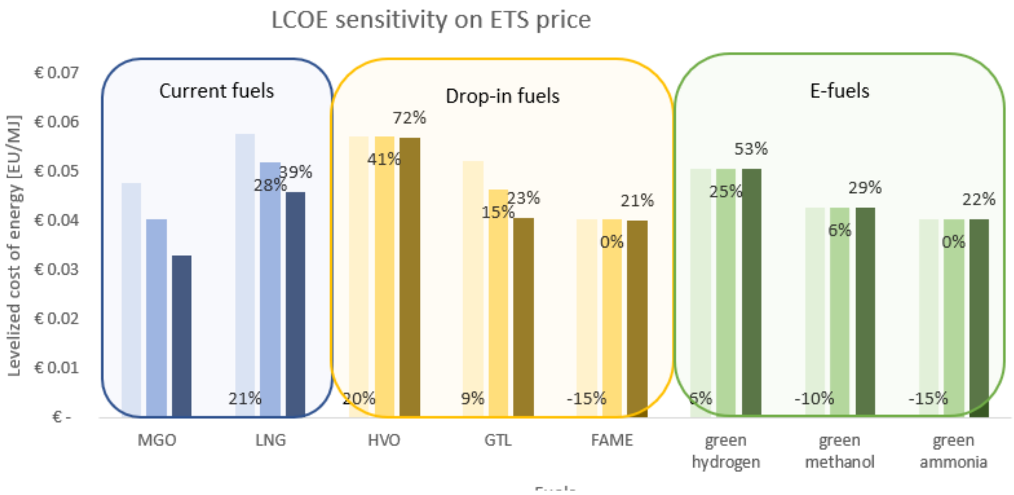

Figure 41 Levelized cost of energy sensitivity analysis on ETS price

The levelized cost of energy is dependent on the capital expenditures of the designated e-fuel tanks. The influence of these prices is shown below in Figure 42. From left to right, the CAPEX is changed: left two times as high, middle one time as high, and left 0.5 as high. Due to its higher specific investment costs, the effect on the LCOE by the increase of CAPEX price is more significant for hydrogen than methanol and ammonia. The effect of an increase in CAPEX is minimal compared to an increase in fuel costs.

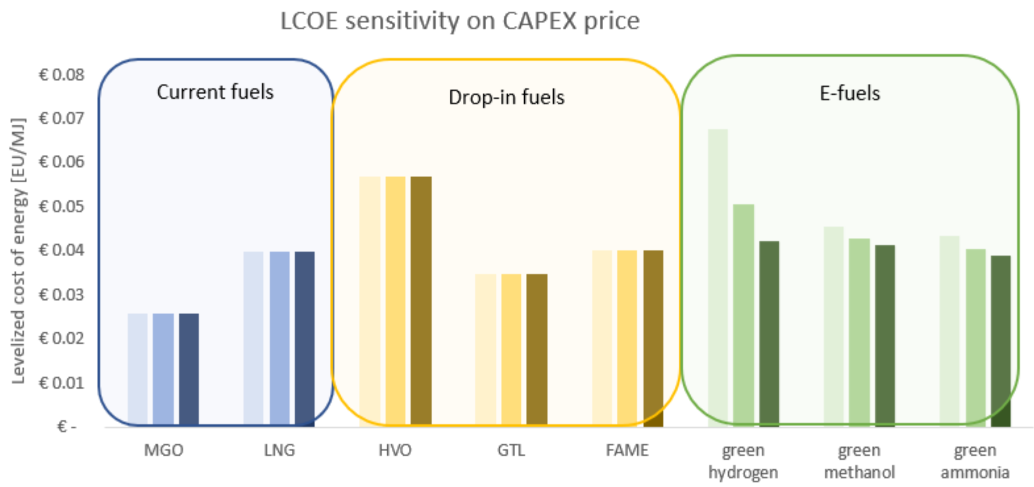

Figure 42 Levelized cost of energy sensitivity analysis on the CAPEX for designated e-fuel tanks.

The last sensitivity examined is the sensitivity to fuel prices, which is shown in Figure 43. The price of hydrogen is linked to that of methanol and ammonia.Therefore the price of hydrogen is changed to see the effect of the OPEX costs. From left to right, hydrogen prices are 7500EU/mT, 4000EU/mT, and 2500EU/mT. What can be seen is that the LCOE of e-fuels is more sensitive to a change in fuel costs than to a change in CAPEX.

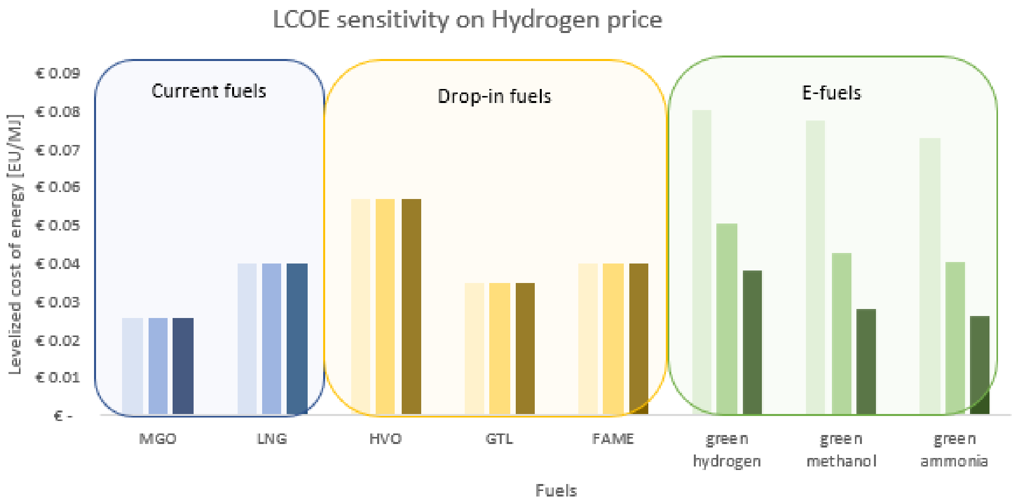

Figure 43 Levelized cost of energy sensitivity analysis on the hydrogen prices

Emission intensity

The emission intensity is calculated in $\left[\frac{kg\ CO_2}{MJ}\right]$ for every emission-abating option in Chapter 0 For the technical adjustments, the emission intensity is calculated using MGO with a battery and CCS in combination with LNG. All the options reduce the CO_2 emissions per MJ. The influence of fuel switches and technologies is shown in Table 28. These emission intensities and the abatement percentages are all visualised in Figure 44. The values in Table 28 are used as inputs in the model.

Table 28 Emission intensity of the fuels

Fuel	MGO	LNG	HVO	GTL	FAME	Hydrogen	Methanol	Ammonia
Emission intensity $[\frac{kg\ CO2}{MJ}]$	0.073	0.059	0.001	0.057	0.001	0.000	0.000	0.000
Emission reduction [%]	0%	-19%	-90%	-21%	-90%	-100%	-100%	-100%

Aegir	Sleipnir		Thialf
MGO+Battery	MGO+CCS	MGO+Battery	MGO+Battery
0.070	0.006	0.072	0.071
-4%	-92%	-2%	-3%

Net-zero methanol emits the same amount of carbon as it captures during production. For green methanol, the assumption is to use a net-zero emission profile for the well-to-wake emission profile. This assumption is because the regulations around methanol well-to-wake emission are not defined yet. When the ETS penalises the tank-to-wake emissions of methanol, methanol becomes less applicable as an emission-abating fuel. The effect of taking the tank-to-wake emission into account for grey methanol is shown in Figure 44 compared to green methanol.

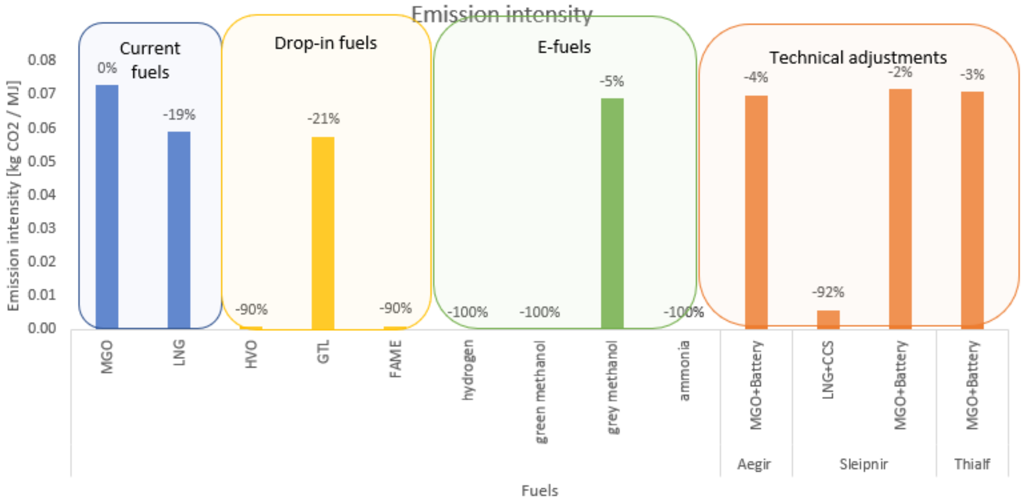

Figure 44 Overview of all emission intensities for the abating options, with abatement percentages

Levelized cost of carbon abatement

The levelized cost of carbon abatement is expressed in $[\frac{€}{mt\ CO2\ \text{abated}}]$. Below in Table 29 all the LCoCA values for the different emission abating options are shown, that are used as inputs in the model.

Table 29 Levelized costs of carbon abatement for the fuels

	MGO	LNG	HVO	GTL	FAME	hydrogen	methanol	ammonia
LCoCA [€/mT CO_2]	-	431.5	431.5	593.6	198.0	108.6	191.8	159.4

Aegir	Sleipnir		Thialf
MGO+Battery	LNG+CCS	MGO+Battery	MGO+Battery
-7.82	204.02	34.25	-93.10

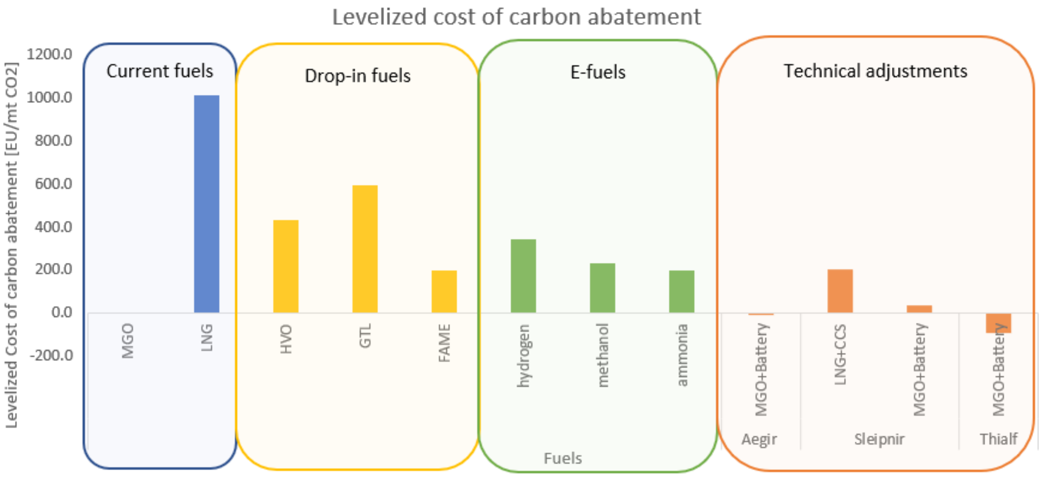

Figure 45 overview of all the LCoCA values calculated

These LCoCA values are also sensitive to the price development of the fuels because the difference in LCOE calculates the LCoCA. From Figure 45, it is possible to tell that emission reduction by LNG, HVO and GTL are expensive solutions. When e-fuels are unavailable, and a maritime company wants to meet its emission reduction objective, the company must implement drop-in fuels in the current energy configuration.

Below is the sensitivity shown of the LCoCA to the different hydrogen price scenarios, the same price scenarios are used as in the LCOE sensitivity analysis. From left to right the hydrogen prices used as inputs are, 2500 EU/mT, 4000EU/mT and 7000EU/mT. The effect, which can be seen in Figure 46 is that the e-fuels only become competitive towards drop-in fuels when hydrogen prices are below +/- 6000EU/mT for hydrogen.

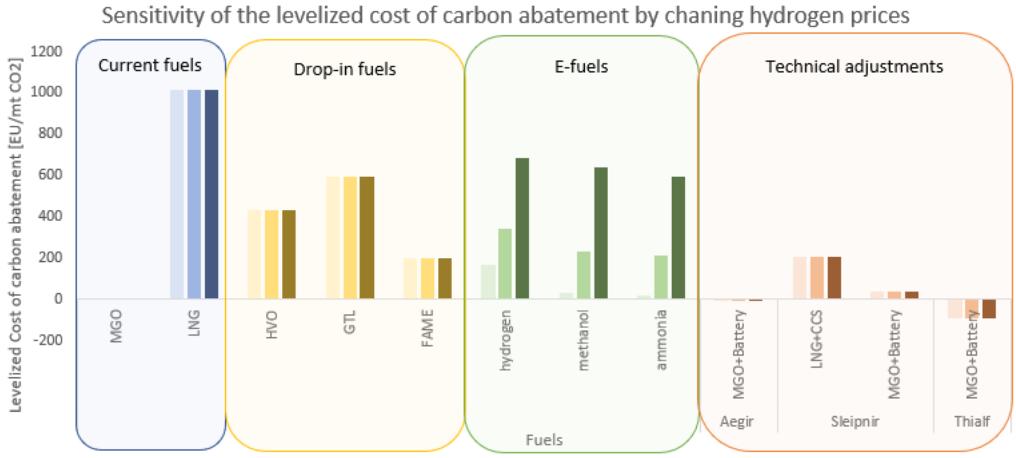

Figure 46 sensitivity analysis on hydrogen prices for the levelized cost of carbon abatement.

Availability Ambition

The availability described in Chapter 0 is based on assumptions from the literature; the CAGR and the price development are both uncertain. For this thesis, as described in the scope, the assumption is made on a wide availability of e-fuels.

Batteries are ready for implementation in 2023 for the Aegir, and the research into CCS is expected to be ready in 2026 and implemented in 2028. The installation of the technologies also depends on the location and the availability of the vessels. For example, the Aegir is working for another year in South-East Asia, so the implementation of a battery system is assumed to be in 2023 for Sleipnir and Thialf; this is expected for 2025.

Within the sustainability department, a roadmap is constructed with the year of implementation discussed based on the locations of the vessels and the readiness of technologies, the following roadmap is designed as shown below in Table 30.

Table 30 expected year of implementation overview

	2022	2023	2024	2025	2026	2027	2028	2029	2030
[redacted]		Drop-in/ Battery			E-fuels				
[redacted]		Drop-in		Battery	E-fuels		CCS		
[redacted]		Drop-in		Battery	E-fuels				

This table is used as scheduled implementation and investment moments, first when no e-fuels are available and drop-in fuels are available, drop-in fuels should be used to meet the emission reduction ambition. Note that in this thesis an assumption is made about the wide availability of e-fuels. With the scheduled year of implementation being 2026, **e-fuel blending is assumed to be possible up to 100%.**

Carbon tax

The carbon tax is expected to increase over the years, which is why the two scenarios are used to calculate the budget. Scenario one, prices increase with the trendline from the past five years. Scenario two, prices stay the same for the duration of the roadmap. The cumulative amounts paid for emissions are shown in Table 31.

Table 31 Budgets of the vessels for the roadmaps

Budgets BAU/Trendline	Aegir	Thialf	Sleipnir
Budget BAU [M euros]	[redacted]	[redacted]	[redacted]
Budget trendline [M euros]	[redacted]	[redacted]	[redacted]

Implementing the maritime sector into the ETS is still uncertain and depends on the development of regulations from the EU. Another uncertainty is the number of free allowances allocated for the maritime sector.

Within the model, the assumption is made that no free allowances are allocated from 2026 onwards. In the case of this scenario, HMC would be charged with costs for the entire amount of its emissions.

7.3 Evaluation of the fuels

Within this subchapter, the evaluation of the discussed emission-abating fuels is given. The most important fuel characteristics are energy density together and emission reduction. When considering the emission intensity reduction of the fuels, a fuel switch from MGO to LNG or GTL for the vessels has a too small impact. LNG and GTL only abate 19% and 21% of the emissions, respectively. To follow the sustainability ambition in Chapter 5, an emission reduction of up to 100% is required. This is the reason why these two fuels are not taken into account in the roadmaps. Furthermore, the drop-in fuel FAME is rejected during the durability test at HMC and is therefore not included in the roadmap for HMC.

HVO, hydrogen, methanol and ammonia are potential fuel switches for the three vessels. This is because of the abatement of 90% for HVO and 100% for the e-fuels. HVO passed the durability and engine tests and the technology around the e-fuels is assumed to develop up to a level at which 100% fuel blends can be used in 2026.

7.4 Evaluation of the technical adjustments.

Considering the described technical adjustments, the battery systems have a negative LCoCA for the Aegir and Thialf. For the Sleipnir a LCoCA of 34.25 EU/mT CO_2 is calculated. Because a battery system will save costs and emissions on all vessels a battery is implemented.

The volumetric energy density and the technology readiness level are the most essential criteria for battery selection. The volumetric energy density is critical because of the limited storage space on board vessels. Here, the lithium-ion battery is selected because of the higher volumetric energy density compared to a redox flow battery, which is 0.9 - 2.4 MJ/L to 0.05 - 0.09 MJ/L. The technology readiness level is higher for the Li-ion battery than the redox flow battery. The year of battery implementation depends on the vessel's location shown in Table 30. From 2024, it is assumed that it will be possible to install a battery that can be connected to different switchboards, for example, using an internal switch.

Ship-based carbon capture and storage is a technology currently under development and is expected to be installed on the Sleipnir because this is the only vessel on which LNG can be used as operational fuel. The technology will be ready from 2026 onwards and is expected to be installed on the Sleipnir from 2028. The use of CCS is a technology that should be used in combination with LNG, at this moment, LNG is expensive, which causes the LCoCA of CCS to be expensive. Another downside to CCS is that whenever a fuel switch to an e-fuel is implemented on the Sleipnir, CCS will become unnecessary due to an emission intensity of zero using e-fuels. These are the reasons why CCS is not included in the roadmap for the Sleipnir.

7.5 Verification of the model

Within this subchapter, the model verification is described. All the inputs are described and analysed in the previous subchapters. The outcomes are compared to previous literature and the current situation (the MGO baseline).

The calculations of the LCOE, by using equation 2 gives an annualised levelized cost of energy. The outcomes are compared to the current cost of energy of MGO on board, and the additional percentages in annual costs are in proportion to the current price.

The values for the emission intensity are based on numbers from the literature and are compared to different literature studies and are assumed to be correct. The values for LCOE and emission intensity result in the calculation of the LCoCA using equation 4. Because these two inputs are verified, this also results in a verified calculation of the LCoCA.

7.6 Validation of the model

The different emission-abating options are calculated from input to outcome to validate the model. The model is tested using different scenarios to show the adjustability. The scenarios are based on the availability of fuels and technologies.

The data input is also tested by changing data, and the changes in outcomes are verified because the model generates different logical outcomes when fuel characteristics are changed. Within HMC, an expert checked and validated the model too. Below are the scenarios described used as a validation for the model.

Scenarios.

Within this thesis, the model is used to design a visualised roadmap for the vessels of HMC. Because of the generic input, it is possible to apply the roadmap to other vessels. The different scenarios that are assumed as feasible by HMC are given below. These scenarios are used and calculated to achieve the emission reduction ambition.

HVO is, at the moment, the only available fuel switch to achieve the reduction ambition, based on the fuel evaluation in Chapter 7.3. From 2026 e-fuels are assumed to be available for fuel blends up to 100%. The e-fuels will be compared financially and technically by using the following scenarios below:

1. A battery system is implemented on board the vessel. No fuel switches are used, so the vessel will continue using MGO.
2. A battery system is implemented on board the vessel. E-fuels will not become available, and the emission-abating ambition will be achieved using HVO.
3. A battery system is implemented on board the vessel. **Hydrogen** is available from 2026 onwards. Until hydrogen is available, the emission reduction ambition can be achieved by using HVO.
4. A battery system is implemented on board the vessel. **Methanol** is available from 2026 onwards. Until methanol is available, the emission reduction ambition can be achieved by using HVO.
5. A battery system is implemented on board the vessel. **Ammonia** is available from 2026 onwards. Until ammonia is available, the emission reduction ambition can be achieved using HVO.

In the next Chapter 8, the model's outcomes are shown and analysed.

8 RESULTS

In this chapter, the outcomes of the model are described. First, the outcomes are visualised and described for the different scenarios compared to the baseline. The outcomes are the LCOE curves for the different emission abatement options, the emission intensity reduction ambition for the different abatement options and the annual investments.

First, the emission intensity baseline is given with the emission reduction ambition. Hereafter the outcomes are visualised one by one. At the end of the chapter, the model's outcomes are analysed on technical and financial criteria. Hereafter the criteria are applied to the vessels within the scope of this thesis. This chapter answers ***sub-question 5:*** *Which emission-abating future scenarios are technically and financially feasible, and how will these roadmaps look?*

8.1 The baseline

The current emission intensity, using MGO, is used as the baseline. All the emission-abating options in this chapter are used to follow the reduction ambition shown in Figure 47 Emission intensity baseline.

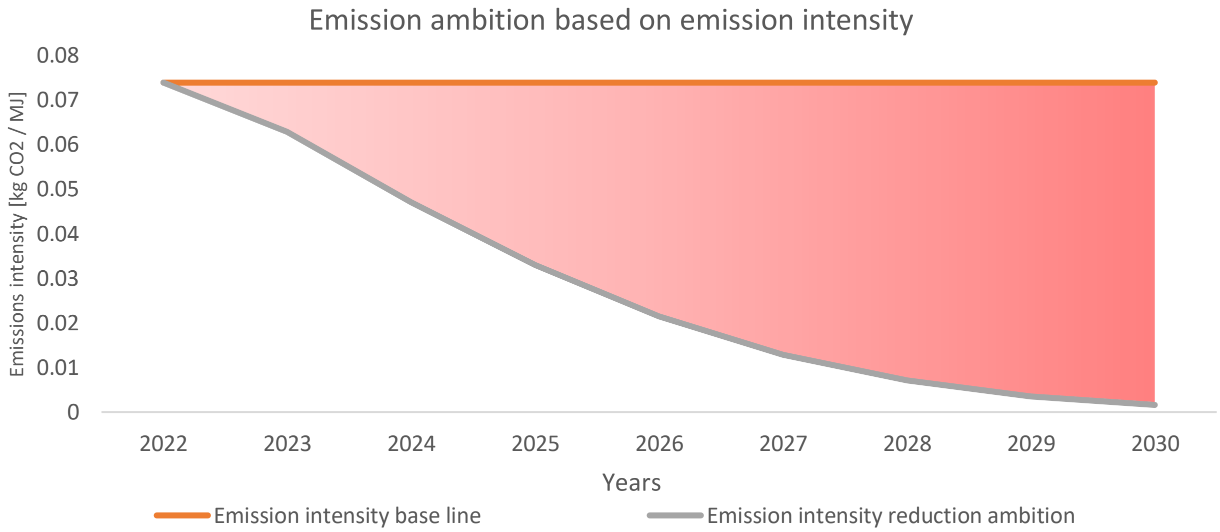

Figure 47 Emission intensity baseline

The emission-abating options are analysed on the decision criteria, and this is evaluated when applied to the vessels. The outcomes of the model are:

- The levelized cost of energy curves are plotted throughout the roadmap for the different fuels.
- The emission intensity reduces for each abatement option and is plotted throughout the roadmap.
- The LCoCA is used to calculate costs over the years during the duration of the roadmap, shown annualised and as initial investments.

8.2 The levelized cost of energy

Within this subchapter, the different emission-abating fuels are examined on the LCOE. For the LCOE, the annualised costs for the investments are considered. Below in Figure 48, the different LCOE of the fuels is plotted over the scheduled implementation moment.

2022	2023	2024	2025	2026	2027	2028	2029	2030
	Battery/HVO			E-fuels/ ETS				

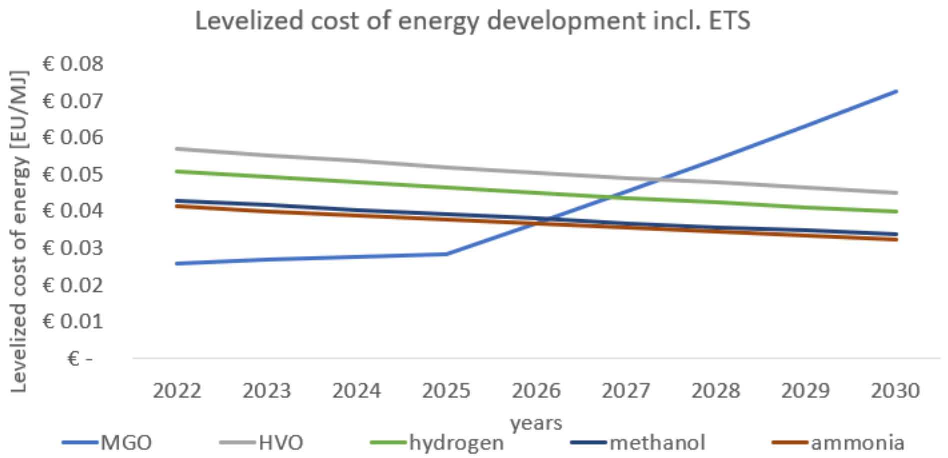

Figure 48 Levelized cost of energy analysis on the e-fuels compared with HVO.

The LCOE curves of the e-fuels decrease based on the reduction assumption of the prices for drop-in and e-fuels. The LCOE of MGO increases due to the implementation of the ETS in 2026. The fuel prices of green hydrogen are linked to the cost of green methanol and green ammonia. With the annualised costs, ammonia has the lowest LCOE of the three e-fuels. This is because the investment costs for ammonia and methanol are equal and lower than that of hydrogen. The energy cost for ammonia is lower than methanol because the energy required for the production of green ammonia from green hydrogen is 7% lower than that of methanol, making it cheaper in $\frac{€}{MJ}$.

8.3 The emission intensity

This subchapter gives the model's outcome for the emission intensity of the different emission-abating options. The influence of the different emission intensity reduction options is shown in Figure 49, plotted over the scheduled moments of implementation.

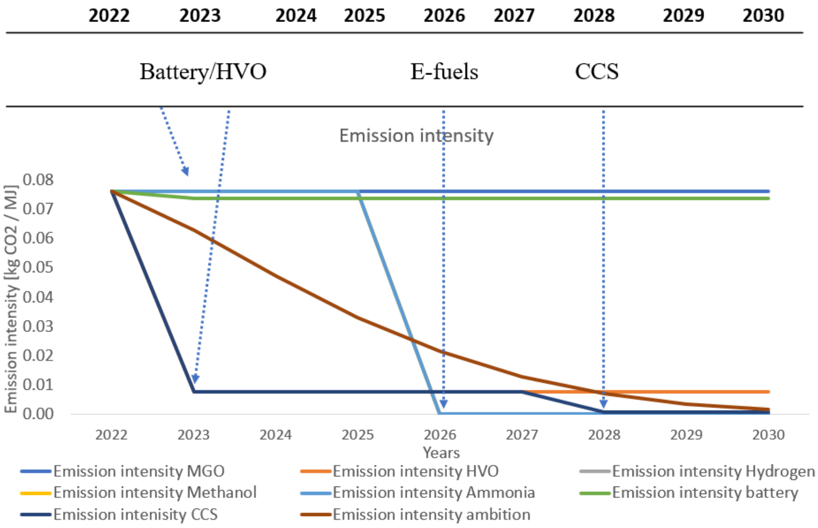

Figure 49 Emission intensity for the emission abating options

The ambition is plotted in brown. The sustainability options which can abate up to the ambition are technically feasible and have a high enough emission reduction.

8.4 The annual costs

This subchapter gives the annual cost for implementing the different emission-abating options. This model outcome is vessel specific because the investment costs per vessel differ for the designated storage tanks; these values are shown below in Table 32.

Table 32 Investment costs per vessel

	Designated fuel tanks			
	Hydrogen	**Methanol**	**Ammonia**	**Battery**
Aegir	€27.46	€4.78	€5.97	€7.00
Sleipnir	€53.61	€9.32	€11.65	€7.00
Thialf	€35.03	€6.09	€7.61	€7.00

These costs are annualised over the vessels' lifetime, and the annual costs are added to the annual fuel and emissions expenses. Below in Figure 50, shows the annualised costs visualisation below for the Aegir.

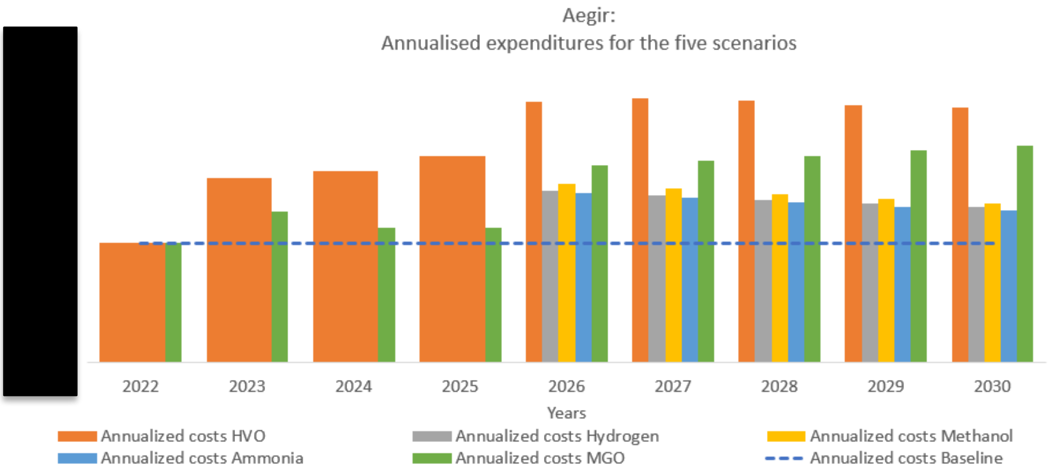

Figure 50 annualised cost visualisation of the Aegir.

It can be seen that the annual fuel cost increased due to the expenses on HVO. From 2026 onwards, the different scenarios can be compared. The annual expenditures increase for HVO and MGO, while for the e-fuels, the expenses decrease.

8.5 Analysis of the outcomes

Within this subchapter, the analysis of the outcomes is described, and different roadmaps are given and quantified. Based on Figure 49 the different possible roadmaps can be constructed to meet the emission reduction ambition. At first, until 2026, only HVO is available as emission-abating fuel, and HVO is with the current energy costs more expensive than MGO. From 2026 a decision is required to continue using HVO or a fuel switch to one of the e-fuels.

Based on Figure 48 and Figure 49, the only available emission-abating fuel is HVO. The LCOE value for HVO is higher than that of MGO, which gives additional fuel costs when switching fuels. These additional costs are calculated by comparing the amount of HVO to meet the ambition until 2030 and the roadmap in which MGO is used. Below in Figure 51, the additional annual costs for using HVO to achieve the sustainability ambition are shown per vessel. The additional fuel costs are compared to MGO because no investments are required into new fuel tanks.

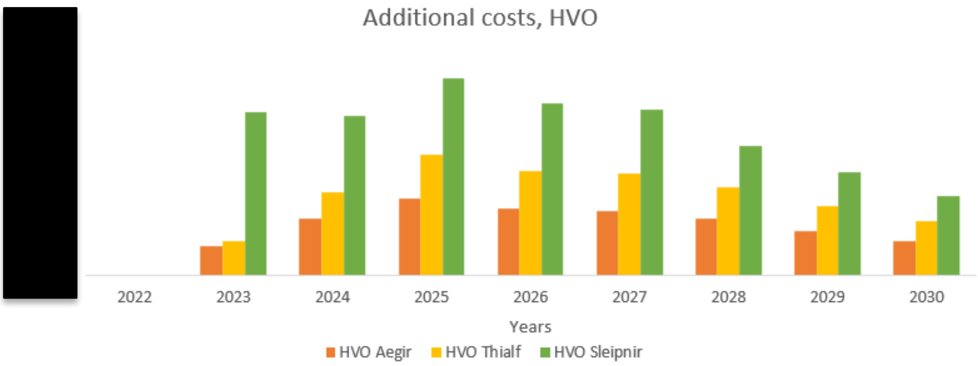

Figure 51 Additional HVO costs to achieve ambition compared to MGO

Figure 51, gives insights into the costs of the ambition. Shown are the additional HVO costs for the three vessels to achieve the ambition. The cost of the ambition up until 2030 is given as output[redacted]

From 2026 onwards, the e-fuels are assumed to be available, in Figure 48, is shown that the LCOE of e-fuels is lower than that of MGO and HVO from 2026 onwards. Together with the fact that e-fuels can be used to reach an emission abatement of 100% shown in Figure 49.

The e-fuels are discussed one by one. From 2026 a fuel switch to hydrogen is assumed to be possible. For hydrogen, an investment is required for the designated fuel tanks, and these investments are given in Table 32. The sensitivity analysis shows that the influence of CAPEX is smaller than that of OPEX.

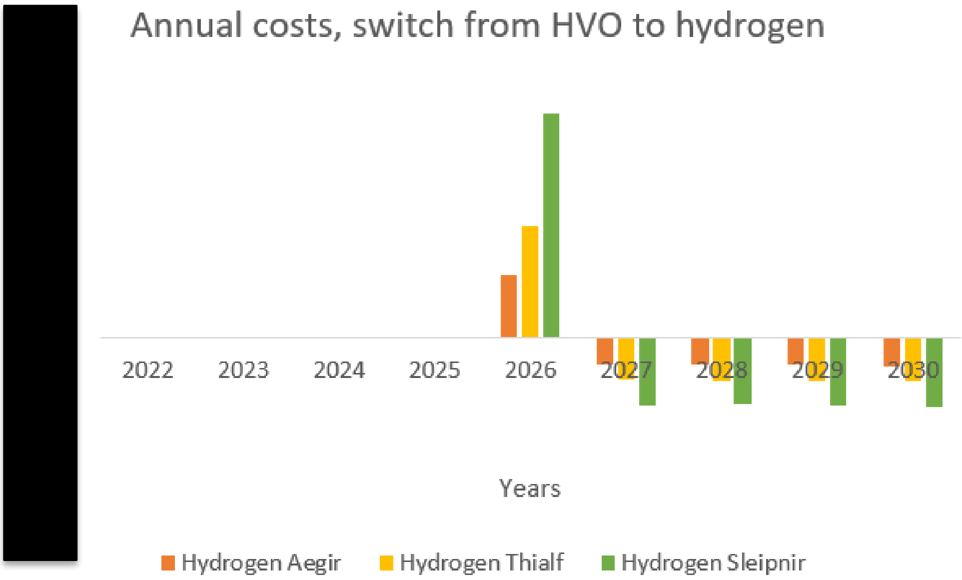

Figure 52 Additional costs for hydrogen compared to HVO.

Figure 52 gives insights into the annual costs of using hydrogen as an e-fuel, compared to using HVO. The investments are made on all three vessels in 2026, and the annual savings are shown hereafter. These annual savings depends on the input price of hydrogen, and if HVO is at a constant price of 2500 EU/mT, hydrogen is only financial more attractive than HVO when the hydrogen prices are below approx. 5000 EU/mT. The cost of the ambition up until 2026 is equal to the additional HVO costs up to 2026, [redacted] The cost of the ambition for 2022-2030 [redacted]. This ambition cost is lower for using hydrogen than for using HVO because the annual expenses of hydrogen decrease compared to HVO, shown in shown in Figure 52.

The fuel switch from HVO into methanol is analysed, and the investment costs for the three vessels are significantly lower than for hydrogen. Figure 53 shows the annual costs of using methanol on board compared to using HVO. Next to the investment costs, the annual fuel cost is significantly lower too. The breakeven point for methanol and HVO is calculated to be below 5700 EU/mT, so from the price for hydrogen below 5700 EU/mT the use of methanol is financially attractive.

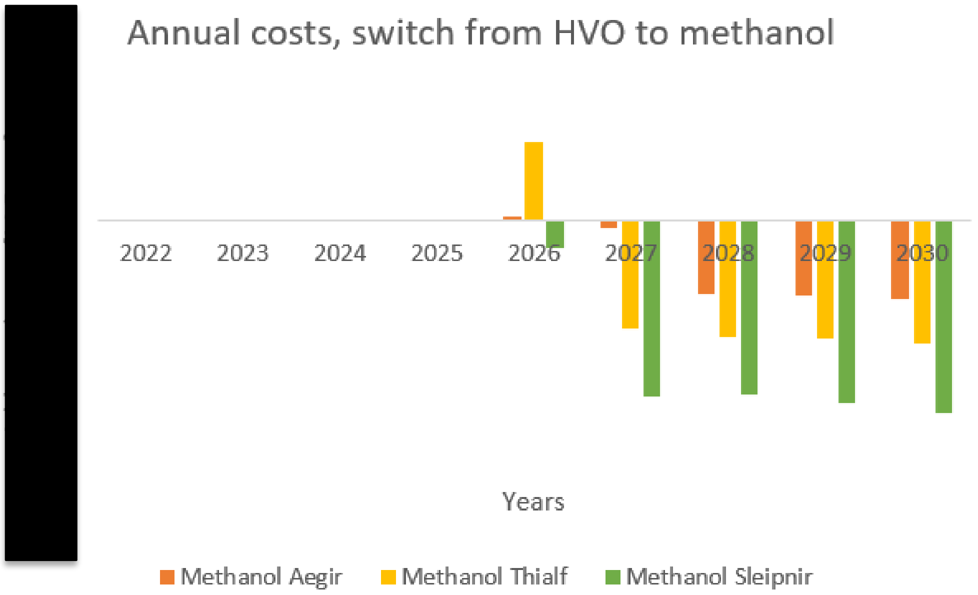

Figure 53 Additional costs for methanol compared to HVO.

The cost of the ambition for the scenario of first using HVO and hereafter using methanol up until 2026 is equal due to the use of HVO. The costs of the ambition up to 2030 are given as output to be -[redacted] and this is because of the large reduction in annual fuel costs.

The fuel switch from HVO into ammonia is analysed, and the investment costs for the three vessels are significantly lower than for hydrogen and comparable to methanol. Figure 54 shows the annual costs of using ammonia on board compared to using HVO. Next to the investment costs, the annual fuel cost is significantly lower too. The breakeven point for methanol and HVO is calculated to be below 6000 EU/mT, so from the price for hydrogen below 6000 EU/mT the ammonia use is financially attractive.

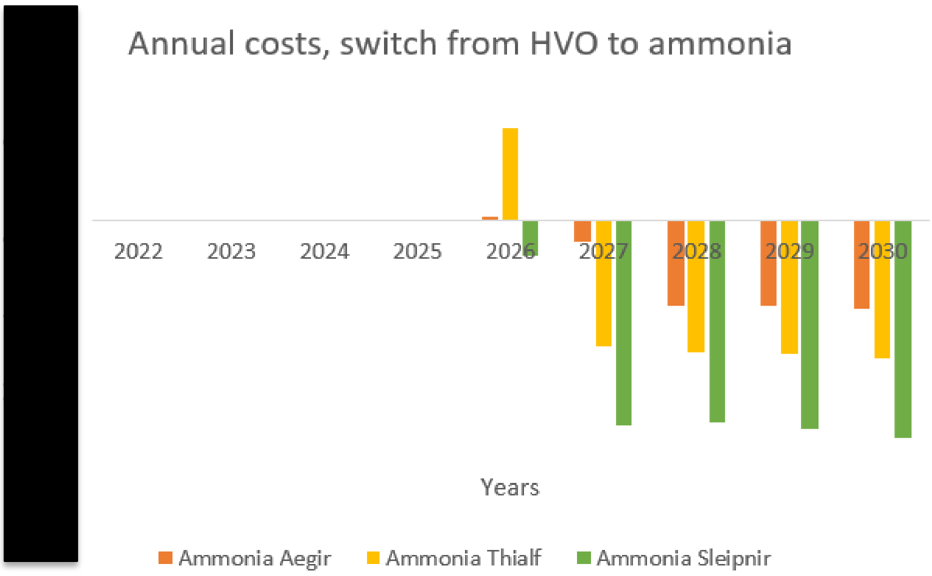

Figure 54 Additional costs for ammonia compared to HVO

The cost of the ambition for the scenario of first using HVO and hereafter using ammonia up until 2026 is equal due to the use of HVO. The costs of the ambition up to 2030 are given as output to be [redacted] and this is because of the significant reduction in annual fuel costs compared to HVO.

Table 33 Summary of the e-fuel scenario ambition costs

HVO			HVO + Hydrogen			HVO + Methanol			HVO + Ammonia		
Aegir	**Thialf**	**Sleipnir**	**Aegir**	**Thialf**	**Sleipnir**	**Aegir**	**Thialf**	**Sleipnir**	**Aegir**	**Thialf**	**Sleipnir**
35.6	54.2	96.6	4.7	14.9	32.2	-1.8	0.1	-11.8	-5.3	-4.1	-21.3

The model's outcomes for each of the above described reduction roadmaps are given above in Table 33.

8.6 Evaluation of decision variables

Within this subchapter the evaluation is done of the analysed decision criteria above together with the availability, it can be concluded that:

- Considering the emission reduction ambition, even with a higher levelized cost of energy, a switch to HVO is required to achieve the ambition. When e-fuels are available, a switch to ammonia is financially the most attractive fuel switch to make.
- Considering the emission intensity, the fuel switch to HVO until e-fuels are available is required. This switch should be done to achieve the sustainability ambition, and a fuel switch to one of the e-fuels should be considered to meet net zero.
- Considering the annual costs of the different sustainability options, the switch to methanol or ammonia is financially more attractive due to the lower capital investments.

Financial feasibility

The model's outcome is analysed based on the decision criteria, the emission abatement ambition will be achieved when first using HVO, and hereafter a switch to one of the e-fuels is required.

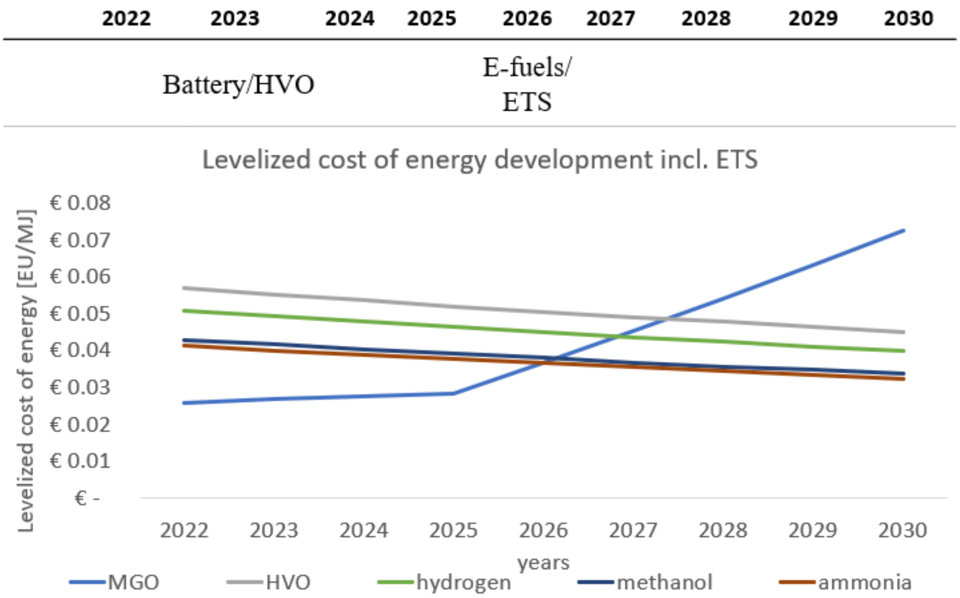

Figure 55 Levelized cost of energy analysis on the e-fuels

Until the ETS penalises the sector, it is cheaper not to change fuels. This analysis is shown in the MGO line above in Figure 48. The difference between the HVO costs and the MGO costs is cost of the ambition. Considering the increase in LCOE, from 2025 onwards, it is not financially attractive to keep using HVO when e-fuels are available.

What can be seen in Figure 48, is that from 2026 e-fuels are available, and from this moment, it will become financially attractive to switch to e-fuels. The lowest annual costs and the lowest LCOE are for ammonia, hereafter methanol and hereafter hydrogen.

Table 34 Financial feasibility summary

	Hydrogen	Methanol	Ammonia
Financial feasibility	(red)	(orange)	(green)

Available storage volume feasibility

Volume available

The volumetric energy density of all e-fuels is lower than that of MGO, making it challenging to fit the amount of energy in the form of e-fuels on board the vessels. When taking the current tank volume from Table 3 into account and comparing the volumes with the minimal required volumes of e-fuels, it can be seen that the available storage volume will be a limiting factor.

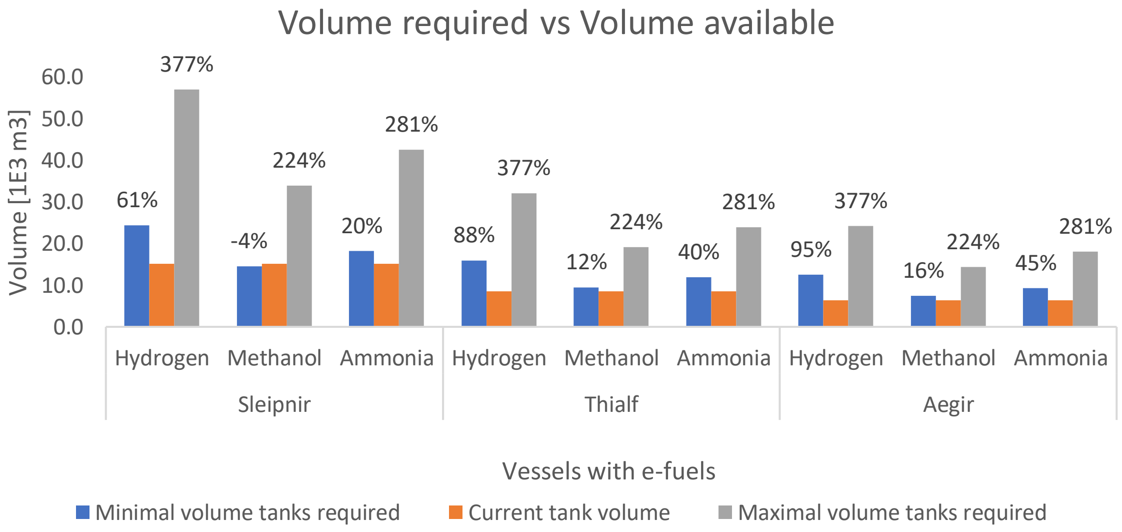

Figure 56 Volume required vs Volume current tanks comparison.

Because as discussed, the volume is the limiting factor on board the vessels. The amount of fuel required in mT converted into m^3 gives insights into the volume required.

For an entire fuel switch to e-fuels, the minimum volume of storage tanks must equal the energy bunkered between two bunkering periods, the minimum required volume shown in Figure 56. The maximal volume required is the total energy content of the tanks when storing MGO when the same amount of energy should be stored in the form of e-fuels.
If the same maximal energy is stored in the tanks, the storage volumes would require 3.8, 2.2, and 2.8 times as large of a volume for hydrogen, methanol and ammonia, respectively, compared to MGO.

Table 35 Summary of technical feasibility of the three e-fuels

	Hydrogen	Methanol	Ammonia
Technical feasibility	(red)	(green)	(orange)

Safety and health feasibility

As described in Chapter 3, next to energy density, health and safety are essential criteria. The safety and health characteristics are summarised below:

- Hydrogen:
  - Stored at -253 degrees Celsius.
  - Non-toxic chemical result in a low health hazard.
  - Very wide flammability range so dangerous when leaked into non-ventilated areas.

- Methanol:
  - Stored at ambient temperatures as a liquid.
  - Toxic chemical results in a high health hazard
    - Storage and logistics is comparable with MGO so the health hazard is thereby minimized.
  - Wide flammability range, while the logistics as a liquid minimizes the risk.

- Ammonia:
  - Stored at -34 degrees Celsius.
  - Very toxic chemical, dangerous for human and can form a danger for the environment when leaked into the oceans.
  - Low flammability, the ignition in the engine should be caused by a mixture of hydrogen.

Hydrogen is the safest of the three chemicals due to its lower toxicity. Ammonia is the most toxic of the three. Methanol storage is the least intrusive and hydrogen the most, with hydrogen having the most comprehensive flammability range. Methanol is analysed to be the safest e-fuel.

Table 36 Summary of the safety and health feasibility

	Hydrogen	**Methanol**	**Ammonia**
Safety and health feasibility			

9 CONCLUSIONS

HMC has a sustainability ambition to make its vessels more sustainable. Within the sustainability department of HMC, a roadmap is designed to reach this sustainability ambition. In this thesis, different sustainability options for the vessels are investigated and compared using a generic model designed based on existing literature. In this chapter, the sub-research questions will be answered, after which the main research question given in Chapter 1 will be answered.

9.1 Answers to the sub-research questions

1. *What are an offshore crane vessel's main operational energy-consuming modes?*

Based on the data from Kongsberg summarised in Chapter 2, six main operational energy-consuming modes cover all offshore crane vessel's different activities. These modes are extracted from the power output data sheets from KIMMS. The power output per operational mode is unique in its range and specific for the different vessels. These operational modes are with the numbers quantified in Table 4 and Table 5:

- Dynamic positioning 2, mild weather
- Dynamic positioning 2, medium weather
- Dynamic positioning 3
- Idle, port or anchorage
- Transit, high speed
- Transit, eco speed

2. *Which fuel switches and blends are technically and financially feasible, and what are the key characteristics of these fuels?*

The different fuels are examined in Chapter 3 in a well-to-wake analysis, including all the energy-requiring production processes. A breakdown has been made between current fuels, drop-in fuels and e-fuels. These e-fuels can be used for blending and are assumed to be used up to fuel blends of 100%. The fuels are selected based on energy density, well-to-wake emission profile, storage, conversion and availability. The energy characteristics of the fuels are given in Chapter 3 and visualised below in Figure 57.

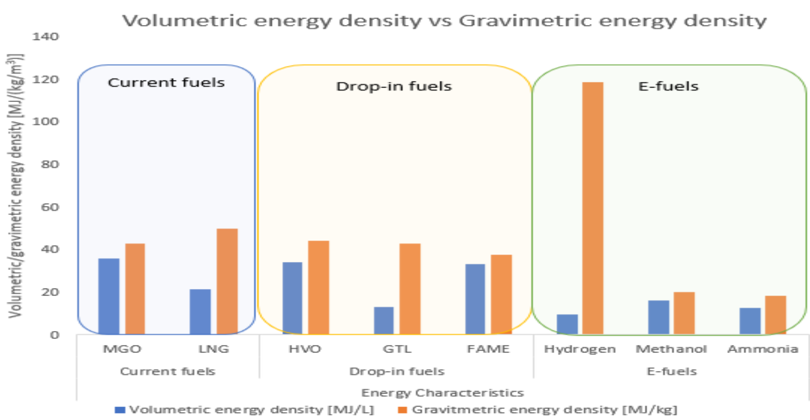

Figure 57 Volumetric vs gravimetric energy density of the fuels

The well-to-wake analysis gives insights into emission abatement of the examined fuels and their costs. The data on the emission profiles gathered and described in Chapter 3 for the fuels are summarized in the figure below.

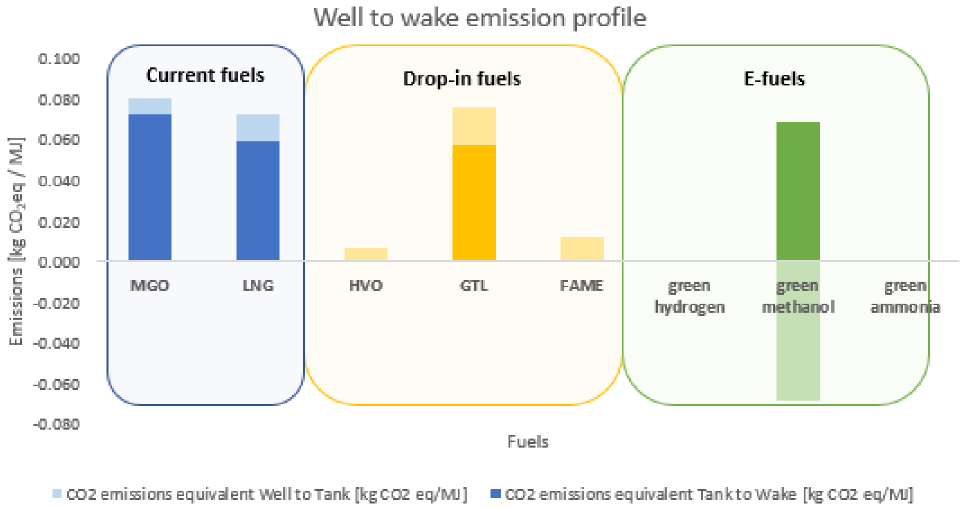

Figure 58 Summary of emission profile for different fuels

Within the scope of this thesis, the availability of all the e-fuels is assumed to be wide from 2026. The availability of the drop in fuels is expected to increase with the CAGR given in Chapter 3 for each fuel.

<u>Fuel switches that are technical and financially feasible for HMC are HVO up to 2026. When the e-fuels are available, the fuel switch to hydrogen, methanol and ammonia is technical and financially feasible.</u>

3. *What are the key characteristics of the ship-based emission-abating technologies like batteries and carbon capture and storage?*

The other emission-abating technologies are implementing a battery and installing a carbon capture and storage system. These technologies are examined on aspects of technical feasibility, logistics and price. Based on the energy density and the technology readiness level, the lithium-ion battery is selected to be implemented on board the vessels. This is done to reduce costs and emissions.

The installation of CCS on board the Sleipnir is examined. CCS is an emission-abating process which requires LNG as operational fuel. Due to the high CAPEX and OPEX and the current high LNG prices, it is not financially feasible to implement the CCS on board the Sleipnir.

<u>For the three vessels, the use of batteries is recommended. For Sleipnir, using CCS is not recommended with the current LNG prices.</u>

4. *What are the current vessel-specific levelized cost of energy (LCOE) and levelized cost of carbon abatement (LCoCA) of the fuel switches and technologies, and how are they expected to develop over time?*

A breakdown is made between the current and drop-in fuels that do not need capital expenditures, such as storage tanks, and the e-fuels that need some additional storage expenditures. These costs are expressed in [€/MJ] storage for hydrogen, methanol and ammonia and added to the levelized cost of energy. Below in Table 19, the investment costs for installing designated e-fuel tanks are shown considering a 100% fuel switch.

Table 19 Investment costs for designated fuel tanks when a blending percentage of 100% is used, given in million euros.

Aegir			Sleipnir			Thialf		
Hydrogen	**Methanol**	**Ammonia**	**Hydrogen**	**Methanol**	**Ammonia**	**Hydrogen**	**Methanol**	**Ammonia**
€27.46	€4.78	€5.97	€53.61	€9.32	€11.65	€ 35.03	€6.09	€7.61

The levelized cost of energy is calculated with and without investment costs. The investment is annualised over the limiting lifetime (the shortest lifetime of the vessel or the lifetime of the technical adjustments). The levelized cost is used to calculate the annual levelized costs of energy throughout the roadmaps.

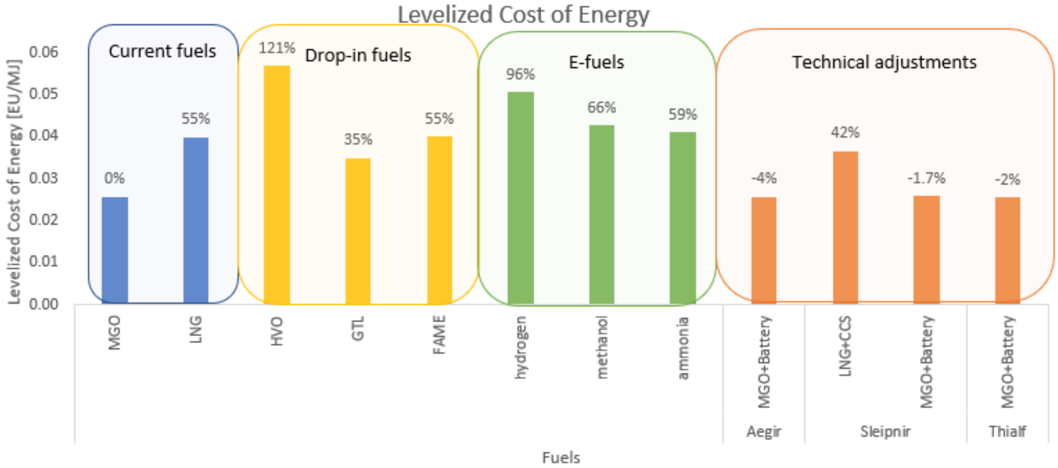

Figure 59 Overview of the levelized cost of energy of the examined fuels

In Figure 59, the levelized costs of energy are shown with an additional cost percentage, using MGO as a baseline. This levelized cost of energy develops over time as the prices of the fuels develop over time, shown in Figure 25. The prices are assumed to increase by 3% for the current fuels, and the prices for drop-in and e-fuels are expected to decrease by 3% annually.

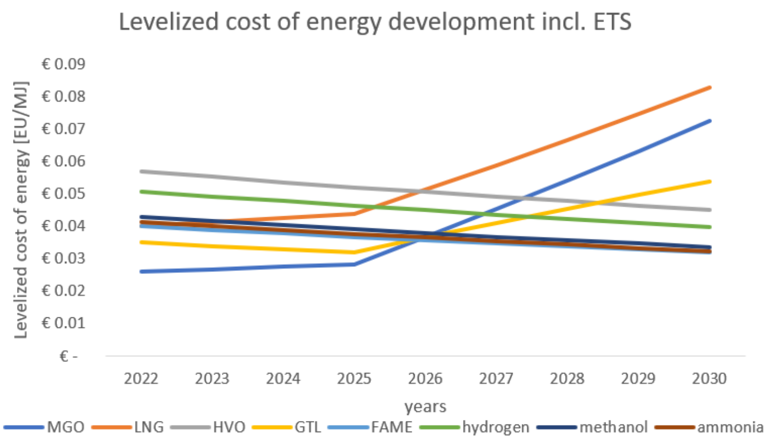

Figure 60 LCOE price development for different fuels including ETS

The levelized costs of energy are used to calculate the levelized costs of carbon abatement for the fuels as well as for the technological adjustments. The LCoCAs for the fuels is not vessel-specific because the LCOE is given in [€/MJ] together with the investment costs.

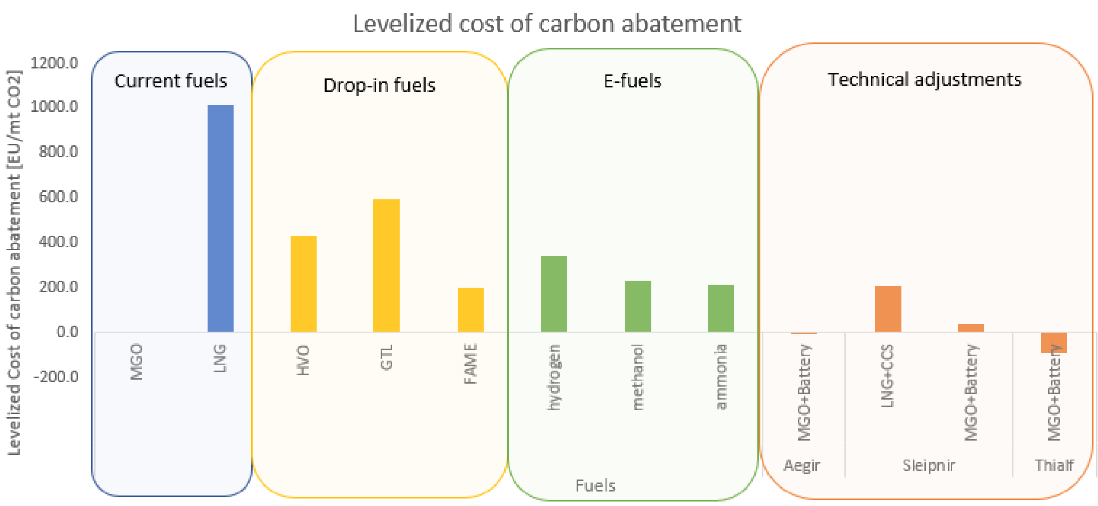

Figure 61 Conclusion on the LCoCA values

In Figure 61, the LCoCA values of the sustainable options are given. The negative values are investments with a payback period less than the lifetime, making the investment into batteries for the Aegir and Thialf profitable. Furthermore, from Figure 61, it can be concluded that a fuel switch to ammonia is the cheapest for the three e-fuels.

<u>In Figure 61 the LCoCA for different fuel switches is shown, based on the LCoCA e-fuels being favourable together with HVO and FAME. Together with the installation of battery systems, FAME is rejected by the durability test and, therefore, not considered for the roadmaps.</u>

5. *Which emission-abating future scenarios are technically and financially feasible, and how will these sustainable roadmaps look?*

Currently, with the ambition to achieve the sustainability goals, the only feasible option is to switch to HVO as a fuel, together with the installation of batteries on the vessels. From 2026, e-fuels are expected to be available as 100% fuel blends and are possible to be implemented. Which e-fuels are best to use is based on the technological feasibility, the LCOE, the LCoCA, the availability and the safety

The financial feasibility is most in favour of the switch to ammonia as an e-fuel. This switch is the most favourable due to the lowest LCOE and low investment costs. All the LCOEs of the different e-fuels are comparable throughout the roadmap. When the ETS is implemented, the option of using MGO and paying the carbon price will be more expensive than the e-fuels.

The technical feasibility is mainly dependent on the storage volume available. Hydrogen storage exceeds the available volume by at least 61%. The vessels should be bunkered more with hydrogen, 1.6 times as much as the current bunkering period. For ammonia, a minimal additional volume is required of 20%, and for methanol with the highest volumetric energy density, only -4% and 16% additional volume is required. This makes methanol the most favourable e-fuel option, considering storage volumes.

- The energy required between two bunkering periods physically **will not fit** in the form of hydrogen.
- The energy required between two bunkering periods physically **will fit** in the form of methanol or ammonia.

The safety of the three e-fuels is examined regarding health hazards (toxicity) and flammability. Ammonia is a chemical that is currently banned from river sailing because of its high toxicity. Methanol and hydrogen are less toxic than ammonia, and hydrogen has the most extensive flammability range, after methanol and ammonia, the smallest. Altogether, methanol seems to have the best safety profile to use as an e-fuel.

The above-described criteria are summarised in the table below for all three e-fuels.

Table 37 Criteria tested for the different e-fuels

Decision criteria	Hydrogen	Methanol	Ammonia
Financial feasibility			
Technical feasibility			
Safety and health feasibility			
Availability			

As shown in this table, methanol has the most favourable characteristics based on the technical, safety, and health criteria as an e-fuel. Ammonia is the cheapest fuel switch, so from a financial point of view, it can be concluded that ammonia is the best feasible solution.

Both e-fuels will fit on board the vessels in the current storage volume because the regulations of the ETS are not clear yet about the tank-to-wake emissions of methanol, whether or not it will be treated as a net-zero fuel. The effect of methanol charged by the ETS is shown in Figure 44.
Considering the assumptions and the input values for the model discussed in this thesis, ammonia is selected as the best match as a fuel for an offshore crane vessel. Accompanied with methanol when its tank-to-wake emissions are not penalised by the ETS.

9.2 Answer to the main research question.

This subchapter describes the conclusions applicable to the vessels of HMC. The three generic outcomes of the model are used to quantify the costs for the three vessels. This answers the **main research question:** *What will be the future energy configuration of the Heerema fleet and the most technical and financial feasible roadmap to meet the sustainability goals look like?*

Emission abatement adjustments with a negative LCoCA are advised to be installed as this is financially more favourable. Installing batteries saves costs and emissions, so installing batteries on the Aegir, Sleipnir and Thialf is recommended. For the Sleipnir and the Thialf, the technology of connecting a battery to different switchboards that are not connected still has to be developed before the installation. It is expected to be ready before 2025 (the year of scheduled implementation). For the Aegir and Thialf, implementing CCS on board is not applicable because these vessels operate on MGO instead of LNG.

HVO is advised during the years that there is no e-fuel available for all the vessels. The e-fuels energy costs are comparable, and the investment costs are the lowest for methanol and ammonia. The current vessels' conversion and storage on board require fewer adjustments for ammonia and methanol than for hydrogen.

The ETS's regulations are unclear regarding the tank-to-wake emissions of green methanol when the ETS penalises tank-to-wake emissions for methanol, its LCOE increases by 16%, shown below in Figure 62.

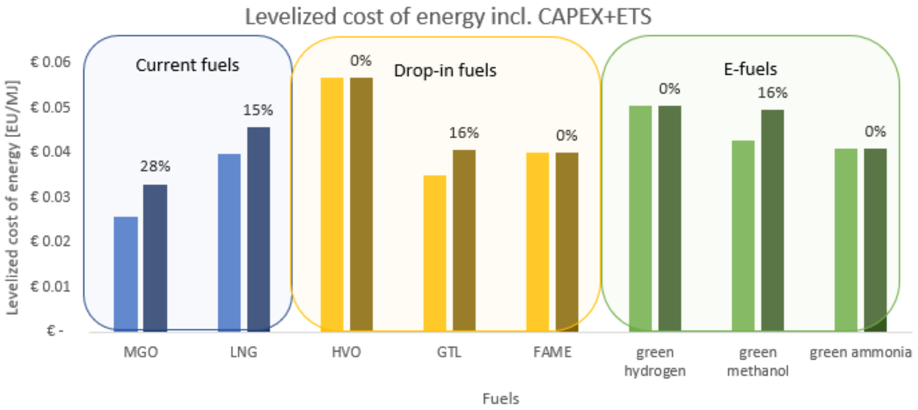

Figure 62 Levelized cost of energy with additional costs for ETS implementation

- Considering the financial evaluation of the decision criteria in Chapter 8.5, the switch to all e-fuels is an attractive switch for the three vessels. This is due to the lower LCOE than for MGO and HVO of the e-fuels and fuels are not charged by the ETS.

- Considering the available storage volume on board the vessels, the implementation of hydrogen is not feasible, whereas, for ammonia and methanol, this is feasible.

- Taking the safety and health hazards into consideration, ammonia is assumed to be the most toxic. While on offshore crane vessels, this risk is minimised because handling toxic chemicals is already done on board.

With this extensive analysis on the e-fuels, hydrogen, methanol and ammonia. The best e-fuel for offshore crane vessels is difficult to select due to the lack of information about the regulations from the ETS and the availability. Therefore, based on the assumption and predictions in this thesis the use of ammonia and methanol as e-fuels on board of the three vessels is recommended.

10 DISCUSSIONS

This thesis examines the different sustainable options for the emission-abating ambition of HMC. This chapter will present a discussion on the content of this thesis, and the different assumptions for the scope of this thesis will be discussed to find recommendations for further research.

10.1 Fuel conversion

- Within this thesis, the specific fuel use per engine efficiency is calculated and assumed to be the same when switching fuels. However, the specific fuel consumption of an engine changes for every efficiency, and this fuel consumption per engine efficiency also depends on different fuels. This change in efficiency means that for different fuels in an internal combustion engine, a difference in required fuel volume is required.

- The use of e-fuels in an internal combustion engine blended with MGO is researched. From the literature, low percentages of volumetric fuel blends are mostly found. However, higher volumetric percentage blends are currently being researched. These percentages are of high potential because the model gives the output that the switch to e-fuels is the most favourable financially. The percentage of a blend is used as input for the model. If future research finds a higher volumetric percentage fuel blend, these can be added to the current model.

- E-fuels can be converted into electricity in multiple ways, for example, using proton-exchange-membrane fuel cells or solid oxide fuel cells, which give higher efficiencies. These possibilities are out of the scope of this research, but when switching drive trains is included, this may be an exciting direction for future research. This is because the higher efficiencies result in a lower required volume of e-fuels.

10.2 Technology readiness level

- The installation of a battery system on board the Sleipnir and Thialf needs to be connected, so there is no way a single point of failure between the switchboards occurs. This adjustment is required for redundancy measures. This technical challenge can be solved by installing an internal switch within the battery to connect to the switchboards. It is assumed that this technical challenge will be solved within the roadmaps, and the batteries can be implemented by 2025. However, batteries will not be implemented on the Thialf and Sleipnir when this technical challenge is not solved.

- Ship-based carbon capture and storage is a technology still in development. With the current expectations, the technology will be ready in 2026, after which it will be applied to the Sleipnir in 2028. There is a possibility that the technology will not become competitive because of the lack of logistics, including transport away from the vessels. A low technology readiness level could be a point of failure for implementing ship-based CCS.

10.3 Company emission reduction ambition

- The emission reduction ambition of HMC is not in line with the objectives of IMO or the EU. HMC strives to abate 50% of its emissions by 2025, while the EU and IMO only obligate an emission reduction of 50% in 2050 for the entire sector. The ambition of HMC is a challenge and is mainly driven by the implementation of HMC into the ETS in 2026, which gives financial incentives to become more sustainable by 2025. When the offshore work vessels are not implemented into the ETS, the financial incentive reduces.

10.4 The model with decision criteria

- The model has a couple of limitations. Firstly, the fuel use prediction is based on a not updated scheduled work portfolio, but ideally should be based on the weekly updated work portfolio. When connected, it will automatically update the total emissions amount and make the emission prediction more precise. Secondly, in the model, the emission reduction ambition of HMC is followed. Different ambitions can be used as inputs for comparison. The model can be expanded by calculating the most efficient cost and technologically effective emission reduction instead of following the ambition of HMC.

- The levelized cost of energy is based on the fluctuating fuel prices, together with the constant energy density. This fluctuation gives uncertainty to the model's outcome, which is examined during the sensitivity analysis. In the model, the calculations of the future fuel prices can be adjusted based on future changes.

- For the levelized cost of energy, the CAPEX and OPEX on designated fuel tanks for the e-fuels are determined from the literature in €/MJ. This value is a rough estimation and could be determined more precisely if a sub-contractor was asked for a quotation for each vessel. When this is done, the new values can be added to the model to make the LCOE estimation more precise. These values are set to be constant over the years, while the price is expected to decrease with time. Therefore the model should be updated when more exact price information is available.

- The emission intensity of the fuels is based on numbers from literature, and the values are given in [kg CO_2 / MJ]. For methanol, the emission intensity is set to be net-zero because the CO_2 captured during production is emitted at the conversion to electricity. When this CO_2 is not captured on board the vessel and penalized by the ETS, the LCOE of methanol will increase shown in Figure 62, which should be considered when this thesis's outcome is interpreted.

- The availability of fuels is based on the compound annual growth rate, which predicts how a fuel market will develop over ten years and brings a particular uncertainty. Because the availability is calculated with the fuel prices, which are again uncertain, the availability is uncertain to these two parameters, which gives strength to the developed model. The model is dynamic and can be changed for future changes.

- The carbon tax and implementation of the maritime and offshore industry into the ETS is an expectations. When this implementation is postponed or rejected, the financial incentive for the company vanishes. Hopefully, the pioneering incentive of

HMC will be large enough to be willing to go forward with the sustainability goal. The price prediction for carbon certificates is estimated using two scenarios: in scenario one, prices stay the same, and in scenario two, prices increase with the same trend as the last five years. Scenario two is considered the most feasible, but it should be noted that other scenarios are also possible, like the implementation of free allowances. Therefore results could be different, which will influence the financial incentive.

10.5 Financial/technical evaluation

- More extensive price development for different fuels can be researched. This thesis makes a couple of assumptions to set fuel price development at a constant annual rate. A more extensive historical data set of fuel prices can predict future prices more precisely.

- HVO is assumed to be more expensive than hydrogen in [$\frac{€}{MJ}$based on the input prices of hydrogen and HVO. The HVO costs are assumed to be constant when the hydrogen prices do not become less than approx. 6000 EU/mT, the fuel switch from HVO to one of the e-fuels will not be financially attractive.

- During the technical evaluation, the most significant focus was on the available volume on board the vessels concerning the required storage volume of the e-fuels. With adjustments on the vessels, more storage space could be available, for example, by using additional containerized fuel storage tanks. Thus, the options now considered not feasible within this thesis could be considered after research into additional storage options.

10.6 Further research

Based on the points discussed above, this section will discuss some essential recommendations and directions for future research. These recommendations are mainly based on expanding the scope of the research.

1. Including the possibility of drive train changes in future research is recommended. This addition will give a complete view of the emission-abating technologies and options. Other promising options that could be considered are the implementation of fuel cells or other new engines, such as dual-fuel engines.

2. More types of batteries should be examined in future research, and the potential of renting batteries. These options can also be implemented in the developed model, giving the advantage of switching to cheaper and better batteries when these become available

3. Further research is advised into hydrogen carriers as this e-fuel is promising because of its low costs. However, due to hydrogen's low volumetric energy density, storing this e-fuel is challenging. Liquid organic hydrogen carriers and borohydrides are promising and should be added to the model when feasible. The fuel characteristics are required as described in this thesis, and the other hydrogen carriers can be implemented into the model.

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12 APPENDIX

12.1 KIMMS data

Time Local	POWER CONSUMPTION (MINUS REVERSE POWER)	HOISTING (MAIN) SPEED	Total Thruster Power	DG1 ACTIVE POWER	DG2 ACTIVE POWER	DG3 ACTIVE POWER	DG4 ACTIVE POWER	DG5 ACTIVE POWER	DG6 ACTIVE POWER	Sum Produced Power
53:36.1	599	0	0	-2.07705	-4.44592	-4.3985	2749.01	4.517222	-4.75343	2731.082
54:36.1	599	0	0	-2.10194	-2.42231	-6.77742	2846.744	3.240318	-5.98399	2809.186
55:36.1	599	0	0	-2.10194	-5.03198	-5.59845	2813.527	2.793168	-3.86632	2814.094
56:36.1	599	0	0	-2.48985	-7.07935	-4.28976	2942.345	2.398482	-0.53763	2863.199
57:36.1	599	0	0.284946	-2.92662	-5.68364	-5.38182	3007.65	3.198513	-4.23328	2953.697
58:36.1	599	0	0.188194	-3.50055	-4.79588	-4.0822	2722.723	3.653989	-4.07293	2827.943
59:36.1	599	0	0	-3.23463	-6.29775	-4.76745	2699.621	4.47358	-2.91501	2754.627
00:36.1	599	0	0	-2.00506	-5.82672	-5.34008	2750.39	2.517912	-5.16668	2709.955
01:36.1	599	0	0	-1.18119	-4.49968	-3.40495	2745.927	5.06324	-3.73064	2693.78
02:36.1	599	0	0	-1.05636	-5.65867	-4.89915	2799.842	1.911139	-3.22401	2780.38

Table 38 Short overview of data from KIMMS a moment from the Aegir showing only one generator is active, so the vessel is in idle, port, or anchorage mode.

12.2 Engine room configurations

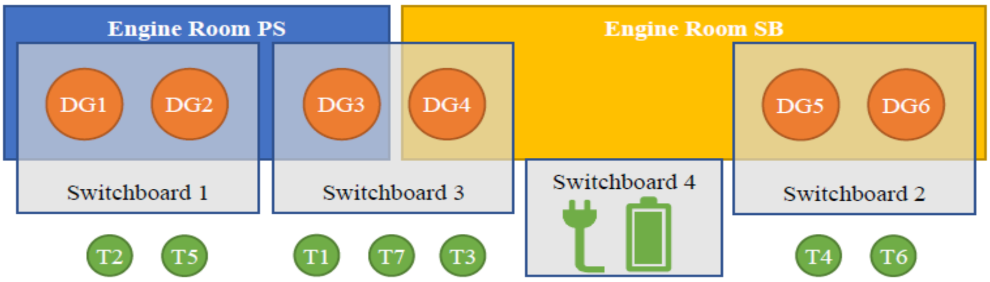


Figure 63 Aegir with battery system connected

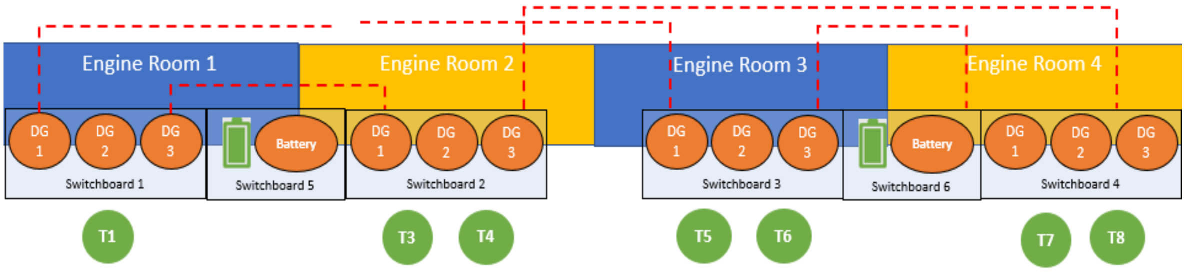


Figure 64 Sleipnir with battery system connected

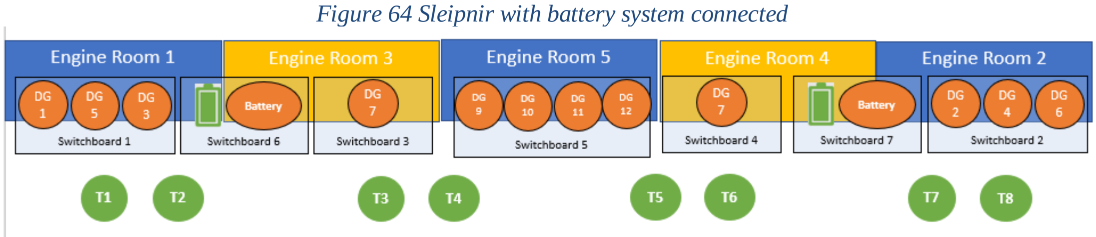


Figure 65 Thialf with battery system connected

12.3 Fuel production processes.

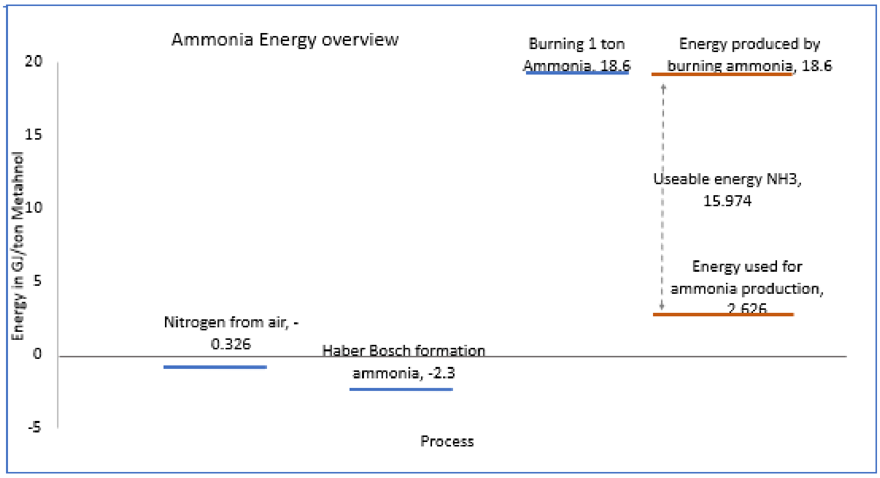


Figure 66 Energy evaluation of ammonia production

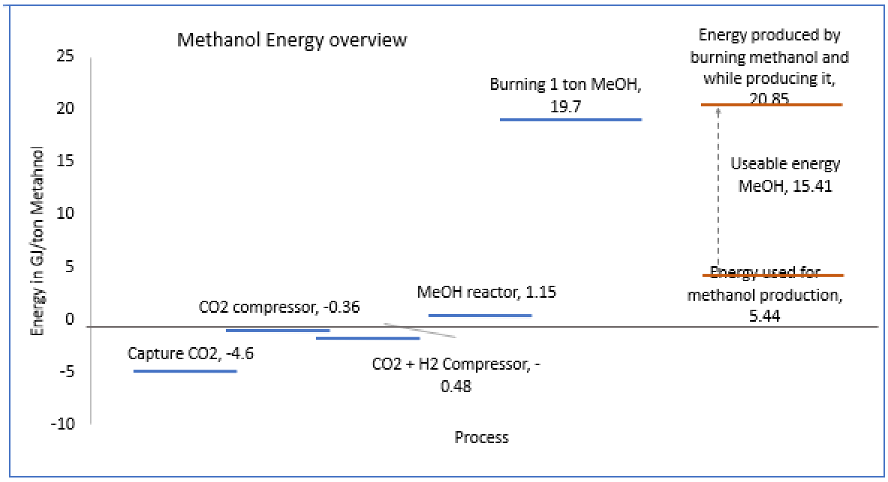


Figure 67 Energy evaluation of methanol production

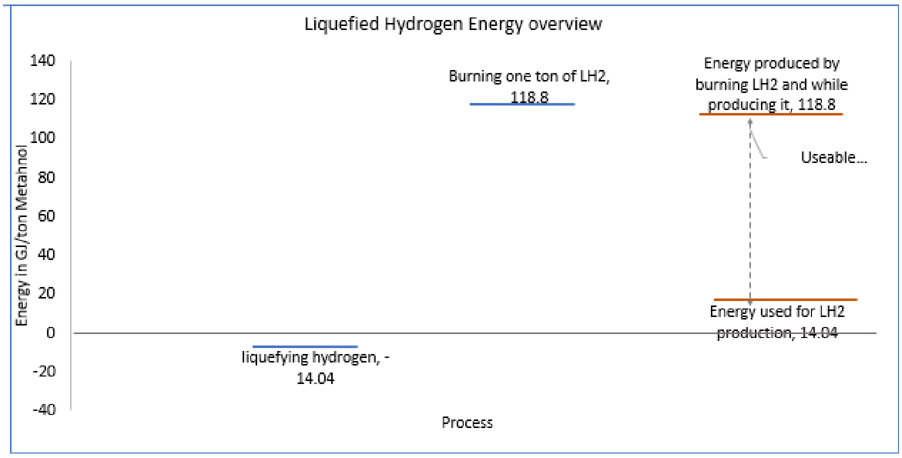


Figure 68 Energy evaluation of liquid hydrogen production

12.4 The model

Input:

Operational profiles

Operational profiles

Frequency slider

Aegir	Frequency [%]	Avg. power consumption [kW]
DP2, mild weather	30%	5500.00
DP2, medium weather	5%	8000.00
DP3	5%	8000.00
Idle, port or anchorage	40%	4000.00
Transit, high speed	15%	18000.00
Transit, eco speed	5%	15000.00
Check 100%	100%	

Thialf	Frequency [%]	Avg. power consumption [kW]
DP2, mild weather	38%	5476kW
DP2, medium weather	8%	8518kW
DP3	2%	8518kW
Idle, port or anchorage	21%	3772kW
Transit, high speed	24%	34600kW
Transit, eco speed	8%	13800kW

Sleipnir	Frequency [%]	Avg. power consumption [kW]
DP2, mild weather	0%	10272kW
DP2, medium weather	0%	15979kW
DP3	39%	15979kW
Idle, port or anchorage	40%	7076kW
Transit, high speed	15%	36066kW
Transit, eco speed	6%	27392kW

	Blending%
Hydrogen	100%
Methanol	100%
Ammonia	100%

Prices

	unit	Costs CAPEX (storage)	OPEX	Price reduction
Hydrogen	[EU/MJ]	€ 0.23	€ -	
Methanol	[EU/MJ]	€ 0.04	€ -	
Ammonia	[EU/MJ]	€ 0.04	€ -	
Batteries	[EU]	€ 7,000,000.00	€ -	10%
CCS	[EU]	€ 50,000,000.00	€ 1,800,000.00	10%
Interest rate	[%]	4%		

Fuel use scheduled.

Fuel use scheduled MGO [mT]

	Unit	2022	2023	2024	2025	2026	2027	2028	2029	2030	
Aegir	[mT]	10345	12687	11033	10664	10664	10664	10664	10664	10664	
Thialf	[mT]	16694	14639	15902	16711	16711	16711	16711	16711	16711	
Sleipnir	[mT]	23893	33268	30619	27360	27360	27360	27360	27360	27360	
Abatement ambition	[%]	95%	85%	75%	70%	65%	60%	55%	50%	45%	ref portfolio Arjan

MARINE CONTRACTORS

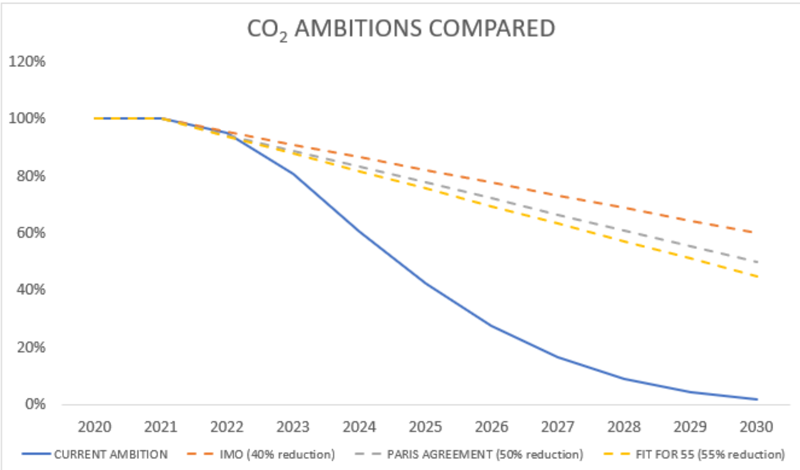
TU Delft Delft University of Technology

Fuel characteristics

Fuel characteristics	Unit	CURRENT		DROP-IN			FUTURE H2 based solutions		
		MGO	LNG	HVO	GTL	FAME	Liquefied green Hydrogen	Methanol	Ammonia
Energy Characteristics									
Energy density	[MJ/kg]	42.7	50.06	44	43	37.5	118.8	19.9	18.2
Volumetric Energy Density	[kWh/L]	10	5.95	9.5	3.595	9.2	2.653	4.46	3.56
Density	[kg/L]	0.8	0.45	0.78	0.778	0.86	0.01	0.792	0.0156
Emission Characteristics									
CO2 emissions Well to Wake	[kg/kgFuel]	3.2499	3.651	0.314	3.274	0.449	0	0	0
CO2 emission Tank to Wake	[kg/kgFuel]	3.206	2.75	0.276	2.471	0.035	0	1.37	0
NOx emission Tank to Wake	[kg/kgFuel]	0.055	0.008	0.008	0.055	0.077	0.000	0.000	0.000
SOx emission Tank to Wake	[kg/kgFuel]	0.0022	0.0000	0.0000	0.0022	0.0477	0.0000	0.0000	0.0000
PM emission Tank to Wake	[kg/kgFuel]	0.0010	0.0001	0.0001	0.0010	0.0073	0.0000	0.0000	0.0000
CH4 emission Tank to Wake	[kg/kgFuel]	0.0001	0.0083	0.0083	0.0001	0.0001	0.0000	0.0000	0.0000
CO2 emissions equivalent Well to Wake	[kg/kgFuel]	3.436	3.641	0.314	3.274	0.449	0	0	0
CO2 emissions equivalent Tank to Wake	[kg/kgFuel]	3.11	2.945	0.038	2.471	0.035	0	1.37	0
Carbon content TtW	[kg CO2 eq / MJ]	0.073	0.059	0.00086	0.057	0.001	0.000	0.069	0.000
Carbon content WtW	[kg CO2 eq / MJ]	0.080	0.073	0.007	0.076	0.012	0.000	0.000	0.000
Production emissions	[kg CO2 eq/kgFuel]	0.326	0.696	0.276	0.803	0.414	0.000	-1.370	0.000
Storage									
Pressure	[atm]	1	3	1	1	1	700 X		1
Temperature	[Celsius]	18	-164	18	18	18	-270 X		-30
Cost Characteristics									
Price	Eu/mT	1100	1872	2000	1161	1510	4000	4720	4440.0
COE	Eu/MJ	0.026	0.037	0.045	0.027	0.040	0.034	0.040	0.037
Change in cost	Eu/MJ	0.000	-0.012	-0.020	-0.001	-0.015	-0.008	-0.014	-0.012
Change in emissions	[kgCO2/MJ]	0.000	0.008	0.073	0.004	0.068	0.080	0.080	0.080
LCOCA	Eu/mT	#DIV/0!	1.50	0.27	0.29	0.21	0.10	0.17	0.14

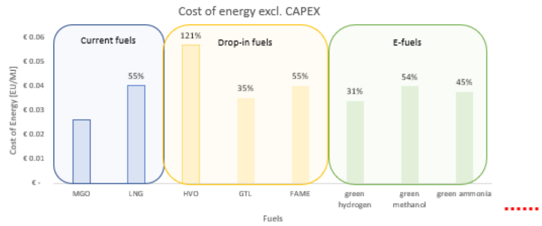
Ambition

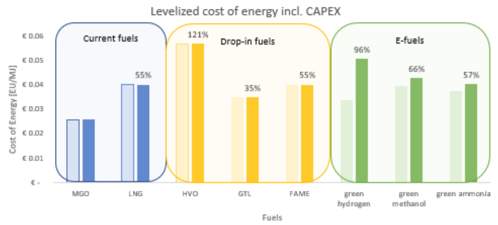
[illegible]	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	
revent								0%	0%	5%	5%	12.5%	25%	25%	25%	25%	25%	25%	
educe								0%	0%	0%	5%	12.5%	25%	55%	55%	55%	55%	55%	
								100%	**100%**	**95%**	**81%**	**61%**	**42%**	**28%**	**17%**	**9%**	**5%**	**2%**	
										0.95	0.85	0.75	0.7	0.65	0.6	0.55	0.5	0.45	
PDATED AMBITION								0%	0%	4%	9%	13%	18%	22%	27%	31%	36%	40%	REDUCTION
								100%	**100%**	**96%**	**91%**	**87%**	**82%**	**78%**	**73%**	**69%**	**64%**	**60%**	NET RESULT
IO (40% reduction)								0%	0%	4%	9%	13%	18%	22%	27%	31%	36%	40%	REDUCTION
								100%	**100%**	**96%**	**91%**	**87%**	**82%**	**78%**	**73%**	**69%**	**64%**	**60%**	NET RESULT
ARIS AGREEMENT (50% reduction)								0%	0%	6%	11%	17%	22%	28%	33%	39%	44%	50%	REDUCTION
								100%	**100%**	**94%**	**89%**	**83%**	**78%**	**72%**	**67%**	**61%**	**56%**	**50%**	NET RESULT
IT FOR 55 (55% reduction)								0%	0%	6%	12%	18%	24%	31%	37%	43%	49%	55%	REDUCTION
								100%	**100%**	**94%**	**88%**	**82%**	**76%**	**69%**	**63%**	**57%**	**51%**	**45%**	NET RESULT

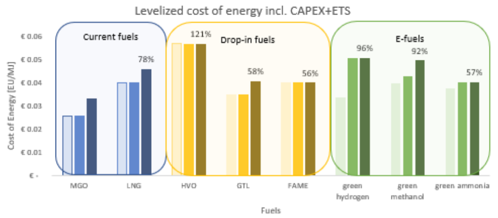


Decision criteria

A	B	C	D	E	F	G
LCOE / LCoCA						
CAPEX fuel switch	CAPEX	unit	[% more MJ required for production]	unit	CRF [years]	4%
hydrogen	I 0.23	EU/MJ	100%	[%]	10	0.123
methanol	I 0.04	EU/MJ	118%	[%]	20	0.074
ammonia	I 0.04	EU/MJ	111%	[%]	30	0.058
		Industrial marge	100%			
	OPEX Fuel	ETS PRICE	0.1		0.1 EU/kg CO2	
MGO	1100	[EU/mT]				
LNG	2000	[EU/mT]				
HVO	2500	[EU/mT]				
GTL	1500	[EU/mT]				
FAME	1500	[EU/mT]				
green hydrogen	4000	[EU/mT]	Range 2.5-6 EU/kg			
green methanol	4720	[EU/mT]				
green ammonia	4440	[EU/mT]				
	OPEX Fuel					
MGO	0.0258	[EU/MJ]	0.093			
LNG	0.0400	[EU/MJ]	0.144			
HVO	0.0568	[EU/MJ]	0.205			
GTL	0.0349	[EU/MJ]	0.126			
FAME	0.0400	[EU/MJ]	0.144			
green hydrogen	0.0337	[EU/MJ]	0.121			
green methanol	0.0397	[EU/MJ]	0.143			
green ammonia	0.0374	[EU/MJ]	0.135			
		additional energy needed 18%				
LCOE excluding CAPEX for e-fuels [EU/MJ]		2022				
	MGO	I 0.026				
	LNG	I 0.040	55%			
	HVO	I 0.057	121%			
	GTL	I 0.035	35%			
	FAME	I 0.040	55%			
	green hydrogen	I 0.034	31%			
	green methanol	I 0.040	54%			
	green ammonia	I 0.037	45%			
LCOE including CAPEX for e-fuels [EU/MJ]		2022				
	MGO	I 0.026				
	LNG	I 0.040	55%			
	HVO	I 0.057	121%			
	GTL	I 0.035	35%			
	FAME	I 0.040	55%			
	green hydrogen	I 0.051	96%			
	green methanol	I 0.043	66%			
	green ammonia	I 0.040	57%			
LCOE including CAPEX for e-fuels + ETS [EU/MJ]		2022				
0.073	MGO	I 0.033				
0.059	LNG	I 0.046	78%			
0.001	HVO	I 0.057	121%			
0.057	GTL	I 0.041	58%			
0.001	FAME	I 0.040	56%			
0.000	green hydrogen	I 0.051	96%			
0.069	green methanol	I 0.050	92%			
0.000	green ammonia	I 0.040	57%			
Delta emission intensity [kg CO2 / MJ]		2022				
0.073	MGO	0.0000	0%			
0.059	LNG	0.0140	-19%			







Calculation sheets same for each vessel

Availability/TRL of scenarios.

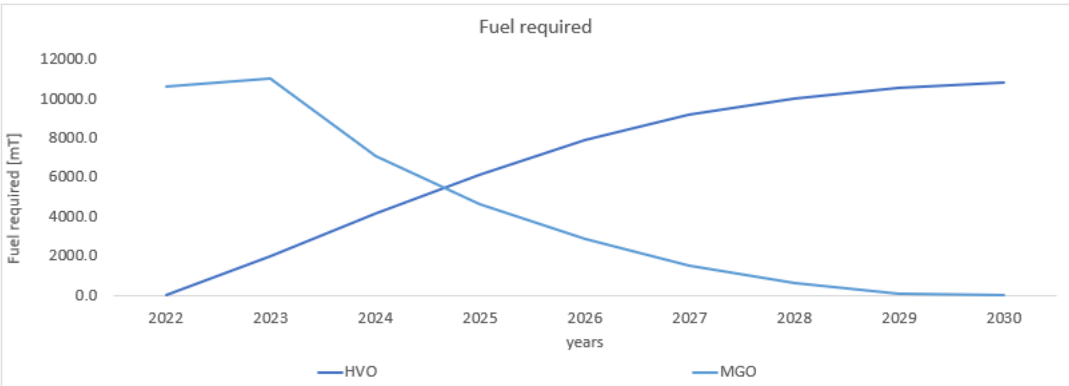
Percentage Available/TRL									
Scenarios Aegir									
TRL/availability S1	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Thialf	0%	100%	100%	100%	100%	100%	100%	100%	100%
HVO	100%	100%	100%	100%	100%	100%	100%	100%	100%
Green hydrogen	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green methanol	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green ammonia	0%	0%	0%	0%	0%	0%	0%	0%	0%
CCS Sleipnir	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRL/availability S2	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0%	100%	100%	100%	100%	100%	100%	100%	100%
HVO	100%	100%	100%	100%	100%	100%	0%	0%	0%
Green hydrogen	100%	100%	100%	100%	100%	100%	100%	100%	100%
Green methanol	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green ammonia	0%	0%	0%	0%	0%	0%	0%	0%	0%
CCS Sleipnir	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRL/availability S3	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0%	100%	100%	100%	100%	100%	100%	100%	100%
HVO	0%	100%	100%	100%	100%	100%	0%	0%	0%
Green hydrogen	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green methanol	100%	100%	100%	100%	100%	100%	100%	100%	100%
Green ammonia	0%	0%	0%	0%	0%	0%	0%	0%	0%
CCS Sleipnir	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRL/availability S4	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0%	100%	100%	100%	100%	100%	100%	100%	100%
HVO	0%	100%	100%	100%	100%	100%	0%	0%	0%
Green hydrogen	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green methanol	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green ammonia	100%	100%	100%	100%	100%	100%	100%	100%	100%
CCS Sleipnir	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRL/availability S5	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0%	100%	100%	100%	100%	100%	100%	100%	100%
HVO	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green hydrogen	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green methanol	0%	0%	0%	0%	0%	0%	0%	0%	0%
Green ammonia	0%	0%	0%	0%	0%	0%	0%	0%	0%
CCS Sleipnir	0%	0%	0%	0%	0%	0%	0%	0%	0%

Emission intensity

Emission intensity									
Scenarios Aegir									
Sleipnir Scenario 1	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
HVO	0.07	0.06	0.05	0.03	0.02	0.01	0.01	0.01	0.01
Green hydrogen	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Green methanol	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Green ammonia	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
CCS Sleipnir	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Sleipnir Scenario 2	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0.0739	0.0709	0.0709	0.0709	0.0709	0.0709	0.0709	0.0709	0.0709
HVO	0.0739	0.0628	0.0471	0.0330	0.0214	0.0709	0.0709	0.0709	0.0709
Green hydrogen	0.0739	0.0628	0.0471	0.0330	0.0214	0.0129	0.0071	0.0035	0.0016
Green methanol	0.0739	0.0628	0.0471	0.0330	0.0214	0.0129	0.0071	0.0035	0.0016
Green ammonia	0.0739	0.0628	0.0471	0.0330	0.0214	0.0129	0.0071	0.0035	0.0016
CCS Sleipnir	0.0739	0.0628	0.0471	0.0330	0.0214	0.0129	0.0071	0.0035	0.0016
	0.07	0.07	0.07	0.03	0.02	0.07	0.07	0.07	0.07
Sleipnir Scenario 3	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0.07386	0.07088	0.07088	0.07088	0.07088	0.07088	0.07088	0.07088	0.07088
HVO	0.07386	0.07088	0.07088	0.03296	0.02142	0.07088	0.07088	0.07088	0.07088
Green hydrogen	0.07386	0.07088	0.07088	0.07088	0.07088	0.07088	0.07088	0.07088	0.07088
Green methanol	0.07386	0.06278	0.04709	0.03296	0.02142	0.01285	0.00707	0.00354	0.00159
Green ammonia	0.07386	0.06278	0.04709	0.03296	0.02142	0.01285	0.00707	0.00354	0.00159
CCS Sleipnir	0.07386	0.06278	0.04709	0.03296	0.02142	0.01285	0.00707	0.00354	0.00159
Sleipnir Scenario 4	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0.0739	0.0709	0.0709	0.0709	0.0709	0.0709	0.0709	0.0709	0.0709
HVO	0.0739	0.0628	0.0471	0.0330	0.0214	0.0129	0.0071	0.0035	0.0016
Green hydrogen	0.0739	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730
Green methanol	0.0739	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730
Green ammonia	0.0739	0.0730	0.0730	0.0730	0.0730	0.0129	0.0071	0.0035	0.0016
CCS Sleipnir	0.0739	0.0730	0.0730	0.0730	0.0730	0.0129	0.0071	0.0035	0.0016
Sleipnir Scenario 5	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HVO	0.07	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386
Green hydrogen	0.07	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386
Green methanol	0.07	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386
Green ammonia	0.07	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386
CCS Sleipnir	0.07	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386	0.07386

Fuel requirement

Fuel requirement										
Scenarios Aegir										
Sleipnir Scenario 1	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
Batteries Thialf										
HVO	0.0	1981.0	4163.3	6147.1	7880.9	9168.9	10038.3	10569.6	10861.8	6
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
MGO	10660.0	11031.9	7078.8	4654.4	2867.8	1540.6	644.8	97.3	0.0	3
	455180000.0	558228000.0	485452000.0	469216000.0	469216000.0	469216000.0	469216000.0	469216000.0	477918956.9	
Sleipnir Scenario 2	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
Batteries Thialf										
HVO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green hydrogen	3857.5	4730.7	4114.0	3976.4	3976.4	3976.4	3976.4	3976.4	3976.4	3
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
MGO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	455180000.0	558228000.0	485452000.0	469216000.0	469216000.0	469216000.0	469216000.0	469216000.0	469216000.0	
Sleipnir Scenario 3	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
Batteries Thialf										
HVO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green methanol	22873.4	28051.7	24394.6	23578.7	23578.7	23578.7	23578.7	23578.7	23578.7	2
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
MGO	0.0	0.0	0.0	0.0	0.0	0.0	[illegible]	[illegible]	0.0	
	455180000.0	558228000.0	485452000.0	469216000.0	469216000.0	469216000.0	4692[illegible] Chart Area	e) Axis [illegible]	469216000.0	
Sleipnir Scenario 4	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
Batteries Thialf										
HVO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green ammonia	25009.9	30671.9	26673.2	25781.1	25781.1	25781.1	25781.1	25781.1	25781.1	23
MGO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	455180000	558228000	485452000	469216000	469216000	469216000	469216000	469216000		
Sleipnir Scenario 5	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
Batteries Thialf										
HVO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
MGO	10660.0	13073.3	11368.9	10988.7	10988.7	10988.7	10988.7	10988.7	10988.7	1
	455180000	558228000	485452000	469216000	469216000	469216000	469216000	469216000		



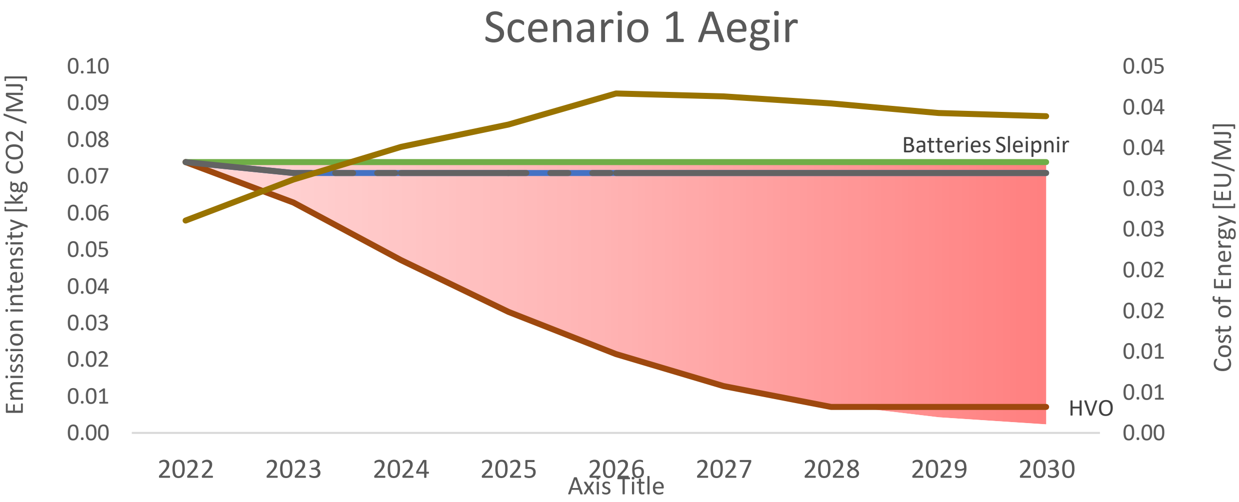
Emissions

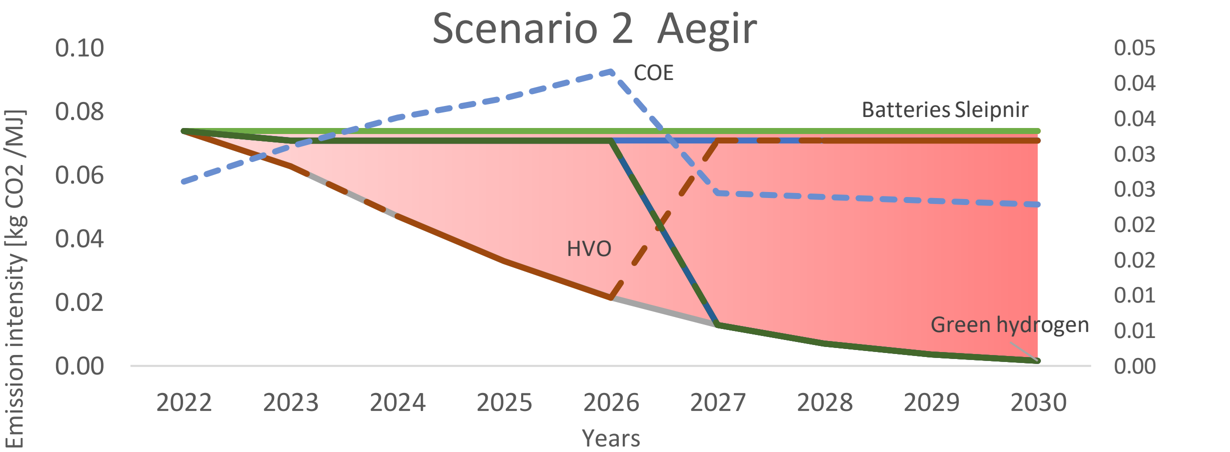
Emissions									
Scenarios Thialf									
Sleipnir Scenario 1	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir									
HVO	0.0	717.7	1884.2	3024.7	3877.8	4511.6	4939.4	5200.8	5344.6
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MGO	55905.6	41368.9	33158.1	23703.7	14605.0	7845.9	3283.6	495.5	0.0
	55905.6	42086.6	35042.3	26728.4	18482.8	12357.5	8223.0	5696.3	5344.6
Sleipnir Scenario 2	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir									
HVO	0.0	717.7	1884.2	3024.7	3877.8	0.0	0.0	0.0	0.0
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MGO	55905.6	41368.9	33158.1	23703.7	14605.0	0.0	0.0	0.0	0.0
	55905.6	42086.6	35042.3	26728.4	18482.8	0.0	0.0	0.0	0.0
Sleipnir Scenario 3	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir									
HVO	0.0	717.7	1884.2	3024.7	3877.8	0.0	0.0	0.0	0.0
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MGO	55905.6	41368.9	33158.1	23703.7	14605.0	0.0	0.0	0.0	0.0
	55905.6	42086.6	35042.3	26728.4	18482.8	0.0000000000000	0.0	0.0	0.0
Sleipnir Scenario 4	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir									
HVO	0.0	717.7	1884.2	3024.7	3877.8	0.0	0.0	0.0	0.0
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MGO	55905.6	41368.9	33158.1	23703.7	14605.0	0.0	0.0	0.0	0.0
	55905.6	42086.6	35042.3	26728.4	18482.8	0.0	0.0	0.0	0.0
Sleipnir Scenario 4	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Batteries Sleipnir									
HVO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MGO	55905.6	49023.7	53253.3	55962.5	55962.5	55962.5	55962.5	55962.5	55962.5
	55905.6	49023.7	53253.3	55962.5	55962.5	55962.5	55962.5	55962.5	55962.5

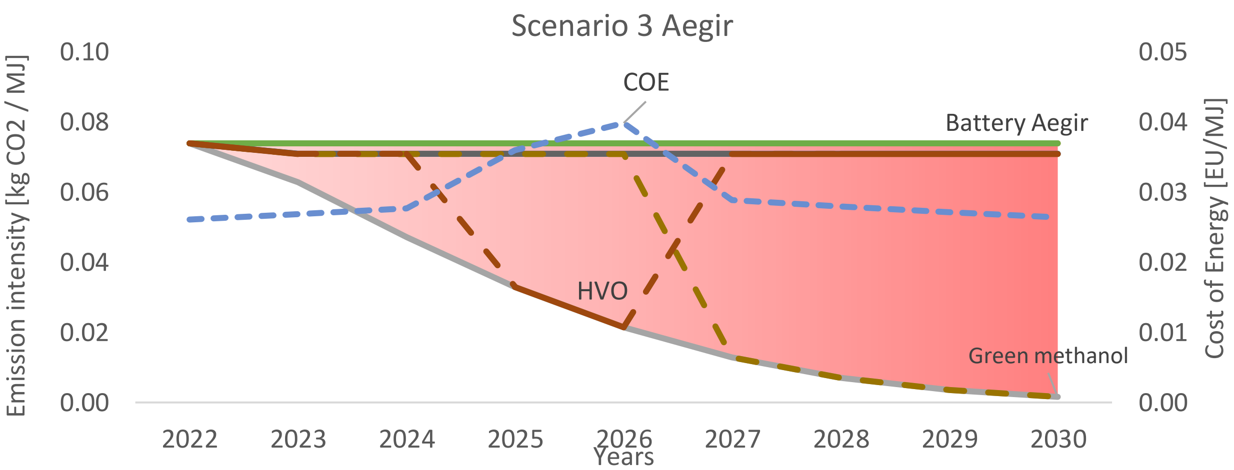
Annualised costs per scenario

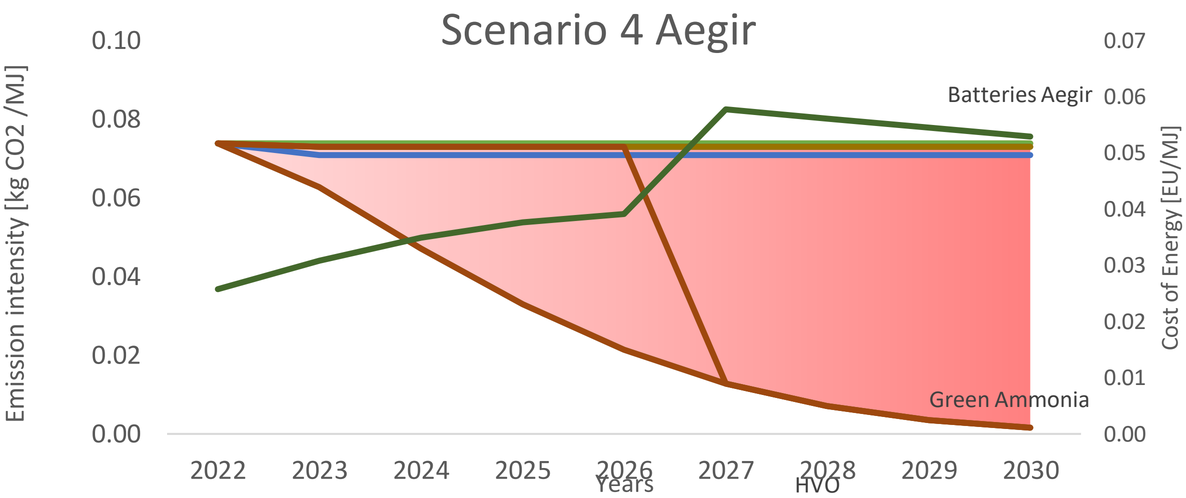
Costs									
Scenario1									
Aegir Scenario 1	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions	138,575.13	145,898.84	97,251.18	68,226.20	1,179,468.32	788,586.88	524,741.90	363,503.31	341,060.35
Designated fuel tanks	-	-	-	-	-	-	-	-	-
CCS Sleipnir	-	-	-	-	-	-	-	-	-
HVO	-	4,803,956.22	9,793,145.46	14,025,752.99	17,442,321.94	19,684,130.96	20,904,042.29	21,350,106.81	21,282,148.23
Green hydrogen	-	-	-	-	-	-	-	-	-
Green methanol	-	-	-	-	-	-	-	-	-
Green ammonia	-	-	-	-	-	-	-	-	-
MGO	11,725,948.48	12,499,177.29	8,260,932.79	5,594,595.46	3,550,510.88	1,964,589.56	846,860.66	131,620.23	-
Batteries Sleipnir	-	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61
	11,864,523.60	18,312,068.96	19,014,366.04	20,551,611.26	23,035,337.76	23,300,344.00	23,138,681.46	22,708,266.96	22,486,245.18
Scenario2									
Aegir Scenario 2	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions	138,575.13	145,898.84	97,251.18	68,226.20	-	-	-	-	-
Designated fuel tanks	-	-	-	-	2,060,893.70	2,060,893.70	2,060,893.70	2,060,893.70	2,060,893.70
CCS Sleipnir	-	-	-	-	-	-	-	-	-
HVO	-	4,803,956.22	9,793,145.46	14,025,752.99	-	-	-	-	-
Green hydrogen	-	-	-	-	14,081,137.33	13,658,703.21	13,248,942.11	12,851,473.85	12,465,929.63
Green methanol	-	-	-	-	-	-	-	-	-
Green ammonia	-	-	-	-	-	-	-	-	-
MGO	11,725,948.48	12,499,177.29	8,260,932.79	5,594,595.46	-	-	-	-	-
Batteries Sleipnir	-	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61
	11,864,523.60	18,312,068.96	19,014,366.04	20,551,611.26	17,005,067.64	16,582,633.52	16,172,872.42	15,775,404.16	15,389,859.94
Scenario3									
Aegir Scenario 3	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions	138,575.13	145,898.84	97,251.18	68,226.20	-	-	-	-	-
Designated fuel tanks	-	-	-	-	358,416.30	358,416.30	358,416.30	358,416.30	358,416.30
CCS Sleipnir	-	-	-	-	-	-	-	-	-
HVO	-	4,803,956.22	9,793,145.46	14,025,752.99	-	-	-	-	-
Green hydrogen	-	-	-	-	-	-	-	-	-
Green methanol	-	-	-	-	16,503,851.53	16,008,735.98	15,528,473.90	15,062,619.68	14,610,741.09
Green ammonia	-	-	-	-	-	-	-	-	-
MGO	11,725,948.48	12,499,177.29	8,260,932.79	5,594,595.46	-	-	-	-	-
Batteries Sleipnir	-	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61
	11,864,523.60	18,312,068.96	19,014,366.04	20,551,611.26	17,725,304.43	17,230,188.89	16,749,926.81	16,284,072.59	15,832,194.00
Scenario 4									
Aegir Scenario 4	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions	138,575.13	145,898.84	97,251.18	68,226.20	0.00	0.00	0.00	0.00	0.00
Designated fuel tanks	-	-	-	448,020.37	448,020.37	448,020.37	448,020.37	448,020.37	448,020.37
CCS Sleipnir	-	-	-	-	-	-	-	-	-
HVO	-	4,803,956.22	9,793,145.46	14,025,752.99	-	-	-	-	-
Green hydrogen	-	-	-	-	-	-	-	-	-
Green methanol	-	-	-	-	-	-	-	-	-
Green ammonia	-	-	-	-	15,524,809.49	15,059,065.20	14,607,293.25	14,169,074.45	13,744,002.22
MGO	11,725,948.48	12,499,177.29	8,260,932.79	5,594,595.46	0.00	0.00	0.00	0.00	0.00
Batteries Sleipnir	-	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61	863,036.61
	11,864,523.60	18,312,068.96	19,014,366.04	20,999,631.63	16,835,866.47	16,370,122.18	15,918,350.23	15,480,131.43	15,055,059.20
Scenario 4									
Aegir Scenario 5	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions	138,575.13	169,947.09	147,791.14	142,848.25	3,571,206.27	3,571,206.27	3,571,206.27	3,571,206.27	3,571,206.27
Designated fuel tanks	-	-	-	-	-	-	-	-	-
CCS Sleipnir	-	-	-	-	-	-	-	-	-
HVO	-	-	-	-	-	-	-	-	-
Green hydrogen	-	-	-	-	-	-	-	-	-
Green methanol	-	-	-	-	-	-	-	-	-
Green ammonia	-	-	-	-	-	-	-	-	-
MGO	11,725,948.48	14,811,998.22	13,267,391.79	13,208,372.16	13,604,623.32	14,012,762.02	14,433,144.89	14,866,139.23	15,312,123.41
Batteries Sleipnir	-	-	-	-	-	-	-	-	-
	11,864,523.60	14,981,945.31	13,415,182.93	13,351,220.41	17,175,829.60	17,583,968.30	18,004,351.16	18,437,345.50	18,883,329.68

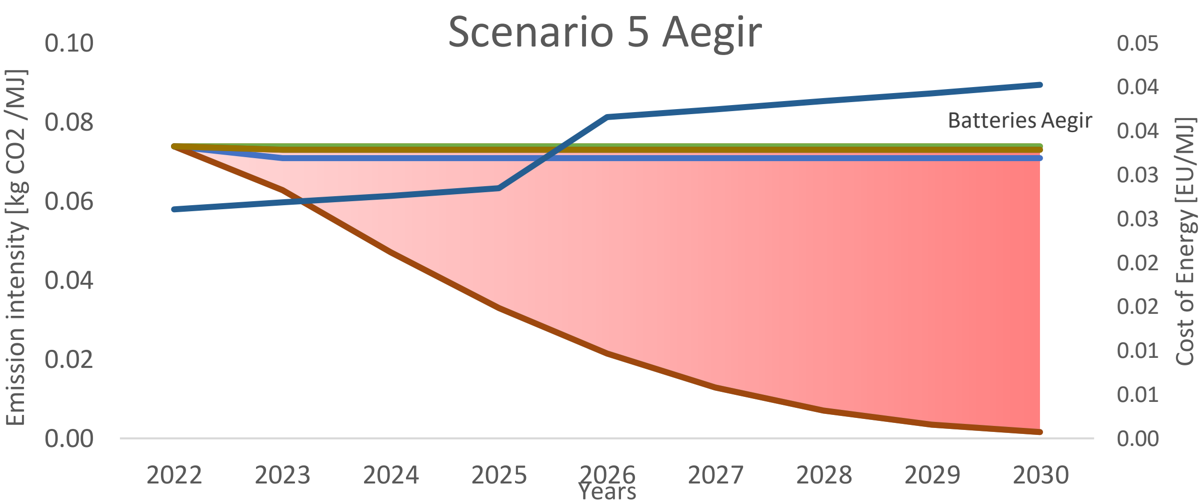
Aegir


Scenario 1 Aegir
Emission intensity [kg CO2 /MJ]
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Batteries Sleipnir
HVO
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
Cost of Energy [EU/MJ]
2022
2023
2024
2025
2026
2027
2028
2029
2030
Axis Title

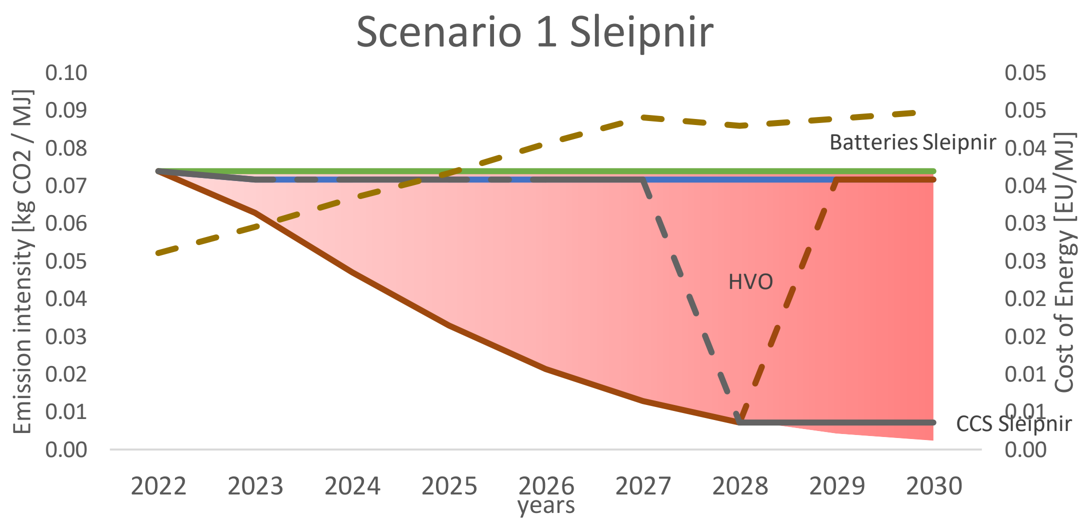

Scenario 2 Aegir
Emission intensity [kg CO2 /MJ]
0.10
0.08
0.06
0.04
0.02
0.00
COE
Batteries Sleipnir
HVO
Green hydrogen
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years

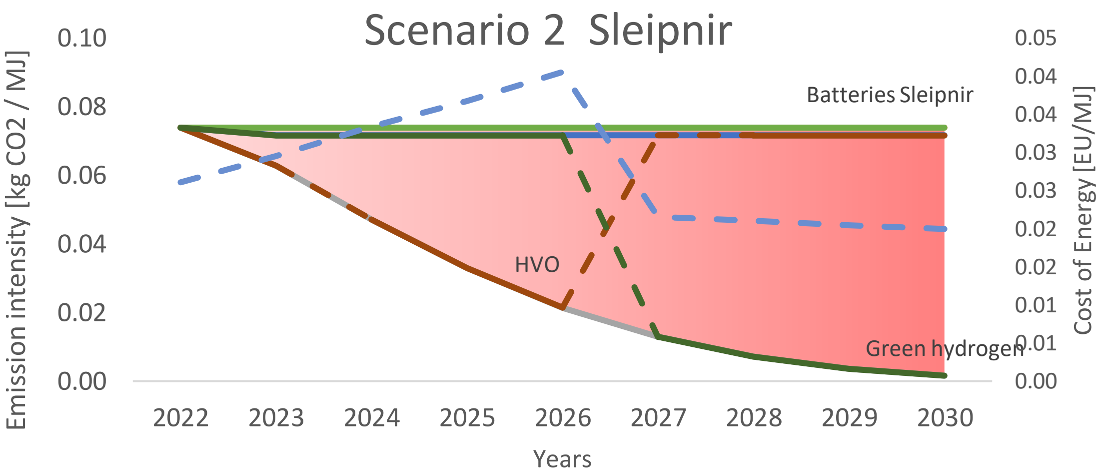

Scenario 3 Aegir
Emission intensity [kg CO2 / MJ]
0.10
0.08
0.06
0.04
0.02
0.00
COE
Battery Aegir
HVO
Green methanol
0.05
0.04
0.03
0.02
0.01
0.00
Cost of Energy [EU/MJ]
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years

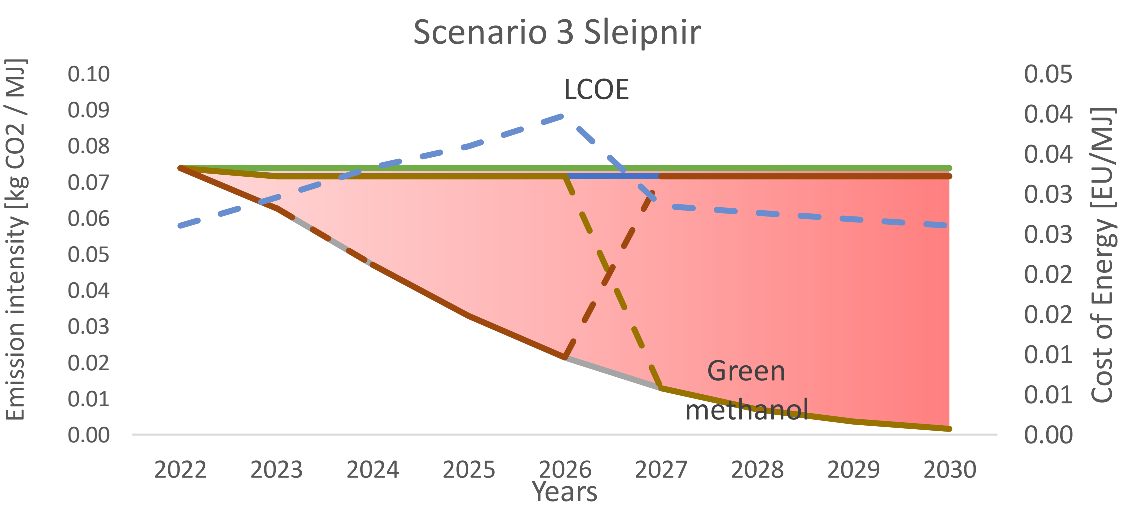

Scenario 4 Aegir
Emission intensity [kg CO2 /MJ]
0.10
0.08
0.06
0.04
0.02
0.00
Cost of Energy [EU/MJ]
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Batteries Aegir
Green Ammonia
HVO
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years

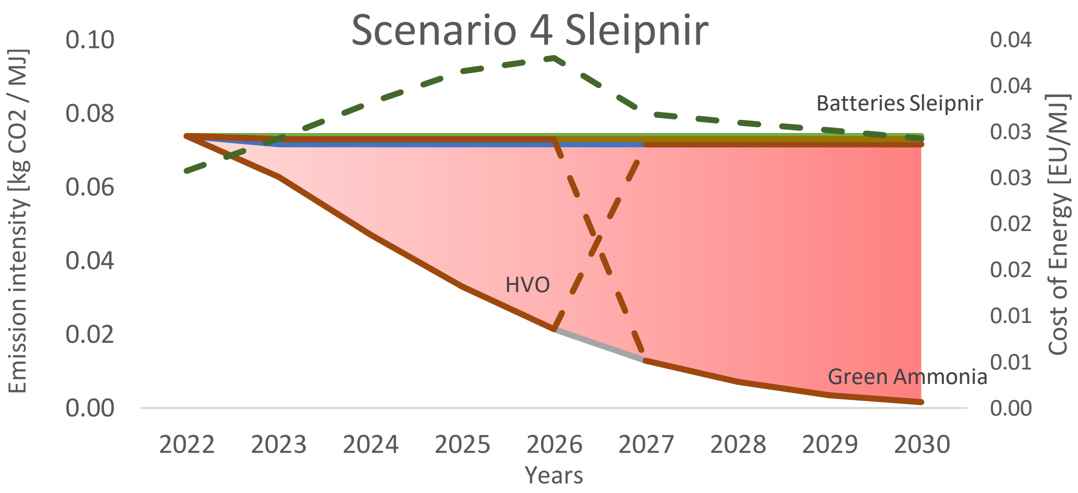

Scenario 5 Aegir
Emission intensity [kg CO2 /MJ]
0.10
0.08
0.06
0.04
0.02
0.00
Cost of Energy [EU/MJ]
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
Batteries Aegir
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years

Sleipnir

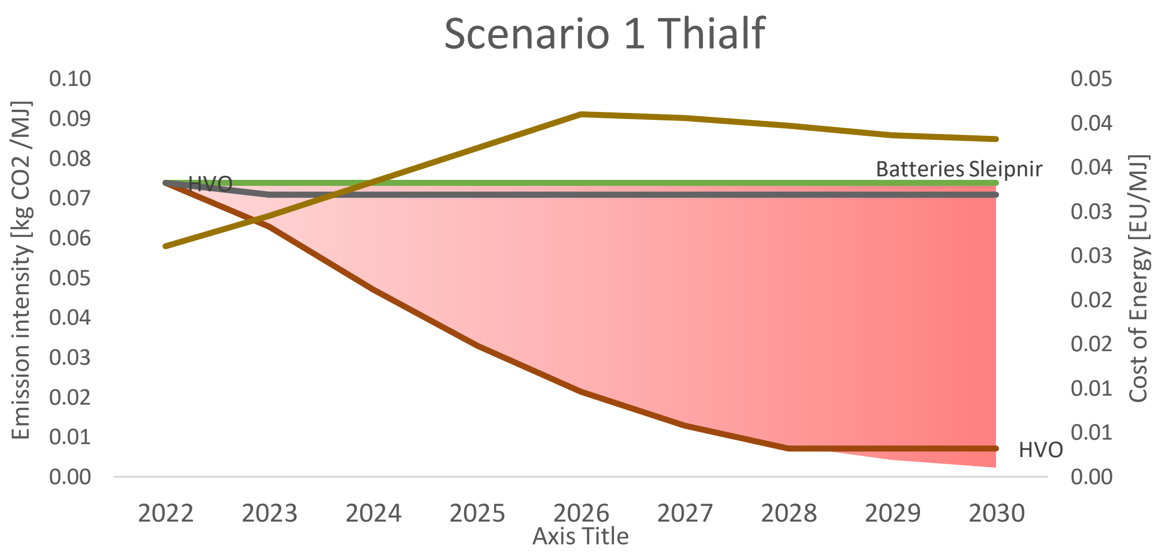

Scenario 1 Sleipnir
Emission intensity [kg CO2 / MJ]
Cost of Energy [EU/MJ]
Batteries Sleipnir
HVO
CCS Sleipnir
years
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030

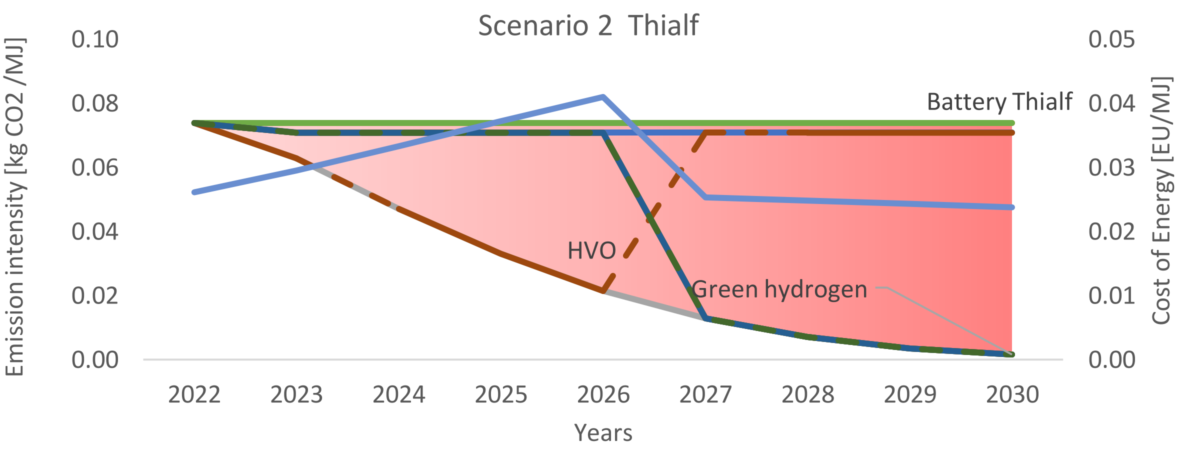

Scenario 2 Sleipnir
Emission intensity [kg CO2 / MJ]
Cost of Energy [EU/MJ]
Batteries Sleipnir
HVO
Green hydrogen
Years
0.10
0.08
0.06
0.04
0.02
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030

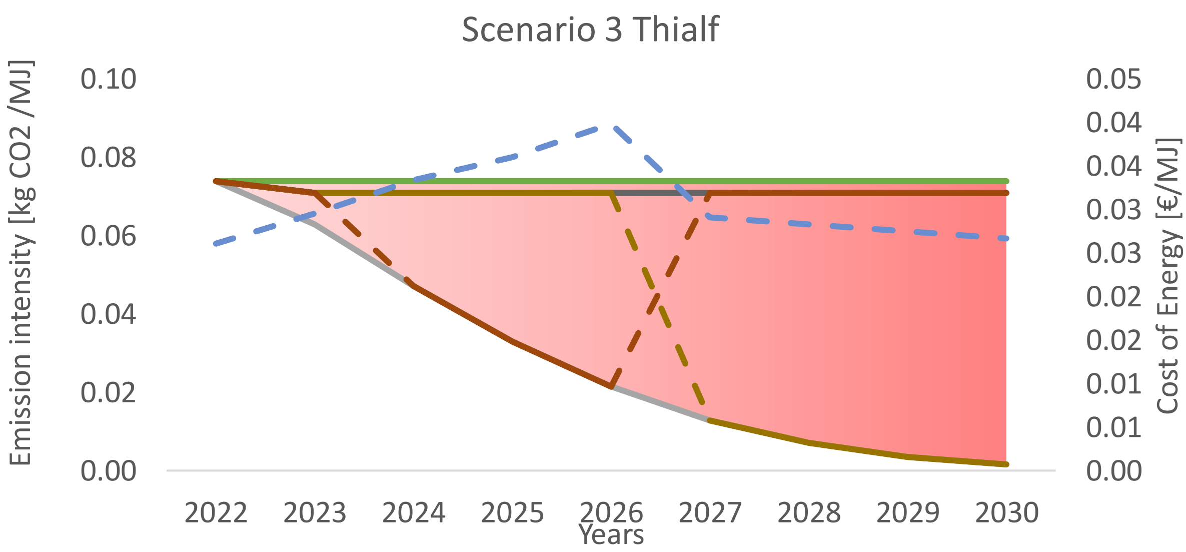

Scenario 3 Sleipnir
LCOE
Emission intensity [kg CO2 / MJ]
Cost of Energy [EU/MJ]
Green methanol
Years
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030

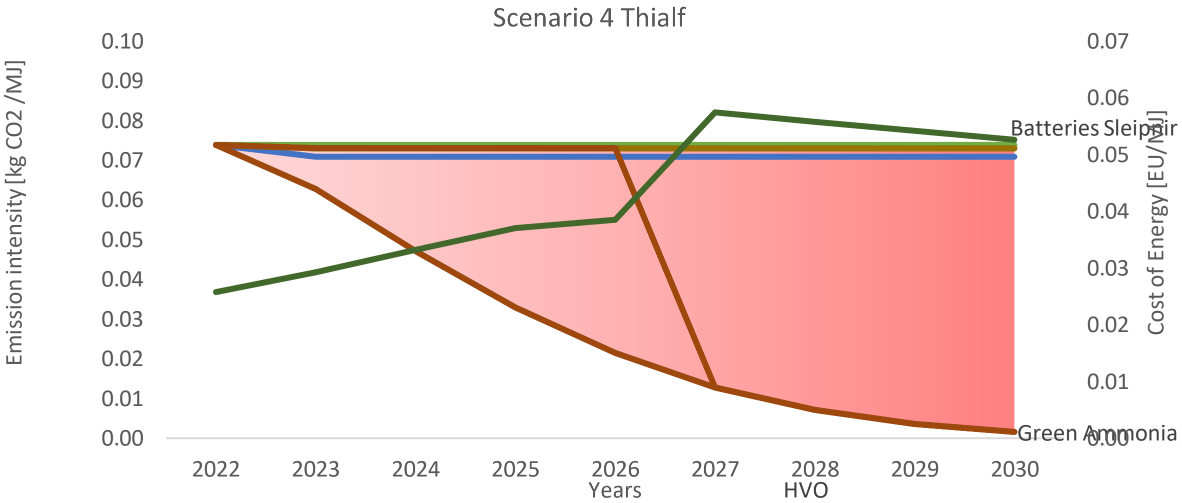

Scenario 4 Sleipnir
Emission intensity [kg CO2 / MJ]
0.10
0.08
0.06
0.04
0.02
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years
Batteries Sleipnir
HVO
Green Ammonia
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
Cost of Energy [EU/MJ]

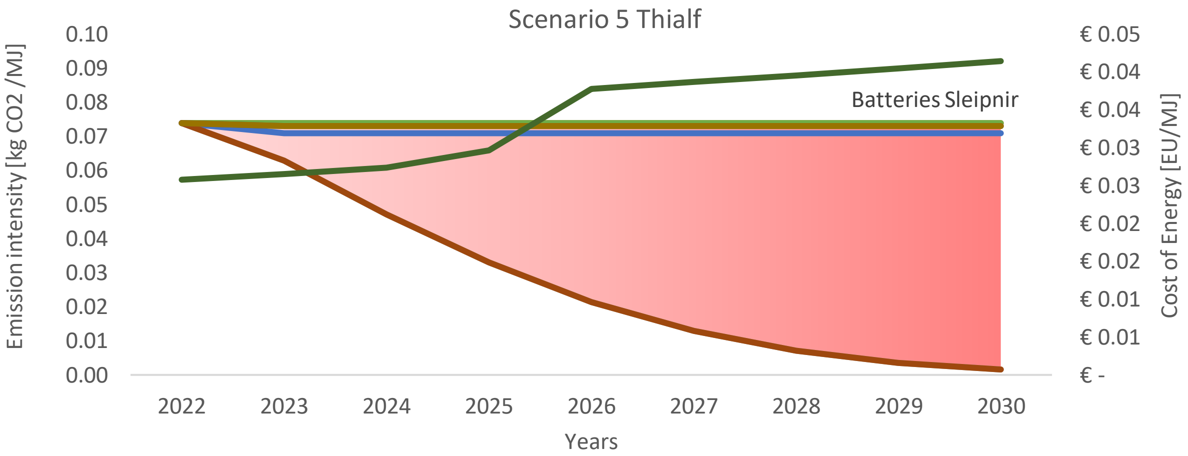
Thialf


Scenario 1 Thialf
Emission intensity [kg CO2 /MJ]
Cost of Energy [EU/MJ]
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
HVO
Batteries Sleipnir
HVO
2022
2023
2024
2025
2026
2027
2028
2029
2030
Axis Title


Scenario 2 Thialf
Emission intensity [kg CO2 /MJ]
Cost of Energy [EU/MJ]
0.10
0.08
0.06
0.04
0.02
0.00
0.05
0.04
0.03
0.02
0.01
0.00
Battery Thialf
HVO
Green hydrogen
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years


Scenario 3 Thialf
Emission intensity [kg CO2 /MJ]
Cost of Energy [€/MJ]
0.10
0.08
0.06
0.04
0.02
0.00
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years


Scenario 4 Thialf
Emission intensity [kg CO2 /MJ]
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years
HVO
Cost of Energy [EU/MJ]
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Batteries Sleipnir
Green Ammonia


Scenario 5 Thialf
Emission intensity [kg CO2 /MJ]
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
2022
2023
2024
2025
2026
2027
2028
2029
2030
Years
Batteries Sleipnir
Cost of Energy [EU/MJ]
€ 0.05
€ 0.04
€ 0.04
€ 0.03
€ 0.03
€ 0.02
€ 0.02
€ 0.01
€ 0.01
€ -