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Alternative fuel selection and operational performance assessment for a 7000 DWT general cargo vessel

Impact assessment of methanol as alternative fuel on the operational performance of the LABRAX series vessels

Delft University of Technology

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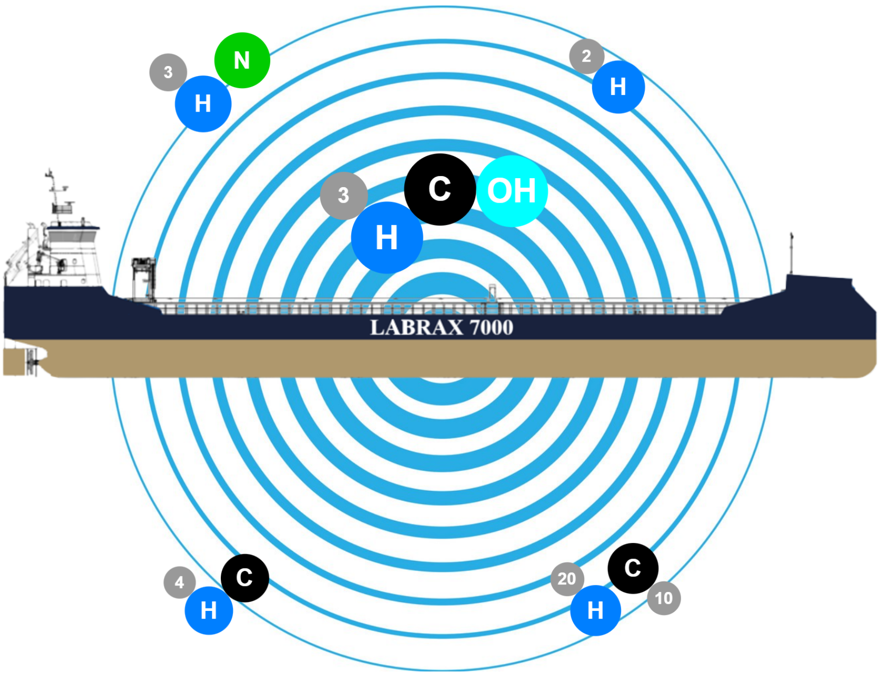

TU Delft

THECLA BODEWES SHIPYARDS

Thesis for the degree of MSc in Marine Technology in the specialization of Marine Engineering

Alternative fuel selection and operational performance assessment for a 7000 DWT general cargo vessel

Impact assessment of methanol as alternative fuel on the operational performance of the LABRAX series vessels

By

S.F.K. Zuidgeest

Performed at

Thecla Bodewes Shipyards

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Preface

This research has been an interesting- and learning experience which will be an indelible part of my life. My journey all started at the University of Twente, where the basis was laid to specialise in Marine Engineering by graduating for my Bachelor of Science in Mechanical Engineering. The maritime sector, especially shipping, is an important part of my life that originates from the interest in inland shipping from childhood, which is initiated by a long family history in inland shipping.
Therefore, to choose the right specialisation after my Bachelor was not an issue and I started the Master Marine Technology at the Delft University of Technology in 2020. After all interesting subjects and projects that covered many aspects of Marine Technology from Maritime Operations and Management to Ship Hydromechanics, my final work began.
This thesis, which started in November 2021, has been dedicated to research in the field of alternative energy carriers. Thecla Bodewes Shipyards gave me the opportunity to conduct an applied research and asses the impact of alternative fuels on a general cargo vessel called the LABRAX.

I am very grateful for this opportunity and would like to thank my supervisors Wim Korterink and Emiel Mocking for their trust in me and giving me a valuable introduction in shipbuilding industry. Furthermore, I would like to thank Pier Meinderts from Thecla Bodewes Shipyards for his guidance in this process, helpful discussions and allowing me to participate in the MENENS-project. Lastly, I would like to thank all other colleagues at Thecla Bodewes Shipyards that helped me during this research.
Regarding the supervision from the TU Delft, I would like to thank my supervisor Peter de Vos for his guidance in this project, giving me the opportunity to conduct research in the field of Marine Engineering and valuable advice in a difficult period. Also my appreciation for Evelien Scheffers as she helped me by giving me constructive feedback on my thesis.
Last but not least, I am grateful for the support my parents gave me during my entire study and especially during my research.

S.F.K. Zuidgeest
Kampen, October 2022

Summary

The current global fleet is still dependent on conventional fuels as energy source to transport there goods to various places in the world. These conventional fuels, such as MGO or HFO, emit large amounts of greenhouse gasses and other pollutant emissions. Regulation concerning these emissions becomes stricter every day, especially close to highly populated area's where general cargo vessels are in operation. Therefore institutions and governments have established reduction targets, for instance IMO has set a reduction in CO_2-emissions of 70% in 2050. To accomplish these reductions, net-zero alternative fuels are serious candidates to investigate.
As a result of these developments, Thecla Bodewes Shipyards is interested in solutions to reduce these emissions for there current general cargo vessel series, the LABRAX. In order to stay ahead of competition, ship design should be prepared for future emission regulation. One of the options to look into in order to reduce the environmental impact, is the implementation of an alternative fuel. Consequently, this research was established with the following research question: *"What is the most suitable alternative fuel power- and energy system on board of a 7000 DWT general cargo vessel?"*.

By performing a general literature study concerning potential alternative fuels, a suitable candidate can be selected for the LABRAX. In this study, potential alternative fuels are selected and analysed on several aspect from production methods to Well-to-Wake emissions. From this extensive analysis, it is concluded that methanol is the most suitable fuel for this particular general cargo vessel. However, based on current information and developments in the alternative fuel market, no certain conclusion can be drawn that this fuel will be suitable for a general cargo vessel on the long term. Although, current availability of the fuel, compatibility with the operational profile and the methanol research project (MENENS) going on at Thecla Bodewes Shipyards where I am involved in, have been deciding factors to choose methanol as alternative fuel for the applied research.

In order to investigate the implementation of methanol as alternative fuel in the LABRAX-series vessels, the object of study needs to be defined with specific boundaries and assumptions of the model. First, general design aspects are discussed, with the focus on characteristics of the aft ship below main deck, fore ship and tanks around the entire vessel. Afterwards, a detailed analysis concerning the power- and energy system is made with specifications of several system components. Together with the power-speed diagram, the fuel consumption is determined per operational mode. In order to compare the current power- and energy system to future power- and energy systems in a case study, performance indicators are established and calculated.
Subsequently, possible energy converters and storage limitations are evaluated to determine concept designs for storage of methanol and power- and energy systems on methanol.

Three concept designs for storage of methanol are created with the focus to preserve the current cargo volume and limit the loss of ballast capacity to assure stability of the vessel. Together with classification regulation and current performance indicators, a combination of integrated tanks in the double bottom at the fore ship and in the fore tanks seems to be most suitable for the LABRAX.
Concerning the methanol power- and energy system, two power plant configurations are proposed based on suitable energy converters on methanol and electrical load balance of the vessel. Two types of energy converters are considered for the power plant configurations, namely one based on a Spark Ignited - Internal Combustion Engine (SI-ICE) and a second one on a High Temperature - Proton Exchange Membrane Fuel Cell (HT-PEMFC). The methanol fuel system is also included in the analysis and worked out.
This research concludes that the range, weight and volume and fuel consumption with the new power- and energy changes significantly. The range decreases respectively by 35% and 45% for cruising speed with an increase in system weight of approximately 10 tonnes and extra fuel weight of 60 tonnes. The fuel consumption per tonne•NM

increases by a factor 2.1-2.4 for methanol. Nevertheless, the specific CO_2-emissions decreases by approximately 10% in cruising mode for a HT-PEMFC power plant on methanol and slightly increases by 7% for a SI-ICE power plant on methanol compared to a diesel power plant. However, a significant difference in reliability and durability between an SI-ICE and a HT-PEMFC is detected, with HT-PEMFC currently less reliable and durable due to the relative new technology. Although rapid developments in the last few decades can solve these problems on a relatively short term.
Last, a cost analysis is made based on current prices of energy converters and fuels. This analysis concludes that the CapEx increases by a factor 4.2 for a HT-PEMFC and a factor 1.7 for a SI-ICE on methanol compared to a CI-ICE on diesel. The OpEx for methanol power plants, in terms of fuel costs, are very similar to a power plant on diesel. However, is should be noted that fuel prices in the future are very dependent on the cost to produce methanol out of renewable feedstocks.

Considering all aspects discussed in this report concerning the application of a methanol power- and energy system on board of a 7000 DWT general cargo vessel, research concludes that a SI-ICE power plant with methanol as main fuel seems most feasible.

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Nomenclature

Abbreviations

A.B. Above Base

AC Alternating Current

AFC Alkine Fuel Cell

AS Aft Ship

AWE Alkine water electrolysis

BLEVE Boiling Liquid Expanding Vapour Explosion

BV Bureau Veritas

CapEx Capital Expenditures

CCS Carbon Capture and Storage

CN Cetane Number

COP26 26th Conference of Parties (UN Climate Change Conference 2021)

DAC Direct Air Capture

DC Direct Current

DE Diesel Engines

DMFC Direct Methanol Fuel Cell

DWAT Deadweight all told

EFD Energy Flow Diagram

EM Electric motor

FAME Fatty Acid Methyl Ester

FC Fuel Cell

FiFi Fire Fighting

FPP Fixed Pitch Propeller

FS Fore Ship

G7 Group of Seven

GHG Greenhouse Gases

GT Gross tonnage

GWP Global Warming Potential

HBP Haber-Bosch Process

HFO Heavy Fuel Oil

HVO Hydrotreated Vegetable Oil

ICE Internal Combustion Engine

IMO International Maritime Organization

KC Keel Cooled

LF Large Flow

LHV Lower Heating Value

LNG Liquefied Natural Gas

LO Lubrication Oil

LOA Length over all

MARIN Maritime Research Institute Netherlands

MCFC Molten Carbonate Fuel Cell

MENENS Methanol als Energiestap Naar Emissieloze Nederlandse Scheepvaart

MeOH Methanol

MGO Marine Gas Oil

NG Natural Gas

NM Nautical Mile

OpEx Operating Expenditures

PEM Proton-Exchange Membrane

PEMFC Proton-Exchange fuel cell

PM Particular Matter

PTI Power Take In

SCC Stress Corrosion Cracking

SFC Specific FUel Consumption

SMR Steam Methane Reforming

SOE Solid-Oxide Electrolysis

SOFC Solid Oxide Fuel Cell

STEL Short-Term Exposure Limit

STP Standard Temperature and Pressure

TCO Total Cost of Ownership

TDC Top Dead Center

TTW Tank-to-wake

TWA 8 hours Time-Weighted Average

WTT Well-to-Tank emissions

WTW Well-to-Wake emissions

Symbols

P_b Brake power

(v/v)% Volume percentage

ppm parts per million

wt% Weight percentage

Chemical structures

$C_{10}H_{20}$ Diesel

$C_6H_{12}O_6$ Glucose

CH_3OH Methanol

CH_4 Methane

CO Carbon monoxide

CO_2 Carbon dioxide

H_2 Hydrogen

H_2O Water

H_2SO_4 Sulfuric acid

HCl Hydrochloric acid

KOH Potassium Hydroxide

N_2 Nitrogen

$NaOH$ Sodium Hydroxide

NH_3 Ammonia

OH^- Hydroxide

1
Introduction

Policies and regulations for reducing greenhouse gas-emissions (GHG-emissions) in the international shipping sector are becoming stricter. Reduction targets, concerning these emissions, have been set by various institutions and governments around the world, such as the International Maritime Organization (IMO) [40]. Therefore, a substantial change is necessary to reduce GHG-emissions. However, these policies and regulation are subject to frequent changes which makes it difficult to select a future proof technology. Hence, gaining technical knowledge by assessing emission reducing technology is crucial to reduce the risk of implementing obsolescence technology.
In more detail, in this research the implementation of alternative fuels in sea-going vessels is evaluated in order to reduce GHG-emissions. The goal is to reduce the research gap that exists between fundamental- and practical knowledge by analysing alternative fuels and assessing the operational performance of vessels. Consequently, a case study is performed with a study object, namely a 7000 DWT general cargo vessel (LABRAX). In the end, the aim is to determine the most suitable alternative fuel power- and energy system.

1.1. Background of problem

Fossil fuels have been the main power source for our global economy for almost 150 years [24]. The first fossil fuel that was being used on a large scale was coal and was applied in the maritime sector for powering steamships in the early 1800's. Currently, many ships are still dependent on fossil fuels and are mostly driven by diesel or heavy fuel oil (HFO) powered internal combustion engines. The total fuel consumption in 2018 by energy content of HFO was still 79% in the shipping sector [26]. In order to reduce Green House Gas (GHG) emissions and keep the global temperature rise within 2 degrees Celsius with the intention to keep it under the 1.5 degrees Celsius according the Paris Agreement, use of alternative fuels that reduces these emissions have to be increased in the following decades. Policies and regulation set up by governments and organizations should force reductions of these GHG emissions. For example, the International Maritime Organization has as goal to reduce carbon dioxide emissions per transport work by at least 40% in 2030 and 70% in 2050 [40]. More recently, all members of the G7 have pledged to phase out subsidies, that keep fuel prices artificially low, for production and consumption of fossil fuels by 2025 during the COP26 climate summit in Glasgow [6].

All these policies and regulations have to be implemented and carried out within a certain time frame. For the shipping sector, this means a possible change in energy carrier and/or energy converter for their freighter. Also other means of energy saving actions, such as lowering the sailing speeds or implementing energy saving devices could play a bigger role in the future. Concerning shipbuilders, ship design should comply with future emission regulations, preferably within the economical lifespan of the vessel. This also raised questions for the future design of the LABRAX dry cargo vessel series which is being build by Thecla Bodewes Shipyards for the shipping company Vertom [59]. Although the design of the LABRAX-series has a higher overall efficiency resulting in lower fuel consumption and GHG emission, it however still includes a diesel-electric power source making it fossil fuel dependent.

1.2. Objective

Research into alternative fuels and implementing one of these in a specific general cargo vessel type will be combined in this research. This is achieved by evaluating alternative fuels and assessing the consequences on the design and performance of the vessel.
Based on literature, a number of alternative fuels is selected that are promising for global shipping compared to the most used fuel in short-sea shipping. A suitable alternative fuel will be selected for further assessment, the objective then is to investigate the impact of this new fuel on the design and operational performance.

First, the objective is to analyse the current vessel in detail with the focus on power- and energy systems and relevant design parameters to determine the boundaries of the study object. Afterwards the goal is to determine the current operational performance which will be used as a reference value for the future operational performance.

To assess the future operational performance, the target is to select suitable energy converters for the alternative fuel and investigate possible storage locations to determine the storage capacity.
Finally, it should become clear what the effects are of an alternative fuel power- and energy systems on the operational performance of the study object with the goal to select the most suitable power- and energy system. For the visualisation of the process a diagram is made, shown in figure 1.1.

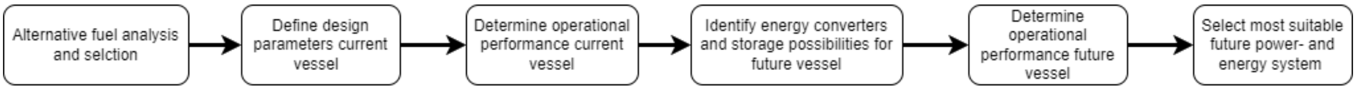


Figure 1.1: Objective process

1.3. Research questions

The research questions help to fulfill the earlier defined objectives of this thesis. The main research question is defined as follows:

- **What is the most suitable alternative fuel power- and energy system on board of a 7000 DWT general cargo vessel?**

This main research question needs to be answered by dividing it into several sub-questions and are defined as follows:

- **How are alternative fuels produced, can it be implemented in vessels, and what are the characteristics?**

- **What is the current design of the power- and energy system on board of the LABRAX general cargo vessel?**

- **What is the current performance of the LABRAX general cargo vessel?**

- **Which power plant configurations can be identified for a methanol power- and energy system?**

- **How does a methanol power- and energy system influence design aspects and performance of the LABRAX general cargo vessel?**

1.4. Research scope

In order to fulfill the objective of this research, a scope is defined. In this way, the area of research and focus becomes clear which makes the study feasible within the given time frame.

As mentioned in the objective, the research is divided into multiple steps with the following goal:

- *Determine the impact of an alternative fuel on the design and performance of the LABRAX-series general cargo vessel*

In the beginning of the research, the most promising alternative fuels are compared to each other with a limitation on the amount of fuels, being within the range of five to eight fuels. In order to narrow down the scope in the next step, a suitable alternative fuel is selected for further research.
In this research, relevant energy converters and storage possibilities are identified and consequences evaluated. Due to the time constraint two categories of energy converters are assessed and three concept designs for storage of the alternative fuel are evaluated.
For further research and to assess the influences on the operational performance of LABRAX-series, one concept design is selected with two specific different energy converter types. In the mean time, relevant design parameters of

the LABRAX-series are described and certain assumptions are made when needed to make the study more feasible.

In short the main scope of this research:

- *Comparison of five to eight promising alternative fuels and one fuel is selected for further research*
- *Evaluation of two energy converter categories and three design concepts for fuel storage*
- *Determination of the consequences of the selected energy converter types with the concept design on the LABRAX-series operational performance*

1.5. Method

This research can be divided into three parts, namely a general literature research, study object literature research and a case study. These three parts will form this thesis and attempts to answer the earlier defined research questions. To structure this process, an outline of this research is constructed which gives an insight of this research in advance.

1.5.1. Literature Review

In the literature review, sufficient information is gathered from academic sources to describe what already has been published and to define specific solvable research questions.

In chapter 2, important aspects concerning alternative fuels are discussed, starting with the analysis of potential feedstocks in section 2.1. The intention of this chapter is to analyse different types of upcoming alternative fuels, namely hydrogen, ammonia, methanol, methane and diesel (renewable) and select one alternative fuel for the case study. Production, chemical properties, technical readiness, safety, emissions and economical aspects are mentioned in order to select the most suitable alternative fuel for further analysis. In combination with the operational profile in section 2.5 of comparable vessels, a choice is made based these aspects and new research questions are formulated based on this alternative fuel.

1.5.2. Object of Study

The first step of the case study research is to define the object of study and use this information to analyse the impact of the alternative fuel on several aspects of the vessel.

In Chapter 3 the object of study is defined starting with the design aspects in section 3.1. By defining the vessel and especially determining the boundaries of the study subject, a basis is laid to assess alternative fuels on the design of the vessel and power- and energy systems. In order to compare the current vessel with potential future vessels on the selected alternative fuel, performance indicators are utilized to rate their performance on different parameters. In section 4.5 the current vessel is assessed on six performance indicators, namely fuel index, energy conversion effectiveness, specific fuel consumption, emission index, range and start-up/load performance. These indicators can be compared directly with the new energy- and power plant and is a key aspect of the impact assessment.

1.5.3. Case Study

Now all aspects of the fuels and case study object are known, the implementation of the alternative fuel can start. The goal is to determine the technical feasibility of the general cargo vessel with the selected alternative fuel.

Chapter 4, starts with an analysis of potential energy converters which is divided into two system categories to convert chemical energy into electrical energy, namely the fuel cell and internal combustion engine. Storage systems are considered in section 4.3.3 and with the help of classification rules and general arrangement several concept designs are created of which one is selected for the performance analysis and comparison. To make feasibility study complete, a small economical analysis is made in chapter 5 concerning the CapEx and OpEx of the vessel in the current and new situation.

In the last chapter of this thesis, conclusions and recommendations are given.

Literature Review

2
Well-to-Wake analysis of alternative fuels

One of the biggest challenges in decarbonizing the economy and in this particular case the marine industry, is the production of alternative fuels. First, the scalability of an alternative fuel from a certain feedstock will decide if this fuel is suitable as a new energy source.
Secondly, the timeline for the availability of alternative fuel technologies is of importance. This gives an indication of the commercial readiness of alternative fuels for the maritime sector in the short and long term.
Lastly, when this is technically possible, the production costs from well to tank should be considered as well, because the alternative fuel needs to be economically viable. In this literature research, the focus will be more on the technical aspects concerning the alternative fuels.

2.1. Feedstocks for the production of fuels

In principle there are three types of feedstock from which alternative fuels can be produced, namely:

- Green electricity
- Biomass
- Natural gas

Two of those are renewable, namely green electricity and biomass. Renewable feedstock has the advantage over that of fossil sources, such as natural gas, because it is replenishable and in a sense inexhaustible. In 2020, over 256 GW of renewable power was added worldwide, with wind and solar power as leaders [76]. This was an increase of 10% in the total renewable power capacity and the additional added power capacity from 2014-2020 can be seen in figure 2.1. Concerning the worldwide electricity generation in 2020, 29% originates from a renewable source [76].

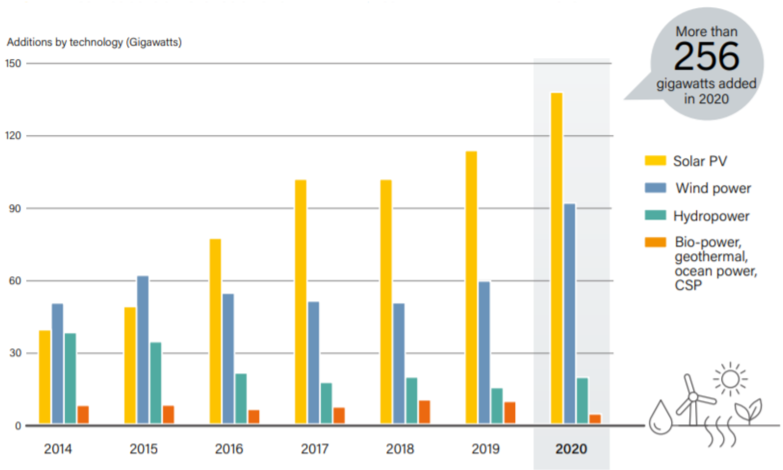


Figure 2.1: Addition of installed renewable power 2014-2020 [76]

So the share of renewable sources in electricity is increasing every year, but the storage of electricity or using electricity when it is generated, brings challenges with it. A simple example is the generation of solar power, which is only generated during the day when the sun shines, but not all electricity is used during the day. This problem could

play a significant role in producing alternative fuels in the future. Energy needs to be stored for a certain amount of time before it is used, so electricity could be used to produce alternative fuels.
In the following sections, the three production methods will be discussed.

2.1.1. Green electricity

Green electricity or green power is energy produced by a natural resource. As mentioned in the previous section, this type of energy is one of the renewable energy sources.
Important resources of the green energy are listed beneath [94]:

- Solar energy
- Wind energy
- Geothermal energy
- Hydro-electric energy

In figure 2.1, it can be seen that solar and wind power are the largest growing alternative power sources, with hydro-power on the third place.
Electricity from these resources can be used to produce alternative fuels. These fuels are known as e-fuels and are usually produced from the following sources: water (H_2O) , carbon dioxide (CO_2) and nitrogen (N_2) [102]. In order to reach net-zero emissions for e-fuels that are originated from CO_2, the production process should be circular, which means that CO_2 should be captured from the air. There are many e-fuel options available, the most promising e-fuels that are being considered as energy source for the maritime industry are shown in the following list [102]:

- e-Hydrogen (H_2)
- e-Ammonia* (NH_3)
- e-Methanol (CH_3OH)
- e-Methane (CH_4)
- e-Diesel** ($C_{10}H_{20}$ to $C_{15}H_{28}$)

**Fischer-Tropsch *Haber-Bosch

The schematic production process of these e-fuels can be visualised in a diagram, shown in figure 2.2.

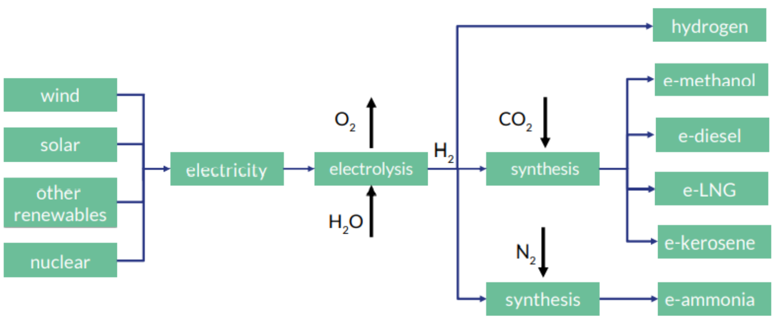


Figure 2.2: Visualisation of e-fuels production process [102]

In this diagram, nuclear energy is also considered as an energy source for producing e-fuels, but as it is not clear whether or not it is green energy, it is not considered in this report. Also e-kerosene is not considered as alternative fuel for the maritime industry, as it has more beneficial properties for the aviation industry.

Using green electricity to produce alternative fuels has some benefits and drawbacks. The first advantage of using resources such as solar and wind power, of which the opposite is true for fossil fuels, is that it is inexhaustible.

Secondly, fuels that are produced by using green electricity do not have well-to-wake emissions if the CO_2 chain is circular. Some fuels such as ammonia and hydrogen do not emit CO_2 at all when used.
The drawbacks of using green electricity, is that large amounts of green electricity (2000 PJ electricity for 960 PJ e-fuel) need to be produced for which more surface needs to be available to place solar panels, wind turbines and other installations [102]. Also large (~ 60% of Maasvlakte 2) and new infrastructure is needed to produce and distribute e-fuels. [102].

Table 2.1: Advantages and disadvantages of using green electricity

Advantages	**Disadvantages**
Inexhaustible source	Producing costs sensitive to electric and partly CO_2 costs
Zero WTW and TTW CO_2 emissions for H_2 and NH_3	Large and new infrastructure is needed
Zero WTW CO_2 emissions for other e-fuels	Large amounts of green electricity needs to be produced

2.1.2. Biomass

Biomass is organic material that originates from plants and animals and contains in principle stored chemical energy originated from the sun. This process of transforming energy from the sun into chemical energy (Glucose: $C_6H_{12}O_6$), is called photosynthesis which is visualised in figure 2.3.

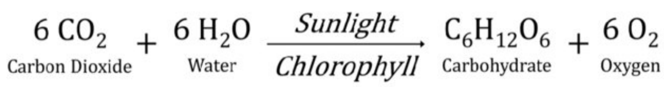


Figure 2.3: Chemical formula of the photosynthesis process [46]

Due to the circularity of the process (uses CO_2 from the atmosphere) of making biomass, it is a carbon neutral energy resource over its life cycle. When this organic material is created, it can be converted to bio-fuels by specific syntheses.
There are two categories of bio fuels, the first category is bio fuels that are produced out of agricultural crops and the second category are produced out of cellulosic materials (inedible portions of plants) [7]. However, there are controversies about using bio fuels made from crops that are also supplying our food chain. Although, solutions are already proposed in order to solve this problem, such as *Double crops and mixing crop systems* or using waste streams such as *Municipal and industrial wastes* [93], it is still difficult to implement theses bio-fuels in terms of cost and technical issues.

The most potential resources for second category biomass are listed beneath:

- Perennial plants on degraded lands
- Crop/forest residues
- Double/mixed crops
- Industrial/municipal waste
- Algae
- Animal wastes

From these resources a number of potential bio-fuels are considered for the maritime industry.

- bio-hydrogen (H_2)
- bio-methane (CH_4)
- bio-methanol (CH_3OH)

- bio-diesel ($C_{10}H_{20}$ to $C_{15}H_{28}$)
- bio-oils ($C_{100}H_{137}O_{55}N_{10}$)

In order to convert these resources to bio-fuel, a specific process has to be followed. In figure 2.4, the two main steps are shown. First, a biomass resource (feedstock) has to be chosen to be converted. Then, the conversion takes place and intermediates are produced by deconstructing and fractioning the biomass. The last phase is upgrading the intermediate products by synthesising it to fuels or other chemicals. This conversion to an end-product can be accomplished by a thermal-chemical and/or biochemical conversion [97].

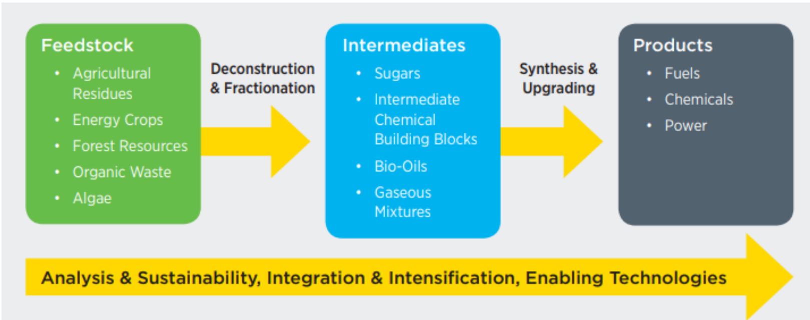


Figure 2.4: Steps from source to product [96]

The deconstruction process of the biomass into smaller chemical components can be accomplished by high temperature and low temperature deconstruction. In table 2.2, the different types of deconstructions methods are visualised.

Table 2.2: Deconstruction methods per temperature type

High temperature deconstruction	Low temperature deconstruction
Pyrolysis (>500 °C)	Hydrolysis (45-50 °C)
Hydro-thermal Liquefaction (200-400 °C)	
Gasification (800-1200 °C)	

High temperature deconstruction can be achieved by three different processes.
Pyrolysis is the decomposition (thermal and chemical) of chemical structures (bio-polymers) by the absence of oxygen. Pyrolysis occurs above 500 °C in order to deconstruct the polymers and produces three products, namely: Bio-oil (liquid), Bio-char (solid) and syngas (gas).
With *Hydro-thermal Liquefaction*, the feedstock is first treated with water before it is heated. Under a pressurized and heated environment between 100-250 bar and 200-400 °C, wet biomass is converted to bio-crude oil [110]. To make Bio-crude suitable as a fuel, it can be upgraded further to lower hetero-atom contents, such as reducing oxygen and nitrogen contents in the bio-crude oil.
Gasification is the decomposition of biomass at high temperatures between 800-1200 °C in combination of a gas [67]. Three types of gasses are usually added, namely sub-stoichiometric air, an oxygen carrier or steam. After the gasification process, a gas cleanup and conditioning takes place. The goal of this process, is to maximize the production of useable (combustible) gases instead of oils.

Low temperature deconstruction uses bio-catalysts to decompose the biomass into intermediates. First, the biomass is pre-treated in order to open up the physical structure. Now the structure is more reachable for enzymes or other chemicals, hydrolysis takes place which means the polymers are broken down in a chemical or enzymatic way. Commonly used chemicals for the breakdown process are acids like sulfuric acid (H_2SO_4) or hydrochloric acid (HCl) and cellulase enzymes for the enzymatic process [8]. The created intermediates (fermentable sugars) after hydrolysis can then be upgraded to bio-fuels by fermentation.

Using bio-fuels can have environmental benefits, namely that ships emit less sulphate aerosols and particular matter decreases when sailing on vegetable oils [7]. Also when an accident happens and fuel is leaking into the sea, bio-diesel degrades more quickly than the fossil version. Last, the toxicity of bio-diesel for aquatic organisms is lower compared to fossil diesel.
There are also disadvantages of using bio-fuels, maintenance of filtration systems increases (clogged up filters) and sludge and bio-film formation increases due to the increase of activity of microorganisms [109]. The most significant disadvantage of biomass is that a lot of space is needed in order to produce a significant amount of biomass for our energy consumption. The power density in terms of surface of land is 1000 times higher for biomass ($0.8W/m^2$ than for natural gas ($1000W/m^2$) [103].
An overview of all advantages and disadvantages of using biomass as feedstock are shown in table 2.3.

Table 2.3: Advantages and disadvantages of using biomass

Advantages	**Disadvantages**
Decrease in sulphate aerosols	Increased maintenance
Decrease in particular matter (PM)	Low power density per surface of land (W/m^2)
More biodegradable than fossil fuels	

2.1.3. Natural gas

Natural gas (NG) is also a possible resource for the production of alternative fuels. Natural gas is a gaseous hydrocarbon mixture that has been formed under the surface by heating and compressing layers of biomass over millions of years. So it is a fossil fuel, which means it is an exhaustible source. However, it is one of the cleanest fossil fuel due to the the low emissions of sulfur-dioxide, nitrogen-oxides and carbon-dioxide when combusted. Despite that is relatively clean, natural gas is a greenhouse gas in itself, because it can contain up to 96% methane (vol%) [28]. Methane released in the atmosphere will cause a greenhouse effect 25 times greater than carbon dioxide [13]. So it is evident that during the production process and usage of alternative fuels, extra attention should be drawn towards the methane emissions.
In order to produce alternative fuels from natural gas, a technique called steam reforming is used which will be explained in more detail in section 2.2.

Potential fuels that are produced by using steam reforming are listed beneath:

- Blue/grey hydrogen
- Blue/grey ammonia
- Blue/grey methanol

Hydrogen is directly produced by steam methane reforming (SMR), but for the creation of ammonia it needs to undergo a second process, called the Haber-Bosch process as mentioned in section 2.1.1. Also for the creation of methanol, an additional synthesis process is needed, namely the reaction of hydrogen with CO_2 and CO which is visualised in equation 2.3.
An overview of advantages and disadvantages of using natural gas as feedstock are shown in 2.4.

Table 2.4: Advantages and disadvantages of using natural gas

Advantages	**Disadvantages**
Currently in large volume available	Exhaustible source (fossil resource)
Cleanest fossil resource (low NO_x, SO_x and CO_2)	Large impact on greenhouse effect (CH_4 = 25x CO_2eq)
Relatively easy to convert into H_2 (SMR)	

2.1.4. Sub-conclusion

In this section, three potential feedstocks were analysed, namely green electricity, biomass and natural gas. It can be concluded that for most of the alternative fuels, all three feedstocks are an option, although certain feedstock are more suitable for the production of a specific fuel than others. Concerning GHG-emissions, fuels produced by using green electricity and biomass have the least impact due to the circularity of CO_2 in the total process. Fuels produced from natural gas will have a bigger impact on the environment.

2.2. Production methods of fuels

The different feedstocks from which alternative fuels can be produced are known, but how can these feedstocks be converter into usable energy carriers? In this chapter, production methods for hydrogen, methanol, ammonia, methane and diesel are evaluated and compared on different aspects, such as efficiency and technical maturation.

2.2.1. Hydrogen production (H_2)

The production of hydrogen is performed in several ways as mentioned in the previous section. The most environmental friendly way is by using green electricity for the electrolysis of water. However, most of the hydrogen is currently produced by using fossil fuels as main feedstock. In figure 2.5, it can be seen that 96 % of hydrogen is produced by using fossil fuels with natural gas (48%) as largest resource. Only 4% of the total production of hydrogen is done via electrolysis and mainly from chlor-alkali processes which produces hydrogen as co-product. In section 2.1, it was approximated that 29% of the total generated electricity comes from a renewable source (wind, sun etc.), which would mean that slightly more than 1% of the produced hydrogen is e-hydrogen (green).

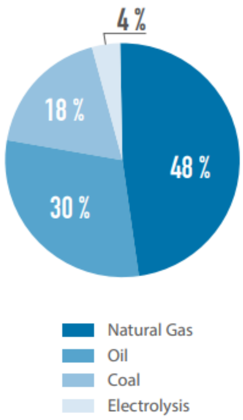


Figure 2.5: Division of resources for hydrogen production [41]

So the largest resource of hydrogen is natural gas. To convert natural gas into hydrogen a certain technique is used, called steam reforming. With this technique hydrocarbons (C_nH_{4n}*) are converted to hydrogen and carbon-oxides (CO_2 and CO). There are more techniques to convert natural gas into hydrogen, but steam reforming is the most used technique in industry. One of the reasons that steam reforming is the most used technique, is that it has the highest hydrogen to carbon-oxides ratio (H_2/CO ratio) compared to other processes, lowest process temperature and oxygen is not used in the process [38]. Unfortunately, the disadvantage of using this technique is it has the highest carbon-dioxide emission compared to other techniques.
In more detail, due to the composition of natural gas, which consist of 85% to 90% methane, the technique is named steam methane reforming (SMR). The chemical equations of steam methane reforming is visualised in table 2.5.
*single bonds

Table 2.5: Steam methane reforming equations (SMR) [63]

Process	Reaction Equation	H_2/CO Ratio	ΔH (kJ/mol)
Steam reforming (SR)	(1) $CH_4+H_2O \rightarrow CO+3H_2$ (2) $CO+H_2O \rightarrow CO_2+H_2$	≥3	206 −41

The first SMR reaction is endothermic which means it requires energy to react. The second equation is exothermic and releases energy. Overall the process requires energy to create hydrogen out of methane due to smaller energy released by the second reaction.

Biomass is an alternative feedstock for producing hydrogen. However, currently the production of hydrogen via biomass is neglectable compared to the overall production. Also, it is more favorable to produce hydrocarbon fuels, such as diesel or methane, because it requires less energy to produce and has a higher volumetric energy density.

The most familiar way of producing hydrogen is via splitting water into hydrogen and oxygen. In principle there are three categories of techniques that can be used to produce hydrogen, namely electrolysis, thermolysis and photo-electrolysis [38].
Electrolysis is the most simplest way to produce hydrogen, because it only uses electricity which is run through two electrodes to create hydrogen. Already multiple commercial electrolyzers are available, with efficiencies around 56-73%.
With thermolysis, heat is required to decompose water into hydrogen, but in order to decompose water a temperature of 2500 °C is necessary. Due to this high temperature technical challenges arise, such as finding material that can cope with these extreme temperatures.
Photo-electrolysis is splitting water by using sunlight (photons) and semiconductor materials. Currently, this technique is still in the research phase and could be useful in the future, because it directly uses a renewable energy resource.

So the production of hydrogen by electrolysis has already a certain level of maturity compared to the other two categories of techniques. There are several technologies that can perform electrolysis, presented in the following list:

- Alkine water electrolysis (AWE)
- Proton exchange membrane electrolysis (PEM)
- Solid oxide electrolysis (SOE)

Alkine electrolysis is a technique which involves an electrolyzer with two electrodes operating in an liquid alkine electrolyte. Usually this electrolyte is Potassium hydroxide (KOH) or sodium hydroxide (NaOH) . The electrodes are separated by a porous diaphragm which prevents the oxygen and hydrogen to mix and lets the ions (OH^-) through for the chemical reaction. In figure 2.6, a schematic overview is given with the chemical reactions.

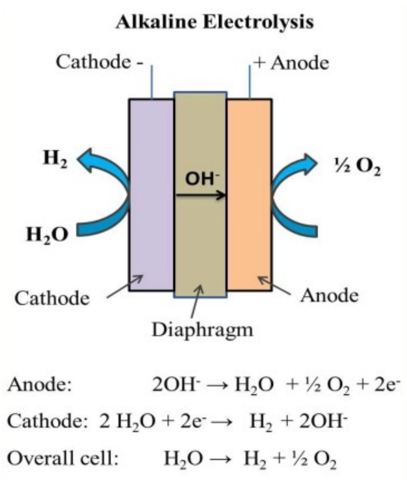


Figure 2.6: Schematic process of an alkine electrolyzer [85]

On the cathode side, water is decomposed into hydrogen and hydroxyl ions (OH-) and on the anode side hydroxyl ions, which traveled through the porous diaphragm under the influence of the electric circuit, are formed into water and oxygen. Net production of hydrogen out of water, is one molecule of water is converted into one molecule of hydrogen.

Solid oxide electrolysis also works with electrodes, but the main difference is in the electrolyte which is now a solid, usually an oxygen ion-conducting ceramic. Also, an oxygen ion travels trough the electrolyte (membrane) of the electrolyzer instead of a hydroxyl ion. In figure 2.7, a schematic overview can be seem with the chemical equations.

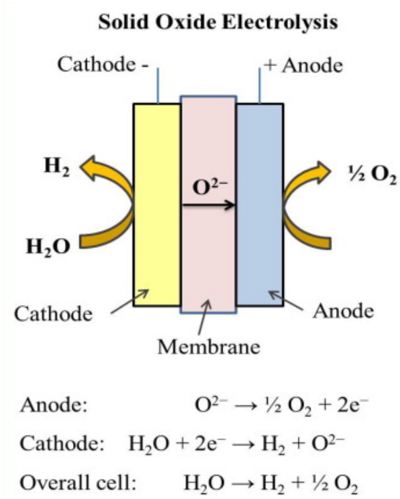


Figure 2.7: Schematic process of solid oxide electrolysis [85]

The reaction starts at the cathode side by splitting one water molecule into one hydrogen molecule and one oxygen ion. This oxygen ion travels through the electrolyte membrane to the anode side to be formed into oxygen.

PEM electrolysis has in principle the same concept in producing hydrogen as SOE and AWE electrolysis, but has a different electrolyte/membrane. Now solid polysulfonated membranes are used to conduct protons (H^+) from the anode side to the cathode side. So the reaction starts at the anode instead of the cathode by splitting a water into protons and oxygen as can be seen in figure 2.8. At the cathode side, this proton is then reacted into hydrogen under the influence of the electric circuit.

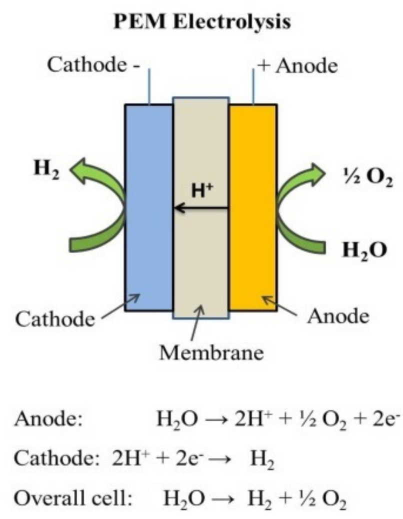


Figure 2.8: Schematic process of PEM electrolysis [85]

To compare the different electrolysis technologies that have been elaborated earlier, advantages and disadvantages are given in table 2.6.

Table 2.6: Advantages and disadvantages of different electrolyzers [85][111]

	AWE	SOE	PEM
Advantages	• Established technology • High power (MW range) • Inexpensive (non noble metals)	• High efficiency (90-100%) • Production of ultra clean hydrogen • Less expensive (non-noble metals)	• High efficiency (80-90%) • Compact design • Fast response • Production of ultra clean hydrogen • High hydrogen production rate
Disadvantages	• Low current densities • Less energy efficiency (70-80%) • Less pure hydrogen (gas crossover) • Slow response	• Low durability • In development • Large system	• High production costs (expensive noble metals) • Low durability • Low power output (kW range) • On short term commercial

On short term the production of hydrogen is most suited for alkine water electrolyzers due to the high power output and well established technology. For the near future, PEM electrolyzers could play a role for the production of hydrogen due to their high efficiency, high hydrogen production and compact design. But first the cost effectiveness should be improved. Solid oxide electrolyzers have great potential, but are still in the developing phase.

2.2.2. Methanol production (CH_3OH)

Methanol can be produced from all three feedstocks. As can be seen in figure 2.9, less than 1% of the total methanol production produced out of a renewable source, such as green electricity or biomass. Almost 65% of the methanol is extracted from natural gas and the rest out of coal.

Figure 2.9: Methanol feedstock [42]

The production of methanol out of natural gas follows the same principle as the production of hydrogen out of natural gas, but an extra step is added to the process after SMR. After SMR, a mixture gas is created, called syngas (H_2, CO and CO_2). This syngas is converted by use of catalysts into methanol at low temperatures and high pressures. The chemical reactions are:

$$\begin{aligned} CO + 2H_2 &\leftrightarrow CH_3OH \\ CO_2 + 3H_2 &\leftrightarrow CH_3OH + H_2O \\ CO + H_2O &\leftrightarrow CO_2 + H_2 \end{aligned} \tag{2.1}$$

Production by this method produces grey-methanol, because CO_2 is not captured and stored before the synthesis happens. If this carbon capture and storage (CCS) does happen after the SMR process, methanol becomes carbon neutral and so blue-methanol.

Bio-mass is a renewable source from which methanol can be produced. All the processes that are mentioned in section 2.1.2 are suitable for the production of methanol. However, gasification of low-moisture biomass is the most suitable process for creating methanol, with an efficiency around 55% [10]. This gasification of biomass can be performed with only oxygen, but also steam can be added to the process which makes the process comparable to SMR. The simplefied chemical reaction with glucose is visualised in equation 2.2. Apart from glucose, many other intermediates from cellulose (main component biomass) can be gasified. The second equation of the gasification process is the water-gas shift reaction, which transforms the CO from the first reaction into hydrogen and CO_2.

$$C_6H_{12}O_6 + O_2 + 2H_2O \rightarrow 2CO + 4CO_2 + 8H_2$$
$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2.2}$$

From the produced hydrogen, methanol can be synthesized by reacting with carbon dioxide by the following reaction;

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \tag{2.3}$$

As a bio-fuel, methanol is the most promising carbon-neutral fuel types for the long term [36]. One reason is the scalability of bio-methanol that has favorable growth potential from 2040s, as can be seen in figure 2.10.This potential can be linked to the bio methanol production which is very suitable for different types of biomass resources, such as agriculture waste, woods&residues and energy crops. From these sustainable global resources (200 EJ maximum), 127 EJ of bio-methanol could be potentially produced [57]. The scalability is again dependent on the production throughput, technological maturation and reliable supply chains, which is also more favorable for bio-methanol [58].

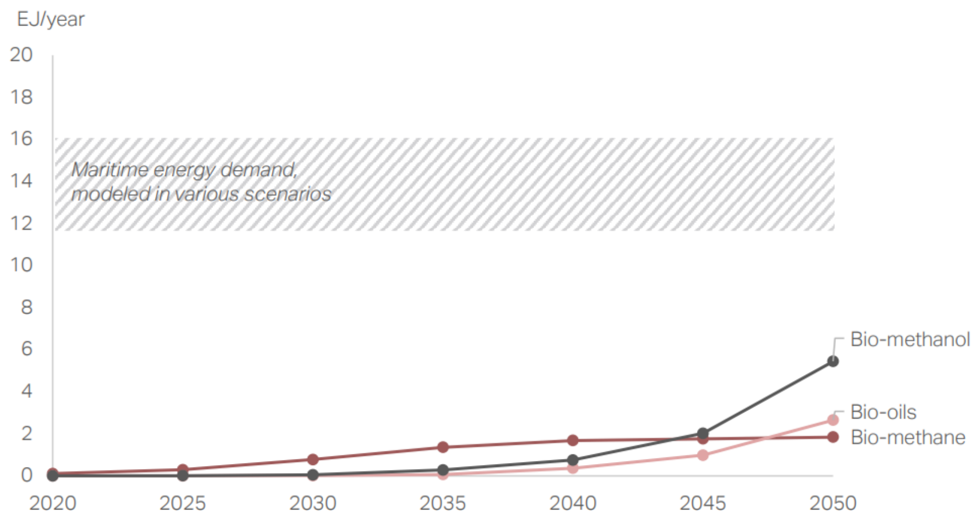


Figure 2.10: Bio-methanol production in Exajoule per year [58]

As an e-fuel, methanol is a promising fuel due to the low carbon intensity. E-methanol is produced by green hydrogen (e-hydrogen) and an additional process. This process is identical to the reaction in equation 2.3, but the hydrogen originates from a different feedstock. The carbon dioxide used in the production process should be circular, so captured from the atmosphere (DAC) or have an bio origin.

2.2.3. Ammonia production (NH_3)

Ammonia can also be produced by all feedstock, but has a slightly different division than hydrogen and methanol, as can be seen in figure 2.11. Overall, the most used feedstock are fossil fuels (98%) with natural gas (74%) as largest resource. The renewable resources, such as green electricity and biomass, will be in the 2% part of the total feedstock. This is comparable to the previous two alternative fuels.

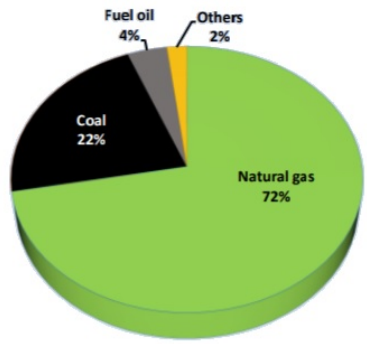


Figure 2.11: Ammonia feedstock [30]

The production of ammonia from natural gas follows the same path in the beginning phase as methanol and hydrogen, but starts to differ after the production of syngas. The hydrogen from the syngas is used to create ammonia by a second process, called the Haber-Bosch process (HBP) . This industrial process which is an electro-chemical process with an iron-based catalyst, makes it possible to produce ammonia by reacting hydrogen with nitrogen at high pressures (150 - 300 bar) and high temperatures (400 - 600°C) [16]. In equation 2.4 the chemical reaction is stated. The nitrogen that is used in the chemical reaction with hydrogen is usually captured from the atmosphere by use of cryogenic air separation units [31].

$$3H_3 + N_2 \rightarrow 2NH_3 \tag{2.4}$$

It depends on the capture of CO_2 after SMR if ammonia produced by natural gas, is grey or blue ammonia.

Ammonia from biomass is a sustainable production method. The ammonia is produced from hydrogen that is extracted from the biomass by one of the methods described in section 2.1.2. After the production of bio-hydrogen, ammonia is produced by the Haber-Bosch process.

Producing ammonia from green electricity can be performed by two methods, namely from hydrogen produced by electrolyzers as described in section 2.2.1 and by use of a solid-state ammonia synthesizer [20]. Compared to Haber-Bosch process there are some differences in synthesizing ammonia from a solid-state ammonia synthesizers. In figure 2.12, an overview is given of the possible routes to produce ammonia.

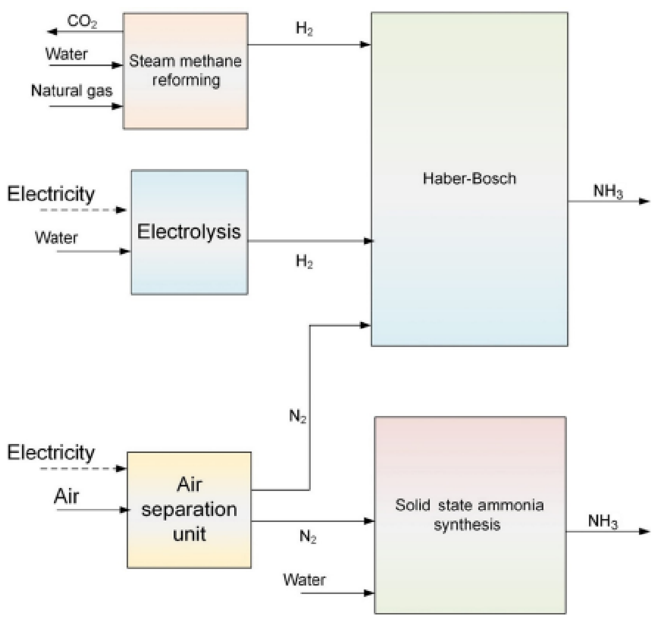


Figure 2.12: Overview of production process ammonia [20]

Here the difference between the two processes is already visible, because the solid-state synthesizer consumes nitrogen and water instead of nitrogen and hydrogen. In equation 2.5 the chemical reaction is shown which takes place in the solid-state reactor.

$$2N_2 + 6H_2O \rightarrow 3O_2 + 4NH_3 \tag{2.5}$$

The advantage of this process over the Haber-Bosch process, is that hydrogen does not have to be produced in advance by SMR or electrolysis of water and has pure oxygen as byproduct (added value). Also, the process is a electro-chemical type of process (same as the electrolyzers) which means that only electricity is the energy source. In figure 2.13, the electro-chemical reaction process is visualised in a schematic manner with the corresponding chemical reactions.

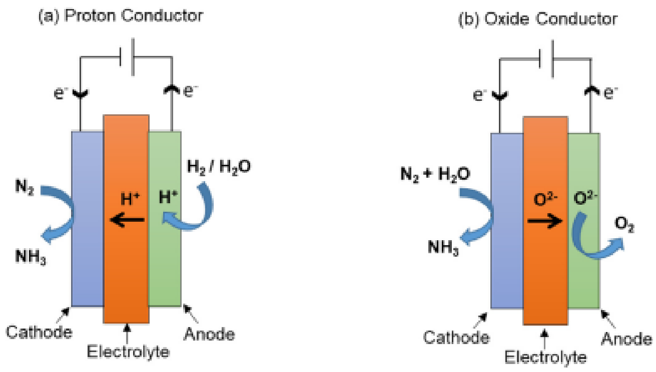


Figure 2.13: Solid state ammonia synthesizer [33]

$$Anode : 6H_2O \rightarrow 12H^+ + 12e^- + 3O_2$$
$$Cathode : 2N_2 + 12H^+ + 12e^- \rightarrow 4NH_3$$
$$Total : 2N_2 + 6H_2O \rightarrow 4NH_3 + 3O_2$$

$$Cathode : 6H_2O + 2N_2 + 12e^- \rightarrow 4NH_3 + 6O^{2-}$$
$$Anode : 6O^{2-} \rightarrow 3O_2 + 12e^-$$
$$Total : 2N_2 + 6H_2O \rightarrow 4NH_3 + 3O_2$$

So there are two possible methods to produce ammonia via a solid state synthesizer, namely with a oxygen ion electrolyte and a proton electrolyte. The disadvantage if this system is that the ammonia yield is quite low compared to the HB-process. Currently, the synthesizers are still in the research phase, but could play a role for small scale production of ammonia in the future due to the highly capital intensive Haber-Bosch process [33]. It could even reduce energy consumption by a factor 1.3 compared to the production of ammonia out of natural gas with HB-process (7500 kWh to 9700 kWh) [33].

2.2.4. Methane production (CH_4)

Methane production is relatively easy when produced from natural gas due to the composition of the gas (up to 96% methane). In order to extract the methane out of natural gas, membranes are used to let CO_2 through and block methane (CH_4) from passing [68]. This process is however not renewable and carbon intensive (high CO_2/CH_4 emissions).

A more renewable method to produce methane is via biomass. Biomass can be converted to biogas by use of gasification, which is the most used process due to the high efficiencies. The biogas then has to be upgraded in order to be used as bio-methane by applying the Fischer-Tropsch process which is visualised in equation 2.6. The process occurs under a pressure of 20-25 bar and at a temperature of 200-350 °C. The upgrade also includes the removal of non-flammable components such as sulfur and CO_2.

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{2.6}$$

The production by use of green electricity as primary feedstock, is also possible with an extra step after the production of hydrogen via electrolysis. This process is called the Sabatier reaction and transforms hydrogen and CO_2 into methane by the following process.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{2.7}$$

The Sabatier reaction takes place at elevated temperatures around 300-400 °C with pressures around 30 bar and by use of a nickel catalyst.

2.2.5. Diesel production ($C_{10}H_{20}$ to $C_{15}H_{28}$)

Diesel as a fuel has been around for quite some time, with the prime model diesel engine created by Rudolf Diesel in 1893 [64]. For decades diesel has been produced from crude oil by a refinery process. But the interest in bio/renewable diesel increases every year due to the stricter environmental regulation and easy adaptations of the engine. A steady increase of bio diesel can be seen in figure 2.14, with a total worldwide production around 45.000 million litres of bio diesel in 2020. Compared to diesel production from fossil resources (crude oil), that is approximately 1.425.244 million litres of diesel per year (2020), when producing 11 gallons of diesel out of 42 gallons of crude oil [98], bio diesel has only a market share of 3.2%.

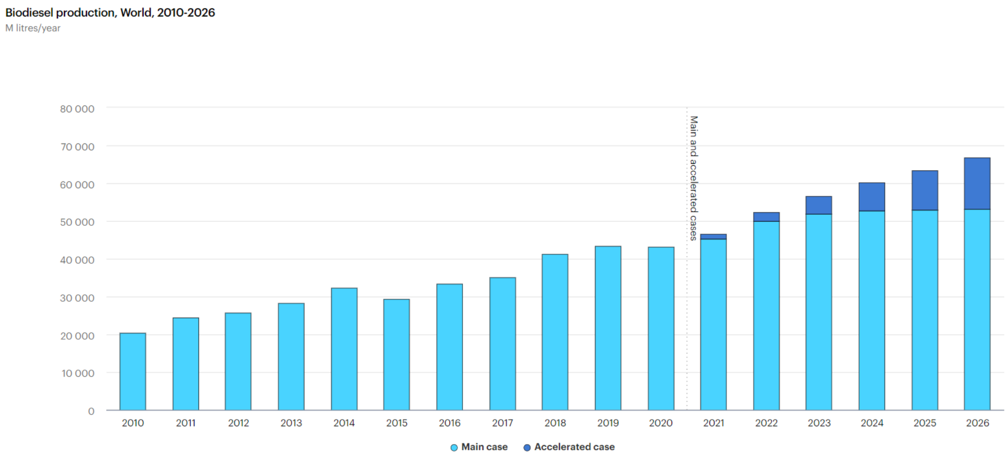


Figure 2.14: Bio diesel production worldwide [39]

The most used technique to produce diesel from a renewable feedstock is by using biomass. Biomass for the production of bio-diesel favors a deconstruction of biomass resources into bio-oils that already have a high CH-number. Pyrolysis is a potential method to produce bio-oil intermediates to be upgraded to bio-diesel in a further stage, but also hydro-thermal liquefaction is an option. Unfortunately, high temperature deconstruction of biomass has a low efficiency, inconsistent quality, low yields and high operational costs [110].

Diesel can also be produced by use of electricity, this type of fuel is also known as e-diesel. E-diesel is a hydrocarbon fuel within a certain CH-range which is visualised in section 2.1.1. Two methods can be used to produce e-diesel, namely via the Fischer-Tropsch process or methanol to diesel synthesis [102]. The Fischer-Tropsch process will have the focus due to the direct synthesis of diesel via hydrogen and CO. The temperature of the Fischer-Tropsch process ranges between 190-350 and pressures between 20-45 bar °C [34]. The chemical reaction is comparable to the equation in section 2.2.4, but now a series of reactions take place of which the main reactions are shown in the following equations:

1. $nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + 2 + nH_2O$
2. $nCO + 2nH_2 \rightarrow C_nH_{2n} + nH_2O$
3. $CO + H_2O \rightarrow CO_2 + H_2$

The first equation is the reaction that takes place to create paraffins (alkanes) which are straight or branched hydrocarbons with single bounds (propane, hexane ect.). The second equation is one of the main reactions that create olefines (alkenes) which are unsaturated hydrocarbons and have at least a double carbon-carbon bound (Propene, hexene ect.). The last reaction is the WGS-reaction (water gas shift) that happens when carbon monoxide reacts with steam. In the end the catalyst type (usually cobalt or iron) and reaction conditions determine the distribution of the hydrocarbon chain lengths which for e-diesel has to lie within the C_{10} to C_{15} range and preferable alkanes [34].

2.2.6. Energy consumption comparison from Well-to-Wake

In order to compare the different fuels and especially alternative fuels, it is necessary to take the whole chain from production to usage into account. In figure 2.15, the total energy consumption is shown for several fuels and batteries, with in green the fuels from the green electricity feedstock and in grey fuels from fossil feedstocks. Batteries seem to be the best solution when looking at the energy consumption, with fossil fuels as second best option. The difference between fossil fuels and batteries, is mainly caused by conversion efficiency of an internal combustion engine (ICE) ($\sim$ 50%). A good reference point to compare the renewable fuels to fossil fuels, would be Marine Gas Oil (MGO) due to the widely usage of this fuel in short sea shipping. MGO has a consumption of 2.4 KWh for 1 kWh at the propeller, which is a factor 2.5 lower than green hydrocarbon fuels, that lie in the range of 6.1 to 7.1 kWh. This means that the energy consumption increases significantly when these renewable/green fuels are implemented in the maritime sector. However due to the relative new techniques and evolving technology, the consumption can be reduced by 10-15 % according to the figure. In the end, the fuel with the lowest energy consumption and produced by using green electricity, is e-ammonia which has also been presented as a promising fuel candidate due to lower production costs [58] [36]. Diesel has the highest energy consumption from well-to-wake, with methanol, methane (LNG) and hydrogen in between those two.

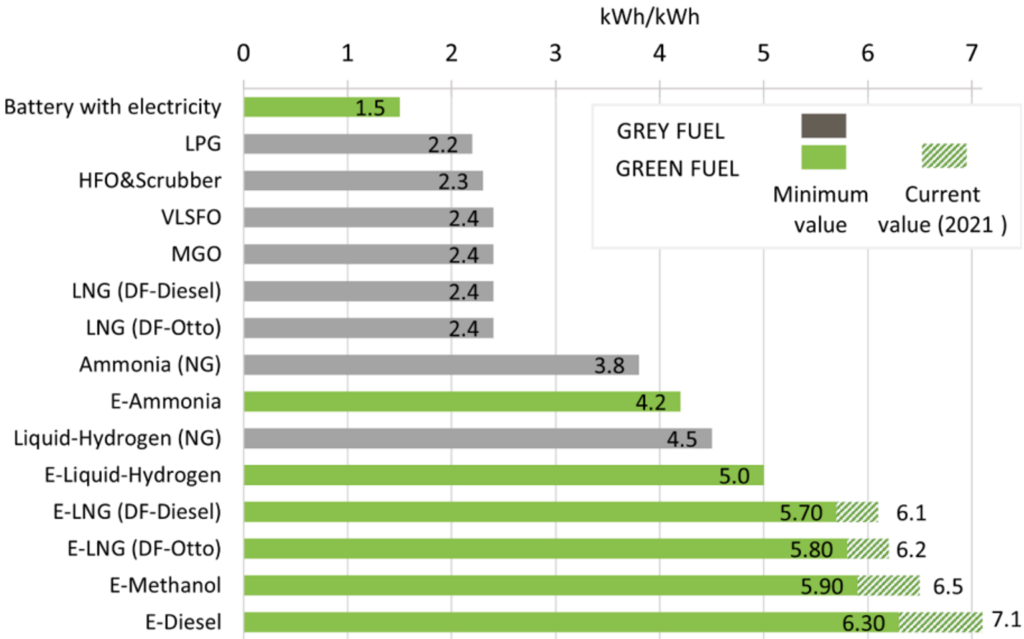


Figure 2.15: Energy needed per fuel type to deliver one kWh at the propeller (Well-to-Wake) [52]

2.2.7. Sub-conclusion

After analysing the production process, it became clear that almost all of the alternative fuels are currently produced out of fossil resources with as main feedstock natural gas. Steam methane reforming (SMR) is the most used technique to produce alternative fuels, with hydrogen as building block. For the future, interesting technology for the production of alternative fuels (direct or indirect) are electro-chemical synthesizers due to the high efficiency and the possibility to use green electricity. Also a comparison was made in the well-to-wake energy consumption of relevant fuels that confirm the additional amount of energy which is needed to produce e-fuels. It could be stated that most of the alternative fuels need 2.5 times more energy to produce the same amount of energy at the wake. Only e-ammonia (1.8 times) and e-hydrogen (2.1 times) where considerably lower in total energy consumption.

2.3. Fuel properties comparison

Now the different feedstocks and production processes are discussed for producing alternative fuels, the alternative fuels are analysed on their properties. Important chemical properties, such as energy density, boiling point, flash point and flammability levels are evaluated.

2.3.1. Hydrogen properties

Hydrogen is the most occurring element in the universe with a simple structure which consist of two hydrogen elements connected by a single covalent bond. It is a non-toxic, odorless, colorless and highly combustible molecule. However, hydrogen does not exist in its pure form in large amounts, because naturally it is bounded to other elements (H_2O, CH_4 ect.). In order to determine the possibility to implement this fuel for maritime purposes, properties have to be described and evaluated. Fuel properties of hydrogen differ due to the different physical states in which it can be stored. In principle hydrogen can be stored as a liquid or gas. In table 2.7, the important properties of hydrogen at specific temperatures and pressures are visualised. Hydrogen has a high mass energy density or lower heating value (LHV) compared to other fuels which makes it the most suitable fuel to be used in the space industry as rocket fuel. However, in the maritime industry the volumetric density is a more important parameter due to the limited space on board of ships and the consequences for the cargo hold dimensions. Due to the low density of hydrogen in gaseous state, it needs to be compressed or liquefied which is an energy consuming process. This increases the volumetric density to a value of 8.4 MJ/L if liquefied which is still approximately 5 times lower than diesel fuels. This brings major challenges with it when implementing this fuel in sea going vessels.

Table 2.7: Properties of Hydrogen [74]

H —— H	**Properties**
Molecular formula	H_2
Molar mass	2.02 g/mol
Volumetric energy density	8.4 MJ/L (Liquefied @-255 °C) 6.8 MJ/L (Compressed @700 bar)
Mass energy density (LHV)	120 MJ/kg
Auto ignition temperature	585 °C
Boiling point	-252.87 °C (@ 1 bar)
Flash point	-253 °C
Flammability level	4-75 (v/v)%

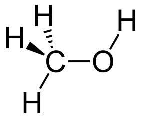
The auto ignition temperature, which is the lowest temperature for fuel to spontaneous combust at atmospheric conditions, is relatively high compared to diesel fuels. This would imply that it makes it less sensitive to ignition, but due to the low minimum ignition energy of 0.017 mJ [32], it is very likely to be ignited by electrostatic discharge when a leakage occurs. Concerning the boiling point, this is very low compared to other gases such as methane, which means a lot of energy is needed to liquefy hydrogen as mentioned before. Also these low temperatures will have an influence on the ships structure, because iron becomes very brittle at cryogenic temperatures. The flash point of hydrogen has also the lowest value for all alternative fuels discussed in this chapter, which means less complicated starting and ignition equipment is needed for hydrogen engines [60]. Easy starting of engines in low temperature environments is even possible. Another positive property of hydrogen is the flammability level, which has a very wide range for hydrogen. This means that fuel-air mixture can be very different and this make the fuel very suitable for many application.

2.3.2. Methanol properties

Methyl alcohol, better known as methanol, is a chemical substance and is the simplest alcohol in the alcohol group. Methanol is at ambient temperature and atmospheric pressure a colourless liquid, soluble in water and biodegradable [47]. The substance has a sweet an pungent odour that is comparable to other alcohols, such as ethanol and is very toxic. Its chemical structures, which is visualised in table 2.8, consist of a carbon element which is connected to three hydrogen elements and one hydroxyl group (-OH) via a covalent bond. Methanol can be produced from various feedstocks as mentioned in section 2.2, with NG currently as largest feedstock for industry. Methanol is also one of the main building blocks for other chemicals which are used to produce a wide range of products, such as paints, polyesters, plastics and many other.

The volumetric density of methanol is significantly larger than that of hydrogen and slightly larger than ammonia. However compared to conventional fuels, such as diesel, the space required to store methanol is 2.2 times larger. Also the mass energy density is 2 times lower than fossil diesel, which means more fuel has to be stored for the same amount of energy or the operation range needs to be decreased. Auto-ignition point of methanol is lower than hydrogen and methane, but still much higher than that of diesel which makes it more difficult to ignite [1].

Table 2.8: Properties of Methanol [47]

	**Properties**
Molecular formula	CH_3OH
Molar mass	32.04 g/mol
Volumetric energy density	15.8 MJ/L (Liquefied @20 °C)
Mass energy density (LHV)	19.9 MJ/kg
Auto ignition temperature	470 °C
Boiling point	64.6 °C (@ 1 bar)
Flash point	12 °C
Flammability level	6.7-36 (v/v)%

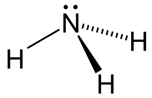
The boiling point of methanol at atmospheric pressure is around 65 °C, so no energy has to be put in to store it in an efficient manner which is an advantage compared to hydrogen and methane (gases). Concerning the flash point, this value is lower than the ambient temperature which means that methanol can create a vapor (methanol-air mixture) at these temperatures which will ignite in an invisible flame when exposed to an ignition source. The flammability levels are within a range of 6.7 to 36 (v/v)% (volume percentage of vapor in air) which is relatively wide and makes it suitable for multiple applications.

2.3.3. Ammonia properties

Ammonia is one of the most produced chemical substance and mostly used for the production of fertilizers. Ammonia is a carbon free and highly toxic substance and the molecule structure consist of a nitrogen element which is connected to three hydrogen elements via covalent bonds as can be seen in the picture of table 2.9. At ambient temperature and atmospheric pressure ammonia is a colorless gas with a strong pungent odour. So in order to store ammonia in a liquid state, ammonia has to be cooled down beneath -33.4 °C (Boiling point) or pressurized to approximately 10 bar [20]. This means that less energy is needed to store ammonia compared to hydrogen and methane.

The volumetric energy density of ammonia is less than that of methanol and significantly larger than hydrogen. However, as energy storage medium for hydrogen, ammonia has a higher hydrogen content in weight percentage than methanol (17.6 wt% over 12.5 wt%) [31]. The mass energy is comparable to methanol and so significantly lower than conventional fossil fuels (diesel).

Table 2.9: Properties of Ammonia [31]

	**Properties**
Molecular formula	NH_3
Molar mass	17.031 g/mol
Volumetric energy density	12.7 MJ/L (Liquefied @ -34 °C or 10 bar)
Mass energy density (LHV)	18.6 MJ/kg
Auto ignition temperature	630 °C
Boiling point	-33.4 °C (@ 1 bar)
Flash point	132 °C
Flammability level	15-28 (v/v)%

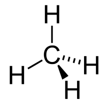
The auto-ignition temperature is the highest of all mentioned fuels and this means it is very hard to burn in its pure form [99]. This is an advantages concerning the safety of the fuel, because it is less likely to ignite.

2.3.4. Methane properties

Methane is the simplest alkane and as mentioned before it is the main component of natural gas. The chemical structure of methane consist of one carbon element connected to four hydrogen elements via a covalent bond. On Earth, methane gas is a relative abundant chemical which makes it suitable to be used as a fuel in economical sense. At ambient temperatures and atmospheric pressure methane is a gaseous substance with a boiling point of -161.5 °C. So if stored in a liquid phase, methane has to be cooled down below the boiling point at atmospheric pressure or cooled down to the critical temperature under a certain pressure (-82.6 °C, 46 bar). Methane is flammable, colourless, non-toxic and naturally odorless gas (usually a scent is added to the gas). If emitted into the atmosphere, methane has a large impact on the greenhouse effect, because it has a 100 year global warming potential (GWP) of 25x CO_2 [5].

The volumetric density of methane is relatively high compared to methanol and ammonia, but still a factor 1.5 smaller than conventional diesel. So, less space is needed to store the same amount of energy compared to methanol and ammonia. Compared to hydrogen (liquefied) it is almost a factor 3 difference in volumetric energy density. It is however dependent on the efficiency of the used energy converter if the same amount of energy needs to be stored compared to conventional fuels such as diesel. Methane also has the largest hydrogen content of 25.13 wt% compared to ammonia and methanol which results a high mass energy density of 50 MJ/kg. This LHV value is even 16.6% larger than that of fossil diesel.

Table 2.10: Properties of Methane [31]

	**Properties**
Molecular formula	CH_4
Molar mass	16.04 g/mol
Volumetric energy density	23.4 MJ/L (Liquefied @ -162)
Mass energy density (LHV)	50 MJ/kg
Auto ignition temperature	595 °C
Boiling point	-161.5 °C (@ 1 bar)
Flash point	-188 °C
Flammability level	4.4-16.4 (v/v)%

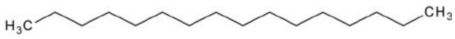
The auto-ignition point of methane is in the range of hydrogen, which means methane is also hard to self ignite. However the flash point is very low, which means it has the same benefits of the less complicated equipment, but the disadvantage to the low flash point is it very flammable and so dangerous when not contained properly.

2.3.5. Diesel properties

Diesel is colorless liquid fuel (if not dyed) and is grouped under the higher alkanes which means it has nine or more carbon atoms in their chemical structure. Diesels are in liquid form under ambient temperatures and atmospheric pressures due to their high boiling point which is caused by the larger attractive intermolecular forces. In table 2.11, two types of alternative diesel fuels with their properties are shown compared to the most used fossil diesel. For all three fuels, the basis of the chemical structure is a straight chain of carbon atoms with hydrogen atoms bonded on the remaining bonding ”spots” (Carbon ”C” has 4 covalent bonding ”spots”). The difference between of FAME bio-diesel and renewable diesel is the additional methyl ester group at the end of the hydrocarbon chain. There are many types of bio-diesels, but FAME-diesel has its origin in vegetable oils which is still the largest type of biomass feedstock [44], so this type of bio-diesel is compared to the renewable and fossil one.

The volumetric density of (bio) diesel has the highest value among all alternative fuels which explains the usage of diesel as marine fuel. Also the mass energy density relatively high compared to methanol and ammonia. Only hydrogen and methane have a significantly higher energy density, but these fuels have to be highly compressed or stored under cryogenic temperatures to increase their volumetric density which is still much lower than diesel.

Table 2.11: Properties of Diesel [17] [66] [27] [21] [104]

	**FAME bio-diesel**	**FT Diesel**	**Fossil Diesel**
Molecular formula	$CH_3(CH_2)_nCOOCH_3$	C_8H_{20} to $C_{15}H_{28}$	$C_nH_{1.8n}$ (C_8 to C_{25})
Molar mass	300-310 g/mol	140 - 208 g/mol	$/sim$ 170 g/mol
Volumetric energy density	32 - 33 MJ/L	33.1 MJ/L	35.4 - 36.1 MJ/L
Mass energy density (LHV)	36 - 38 MJ/kg	43.3 MJ/kg	38 - 43 MJ/kg
Auto ignition temperature	-	-	250/360 °C
Boiling point	330-350 °C	200 °C	150-380 °C
Flash point	91-135 °C	100-180 °C	77 °C
Flammability level	0.6-7.5 (v/v)%	-	-

The flashpoint which is depend on the type of diesel, but varies between 77 and 180 °C which is well above the ambient temperatures and higher than all the other alternative fuels. That makes it a safer fuel concerning explosion caused by diesel-air mixtures.

2.3.6. Sub-conclusion

By analysing the properties of the alternative fuels, it can be concluded that the volumetric and for some cases the gravimetric energy density decrease significantly compared to conventional fuels. Many alternative fuels need more than twice the amount of space to store the same amount of energy compared to diesel, which will have a large impact on the operationality and design of a vessel. Also the flashpoints of many alternative fuels are quite low and in combination with a wide flammability level, this can cause safety issues.

2.4. Fuel utilization comparison

The most important properties of the fuel are known now, so a comparison will be made of several the characteristics. In this way, it becomes more clear which consequences alternative fuels have when they are used. In this chapter, consequences on the energy density, technology readiness, safety, emissions and economics are evaluated and compared to each other.

2.4.1. Gravimetric- and volumetric energy density

In the previous sections, already some comparisons have been made between different fuels and their energy densities. Now in more detail, the differences in gravimetric and volumetric densities are plotted in a graph. In figure 2.16, all fuels that have been mentioned in the previous sections are plotted in one figure. For simplification and to make it possible to compare all alternative fuels, FT diesel is equal to synthetic diesel (type of synthetic diesel) and LNG is assumed to be equal to liquefied methane due to the high volume percentage of approximately 95% in LNG [90]. Also a common way to produce synthetic diesel is by performing the Fischer-Tropsch process.

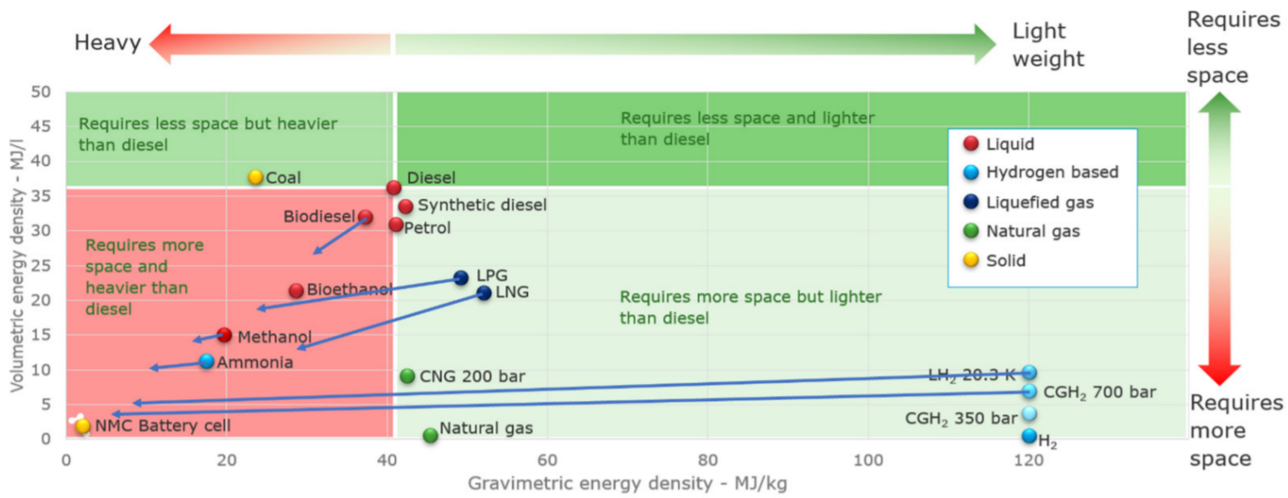


Figure 2.16: Comparison of alternative fuels on gravimetric and volumetric density [79]

In this comparison graph, it can be seen that all the alternative fuels have a reference fuel which is diesel. This makes it easier to identify the impact on space requirements, weight increase and operational requirements of vessels. Another noticeable depiction of the alternative fuels in the graph are the blue arrows which portrays the impact of the storing systems on the gravimetric and volumetric energy density. These values are indication values, so should be interpreted as such.

As can be seen in figure 2.16, all alternative fuels (Hydrogen, Methanol, Ammonia, Methane and bio/synthetic diesel) have a lower volumetric energy density than diesel. Concerning the gravimetric energy density, only hydrogen and methane (LNG) have a significantly larger value. Then again, due to the impact of storage systems of these gases, even more space and weight could be needed than diesel. The reason behind this decrease in volumetric and gravimetric energy density of these gaseous alternative fuels will be discussed in part II of the report.
Furthermore, only bio-diesel and synthetic diesel come close to the beneficial properties of fossil diesel with a few percentage of decrease in volumetric energy density and a couple of percentage of increase in gravimetric energy density for synthetic diesel (FT-diesel).
Methane (liquefied) is the first alternative fuel that is significantly different than diesel in terms of the chemical structure and has the largest volumetric and gravimetric density compared to the analysed alternative fuels. Despite the most beneficial fuel concerning these two properties, a decrease of approximately 40% in volumetric energy density is visible. Methanol and ammonia even decrease respectively by 60% and 65% in volumetric energy density. The consequences for the gravimetric density are also significant, because this will decrease by approximately 50%.

2.4.2. Technology readiness

Many alternative fuels are being considered for only a short amount of time. The Paris agreement, which is a binding international treaty between many countries to reduce the environmental impact, has been signed only 6 years ago. So it is not a long time ago that we agreed on reducing global warming. Technology and infrastructure to use these alternative fuels are also under development to become commercially available or still in the research phase. The time to develop a technology for a certain alternative fuel is dependent on current barriers, such as safety regulation or investment costs. Every new fuel has its challenges to become an energy carrier that can be used on a large scale in the maritime sector. However some fuels are further in the development process to become the new fuel than others.
In this section, methane and diesel are not of interest due to the already commercial application of these fuels.

As can be seen in figure 2.17, an outlook has been created for ammonia, hydrogen and methanol. There has been made a distinction in energy converter due to the difference in maternity. Fuel cells are relatively underdeveloped compared to internal combustion engines (ICE), because research is still being performed in developing phase for most of the fuel cells. However they are not unimportant for the creation and conversion of fuels, because of their potential to increase well-to-propeller efficiency which results in fuel savings [83].
The colours indicate the level of readiness and when the timeline reaches the green part of the bar, it can be commercially applied in the maritime sector. For ammonia and hydrogen the developments are still in an early phase and

not ready for a commercially application. For methanol it is a different story concerning the commercial readiness for applying an ICE on board of vessels. This is due to the fact that there are currently less barriers than ammonia or hydrogen. Multiple reasons are already mentioned in this report, such as the storage in liquid form at ambient conditions and solutions are propose to solve the low flashpoint properties. Another big advantage is the availability of two stroke engines that can run on methanol with an operating time over 100.000 hours [36].

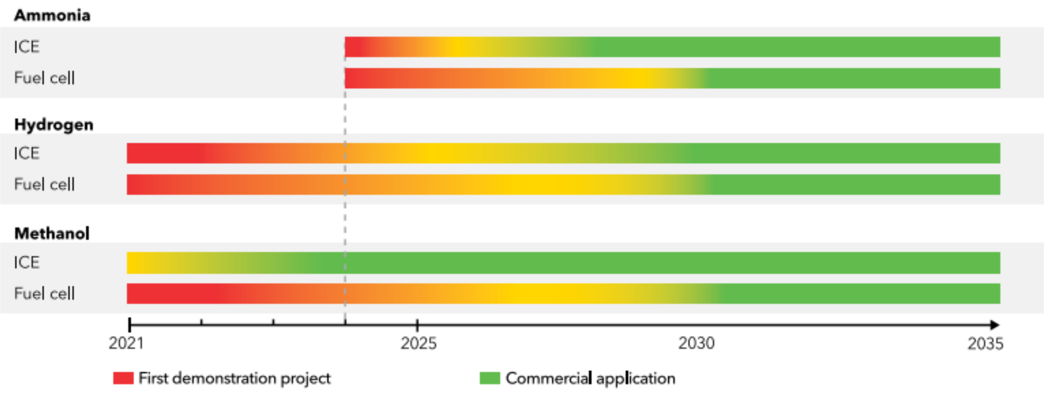


Figure 2.17: Timeline of technological readiness of three alternative fuels [36]

Due to the high level of readiness, the alternative caught some interest of maritime companies. In cooperation with the Dutch government, 22 companies and institutions are performing research on the application of new power- and energy systems with methanol as main fuel. This project, called "Methanol als Energiestap Naar Emmissieloze Nederlandse Scheepvaart" (MENENS) , has as goal to verify and validate safe, modular and forward compatible power- and energy systems with methanol. As one of the members of this project for Thecla Bodewes Shipyards knowledge is shared to develop these methanol systems and make it possible to implement them in coasters. So as primary energy carrier, methanol is being considered as suitable replacement for conventional fuels.

2.4.3. Fuel safety aspects on board of vessels

Concerning the safety of the alternative fuels onboard of seagoing vessel, there are several aspects which could play a role. Hazards associated with fuels is not something that is recent or only associated with alternative fuels, but have been around for a long time. Safety issues that are discussed in this report are categorised into three categories which are listed beneath:

- Health
- Flammability
- Reactivity

Health

Health issues can be caused by leakage or improper handling of fuels. This research will focus on the impact of exposure of substances to humans and the environment. For example inhalation of gases in certain concentration or direct contact of the substance with the skin. In figure 2.18, a table with graph is shown with safety hazard levels of alternative fuels.

The most dangerous fuel in terms of health issues is ammonia, due to the high toxicity. Low concentration in the air can already have serious consequences on the health of humans, with dangerous concentration above 300 ppm. European regulation has a TWA (8 hours Time-Weighted Average) of 20 ppm and a STEL (Short-Term Exposure Limit) of 50 ppm [69], which are relatively low concentrations compared to methanol that has a TWA of 200 ppm [70] and no specific values for STEL are mentioned.

Methanol is however at atmospheric pressure and ambient temperature liquid and could get into contact with the skin/eye tissue or could be ingested. Ingestion of 20 ml of methanol can be lethal and lower amounts could cause blindness [42]. Concerning the environment, ammonia has an impact on the environment in terms of negatively impacting the biodiversity due to acid deposition and eutrophication, however this only happens when emitted in large

quantities [25]. Methanol spillage into the environment has a low impact on the environment due to biodegradable properties and therefore the low chance of accumulation in groundwater [42].
Hydrogen is a non-toxic substance, so there are no consequences for health issues when inhaling hydrogen gas in small quantities. Although caution should be taken with hydrogen in high concentrations due to asphyxia, because hydrogen gas can displace oxygen. Natural gas (∼ 95% Methane) is a non-toxic gas, but in large concentrations it is an simple asphyxiant gas with a TWA of 1000 ppm [72].
Diesel, a slighter heavier fuel than gasoline (longer hydrocarbon chains), is a relatively low toxic fuel. When inhaled (fumes) or skin contact with diesel does not result in long term health effects. Large quantities of inhaled diesel or longer exposure to skin could cause health effects such as sever lung damage (pneumonitis) and eczema (dermatitis) [37].

Substance	Health	Flammability	Reactivity
Ammonia	3	1	0
Hydrogen	0	4	0
Gasoline	1	3	0
LPG	1	4	0
Natural Gas	1	4	0
Methanol	1	3	0

0=No hazard, 4=Severe hazards

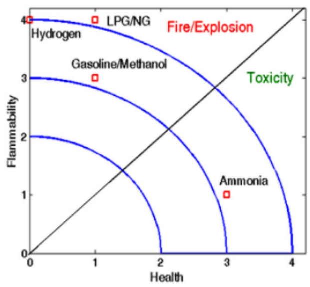


Figure 2.18: Safety comparison of several alternative fuels [99]

Flammability

Flammability of a fuel can be described as "the ease with which a material is ignited, the intensity with which it burns and releases heat once ignited, its propensity to spread fire, and the rate at which it generates smoke and toxic combustion products during gasification and burning" [51].
Flammability risks of ammonia are considered to be the lowest among alternative fuels. This is due to specific properties of ammonia, with as main property the slow reaction characteristics. Ammonia needs more energy to be able to ignite (2-3 times more than hydrocarbons) and has a low laminar burning rate compared to other fuels [25]. Also the flammability limits are relatively close to each other compared to methanol and in particular hydrogen which is in the range of 4-75 (v/v)%. However, ammonia vapor in air is flammable and can explode when ignited.
Methanol is a highly flammable substance with a non-luminous flame and when ignited it doesn't create smoke [42]. This makes it difficult to detect fire with methanol, on the other hand it gives safety benefits in terms of health risks (inhalation of smoke) and also visibility is increased when rescue operations are necessary. Also, it is relatively easy to make the flame luminous by blending it with a different non-alcoholic fuel. In a more general sense, methanol has a similar flammability index as diesel [56], yet methanol fires can be extinguished with water due to its miscibility [47].
As already have been mentioned, hydrogen has the widest flammability range as can be seen in figure 2.19, which makes it very easy to ignite with different concentrations. Also mentioned in section 2.3 is that hydrogen has a high sensitivity to detonation, but without an external ignition source hydrogen is very difficult to ignite due to the high auto-ignition temperature. Overall, hydrogen is a very flammable substance and therefore has the highest hazard level of all alternative fuels.
Methane has comparable properties with hydrogen concerning safety hazards. It is a gas at atmospheric pressure and ambient temperature with a very low flash point and a minimum ignition energy which is 100 times lower than marine distillate fuels [90]. However, the flammability limits are a lot closer to each other than hydrogen. Boiling liquid expanding vapour explosion (BLEVE) is also a concern when handling methane in liquid (LNG) form which is caused by an external heat source near a storage tank. Pressures will build up and the storage tank ruptures which leads to high evaporation of liquid methane and an explosion afterwards.
In the graph and table of figure 2.18, diesel is not included. However gasoline, which is a slightly lighter fuel than diesel has comparable safety hazard, but diesel has properties that make it less flammable than gasoline. Bio-diesel has a flash point around 100 °C, which means it has to heated up to create fumes that can be ignited, compared to gasoline, which has a flash point of -40 °C, it is relatively safe fuel. Also the flammability range is very small and this makes it less likely to be ignited. However it has the lowest auto-ignition among the alternative fuels, which makes the fuel easier to ignite without an ignition source.

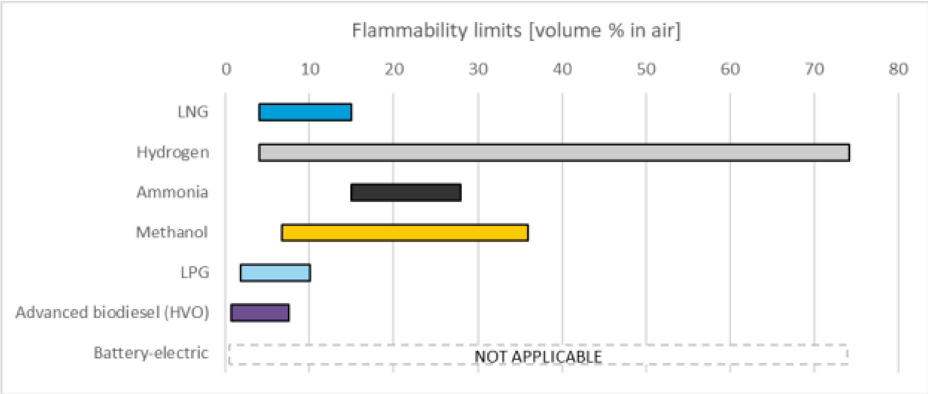


Figure 2.19: Maximum and minimum flammability limit (v/v)% in air [79]

Reactivity

Reactivity is the impact of fuels on the material of certain systems that are in direct contact, such as pipelines and storage tanks. For every alternative fuel that is considered in this report, an identification of relevant materials and substances on board of ships is made which reacts with the alternative fuel.
Using ammonia in its pure form has some consequences on the material choice, because ammonia is corrosive to brass, copper and zinc alloys. For most used steels, such as carbon steel it only has minor effects with stainless steel as most suitable steel [99].
Methanol in its pure form is a corrosive substance to some alloys, rubbers resins and plastics due to the electric conductivity properties. Especially aluminium and titanium alloys need to be avoided when working with methanol. Stress corrosion cracking (SCC) in welded heat-affected zones is also a problem that needs to be taken into account when chosen the proper material [62].
Hydrogen can be corrosive and create problems with metal structures (steels) that become brittle due to diffusion of hydrogen atoms trough metal, which is also known as hydrogen embrittlement [60]. Other substances that react heavily with hydrogen are lithium, chlorine, iodine and barium.
Methane is not corrosive to metals, but can react with other substances which could lead to explosions, such as chlorine, nitrogen oxides and liquid oxygen [72].
Diesel also does not react with metals, however it should be avoided that it comes in contact with strong oxides.

2.4.4. Greenhouse gas emissions from Well-to-Wake

The goal for IMO is to decrease the amount of GHG-emission by 40% in 2030 for the maritime sector. In order to accomplish this target, the well-to-wake emissions have to be decreased. Alternative fuels are considered to be a promising solution to reduce these GHG-emissions from well to wake. WTW-emission are the emissions of the production of the fuel, transport, storage, combustion and any other necessary process step.
For fossil fuels, the well-to-tank emissions (WTT) contributes 20% to the total GHG-emission, while the tank-to-wake has the largest GHG-emission of 80% [22]. For zero carbon fuels and hydrocarbon e-fuels this is quite different, because for zero carbon fuels, no CO_2 is emitted. Hydrogen does not even emit any GHG when combusted, however ammonia does emit nitrite oxides (N_2O) which has a larger impact on the greenhouse effect than CO_2 (298 kg CO_2-eq). For hydrocarbon e-fuels, where CO_2 is captured form the air when producing these fuels, the same amount of CO_2 is emitted as captured.
So the most valuable GHG-emission analysis for alternative fuels is from well-to-wake and taken into account that other gasses can be emitted that could have a larger impact on the greenhouse effect than CO_2, for example methane or nitride oxides, all GHG-emissions are considered and converted in CO_2-equivalent values. In figure 2.20, the WTW emissions are visualised for several e-fuels and fuels generated from other feedstocks such as NG and crude oil.

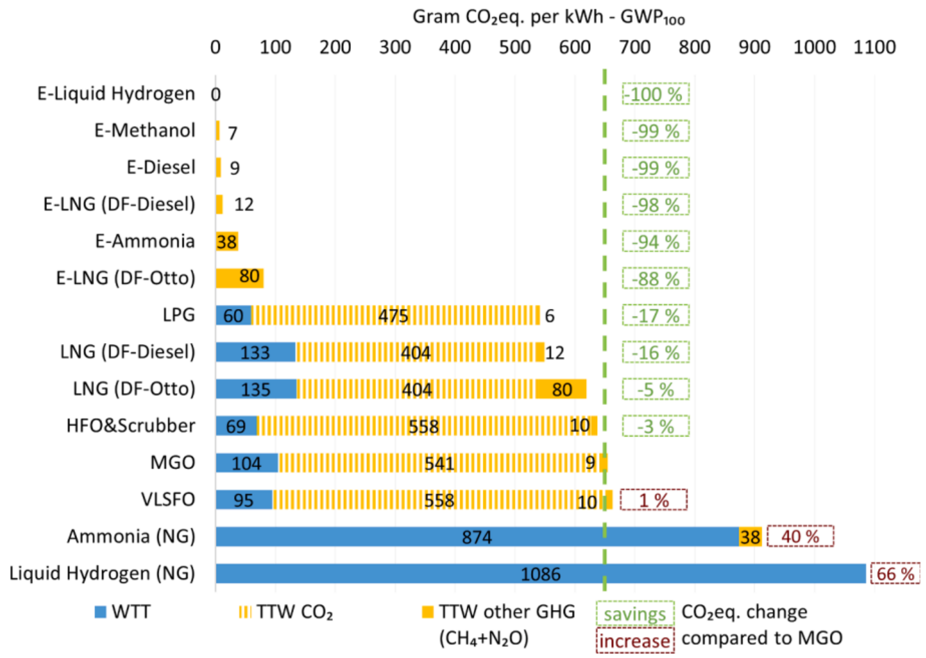


Figure 2.20: Emissions (CO_2-eq) of alternative fuels from well-to-wake [52]

Colours in this figure are used to visualise the difference in well-to-tank (Blue) and tank-to-wake (Yellow) CO_2-eq emissions and a distinction has been made in order to separate CO_2 from other greenhouse gases. The green line is plotted in order to compare with the current situation when MGO is used as main energy source with as feedstock crude oil.
The first six fuels in figure 2.20 are e-fuels and are produced by green electricity. These e-fuels have a large impact on the reduction of GHG-emissions, with hydrogen as best performing e-fuel. Almost all e-fuels reduce GHG-emissions by 90%, with e-LNG (methane) and e-ammonia as largest emitters of GHG due to methane and nitrite oxides emissions. If alternative fuels are produced by using NG as feedstock, the equivalent CO_2 increases significantly, by respectively 40% and 66%. GHG-emission of methanol from NG will lay in the range of ammonia, because it is also produced by transforming hydrogen, retrieved from NG, into fuel (methanol).

2.4.5. Alternative fuel costs and total cost of ownership

Economics are also a big drive for companies to choose a certain alternative fuel and therefore economics should be mentioned in order to determine the most suitable alternative fuel. Nonetheless, economics of certain alternative fuels can change rapidly and become economically viable in short term due to rapid developments in these areas of research and production on larger scale.

In this section, recent research on the costs of alternative fuels is shown in order to make the analysis as realistic as possible. First, fuel costs are discussed which are dependent on several factors and are visualised in figure 2.21 with green representing the lowest costs and red the highest cost. Six factors are mentioned concerning the fuel costs of alternative fuels, with electrolysis efficiency and cost as main factor for determining the price for e-fuels and biomass costs for bio-fuels. For the cost of fuels, it can be seen that methanol is the least expensive fuel in the base-case and could become cheaper with higher electrolysis efficiency and decreasing electrolysis costs. Diesel fuels are the most expensive fuels, especially e-diesel.

		Base case	Increased electricity cost	Grid electricity cost	High biomass cost	High carbon capture cost	Low electrolysis cost	High-efficiency electrolysis with low cost
Biofuels	Biomethanol	69			92			
	BioDME	73			98			
	Biodiesel	95			122			
	BioLMG	91			113			
	BioLBG	86			100			
	HVO	89			134			
Bio-electrofuels	E-biomethanol	89	104	94	101		83	79
	E-bioDME	94	110	100	107		89	84
	E-biodiesel	116	134	122	127		109	104
	E-bioLMG	115	132	121	125		108	104
	E-bioLBG	113	126	117	123		108	105
Electrofuels	E-methanol	119	149	129		142	108	100
	E-DME	126	156	136		149	114	106
	E-diesel	158	193	170		185	145	135
	E-LMG	142	172	152		160	131	123
	Ammonia	120	149	129			109	102
	LH_2	153	182	157			135	128

Figure 2.21: Fuel costs of e-fuels and bio-fuel for different cases in €/MWh [48]

Fuel costs are not the only costs that are related to applying alternative fuels on board of ships, but also propulsion and storage play a role in the cost analysis. This total cost analysis is called the total cost of ownership (TCO) . In figure 2.22, the total ownership for a general cargo ship is shown with different trip duration and energy converters. It can be concluded that methanol is the most suitable, with bio-methanol in an internal combustion engine as most suitable alternative fuel when looked at the economical factors.

	Utilisation/trip	Short		Medium		Long	
	Propulsion	ICE	FC	ICE	FC	ICE	FC
	MGO	1.3		1.5		1.8	
Biofuels	Biomethanol	3.0	3.8	3.7	4.4	4.6	5.1
	BioDME	3.3		4.0		4.9	
	Biodiesel	4.0		4.8		5.8	
	BioLMG	4.2	4.8	5.1	5.6	6.2	6.6
	BioLBG	4.0	4.6	4.8	5.4	5.9	6.4
	HVO	3.6		4.3		5.2	
Bio-electrofuels	E-biomethanol	3.8	4.5	4.7	5.2	5.8	6.1
	E-bioDME	4.1		5.0		6.2	
	E-biodiesel	4.8		5.8		7.0	
	E-bioLMG	5.1	5.6	6.2	6.5	7.7	7.7
	E-bioLBG	5.1	5.5	6.1	6.5	7.5	7.7
Electrofuels	E-methanol	5.0	5.5	6.1	6.3	7.6	7.5
	E-DME	5.4		6.5		8.0	
	E-diesel	6.5		7.8		9.5	
	E-LMG	6.2	6.4	7.6	7.6	9.3	9.0
	Ammonia	5.3	5.6	6.4	6.5	8.0	7.8
	LH_2	7.0	6.5	8.7	8.0	11.0	9.9

Low TCO M€/year — High TCO M€/year

Figure 2.22: Total cost of ownership for general cargo vessel in M€/year (million euros per year) [48]

2.4.6. Sub-conclusion

Consequences concerning the usage of alternative fuels have been analysed for several characteristics. For the energy density, it could be concluded that the impact of storage systems can have a great impact on on the gravimetric and volumetric density. For almost all fuels, it resulted in a decrease in gravimetric and volumetric density and gaseous fuels had the largest decrease in energy density.
Another important characteristic that was investigated, was the technology readiness of the alternative fuels. From the fuels ammonia, hydrogen and methanol, methanol seemed to be the fuel with the highest technology readiness. Health safety issues were the most relevant for ammonia and methanol, with ammonia the most toxic substance. Flammability hazards were for gases most severe, with ammonia as safest fuel concerning flammability. Reactivity of alternative fuels with steel were minor, although caution should be taken when using certain alloys, such as aluminium for methanol.
From the analysis of the well-to-wake GHG-emissions, it can be confirmed that the e-fuels have the lowest GHG-emission with an CO_2-eq change in the range of 90% compared to MGO. However, alternative fuels produced from NG could emit even more GHG-emissions than MGO.
Lastly, economics for e-fuels and bio-fuels were evaluated depending on multiple factors for which methanol and in particular bio-methanol had the lowest cost in €/MWh. Regarding the TCO, the most suitable combination (with lowest TCO) was an ICE running on bio-methanol.

2.5. Operational profile of the LABRAX

The evaluation of a fuel based the operational profile is very important for the selection of the alternative fuel. In this chapter, the operational profile of the LABRAX-series will be analysed for the shipping company Vertom. Certain aspects that determine the operational profile will be discusses, such as the operational area and design speed. The operational profile can be as detailed as preferred, but in this section it will be limited to the most relevant aspects.

2.5.1. Operational area

Vertom is a shipping company with 81 ships under their control, mostly dry cargo coasters in the range of 1.500 to 10.000 DWAT. For the operational profile, an operational area has to be defined which is done by analysing AIS data. Eight vessels with almost the same dimensions and DWAT were analysed, namely a DWAT of 6500 to 6510 tonnes and a length over all (LOA) between 118.40 and 118.90 meters. The dimensions and loading capacities are comparable with the LABRAX-series vessels. In figure 2.23, the trade routes of the vessels are shown. It can be concluded that most of the time the vessels stay within Western, Northern and Southern Europe with some outliers to South America and Central Africa.

Figure 2.23: Trade routes of eight Vertom ships [101]

Most of the port calls are concentrated in France, Belgium and Spain as can be seen in the table of figure 2.24. The longest route to a destination in the top ten ports visited, is from Gent to Sagunto which is approximately 1800 NM. Although longer routes should be considered within Europe. It is assumed that the longest routes will originate from a port with the most calls to a port that is located in Western, Northern or Southern Europe. It is assumed that the route from Rouen (France) to Athens (Greece) is the longest travel distance and approximately 2700 NM.

Top 10 ports visited
[by number of port calls]

ToPort name	ToPort Country	#Count of port calls
Dunkerque	France	57
Gent (Ghent)	Belgium	34
Rouen	France	32
Gijon	Spain	24
Rotterdam	Netherlands	22
Gibraltar	Gibraltar	19
Palmones	Spain	16
Saint-Nazaire	France	16
Cartagena	Spain	14
Sagunto	Spain	14

Figure 2.24: Port calls of eight Vertom ships [101]

2.5.2. Sailing profile

From the analysis of the routes and port calls the distribution of the operational status is determined. Three kind of operations are defined, which is waiting before entering or leaving the port, sailing to or from a destination and loading and unloading in a port. In figure 2.25 the time distribution of the three operations of the eight Vertom vessels is visualised in a pie chart. What already stands out, is the distribution between sailing and standstill (waiting and (un)loading) which is almost equally divided. So the vessels are almost half of the time not sailing when in operation.

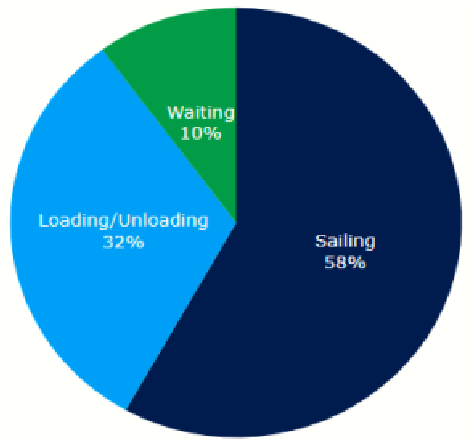


Figure 2.25: Average time distribution of operations from eight Vertom vessels [101]

When these ships are sailing, a distribution in ship speeds can be made according to global AIS data from the DNV-GL database which is visible in figure 2.26. More than half of the time (25% + 29%) when the ship is sailing, it is sailing between 9 and 11 knots which is cruising speed. The design speed is placed within the 10 to 11 knots region, because most of the time the vessel sails at that speed. So it has the highest propulsion efficiency at that speed, which in the end results in the highest energy efficiency for this operational profile. Slow steaming is defined when the speed is below 9 knots and happens 28% of the time that the vessel is sailing. Slow steaming results in a lower fuel consumption and GHG-emissions, but has a lower propulsion efficiency, because the design speed is at 10.8 knots. When a speed above 11 knots is reached, the vessel is in sprint mode (18% of the time) which will increase the fuel consumption significantly due to the decrease in propulsion efficiency with a fixed pitch propeller (FPP) and increase in ship resistance.

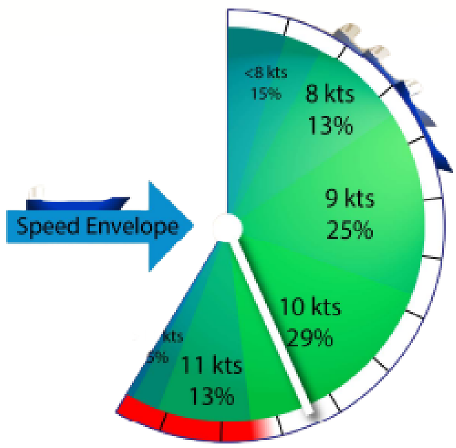


Figure 2.26: Average speed envelope of the eight Vertom vessels [101]

2.5.3. Sub-conclusion

The operational profile will have a great impact on which alternative fuel is most suitable as main energy source. For the range, it can be concluded that a minimum range of 2700 NM is needed in order to travel from port to port. Travel routes from Europe to South America and Central Africa are neglected due to the travel frequency, which is very low. Also, compromises has to be made when implementing alternative fuels which have lower densities.
The sailing profile indicated that slightly more than 50% of the operating time, the vessels are sailing. The rest of the time, the vessels are waiting (10%) or (un)loading (32%). The average speed when these vessels are sailing 54% of the time they are sailing between 9 and 11 knots, with a design speed of 10.8 knots. So for the energy consumption, it is assumed that the vessel can sail at design speed over a distance of 2700 NM.

2.6. Conclusion

So the biggest challenges of decarbonizing the marine industry are scalability, technological readiness (timeline) and economic viability of the alternative fuel. These challenges have been investigated by doing literature research on several aspects concerning alternative fuels.

From this literature research, a lot of information has been gathered concerning alternative fuels for coasters and many comparisons have been made on aspects such as energy densities, production methods and many other aspects. Based on information from current research, it is not possible to conclude with certainty which alternative fuel would be most suitable for a coaster. However, based on the availability, operational profile and the research project MENENS going on at Thecla Bodewes Shipyards where I am involved in, it is decided to focus on the challenges of implementing methanol in the case study (LABRAX-series vessels).

So in the next phase of this research, methanol will be investigated as primary energy carrier by doing a case study. The influence of methanol on the power- and energy systems of the vessel will be evaluated and compared to the original situation. First, the original situation will be analysed, focusing on the power plant design. Characteristics, such as power plant configuration and efficiencies will be addressed in the analysis. After the dimensions of the object of study are described, the performance of the vessel is determined by means of the operational profiles which will give performance indicators in the end.
Now the original situation has been determined, different power- and energy systems are described with methanol as alternative fuel. These power- and energy systems are linked to different power plant configurations with different engine types and will be evaluated on ship performance and design impact. The focus of this research will be on the ship performance with a limited design impact analysis. In the end, the performance and design impact of the different power- and energy systems are compared to the current situation and if possible the most suitable power- and energy system is proposed as promising solution to decrease the GHG-emissions of the case study.

Looking back at the research questions, stated in section 1.3, the following research question has been answered by the literature research:

- *How are alternative fuels produced, can it be implemented in vessels, and what are the characteristics?*

Additional to this research question, methanol is selected for further research and will be applied to a specific case.

II

Object of Study

3
Current vessel design and performance from Tank-to-Wake

At the end of the literature study, methanol has been chosen as alternative to be further investigated with the help of a case study. The first sub-question that initiates the case study research, is defined as follows: *"What is the current design of the power- and energy system on board of the LABRAX general cargo vessel?"*. This chapter aims to answer this question by defining the LABRAX-series as it is currently being designed with relevant dimensions and power plant specifications. Furthermore, the performance characteristics for defined operational modi of the vessel will be determined. These results will be compared and utilized as reference value for the performance of the LABRAX with a power- and energy system on methanol in section 4.5.

3.1. Design aspects

3.1.1. General ship dimensions

As mentioned earlier, the case study concerns a specific coaster type, namely a dry cargo coaster. The dry cargo coaster series, named LABRAX, will be utilized as a study object of which six almost identical vessel are build at Thecla Bodewes Shipyards. For this study the original design and specifications of the first vessel (Vertom Patty) will be used of which general ship dimensions are shown in table 3.1. For convenience, the study object will be mentioned as the LABRAX in the remainder of this report.

Table 3.1: Main dimensions and weight specifications [91]

LABRAX	
Length over all	118.60 m
Breadth moulded	14.30 m
Depth moulded	8.50 m
Draught design	6.20 m
Gross tonnage	4750 GT
Deadweight tonnage	7000 t

The total length of the vessel is 118.60 m with a width of 14.30 m and is designed to have a deadweight of 7000 tonnes at design draught of 6.20 m. The deadweight of the vessel is the total weight carrying capacity excluding the lightweight of the vessel. The gross tonnage (GT) can be determined by measuring the overall internal volume of a vessel which represents the overall size.

Now the general dimensions are known, it is necessary to define specifications of other relevant structures of the LABRAX, starting with the cargo hold. The cargo hold is divided into two unequal cargo holds of which the dimensions are shown in table 3.2.

Table 3.2: Cargo hold dimensions [91]

LABRAX	
Number of holds	2
Hold height	9190 mm
Hold length fore	37100 mm
Hold length aft	49000 mm
Total hold length	86100 mm
Hold width	11800 mm
Hold volume	9336 m^3

The hold is fully boxed shaped and is confined by several structures, such a double bottom and side tanks which are suitable for storage of ballast water. A fully boxed shape hold means that the hold has a constant width and height over the total length. Also a central pipe duct is constructed inside the double bottom of the vessel to provide space for fuel oil transfer pipes, ballast pipes, bilge lines and cables.
The hold divisions bulkhead dividing both cargo holds is equipped with ventilation channels to ventilate cargo during transit. In order to protect cargo from weather influences, hatch covers are placed on top of the cargo area. These hatch covers have a double function, because they can also be utilized to store deck cargo (wood, containers etc.).

At the aft of the ship, after the engine room bulkhead, the technical spaces are located and separated by two decks, namely the tank top and tween deck as can be seen in figure 3.1. The lowest deck is located at 1030 mm above base (A.B.) and this is where the propulsion room is located. On tween deck, which is located at 5300 mm A.B., the engine room is located. The dimensions of the particular spaces are visualised in table 3.3.

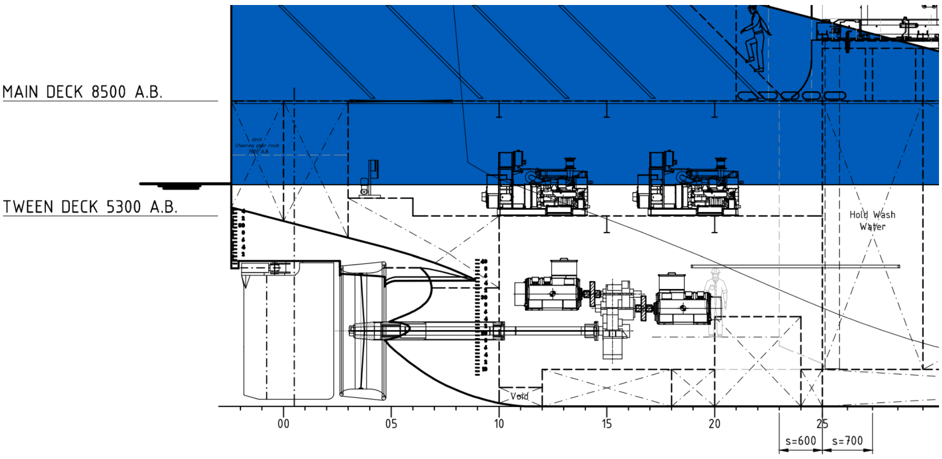


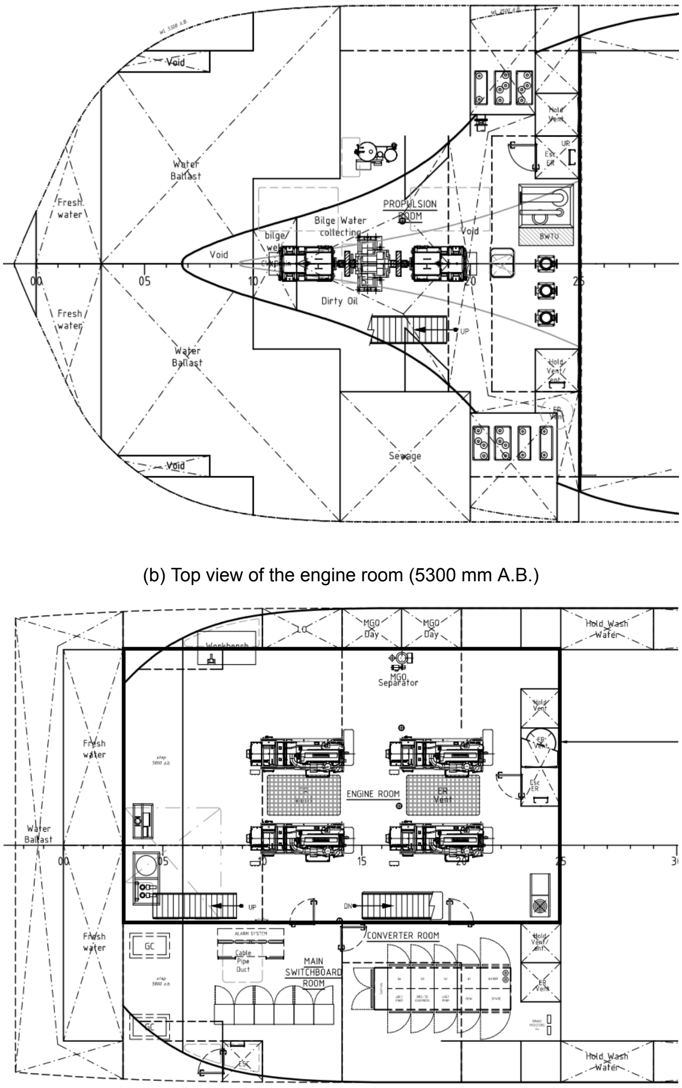
Figure 3.1: Side view of the propulsion- and engine room

Table 3.3: Dimensions and volume specifications of the propulsion- and engine room

LABRAX	**Propulsion room**	**Engine room**
Length	9000 mm	13200 mm
Height	5300 mm	3200 mm
Width	1900 mm - 8200 mm	8300 mm
Surface	46 m^2	108 m^2
Volume	242 m^3	346 m^3
Frame spacing	600 mm	600 mm

The dimensions of the propulsion room are restricted by the hull and sea chests at the sides, engine room bulkhead, keel and the stern tube void as can be seen in figure 3.2 (a). In the longitudinal direction, the propulsion room covers

the space between frame 10 and 25 and has a minimal width of 1900 mm at the stern and maximum width of 8500 mm between the sea chests.
The dimensions of the engine room are restricted by tanks (lubrication oil (LO), gas oil (MGO) and freshwater) and the electrical rooms (converter- and switchboard room). In the longitudinal direction, the engine room covers the space between frame 3 and 25 and has a relative constant width of 8300 mm as can be seen in figure 3.2 (b).
The surface and volume of both rooms are indicated values and determined by AutoCAD drawings.



(a) Top view of the propulsion room (1030 mm A.B.)

(b) Top view of the engine room (5300 mm A.B.)

Figure 3.2: Technical drawings per technical floor

The division of the technical room is visible in figure 3.1 and characterises the all electric ship concept.

> (Woud et all., 2002, p.118) defined the all electric ship concept as "a number of engines, not necessary of the same size, feed one net and the propulsion system and ship services draw energy from one primary net" [108].

There are several configuration of an all electric ship concepts. The LABRAX has a diesel-electric drive configuration, with a diesel-electric power plant connected to a main switchboard that feeds the electric motors and auxiliary systems. The advantage of a more modular design of this diesel-electric drive, is the possibility to the change power generation system without replacing or adapting the power train which results in a more future proof vessel.

In the propulsion room, shown in figure 3.2 (a) and 3.1, two electric motors are connected to one reduction gearbox with one outgoing shaft to the propeller. At tween deck in the engine room, shown in figure 3.2 (b) and 3.1, four conventional diesel engines with each a generator are located and generate electricity for the electric motors. The converter- and switchboard room are located at SB-side and convert and divides the electricity before it is utilized by consumers (Electric motors, hotel load, etc.).

3.1.2. Tank specifications

In the previous section, several technical drawings of the aft part were visualised. In the side- and top view, multiple tanks are visible and these are examined in more detail in this chapter. An overview of several constructed tanks inside the LABRAX with their storage capacities are shown in table 3.4.

Table 3.4: Relevant tank capacities

Tank	Quantity	Volume	Tank number
Water ballast	20	2550 m^3	622 to 601
Fresh water	2	55 m^3	680 to 681
Gas oil bunker	2	172 m^3	641 to 642
Gas oil day	2	8 m^3	644 to 645
Gas oil overflow	1	7 m^3	643
Gas oil emergency	1	1 m^3	646

For this study, the most relevant tanks on board of the LABRAX are the gas oil tanks and other large storage tanks such as the fresh water- and water ballast tanks. These tanks could play an important role in placement of additional fuel tanks. The volumes presented in table 3.4 are total volumes.

The water ballast tanks are divided over the total length of the ship. The largest water ballast storing capacity can be found in the mid-ship, namely in double bottoms and side tanks. Remaining water ballast tanks can be found in triplicate in the fore- and aft ship, shown in figure 3.3 and 3.5 with a combined capacity of 293 m^3 (FS) and 150 m^3 (AS).
Gas oil tanks are divided over the fore- and aft ship, with the largest storing capacity in the fore ship. The total fuel capacity of the LABRAX is equal to 180 m^3 (bunker- and day tank) excluding the gas oil overflow- and gas oil emergency tank which will be left out in the analysis. These tanks will be left out, because in normal operating conditions the emergency generator is not used and the overflow tank should remain empty for possible overflow of the bunkertanks. The gas oil day tanks are located at the aft ship in the engine room at port side which is visible in figure 3.2 (b). On the contrary, the bunker tanks and overflow tank are located at the fore ship, which can be seen in figure 3.3. Detailed information of the fuel oil transfer line can be found in appendix D.1.

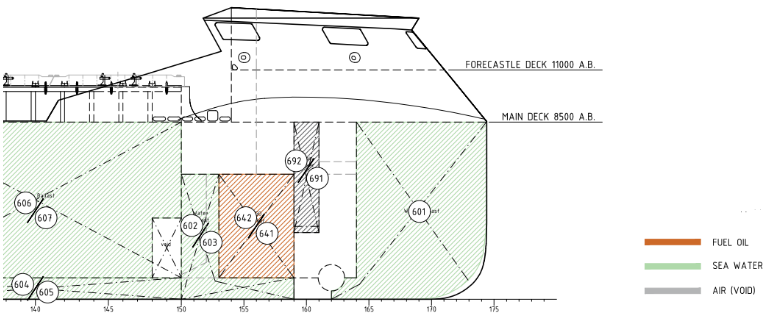


Figure 3.3: Fore side view of storage tanks

Besides water ballast, fresh water and gas oil, other fluids are stored on board as well, as can be seen in 3.3. In the legend, next to the side- and top view of the vessel (figure 3.3, 3.4 and 3.5), other fluids can be recognized such as potable water and waste media. Ballast water is visualised in green and usually consist of sea water. The vessel is obligated to have a certain amount of ballast water on board before the vessel is permitted to sail according to stability requirements.
However not all tanks store fluids, tanks 691 and 692 are designed as chain lockers.

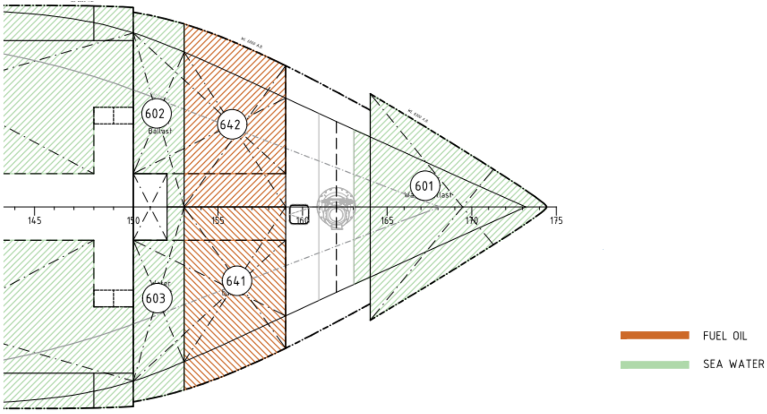


Figure 3.4: Fore top view of storage tanks

As mentioned in this section, gas oil day tanks are located in the aft, so the gas oil needs to be pumped from the fore gas oil bunker tanks to the gas oil day tanks through a pipeline in the pipe duct which is located in the center of the double bottom.
Tanks are usually placed at the lowest possible point of the vessel to increase stability. When placing new tanks or using existing tanks to store fuel the influence on the stability has to be taken into account as well.
Tanks that haven't been mentioned yet, are waste water tanks which are located at the keel (655,685 and 686) and in the side tanks (687). These are used for storing several waste products, such as dirty oil and hold wash water.

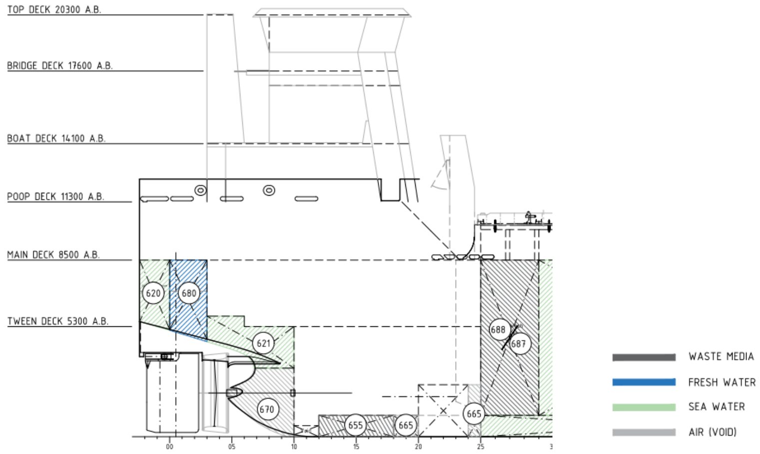


Figure 3.5: Aft side view of storage tanks

3.2. Power- and energy systems

3.2.1. Diesel-electric power plant

In this section, the layout and specifications of the current power plant is analysed in more detail. The results of this analysis will help to determine the performance of the current vessel which will be the reference value for methanol fuelled power- and energy systems.

First, a power plant layout is created by using figure 3.1 and 3.2 as a resource [91]. In figure 3.6 the schematic layout of the power plant is shown, where the engine- and propulsion room is divided over two separate decks. On tween deck the four diesel engines (DE) with generator are located and on tank top level two electric motors (EM) are connected to a reduction gearbox with a twin input - single output arrangement. The outgoing shaft is connected to a fixed pitch propeller (FPP) with nozzle for the generation of thrust. Specifications of the gearbox, propeller and diesel engines will be discussed further on.

Already mentioned briefly in section 3.1, the LABRAX has a diesel-electric drive with four energy converters producing electricity for the main propulsion (two electric motors), board net and other users which is visualised in more detail in figure 3.8. The diesel-electric drive has the advantage to match the energy demand with supply and can therefore operate in a more efficient manner. For every operational profile, the number of operating engines can be changed in such a way that they operate at their relative peak efficiency. Another advantage of applying multiple engines for power generation is the redundancy of the power supply which benefits the reliability of the system. A diesel-mechanical drive with four diesel generators to match power demand and supply would be a less suitable due to a larger mechanical propulsion system in the propulsion room and matching problems with a FPP.

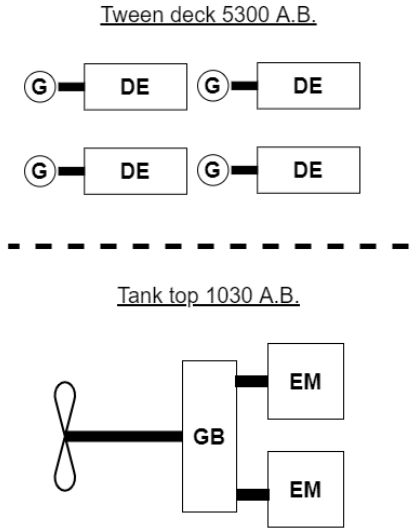


Figure 3.6: Schematic diesel-electric power plant layout

In figure 3.7, the electrical system has been added to the power plant. This electrical power plant layout consist of multiple AC/DC converters and a DC bus with circuit breaker. The generators connected to the DC-bus can also be disconnected by a circuit breaker if necessary. On the right in figure 3.7 four generator sets, consisting of a diesel engine (DE) built together with a generator, are individually connected to a rectifier which transforms alternating current (AC) into direct current (DC). From the DC switchboard (930V), electricity is transformed again to AC by a variable frequency transformer. In the end, the DC switchboard supplies electrical energy for two electric motors and a bow thruster as can be seen in figure 3.8.

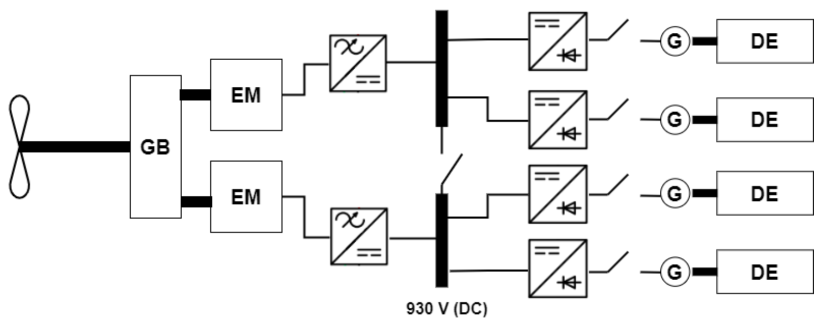


Figure 3.7: Power plant layout with part of electric system

From the last two figures (3.6 and 3.7) the energy flow on board was not visible in its entirety. Therefore, an energy flow diagram (EFD) is created that includes other electrical consumers and gives a more detailed description of the energy demand.
In figure 3.8, the energy flow starts with an energy source (ES) in the left top corner of the diagram. The energy source (gas oil) is transferred to energy converters (main/emergency engines) that convert chemical energy into mechanical energy. In normal operations, the emergency generator is deactivated and the flow goes directly to the main engines. Afterwards, the mechanical energy is directly converted to electrical energy by the generator and converted from AC to DC by a rectifier. The DC switchboard then divide the electric power over the main propulsion, transversal propulsion (bow thruster) and other electrical consumers. The advantage of using a DC switchboard instead of a AC switchboard, which seems more logical in this case, is the less heavier electrical system, faster

electrical synchronization when power is supplied by the generators and energy storing systems (batteries) can be easier added to a DC-switchboard compared to a AC-switchboard [73]. This creates a more future proof design.

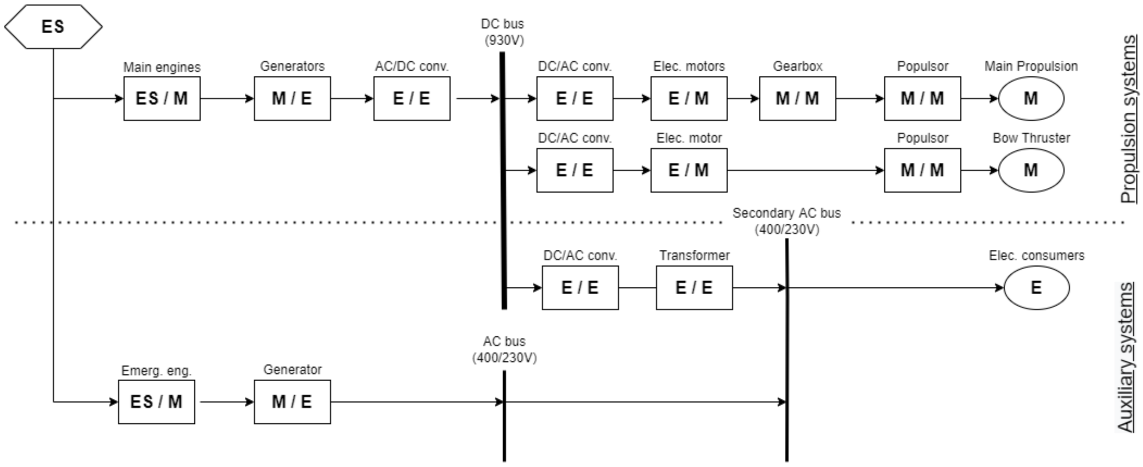


Figure 3.8: EFD of the LABRAX

3.2.2. Power train components

An overview the components mentioned in the previous sections are shown in table 3.5. Additional information concerning the specifications of the components are displayed in appendix B.1.

Table 3.5: Propulsion- and engine room components

Category	Type	Appendix	Quantity
Main engine	Volvo Penta D13-MG	B.1.1	4
Generator	Stamford S5L1M-F4	B.1.2	4
Electric motor	Electro Adda W40 LX 6	B.1.3	2
Gearbox	Renk $T^2 RECS - 630HR$	B.1.4	1

The main engines each have a maximum brake power (P_b) of 400 kW at 1800 rpm which results in a maximum total brake power of 1600 kW. The main engines will be installed with a keel cooled system (KC) and comply with IMO Tier II emission regulation.
The generators, which are directly connected to the main engines, could generate a maximum kVA of 565 kVA, but due the maximum brake power of 400 kW a maximum apparent power of 505 kVA is delivered.
The electric motors placed on both sides of the gearbox (power take in (PTI) and input shaft) utilize the electrical power to create thrust at the propeller. Each electric motor has a maximum power of 650 kW at 900 rpm, which results in a total power of 1300 kW at the outgoing shaft. The remaining 300 kW is used for hotel load (~100 kW) and lost in the power train (~200 kW) from output shaft engine to propeller shaft.

3.2.3. Power train efficiencies

Now all the specifications are clear, the performance of the power plant will to be investigated. The performance of the power plant is closely related to the efficiencies of components. In table 3.6, efficiencies of the total power chain are given.

Table 3.6: Efficiencies of the power train

	Efficiency
Gearbox efficiency (η_{GB})	99.0%
Shaft efficiency (η_S)	99.0%
Electric motor efficiency (η_{EM})	96.4%
Generator efficiency (η_{GEN})	95.0%
Variable frequency drive efficiency (η_{FD})	97.0%
Effective engine efficiency (η_E)	42.4%
Transmission efficiency (η_{TRM})	98.0%
Electrical system efficiency (η_{EL})	88.8%
Total efficiency from fuel to power at propeller (η_{TOT})	36.9%

All efficiencies are pre-determined by the manufacturer at maximum rpm or MCR. The efficiency of the Volvo Penta engines are calculated by using the Specific Fuel Consumption at maximum P_b in table B.1 and shown in appendix A.1.1.
A visualisation of the power train can be seen in figure 3.9.

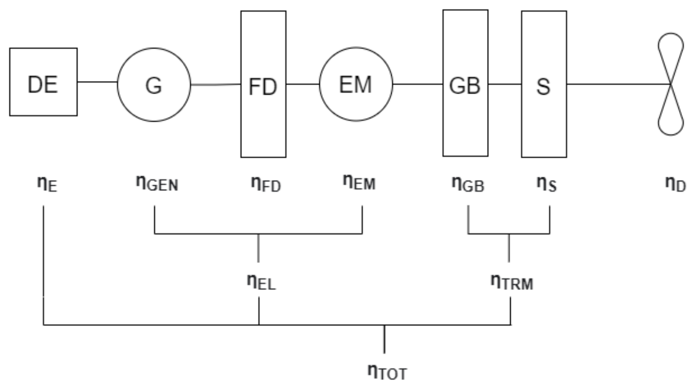


Figure 3.9: Power train of the propulsion

Usually the highest losses in the power train are linked to mechanical losses, but due to the all electric ship concept, also electrical losses play a significant role.
A conventional power train (mechanical) has losses at the gearbox (η_{GB}) and shaft (η_s) which results in a certain transmission efficiency (η_{TRM}). For this particular case the transmission efficiency equals 98.0 %.
For a diesel-electric drive, electrical losses at the electric motor (η_{EM}), generator (η_{GEN}) and the variable frequency drive (η_{FD}) result in an additional electrical system efficiency of 88.8 %.

This means an additional 11.2% of energy is lost compared to the mechanical system. In total, the diesel-electric power configuration loses 13% from engine output shaft to propeller shaft.

3.2.4. Power estimation per operational mode

In section 2.5 of the literature research, a general operational profile has been defined based on comparable vessels. From this operational profile three different modi came forward, namely slow steaming, cruising and sprint.
However, the LABRAX has a less power to weight ratio compared to the comparable vessels and therefore the ship speed decreases slightly per mode. In the end, the sprint mode is defined as ship speed at maximum brake power, cruising speed as ship speed at 75% of maximum brake power and slow steaming as ship speed at 8 knots.

In order to determine the ship speeds (sprint and cruising) at the specified brake power and brake power needed to sail at 8 knots, a speed-power curve is utilized. The speed-power curve, shown in figure 3.10, is created by MARIN based on CFD calculation of the hull with propeller. For this particular case study, a maximum propeller speed of 141 rpm with a sea margin of 15% is chosen (service line).

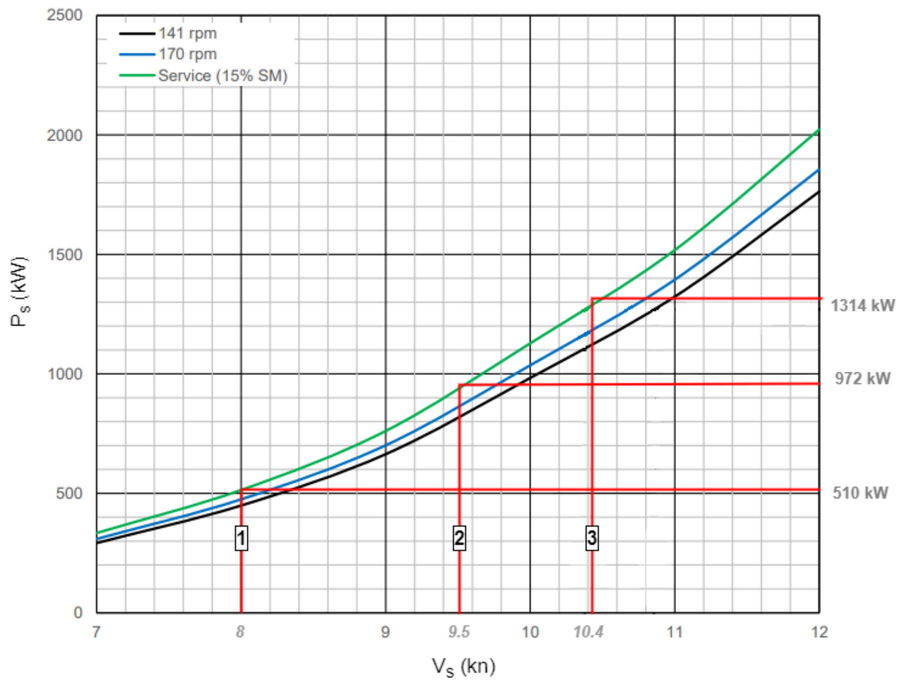


Figure 3.10: Power-speed curve

The red lines indicate the three different operational modi with on the x-axis the ship speed in knots and y-axis the shaft power in kW. In table 3.7, the results of the three operational modi (1,2 and 3) are visualised. The brake power is calculated by adding the losses in the power train presented in table 3.6 and a hotel load of 100 kW.

Table 3.7: Specifications of operational modi

Mode	Ship speed (V_s)	Brake power (P_b)	Shaft power (P_s)	N°op. eng.	Load	Time
1	8 kn (Slow steaming)	685 kW	510 kW	2	85.6%	28%
2	9.5 kn (Cruising)	1200 kW	972 kW	4	75.0%	54%
3	10.4 kn (Sprint)	1600 kW	1314 kW	4	100%	18%

N°op. eng. = Number of operating engines

3.3. Performance indicators

The aim of this section is to provide an answer to the following sub-question: *"What is the current performance of the LABRAX general cargo vessel?"*. This will be achieved by evaluating the performance of the diesel-electric power plant for several operational modi.

In more detail, three operational modi will be assessed on several aspects associated with ship performance. A well known example of a performance aspect is fuel consumption and emissions. These performance aspects are utilized to determine the performance indicators, such as fuel- and emission index [88].
The results of this analysis will be used as reference points for the comparison with the methanol-electric power plant configuration.

3.3.1. Energy indicators

Using energy in an efficient way, will result in a more profitable and sustainable way of transporting goods overseas. By using specific performance indicators, the energy efficiency of a certain vessel can be measured and compared to other vessels and even different forms of transportation.

Fuel consumption is one of the key parameters that will be analysed based on ship operation profile. Fuel consumption is a direct measure for profitability of the vessel and in a sense the amount of emitted pollutant gases (CO_2, NO_x, SO_x, etc.).

Principally, fuel consumption starts with the Specific Fuel Consumption (SFC) of the energy converters, which are four compression ignited diesel engines. SFC is a measurement of the amount of gram fuel is used per generated energy in kWh. In figure 3.11, the Specific Fuel Consumption is shown for several loading conditions. A trend line has been added to the figure to visualise the greatness of the increase/decrease of the SFC over the load. An large increase in SFC can be noticed when the engine operates below 50% of its maximum power and will increase even further below 25% if the trend line is followed. Another interesting feature of the engine is the relative constant SFC from 50 to 100% MCR. So the load can be varied substantially without decreasing engine efficiency (η_E). However, the engines should not be loaded below 50% MCR, otherwise a considerable amount of energy is lost.

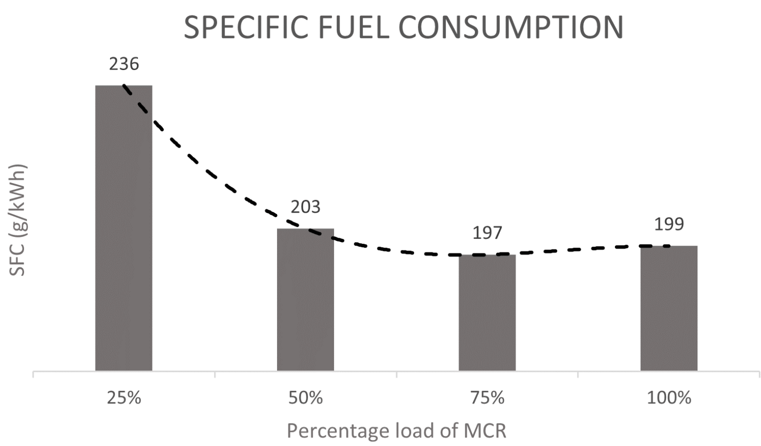


Figure 3.11: Energy conversion effectiveness LABRAX

From the SFC, the fuel consumption can be easily calculated by the following formula:

$$SFC = \frac{\dot{m}_f}{P_b} = \frac{m_f}{W_e} = \frac{1}{\eta_e \cdot h^L} \tag{3.1}$$

As can be seen in formula 3.1, the specific fuel consumption is related to the engine brake power (P_b) and fuel mass flow $\dot{m}_f$. This can be rewritten to fuel mass injected per cycle m_f per effective work output W_e which is inversely proportional to the effective engine efficiency η_e times the lower heating value h^L.

The fuel consumption is calculated and presented per operational mode in table 3.8.

Table 3.8: Fuel consumption per operational mode

Ship speed (V_s)	**Fuel consumption ($\dot{m}_f$)**
8 kn (Slow steaming)	135.6 kg/h
9.5 kn (Cruising)	236.4 kg/h
10.4 kn (Sprint)	318.4 kg/h

The absolute difference in fuel consumption between slow steaming and sprint mode is 182.8 kg/h, approximately an increase of 2.3 times. The speed however increases only by 1.3 times, which explains the significant decrease in fuel index and energy conversion effectiveness in figure 3.12 and 3.13.
Before the results of the first two performance indicators are discussed, a small description is provided.

The **fuel index** is in principle the fuel consumption of the vessel at a certain ship speed with a certain cargo weight. In equation 3.2 the relation between the variables are shown with Φ_{fuel} (g/h) fuel mass entering the engines, m_d (t) deadweight tonnage and V_s (kn) ships speed.

$$FI = \frac{\Phi_{fuel}}{m_D \cdot V_s} \tag{3.2}$$

For this analysis the ship speed will be varied over three speeds, namely slow steaming, cruising and sprint. For all operational modi, the ship will be fully loaded.

The **energy conversion effectiveness** is in principle the inverse of the fuel index, but includes a hub distribution factor. Sui (2021) proposed to include a factor that defines the useful energy for ship propulsion against the total generated power. The useful energy is the energy to propel the ship and the remaining energy is defined as less useful, for example the hotel load of 100 kW.
To be more precise, the hub distribution factor defines the 'energy management factor' instead of the 'energy usage efficiency' [88].
In equation 3.3, the Energy Conversion Effectiveness is defined with Φ_{FE} (J/s) fuel energy flow entering the engines, W_d (N) deadweight tonnage, V_s (m/s) ships speed and P_{SP} power required for ship propulsion.

$$\epsilon_{EC} = \frac{W_D \cdot V_s}{\Phi_{FE,main} + \Phi_{FE,aux}} = \eta_{eng} \cdot \epsilon_{hub} \cdot \epsilon_T \tag{3.3}$$

with

$$\epsilon_T = \frac{W_D \cdot V_s}{P_{SP}} \tag{3.4}$$

For the analysis of the Energy Conversion Effectiveness, the same conditions as for the Fuel Index are applied.

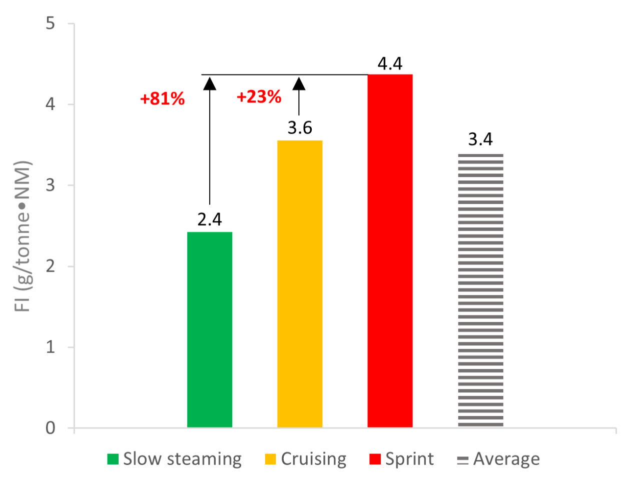


Figure 3.12: Fuel index (FI) per operational mode (Red % = negative consequence)

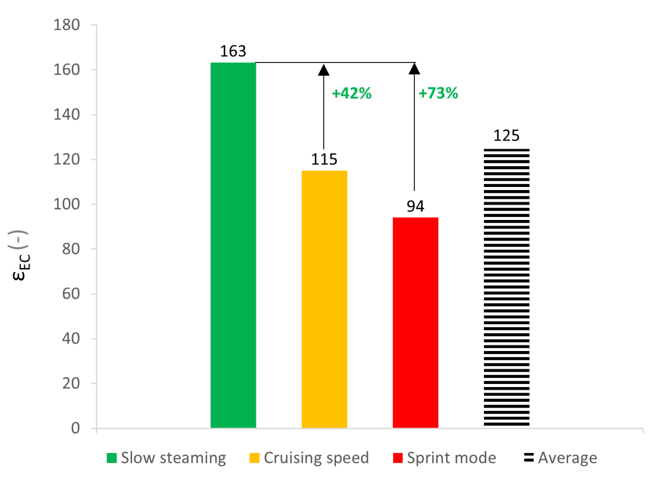


Figure 3.13: Energy conversion effectiveness (ϵ_{EC}) per operational mode (Green % = positive consequence)

The results of the fuel index are visualised in figure 3.12 and shows a specific pattern. The fuel consumption per tonne•NM increases per operational mode due to the non-linear relationship between ship resistance and speed. Therefore ship resistance will increase faster with increase in ship speed.
This results in an increase of 81% in FI from slow steaming to sprint. So an increase of 30% in ship speed, will result in a fuel index increase of 81%, which means almost 2 times more fuel will be used per tonne•NM in sprint mode compared to slow steaming. The average value for the fuel index is shown next to the operational modi and is a time average based on the time division of the sailing profile in section 2.5. The average value of the FI is slightly lower than the FI of cruising. This can be clarified by the difference in sailing time in sprint mode (18%) versus slow steaming mode (28%).

As expected from the fuel index, the energy conversion effectiveness increases significantly for the slow steaming mode (8 kn) compared to cruising (9.5 kn) and sprint mode (10.4 kn). Thus, slow steaming is the best operational mode to reduce the energy usage per tonne•NM. Compared to the sprint mode a increase of 73% in energy conversion effectiveness is realised. Now the average value of the energy conversion effectiveness is slightly higher than cruising mode, which is as expected to to the inverse relation with the fuel index.

3.3.2. Emission indicator

Converting energy into useful energy is associated with emissions of pollutant gasses. This section aims to map these emissions, focusing on GHG-gases when combusting Marine Gas Oil Fuel (MGO). In this way, the environmental impact of the vessel can be determined.

For this analysis a complete combustion of MGO is assumed. The combustion reaction of MGO with oxygen is visualised in equation 3.5.

$$C_{12}H_{24}\ (l) + 18O_2\ (g) \rightarrow 12CO_2\ (g) + 12H_2O\ (l) \quad (\Delta H_C{}^{\circ} = -7925.9\ kJ/mol) \tag{3.5}$$

The exothermic reaction produces a total heat of 7925.9 kJ/mol and emits per $C_{12}H_{24}$ molecule (MGO) 12 CO_2 molecules [87].

With the stated CO_2-emissions, an emission index can be created [88]. In order to determine this index, equation 3.6 is defined with $\Phi_{Emission}$ (g/h) emission flow, V_s (kn) ship speed and M_D (t) deadweight.

$$EI = \frac{\Phi_{Emission}}{M_D \cdot V_s} \tag{3.6}$$

The emission flow has been calculated only for CO_2-emissions with a complete combustion of MGO. So other emissions that have a CO_2-equivalent emission, such nitrous oxide (N_2O), are not incorporated into the analysis. This would mean that an extensive emission model has to be created for all energy converters which is out of the scope of this research.
Other conditions concerning ship speed and deadweight remain the same as in the previous section.

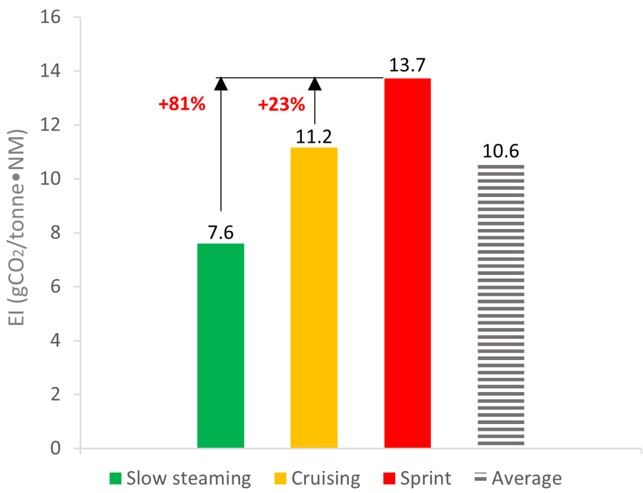


Figure 3.14: Emission index (EI) per operational mode (Red % = negative consequence)

In figure 3.14, the **emission index** of the LABRAX is shown. As can be expected from the fuel index, the EI for slow steaming has the lowest CO_2-emissions per tonne•NM. The direct link with the Fuel Index is also visible, since the decrease in gram CO_2 per tonne•NM from sprint- to slow steaming mode is identical to the decrease in fuel consumption per tonne•NM. The average value based on the time division is slightly less than EI at cruising speed as expected from FI.
To put these values into perspective, specific CO_2-emissions of rail- and road transport in Europe are mentioned in table 3.9. Also an average EI value of general cargo vessels with a DWT between 5,000-9,999 is given.

Table 3.9: Emission Index per transport mode [61] [11]

Type	Size	Average Emission Index
LABRAX	7,000 DWT	10.6 gCO_2/tonne•NM
General cargo vessel	5,000 - 9,999 DWT	18.7 gCO_2/tonne•NM
Road transport	40 - 44 tonnes	99.3 gCO_2/tonne•NM
Rail transport	~ 4,440 tonnes	35.2 gCO_2/tonne•NM
Air freight	~ 140 tonnes (747-400F)	1115 gCO_2/tonne•NM

The LABRAX has an average emission index which is a factor 1.8 lower than the current general cargo fleet. Train freight has a slightly higher EI than general cargo vessels, but this value can vary significantly per country due to the different sources for electrical power generation and ratio between diesel- and electric locomotives. Road transport scores worst for the specific emission with an increase of almost 10 times in emitted CO_2 per tonne•NM compared to the LABRAX.

3.3.3. Range and operation time

In the previous section, efficiency and consequences of using certain energy sources are discussed. In this section the aim is to determine the distance the vessel can travel with a certain amount of energy content.
Range is a specific indicator that determines the distance the vessel can travel without being refuelled. In the literature research, an approximation of the necessary range of comparable vessels is made. Now, according to building specifications, an calculation is performed to determine the range per operational profile. In figure 3.15, the sailing time at a specific operational mode (ship speed) is shown as well in a column next to the travel distance.

In the building specifications, tank volumes are specified which determines the range significantly. In table 3.4, it can be verified that a total bunker capacity of 172 m^3 is available. Another 8 m^3 of storage is available from the day tanks which makes the total fuel carrying capacity of the vessel equal to 180 m^3.
The calculated values are based on the engine specifications defined in table B.1 and a fuel density equal to 845 kg/m^3.

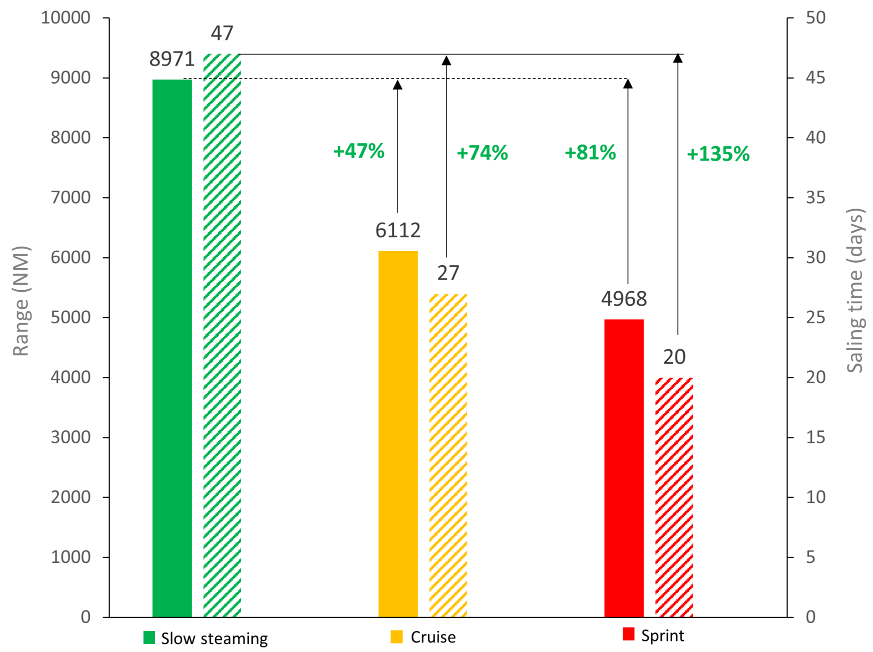


Figure 3.15: Range and sailing time per operational mode (Right striped bar = Sailing time, Left filled bar = Range)

The maximum range of the LABRAX (slow steaming mode) is close to 9000 NM, which is a factor 3.3 higher than the specified necessary range of 2700 NM defined in section 2.5 of the literature research. Even in sprint mode the range is sufficient to reach most of the ports. The direct link with the fuel index is visible in the increase of travel distance between sprint mode and slow steaming (+81%).

3.3.4. Power system reaction

The performance of a vessel is also dependent on system reactions, such as the reaction time to electrical load changes or time to reach a certain power output.
These time aspects are important for the operability of the vessel and especially for the maneuvering aspects which require sudden load changes.
In the data sheet of the Volvo D13-MG main engine, a single step load performance at 1800 rpm and a cold start performance has been defined [2]. The results of the dynamic response (single step load performance) and start-up time (cold start performance) are shown in table 3.10.

Table 3.10: Response time diesel engine (Volvo D13)

	Definition	**Time**
Single load	Recovery time 0-100% load	2.2 s
Start up time	Stay within 0.5% of no load speed	4.6 s

The start up time of the 400 kW diesel engines lies within 5 seconds, which means the electricity generated by the diesel generator set can be used after 4.6 s at ambient conditions (20°C). This start up time is fast compared to other energy converters such as fuel cells. Fuel cells, especially high temperature fuel cells, have a start up time which lies higher than internal combustion engines and can be in the range of a couple of minutes to hours [55] [95]. The dynamic response of these diesel engines is also much faster than fuel cells which have a dynamic response in the range of 600s for a SOFC (50% power increase) [82].

III

Case Study

4
Future vessel design and performance from Tank-to-Wake

In the previous chapter the current design and performance of the LABRAX has been defined and determined. With this information a comparison can be made between the future vessel on methanol and current vessel on diesel. This chapter aims to answer the remaining sub-questions, namely: "Which power plant configurations can be identified for a methanol power- and energy system?" and "How does a methanol power- and energy systems influence design aspects and performance of the LABRAX general cargo vessel?". First, methanol energy conversion systems are analysed and suitable storage locations are identified. With a selected concept design and energy converter, the operational performance of the vessel is determined and compared with the current operational performance from section 3.3.

4.1. Methanol energy conversion systems

Methanol is a chemical substance that contains chemical energy. In order to use this energy for propelling the vessel, methanol needs to be converted to electrical energy. The conversion can be performed by several converters of which the internal combustion engine (ICE) is currently most applied in the maritime industry. Other upcoming technologies are considered as well for power generation on board. Fuel cells are currently considered as possible alternative energy converters due to their higher efficiency and compatibility with alternative fuels.
This chapter investigates available energy converters on methanol with the goal to determine the most suitable energy converter for the LABRAX.

4.1.1. Internal combustion engine (ICE)

The internal combustion engine (ICE) converts chemical energy into mechanical energy in two steps. First chemical energy is converted into thermal energy by combusting fuel with air (oxygen) in a confined space. Subsequently, due to thermal expansion of the medium inside the cylinder, the piston connected to crankshaft moves and creates work (mechanical energy) at the output shaft. In principle, there are two types of internal combustion engines, namely the spark ignited internal combustion engine (SI-ICE) and the compression ignited internal combustion engine (CI-ICE). In the SI-ICE the air-fuel mixture inside the cylinder is ignited by a spark plug and in a CI-ICE the air-fuel mixture is ignited by spontaneous ignition due to high temperatures and pressures.
Both types of internal combustion engines, with methanol as main fuel, will be analysed in this section.

SI-ICE

The SI-ICE is suitable for the combustion of pure methanol, however blends with other fuels are also possible (Dual fuel). Blends compatible with the SI process are usually applied, such as a methanol-gasoline mixture.
When combusted in pure form, the chemical reaction can be described by equation 4.1.

$$2CH_3OH\ (l) + 3O_2\ (g) \rightarrow 2CO_2\ (g) + 4H_2O\ (l) \quad (\Delta H_C{}^\circ = -726.3\ kJ/mol) \tag{4.1}$$

The complete combustion of methanol still produces GHG-emissions, namely per mol methanol one mol carbon-dioxide is emitted. These CO_2-emissions are comparable to diesel due to the low energy release during the combustion of methanol. However the combustion is much cleaner due to less NO_x, PM and no SO_x-emissions. NO_x formation is usually in the form of NO and is a reaction of oxygen (O_2) with nitrogen (N_2) from air at elevated temperatures (>1300°C). Usually maximum temperatures around 1400 K (1673°C) are reached in SI-ICE's on methanol compared to 1800-2100 K (2073-2373°C) for a CI-ICE on diesel [9].

The method of ignition makes it suitable for combusting methanol due to certain characteristics, which are mentioned in table 4.1:

Table 4.1: Advantage of SI-ICE characteristics [105]

Characteristics	Advantage
Low flash point	Easy to ignite
High auto-ignition temperature	Good ignition when spark ignited
High heat of evaporation	Lower cooling losses and increase in overall engine efficiency
Wide flammability range	Ignite with different air-to-fuel ratios
Low stoichiometric air-fuel ratio	High cooling of charged air, reduction of NO_x-emissions and knocking
High flame speed	Less knocking and beneficial for methanol injection (twice the injection duration of diesel)

There are also some disadvantages of using methanol in a SI-engine, such as the low lubricity of the fuel (problem for fuel injectors). Also material compatibility (elastomers and certain metals) is an issue due to the corrosive behaviour of methanol, but this is an issue for both engine types.
In general, the overall engine efficiency increases when methanol is used in a SI-engine instead of natural gas due to lower cooling losses.

CI-ICE

As mentioned in the previous section, methanol is very suitable to be combusted in a SI-ICE. On the other hand, for commercial applications such as in sea going vessels, CI-ICE's are predominately used. Therefore applications of CI-ICE's with methanol is preferable due to comparable characteristics, especially when converting a diesel CI-ICE into a methanol-diesel CI-ICE. In contrary to a SI-ICE, a CI-ICE creates a high temperature environment to ignite the fuel by compressing air inside the cylinder. The fuel is injected just before TDC (highest pressure) and automatically ignites without an external ignition source.

Pure methanol is not suitable to combust in a CI-ICE due to the low cetane number of methanol which indicates the auto-ignitibility of the fuel. Nonetheless, there are two options to solve this problem.

The first option is to apply an ignition improver to increase the combustability of methanol. Normally a mixture of 5% ignition improver with 95% pure methanol is applied in a CI-ICE [49].
Another option is to use a second fuel, such as diesel, to increase the cetane number of the mixture (CN). The ratio of this mixture can be in the range of 70-85% of methanol in energy content [105]. The dual-fuel option is a more common option due to the less complicated conversion of the diesel systems. Although other problems arise, such as bad lubricity characteristics of the fuel mixture and possible loss of rated power due to the lower volumetric energy density [105].

In terms of efficiency, CI-engines running on methanol can theoretically reach gross indicated efficiencies around 50% for a single cylinder heavy-duty engine [84]. In potential, CI-engines can reach high efficiencies, but more research has to be performed to validate this.

4.1.2. Fuel cell (FC)

Fuel cells are electro-chemical energy converters. This means that fuel cells convert chemical energy directly into electrical energy via oxidation-reduction reactions. The conversion is fundamentally more thermodynamic efficient than heat engines, because a fuel cell is not limited by the Carnot cycle.

In part I of this research, electrolyzers have been analysed which is in principle a fuel cell that works in the opposite direction as can be seen in figure 4.1. Instead of applying a current to the electro-chemical cell, a current is created by feeding the system with a fuel.

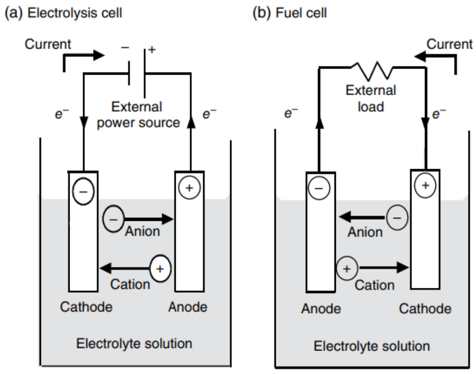


Figure 4.1: Working principle of an electrolyzer and fuel cell [18]

There are many types of fuel cells that have been developed over the past few decades which be categorised in three different operating temperatures. In principle there are six types of fuel cells with the following operating temperature division [18]:

- Low temperature (50-150 °C): AFC, PEMFC and DMFC
- Medium temperature (~ 200 °C): PAFC
- High temperature (600-1000°C): MCFC and SOFC

The **alkine fuel cell (AFC)** is the first fully developed fuel cell and used by NASA for the Apollo space program in the 1960's [18]. The operation temperature are usually below 100°C, which makes them low temperature fuel cells. The alkine fuel cells have an aqueous alkine solvent (KOH) as electrolyte which is sensitive to CO_2 poisoning. So a supply of pure oxygen and hydrogen is necessary for a reliable operation.

The **proton-exchange fuel cell (PEMFC)** is a fuel cell with a solid polymer as electrolyte. Protons can move through this solid polymer to create an electrical current. The operating temperature of the PEMFC is slightly lower than the AFC and lies in the range of 60 to 80 °C [78]. PEMFC's also need high purity hydrogen as fuel in order to operate properly.
In more detail, there are two types of PEMFC's, namely a high temperature- (160-180°C) and low temperature version (40-80°C). A LT-PEMFC is very sensitive to impurities, especially to carbon monoxide (CO). This disadvantage makes it unsuitable to be fed with reformed methanol (Syngas: H_2,CO,CO_2) without purification. The HT-PEMFC is less sensitive to carbon monoxide, but has longer start up times and the purchase cost is dependent on the price of the expensive platinum-based anode and cathode [81].

The **direct methanol fuel cell (DMFC)**is a variant of the PEMFC operates at low temperatures as well. The fuel cell has been adapted to cope with methanol as fuel due to the liquid properties of methanol at STP. DMFC has however very limited in producing high levels of power, which makes it only suitable for low power systems.

The **phosphoric acid fuel cell (PAFC)** is a fuel cell with a liquid phosphoric acid electrolyte and operates at a medium temperature of 220°C. PAFC's run mainly on hydrogen, but can also operate on different fuels such as gasoline. The condition for running on other fuels, is a low sulfur content in the fuel. Another advantage of the PAFC is the tolerance to CO_2 and small concentrations of CO. However durability and power density are an issue for these type of fuel cells [100].

The **molten carbonate fuel cell (MCFC)** operates at the lowest temperatures in the high temperature range (600-1000°C), approximately at 650°C. The electrolyte consist of a hot corrosive molten mixture of potassium, lithium and sodium carbonates. The MCFC can be fed with multiple hydrocarbon fuels (Methane, coal gas, etc.) and hydrogen without external reforming.

The **solid oxide fuel cell (SOFC)** operates at the highest temperatures (600-1000°C) and have an electrolyte made out of ceramic materials. The high temperatures create an environment in which high reaction rates can be achieved and expensive catalyst are not required. Hydrocarbon fuels can also be directly used, without reforming them in advance which makes these fuel cells very flexible.

In order to compare the fuel cells on their capabilities which are important for the implementation of fuel cells on board of the LABRAX, a comparison is made based on efficiency, power output and reliability.

Table 4.2: Fuel cells: Efficiency and power

Fuel cell	Electrical efficiency[2]	Power range[2]	Gravimetric power dens.[3]	Volumetric power dens.[3]
AFC	~ 60%	<1 - 100 kW	-	-
PEMFC^M	~ 60% (direct H_2)	1 - 100 kW	250-1000 W/kg	300-1150 W/L
DMFC	~ 30% (direct CH_3OH)	<5 kW	-	-
PAFC	~ 40%	5 - 400 kW	11.0-14.7 W/kg[1]	3.9-6.0 W/L[1]
MCFC^M	~ 50%	300 kW - 3 MW	7.75 - 25 W/kg	1.75-20 W/L
SOFC^M	~ 60%	1 kW - 2 MW	8-80 W/kg	4-32 W/L

[1]Robert J. Remick et al. [75] [2]U.S. Department of Energy [95] [3] L. van Biert et al. [100] ^{M} = Marinisation

The first characteristic of the fuel cells and probably the most important one is, the electrical efficiency. The electrical efficiency is the efficiency of the conversion from chemical energy (fuel) to electric energy. The values in table 4.2 give an indication of the efficiency and power densities of the fuel cell types and are based on multiple fuel cells that are currently available on the market. So these values are current efficiencies and could be improved significantly due to rapid developments in this area. For example, a PEMFC has a theoretical maximum efficiency of 83%, which is an increase of 38% compared to the current electrical efficiency [50].
For high temperature fuel cells it is more convenient to recover waste heat from the exhaust. With these hot exhaust gases, turbines can be driven or accommodations could be heated which will increase the overall efficiency of the system. However, the effectiveness is dependent on multiple factors and is case dependent. WHR-systems are not considered in this report, because it is out of the scope of this research.

Marine application

The power range of the fuel cell is an important aspect for the application on board, because sufficient power should be available to propel a vessel. The gravimetric power density (W/kg) and volumetric power density (W/L) could play a more significant role, because it determines the size and weight of the energy converter. Furthermore, space inside the engine room of a vessel is limited and a higher system weight implies less payload. In table 4.2, values for the power densities are given for several fuel cells.

The PEMFC has the largest gravimetric and volumetric density, which means less space and weight is needed in order to produce the same amount of power. Even compared to a diesel generator set, which has a power density in the range of 45-71.5 W/kg and 32.5-55 W/L, the PEMFC has a higher energy density. However, for marine applications it is less suitable due to the limited power range and sensitivity to fuel impurities. Also internal reforming is not possible, so a separate reformer unit has to be installed if a different fuel is fed into the system (methanol, methane, ect.) [55].

Alkine fuel cells (AFC) also have a limited power range and are very sensitive to CO_2 poisoning. So air needs to be purified or pure oxygen (O_2) needs to be fed. Moreover, the developments in the area of fuel cells are more focused on the other types of fuel cells, especially in the maritime sector. Noticeable fuel cell types applied in maritime research projects are PEMFC, MCFC and SOFC [100].

Although DMFC's can directly use methanol as fuel, it has a limited maximum power that is lower than 5 kW. Also the electrical efficiency is poor compared to other fuel cells and even more methanol has to be stored on board to maintain a certain range.

The phosphoric acid fuel cell (PAFC) is the first fuel cell that is in the range of power currently installed on board of the LABRAX (400 kW). The efficiency is relatively poor compared to high- and low temperature fuel cells and the power densities are on average lower than MCFC, PEMFC and SOFC. For the application on board of vessels these characteristics are of importance due to the space limitations.

The MCFC has a better electrical efficiency and can deliver more power than the PAFC (3 MW) which means one power unit can be sufficient to provide enough power for the LABRAX. The gravimetric- and volumetric energy density are slightly higher than the PAFC, but comparable. The largest advantage of the MCFC, is the fuel flexibility due to the internal reforming possibilities (high temperatures). A waste heat recovery system can also be implemented to increase the efficiency. Multiple MCFC maritime project have been completed (1997-2013) with an actual implementation of a 330 kW LNG fuelled MCFC in an offshore supply vessel (2009) [100].

The SOFC has the highest electrical efficiency in the medium to high temperature fuel cells and has the widest power range, which makes it very flexible in terms of application. The gravimetric- and volumetric density are increased as well compared to the MCFC. This combination results in the most compact fuel cell that needs the least amount of fuel. The fuel flexibility makes it very suitable for the implementation on board of vessels. SOFC projects have been performed, with small SOFC installations (27 kW and 20 kW) on board of a multipurpose ship and car carrier [100].

4.2. Energy converter selection

In the previous section, several energy converters are analysed on different characteristics with the focus on marine application. Important characteristics are good compatibility with methanol as main fuel and power densities of the energy converter.
Based on these characteristics several options are available for the conversion of methanol into electrical energy. For this research two energy converters are assessed, one in the category of ICE's and one in the category of fuel cells. In this way, both types can be compared to each other in terms of performance.

In the category of internal combustion engines, the spark ignited internal combustion engine (SI-ICE) and compression ignited internal combustion engine (CI-ICE) are potential energy converters for methanol. The spark ignited engine (SI-ICE) has preferable characteristics for a single fuel installation as mentioned in table 4.1 and needs a less advanced fuel system to support the power plant. Also the combustion temperatures are lower for SI-ICE compared to a CI-ICE which result is a decrease in NO_x emissions. Therefore, a SI-ICE is analysed in more detail and used for determining the operational performance of the LABRAX on methanol.

Concerning the fuel cell types, SOFC's and PEMFC's are great candidates to be applied on board due to beneficial characteristics, such as high efficiency ($\sim$ 60%) and gravimetric- and volumetric density. However, the maturity of the technology is crucial for the implementation and therefore PEMFC's has the benefit over SOFC's, although it needs a reformer to convert methanol into hydrogen. Also the gravimetric- and volumetric density of a PEMFC are higher and favorable for the limited space on board of vessels. In more detail, the high temperature PEMFC version (HT-PEMFC) is considered as energy converter due to specific advantages over a LT-PEMFC mentioned in 4.1.2.

4.3. Storage systems

Storage of fuel on board of a vessel has challenging aspects. One of the reasons is strict safety regulation concerning storing flammable, explosive and/or toxic fuels. Another aspect is the space limitations to store fuel on board of a vessel, especially for fuels with a low energy density. Loss of volume due to cofferdams or impractical tank shapes should be closely monitored and avoided when possible.

4.3.1. General storage considerations

The properties of methanol makes it suitable to be stored in conventional storage tanks which will have less technical challenges. As mentioned in section 2.3, methanol is a liquid at standard temperature and pressure (STP) which means a pressure tank is not needed. Therefore, less space is necessary for placing the same amount of volume due to the design of the fuel tank as can be seen in figure 4.2.

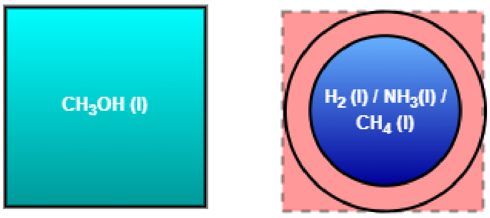


Figure 4.2: Types of storage tanks

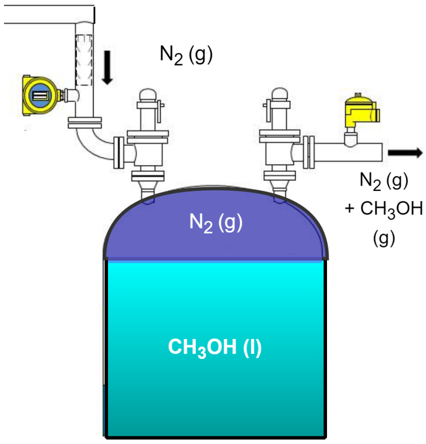


Figure 4.3: Methanol storage tank with inert gas system [4]

There are some challenges with storing methanol on board of vessels that are mostly related to safety issues. These safety issues have also been discussed in section 2.4.3. The low flash point of methanol is one related issue, because it creates a vapor that accumulates inside the empty spaces of the tank and could produce an explosive mixture with oxygen. Therefore nitrogen blanking is necessary to decrease explosion risks which is also a class rule by Lloyd's Register. Nitrogen blanking is adding nitrogen (inert gas) into the empty space of the fuel tank to keep oxygen levels low at all times. In figure 4.3 a schematic drawing is given of a fuel storage tank with an inert gas system.
Another issue of storing methanol inside a tank, is corrosion. Methanol is a polar and conductive solvent and materials in direct contact should be protected accordingly. Galvanic corrosion could occur when incompatible materials are being used for storage- and fuel systems. Hence, it is very important to have cathodic protection, special coating such as inorganic zinc silicate and regular inspections of the tank to prevent contamination of the fuel and failure due to corrosion.

4.3.2. Classification rules

In the previous section, classifications rules were briefly mentioned and will be discussed in more detail in this section.

In order to determine possible fuel storage locations on the LABRAX, it is valuable to examine current classification rules for storage of methanol on board of ships.
Different classification bureaus have guidelines or rule notes for methyl alcohol fuelled ships. The LABRAX is currently classified under the rules of classification bureau Bureau Veritas (BV), so rules established by BV concerning the application of methanol on board will have preference.
Bureau Veritas has created a rule note for methyl/ethyl alcohol fuelled ship with rule note number: NR 670 DT R00 E [12]. The document is divided into 13 sections with the focus on safety risks. Relevant sections for the implementation of methanol on board of the LABRAX are related to placement of fuel tanks.

Section 3 is one of those sections that is relevant for the implementation of fuel tanks for alcohol fuels. Three different types of fuel tanks are mentioned which can be applied on board of vessels.

The first type is the integrated fuel tank which is the most applied type of tank to store conventional fuels. An integrated fuel tank is placed in the structure of the ship, usually nearby or in an engine room as shown in figure 4.4. Current design of the LABRAX has integrated fuel tanks with main fuel tanks in the fore ship and two day tanks in the aft ship, mentioned in section 3.1.2.
The second type of fuel tank, is the independent fuel tank which is placed outside the structure of the vessel. The tank is usually placed on deck and fixed connected to the structure as can be seen in figure 4.5. For LNG powered vessels, this type of tank placement is often applied to decrease the impact on the cargo capacity.
Portable fuel tanks can also be used to store fuels on board of vessels. These types of fuel tanks can be removed if necessary and replaced by a full fuel tank. An example of a portable tank in shown in figure 4.6.

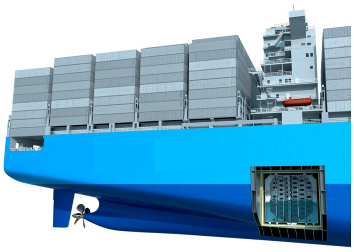


Figure 4.4: Integrated fuel tank [54]

Figure 4.5: Independent fuel tank [53]

Figure 4.6: Portable fuel tank [45]

Concerning the placement of these fuel tanks, the following requirements that have the largest impact on ship design will be taken into account:

- Fuel tanks should not be placed inside accommodations or machinery spaces of category A
- Integrated fuel tanks that are not located below the waterline need to be surrounded by a cofferdam
- Fuel containment systems need to be located abaft the collision bulkhead and forward of the aft peak bulkhead
- A flat fuel tank needs to at least 600 mm high
- Outlets of tank ventilation need to be constructed 3 m above deck and 10 m from opening of an accommodation, service space and ignition source
- Instead venting 3 m above deck, ventilation outlets may be situated under water
- Fuel tanks need to be separated from a category A room with an isolated cofferdam
- Fuel tanks on open deck need a FiFi-system
- Fuel pipes need to be constructed 800 mm from the sides of the ship
- Fuel pipes are not constructed directly through accommodations, service spaces and electrical equipment rooms

The requirements are mainly focused on the separation of the methanol from certain ”risk” areas and safe ventilation of methanol vapours from the fuel tank. All other relevant rules constructed by BV are displayed in appendix C.1.

4.3.3. Fuel storage options

In this section, possible spaces to store methanol on the LABRAX are identified and rated with the help of classification rules on their pros and cons.

Three types of fuel tanks, defined in section 4.3.2, are investigated for storage of methanol which are:

- Integrated fuel tank
- Independent fuel tank
- Portable fuel tank

Placement options are analysed per defined section which are:

- Fore ship
- Mid ship
- Aft ship

These general locations can be divided into smaller and specific spaces, such as engine room in the aft ship. The following spaces are excluded in advance due to regulation restrictions:

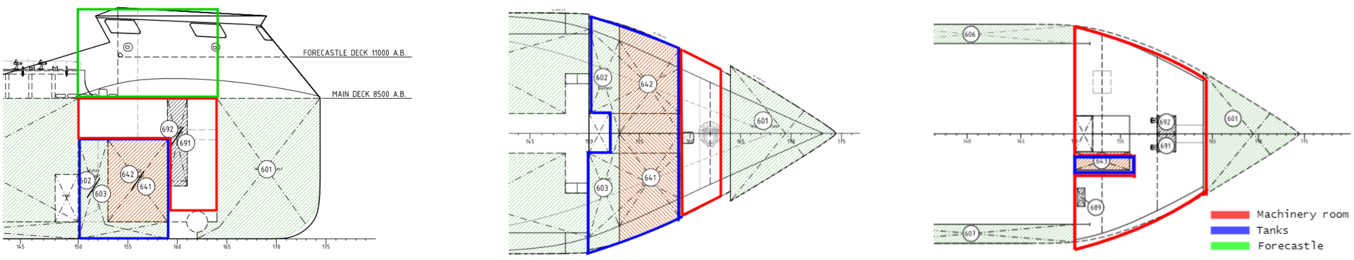
- Inside the superstructure (accommodation, wheel house, etc.)
- Space from collision bulkhead fore ship to bow
- Space from collision bulkhead aft ship to stern

Fore ship

In regard to the fore ship, the following division in spaces are defined:

- Machinery room
- Forecastle
- Tanks (fuel- and ballast tank)

In figure 4.7, the spaces are visualised with coloured boxes, with in red the machinery room, green the forecastle and blue the tanks.



(a) Side view: 0 mm - 13990 mm A.B. (b) Top view of tank top: 1030 mm A.B. (c) Top view of tween deck: 5300 mm A.B.

Figure 4.7: Potential spaces to store methanol in fore ship

Advantages and disadvantages per potential storage space in fore ship are shown in table 4.3. These factors are based on regulation and shipbuilding knowledge.

Table 4.3: Advantages (A) and disadvantages (D) of storing methanol in fore ship

Machinery room (Red)		Tanks (Blue)		Forecastle (Green)	
A	**D**	**A**	**D**	**A**	**D**
Adjacent to tanks	Limited fuel storage available	All storage available for fuel	Loss of ballast capacity	Large volume	Limited fuel storage available
	Cofferdam needed	Already tanks	Partly cofferdam needed	Suitable for independent tank	Cofferdam needed
	Medium stability influence	Small stability influence			Large stability influence

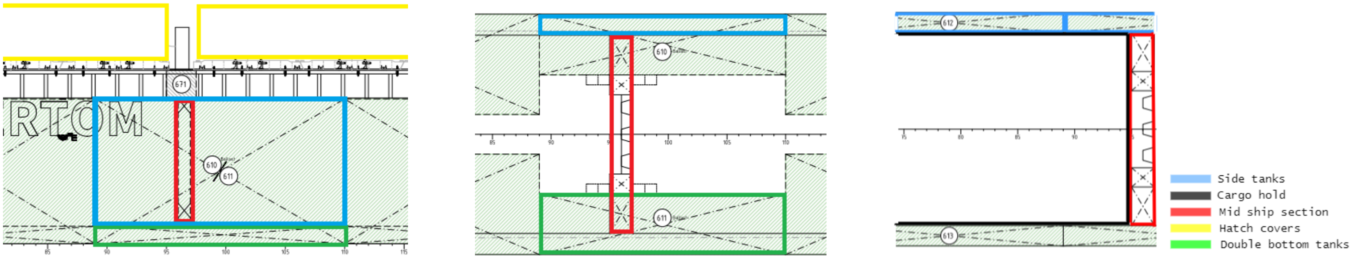
Overall, the advantage of placing methanol fuel tanks in the fore ship is the safety distance to the accommodation. The main disadvantage of methanol fuel tanks in the fore ship is the distance to the main engine room where the fuel is usually used. Especially when methanol fuel pipes need to be double walled and placed over a distance of approximately 80 m with a minimum distance of 800 mm from the sides. Also the space for fuel storage, except for the current fuel tanks, is limited due to the shape of the bow and installed machinery. Another large disadvantage of storing methanol close to or in a category A room, is the requirement to have an isolated cofferdam between those spaces.

Mid ship

In the mid ship, the following division in spaces are defined:

- Side tanks
- Cargo hold
- Mid ship section
- Hatch covers
- Double bottom tanks

In figure 4.8, the spaces are visualised with colours, with in red the mid ship section, in yellow the space above the hatch covers, in blue the side tanks, in green the double bottom tanks and in black the cargo hold.



(a) Side view: 0 mm - 12700 mm A.B.

(b) Top view of tank top: 1030 mm A.B.

(c) Top view of tween deck: 5300 mm A.B.

Figure 4.8: Potential spaces to store methanol in mid ship

Table 4.4: Advantages (A) and disadvantages (D) of storing methanol in mid ship

Mid ship section (Red)		Side tanks (Blue)		Double bottom tanks (Green)	
A	**D**	**A**	**D**	**A**	**D**
Limited loss of volume	Limited fuel storage available	All storage available for fuel	Loss of ballast capacity	Large volume	Loss of ballast capacity
No cofferdam needed	Medium stability influence	Already a tank	Partly cofferdam needed	Already a tank	Not accessible with cargo on top
Large distance to aft			Medium stability influence	Small/medium stability influence	When partly filled, free surface effect
				No cofferdam needed	

Hatch covers (Yellow)		Cargo hold (Black)	
A	**D**	**A**	**D**
Large fuel storage available	Large influence on stability	Large volume	Loss of cargo volume
Suitable for portable tanks	Difficult access to the pipe-duct	Flexible placement options	Large constructional change
Flexible placement options	Obstruction for (un)loading		Medium influence on stability
			Partly cofferdam needed

The mid ship section, that extends from the bulkhead of the engine room to the bulkhead of the fore ship, has several advantages. The main advantage is that less cofferdam is needed to store methanol and a considerable space is available for fuel storage. This space is only available if the stability is maintained due to the decrease in ballast capacity.
The blue storage spaces are side tanks of which 12 tanks are constructed. These side tanks are partly under the waterline, but mainly above the waterline when the vessel is unloaded. Due to the space limitation inside the side tanks (1250 mm), it is very difficult to construct a cofferdam (600 mm) in a working space with a width of approximately 650 mm.
The green spaces are the bottom tanks of which also 12 tanks are constructed. The bottom tanks are in its entirety under the waterline which means no cofferdam is needed and full storage capacity can be utilized. For the stability of the vessel when sailing unloaded, most of the ballast tanks need to be filled. However the bottom tanks adjacent to the fore hip are less essential for stability.
The yellow spaces on top of the hatch covers can be used to store methanol as well. A great advantage of this space is, the large amount of space available for storing methanol on board of the vessel. Although, it is limited due to the high center of gravity. Another consideration when storing fuel on top of the hatch covers is, the ability to move the tanks during (un)loading of cargo, which makes it particularly suitable for portable tanks.
The cargo hold has the largest available volume for storing methanol, but also needs a cofferdam when placed against the fore- and aft bulkhead. If volume of the cargo space is used for storage of methanol, less cargo can be

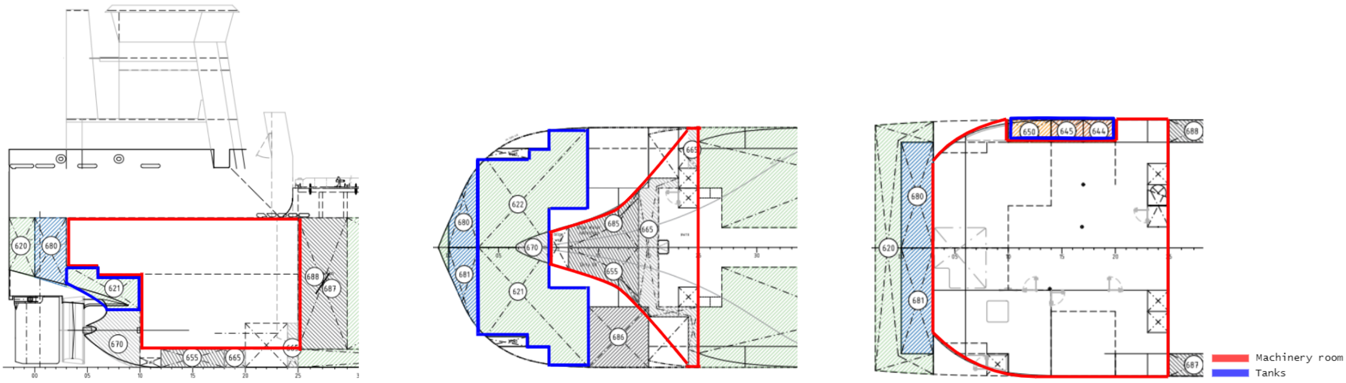
stored which can have a large influence on the economics of the vessel. Only in or against the red space would be suitable for methanol storage without the obligation of applying cofferdams.

Aft ship

At the aft of the ship, the following division in spaces are defined:

- Machinery room
- Tanks (fuel- and ballast tank)

In section 3.1, already a top view and side view has been shown for the aft section with a technical drawing for the engine- and propulsion system room. In figure 4.9, the tank and machinery room are outlined with blue and red lines.



(a) Side view aft ship: 0 - 20300 mm A.B. (b) Top view of tank top: 1030 mm A.B. (c) Top view tween deck: 5300 mm A.B.

Figure 4.9: Spaces for methanol storage in aft ship

Table 4.5: Advantages (A) and disadvantages (D) storing methanol in aft ship

Machinery room (Red)		Tanks (Blue)	
A	**D**	**A**	**D**
Adjacent to tanks	Limited fuel storage available	All storage available for fuel	Loss of ballast capacity
Service tanks already incorporated	Cofferdam needed	Already tanks	Cofferdam needed
	Medium influence on stability		Medium influence on stability
			Adjacent to potable water

For both spaces in the aft ship, it is evident that the distance from fuel storage to energy converter is the shortest compared to the mid- and fore ship section. This means less piping (double walled) is needed to transfer the fuel along the vessel. However, for the red space, there is a limited amount of space available to store fuel due to the installed main engines and propulsion system. Also an isolated cofferdam is necessary to store methanol, because it is above the waterline and in a category A room.
The blue spaces are current fuel- and ballast tanks that are located above the the waterline and adjacent to category A rooms. Isolated cofferdams are therefore needed all around the tank, which implies a significant loss of storage capacity and a large adaption when refitting the vessel with an methanol energy system.

4.3.4. Fuel storage- and engine placement

Now the consequences of fuel storage are known and several energy converters are evaluated, concept designs of fuel storage and energy converters are analysed. Due to the design of the main engine room, which is modular due to the separation of energy converter and propulsion system, the most suitable place to store new energy converter(s) are in the engine room at tween deck.

The concept designs are based on the placement analysis in section 4.3.3. In the literature research, a minimum range of 2700 NM was determined to sail from port to port, which will be the reference point for the analysis of the concept designs.
Only single fuel installations will be considered in this analysis in order to directly compare methanol to diesel as energy source for the LABRAX in the transport performance.
Independent fuel tanks are not taken into consideration for the concept designs due to the limited space to place a fixed tank on deck.
For all concept designs two integrated service tanks are placed in the vessel with a minimum capacity of 9 m^3 each, according to regulation. The location is chosen based on the available volume below the waterline which is largest in the aft section of the vessel (empty). Also the distance between energy converters and service tanks is kept to a minimum value.

Concept design 1: Internal

The first concept design considers integrated fuel tanks at two locations and energy conversion in the aft ship.
The first methanol fuel tank is located in the front double bottom, where currently ballast tank 604 and 605 are placed. The second methanol tank is placed below the waterline partly in ballast tank 603 and 602 and Marine Gas Oil tank 641 and 642. These tanks are located after the bulkhead in the fore ship and shown in figure 4.7.

In figure 4.10, the combination of energy converter and methanol fuel storage is shown. In red, a schematic representation of the fuel line is drawn from the main tanks to the service fuel tanks (day tanks) and again to the energy converters. The fuel pipes are drawn in the pipe duct which is located in the center of the double bottom.

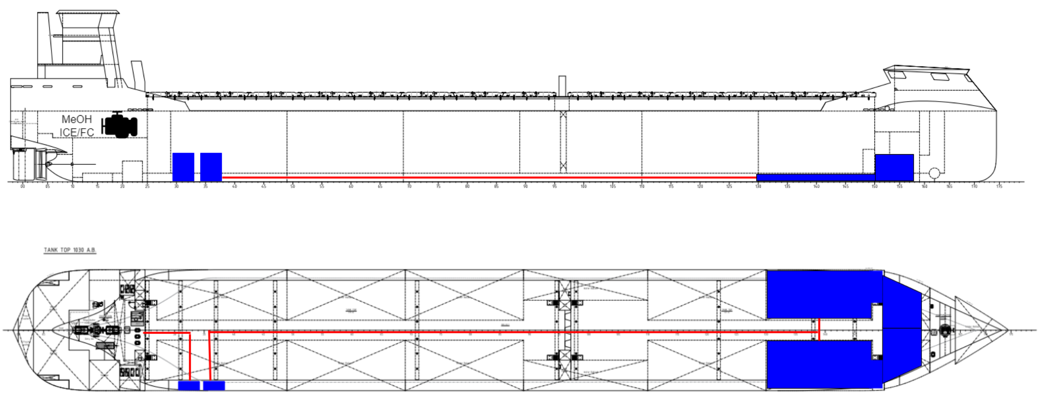


Figure 4.10: General arrangement drawings of concept design 1 with methanol storage

The configuration has certain advantages that will be explained further on, but first specific properties of the concept design are mentioned and compared to the original situation.

Table 4.6: Storage properties of concept design 1

	Bottom tank	Fore tank	Total	Total current	Difference
Storage volume	146 m^3	113 m^3	259 m^3	172 m^3	+51%
Fuel load	116 t	89 t	205 t	145 t	+41 %
Ballast volume	-146 m^3	+51 m^3	2455 m^3	2550 m^3	-4%
Cargo hold volume	+0 m^3	+0 m^3	9336 m^3	9336 m^3	0%

Service tanks are left out in the analysis

The choice for this concept design is based on minimum loss of ballast capacity and cargo hold volume as can be seen in table 4.6. This was achieved by storing methanol under the waterline where no cofferdam is needed. Also the influence on the stability of the vessel is minimized by placing fuel tanks in the fore ship. The column named ”difference” is the difference in percentage with the current design of the LABRAX of which values are mentioned in section 3.1.

Concept design 2: External

The second concept design considers an external storage of methanol. For external storage of methanol on the LABRAX and in particular on the hatch covers, a portable fuel tank is considered. These can be placed on the hatch covers where a connection is possible to the main fuel line.
The placement of these tanks are flexible and the number of tanks can be adjusted to the needs which makes them in principle range extenders. In figure 4.11 the range extenders are placed at the fore ship which is the largest distance to the accommodation. The range extenders are assumed to have a volume of 47 m^3 for a 40ft ISO tank (container size) and four pieces can be placed next to each other.
Regarding the energy converters, the same types are considered as in concept design 1.

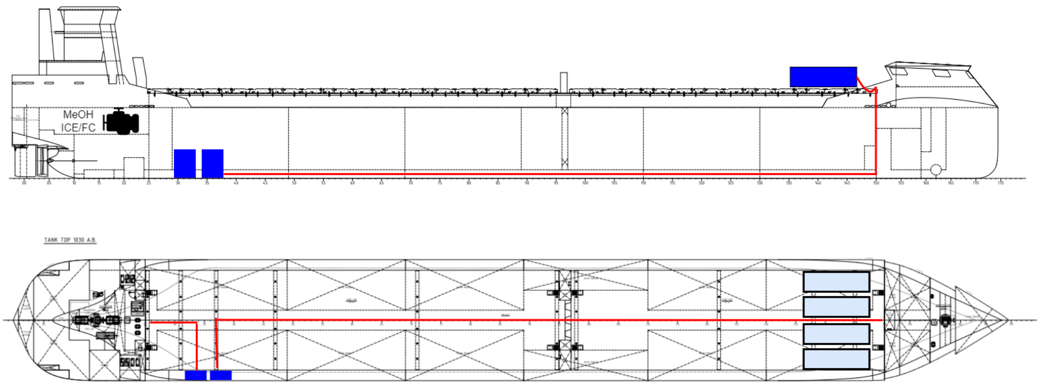


Figure 4.11: General arrangement drawings of concept design 2 with methanol storage

Table 4.7: Storage properties of concept design 2

	Range Extnr.	Total	Total current	Difference
Storage volume	47 m^3	188 m^3	172 m^3	+9%
Fuel load	37 t	148 t	145 t	+2%
Ballast capacity	+172 m^3	2722 m^3	2550 m^3	7%
Cargo hold volume	+0 m^3	9336 m^3	9336 m^3	0%

Service tanks are left out in the analysis

Also this concept design was based on minimum loss of ballast capacity and cargo hold volume, but had an extra focus on a flexible fuel carrying capacity.

Concept design 3: Combination

The second concept design considers a combination of concept design 1 and 2. In this way maximum storage capacity is reached with an option to remove a part of the capacity if necessary. In figure 4.12, the general arrangement of the combination with the shortest distance of the range extenders to the fore ship and bottom tank.

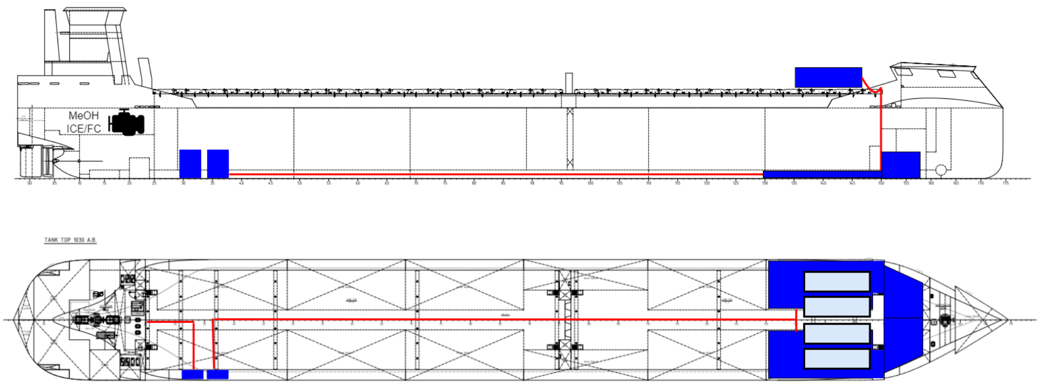


Figure 4.12: General arrangement drawings of concept design 3 with methanol storage

Table 4.8: Storage properties of concept design 3

	Bottom tank	Fore tank	Range Extnr.	Total	Total current	Difference
Storage volume	146 m^3	113 m^3	188 m^3	447 m^3	172 m^3	+160%
Fuel load	115 t	89 t	149 t	353 ton	145 ton	+143 %
Ballast change	-146 m^3	+51 m^3	+0 m^3	2455 m^3	2550 m^3	-4%
Cargo hold volume	+0 m^3	+0 m^3	+0 m^3	9336 m^3	9336 m^3	0%

Service tanks are left out in the table

This concept design is again based on minimum loss of ballast capacity and cargo hold volume and maximizes the fuel carrying capacity. In table 4.8, the difference with the current situation is shown with an increase in fuel storage volume of 160%.

4.3.5. Concept design selection

Three different concept designs are mentioned in the previous section with an internal and external solution for storing methanol. In this section, the most suitable concept design will be selected based on specific demands and wishes.

The first demand of the vessel is the minimum determined range of 2700 NM which is directly linked to the fuel storage capacity. With the current configuration and applying the least efficient energy converter (η_e = 40%), the range of the concept designs at design speed (9.5 kn) are:

- Concept design 1: 3844 NM
- Concept design 2: 2863 NM
- Concept design 3: 6457 NM

As expected the highest range is the combination of the two concept designs, with a range of almost 6500 NM which is even slightly more than the current range of the LABRAX at design speed with a CI-ICE on MGO as can be seen in transport performance section 3.3.3. Also the first and second concept design comply with the minimum set range, with a difference in range of approximately 1000 NM.

A wish in terms of cost and technical feasibility is constructional complexity. For concept design 3 this is most challenging due to the double storage types and fuel connections. Also multiple safety zones for venting, due to two separate location, could increase the complexity of the system. The fore tank, in both concept design 1 and 3, needs to have a cofferdam between the storage tank and category A room. The range extenders from concept design 2 and 3 can be placed without any constructional changes which is a benefit, but the removal of the portable fuel tanks during (un)loading could cause problems. The vessel will be dependent on available cranes to remove the portable fuel tanks or a large constructional change needs to be performed in order to move these fuel tanks (vessel crane). Also deck payload is decreased due to the presence of portable tanks on the front hatch covers.

All concept designs do not take up any cargo space in the hold or large amounts of ballast capacity for stability at discharged conditions. In terms of cost and complexity which determines the feasibility of this solution concept design 3 is not suitable to implement although it has the highest range. Concept design 1 and 2 are within the minimal range, but the range at design speed of concept design 3 is closer to the current range visualised in figure 3.15. This range margin should give the option to sail at higher ship speeds when necessary and creates more value for the shipping company due to the increased flexibility. Other disadvantages, such as the uncertainty to move the portable fuel tanks when (un)loading and loss of deck payload capacity, will result in concept design 1 to be most suitable for this vessel.

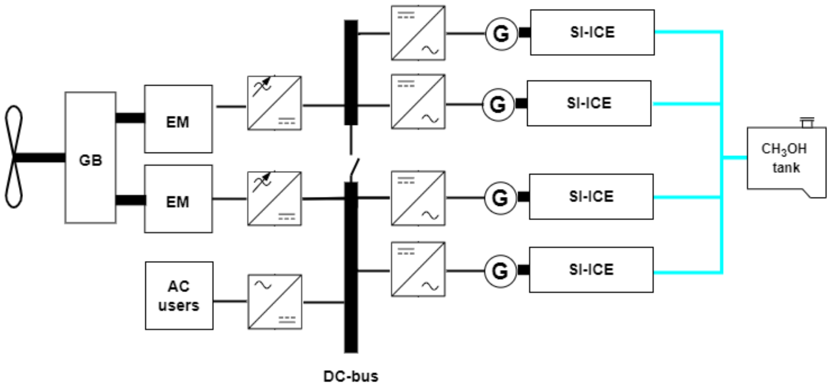
4.4. Power- and energy systems

For the new power- and energy system, the mechanical, electrical and heat aspects are analysed. The mechanical aspects of the propulsion system are less important, because this system remains identical to the current power plant.

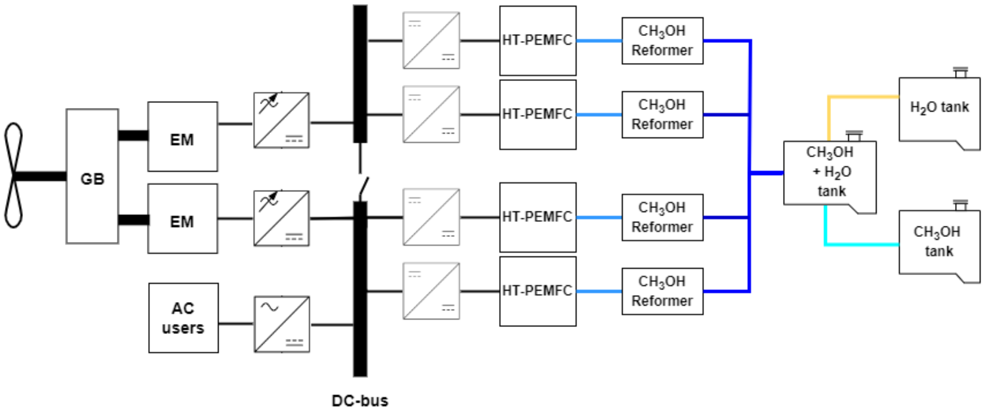
4.4.1. Methanol-electric power plants

The power plant with methanol as main fuel can be divided into two categories, namely a configuration with an internal combustion engine (SI-ICE) and a fuel cell (HT-PEMFC).
In figure 4.13 two possible power plant configurations are shown. The HT-PEM fuel cell system, shown in figure 4.13b, has the largest system changes compared to the original situation in figure 3.6. The first notable difference is the need for a methanol reformer, because (HT)-PEMFC's can only operate on pure hydrogen. Therefore, methanol (CH_3OH) will be converted into hydrogen (H_2) and carbon dioxide (CO_2) by reacting with water/steam (H_2O) before it enters the fuel cell. Hence, an additional water tank is needed. Water from the water tank is mixed in the last tank with methanol ($CH_3OH + H_2O$) before it enters the methanol reformer.
The electrical system is also slightly different, because direct current (DC) is generated by the fuel cell instead of alternating current (AC) by a generator. Hence, instead of a AC/DC converter, a DC voltage regulator is needed before electricity is fed into the DC-bus (main switchboard).

For the methanol-electric power plant, the layout change is minimal due to comparable characteristics with the diesel-electric configuration. In principle, diesel engines (CI-ICE) could be directly replaced by methanol engines (SI-ICE) with an adapted fuel system.



(a) Power plant layout with an SI-ICE on methanol



(b) Power plant layout with a PEMFC on methanol

Figure 4.13: Power plant layouts with methanol as main fuel

Energy balances of both configuration will be established and checked under specified conditions, stated in table 4.9. These conditions will result in the highest power usage on board of the LABRAX of which more detailed data can be found in appendix B.2. In this way, it can be verified that the power generation is sufficient with the new power plant configuration with additional systems.

Table 4.9: Operational conditions

Characteristic	Condition
Season	Winter
Operation	Sailing
Propulsion power	1300 kW
Power usage	>0%

4.4.2. SI-ICE fuel system characteristics

Now the configuration of the power plant is clear, a more detailed analysis of the fuel system is performed.
First, a layout is created with essential fuel system components and energy converter. Afterwards, specifications of components within the fuel system are determined in order to verify the mass-, heat- and electrical balance of the total system.
This analysis will determine if the current installed power (1600 kW) is sufficient to support the additional fuel system components.

In figure 4.14, a layout diagram of a 100% methanol SI-ICE fuel system is defined. The fuel diagram is based on the research performed on a CAT G3508A SI-ICE of which the fuel system can be seen in appendix D.2 [9].

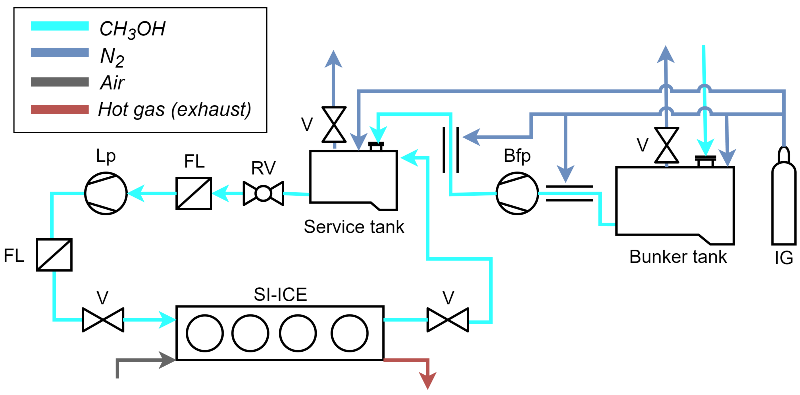


Figure 4.14: Layout of a 100% methanol fuel system with a SI-ICE

In the fuel system several supporting components/systems can be identified, namely:

- Low-pressure fuel pump (Lp)
- Safety and control valves (V and RV)
- Filters (FL)
- Bunker fuel pump (Bfp)
- Inert generator (IG)

The fuel system and SI-ICE have certain specifications which are mentioned in table 4.10 and 4.11.

Table 4.10: Fuel system specifications

	Fuel system
Fuel injection pressure	5 bar
Low-pressure fuel pump flow	500 L/h
Fuel temperature before injection	40°C
Filter particle rating	75 & 10 micron

Table 4.11: Engine specifications [9]

	SI-ICE
Rated brake power	500 kW
Rated engine speed	1500 rpm
Compression ratio	12:1
Effective engine efficiency	37.6 %
Generator efficiency	95.0%
Electrical efficiency	35.7 %

The methanol fuel system is comparable to the diesel fuel system, but has some differences due to the toxicity- and flammability of the fuel.
One significant difference can be seen in the fuel pipes which need to be double walled when sufficient ventilation is not possible. This will probably be the case for fuel pipes installed in the pipe-duct due as can be seen in figure 4.14. These pipes run from the bunker tanks in the fore ship to the service tanks in the aft ship.

In addition to a double walled pipe, an inert generator needs to be installed for safe use of methanol. Usually an inert generator produces pure nitrogen (99.9% N_2) from captured air, although it also possible to produce low purity nitrogen gas (95% N_2). Nitrogen needs to be added to the fuel piping system (if ventilation is not possible) and fuel tanks in order to keep the oxygen levels below certain threshold (<8% vol). The nitrogen methanol vapor mixture in the fuel tanks needs to be ventilated as well by vent pipes. In figure 4.14, the outgoing flow from the tanks are indicated as nitrogen only, but in reality it will be a gas mixture of nitrogen with methanol.
The data sheet of the specific nitrogen generator which is used for determining the power consumption can be found in appendix E.2.

A bunker- and low pressure fuel pump are integrated into the methanol fuel system to transfer the methanol from the bunker tank to the engines. From the service tank, methanol is transferred under pressure (5 bar) to the engines. A single operating bunker fuel pump is needed (with one back-up) to transfer fuel from the bunker tank to the service tanks. However, each engine needs its individual low pressure pump, filters and safety valves for optimal operation. Pressure relieve valves are installed to release methanol when the pressure increases significantly.

Unfortunately not all energy stored in fuel is converted into electrical energy. Losses of the engine with generator, of which the setup is shown in figure 4.15, are in the range of 64.3 %. Most of the energy is converted into heat. In figure 4.16, an energy balance of the SI-ICE with a brake power of 400 kW is given. The maximum brake power of this engine is 500 kW, but to compare the mass flow and heat loss at the same power as the diesel CI-ICE engine, the balance is evaluated at 400 kW. In this balance, it is assumed that the reaction between methanol (CH_3OH) and oxygen (O_2) is complete and no other reactants are formed besides carbon dioxide (CO_2) and water (H_2O) as stated in chemical equation in figure 4.16.

Figure 4.15: Setup of a CAT G3508A on methanol [9]

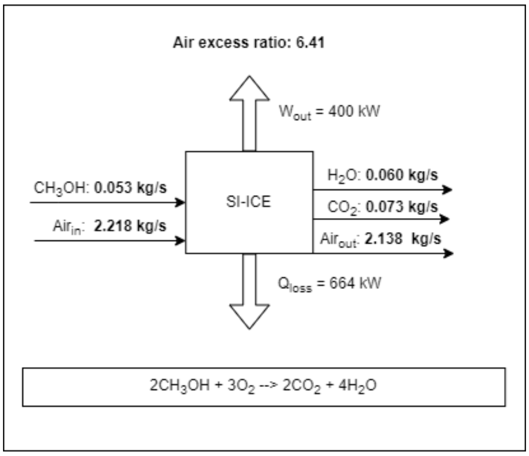


Figure 4.16: Mass- and heat balance of a 400 kW methanol SI-ICE

In the mass and heat balance of 4.16, it can be verified that fuel mass flow into the engine is equal to 0.053 kg/s. This equals a volume flow of 241 L/h for a power of 400 kW. With four engines at 1600 kW brake power, the total volume flow will be 964 L/h, which lies in the range of 2.4 times the volume flow of diesel. Detailed analysis of the fuel consumption and corresponding range of the SI-ICE power- and energy system will be performed in section 4.5.

As mentioned in the beginning of this chapter, the electric consumption of fuel system components needs to be checked in order to verify the electrical balance of the total power- and energy system. The inert generator, low-pressure fuel pump and bunker fuel pump are main fuel system components with an electrical power consumption. The methanol bunker fuel pump has to pump a certain energy content, similar to the diesel bunker fuel pump. However, the volume flow will be higher due to the lower volumetric energy density with an equivalent engine efficiency ($\sim 40\%$). Calculations and estimations of electrical power consumption are given in appendix A.2. In table 4.12, the results of electrical power consumption is shown for all fuel system components with a total electrical power demand at the end.

Table 4.12: Electrical power consumption of additional fuel system components

Type	Power	Active power
Bunker fuel pump	4.0 kW (1x)	0.4 kW (10%)
Low-pressure pump (LP)	0.9 kW (4x)	0.9 kW (100%)
Inert generator	3.6 kW (1x)	3.6 kW (100%)
Total	8.5 kW	4.9 kW

For a 100% methanol SI-ICE fuel system, a total active power demand of 4.9 kW is needed for the conditions defined in table 4.9. The electrical load balance integrated with the new fuel system is visualised in figure 4.17.

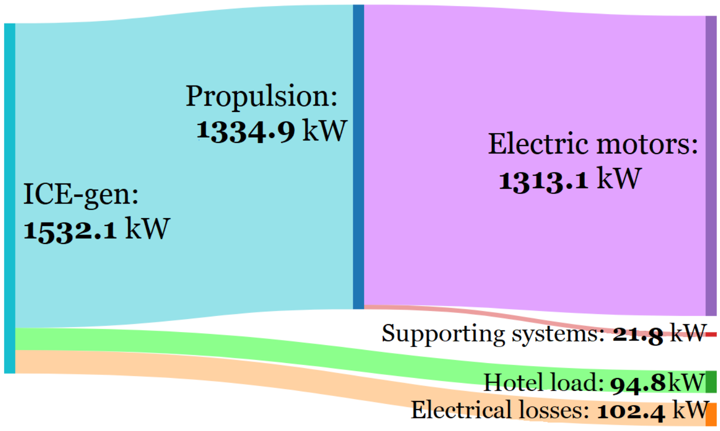


Figure 4.17: Sankey diagram of the electrical load for winter sailing for an SI-ICE power plant

The diesel-electric load diagram is very similar to the methanol-electric load diagram with a SI-ICE power plant. Only an increase in power demand for supporting systems (for the fuel system) of 4.8 kW is identified. The difference of 0.1 kW between the total active power in table 4.12 and increase in power demand (4.8 kW) can be linked to the replacement of fuel pump in the diesel configuration, which has an active power of 0.1 kW.
The total electrical load of 1532.1 kW results in a needed brake power of approximately 1613 kW (η_{gen} = 95%). This means that 1600 kW of brake power is not sufficient to support the systems at the specified conditions stated in table 4.9. However, the CAT-engines have a maximum brake power of 500 kW, so four pieces result in a maximum total brake power of 2000 kW. Hence, sufficient power is available with a margin of ~ 387 kW, but this is significantly more power than necessary which influences the operational performance

4.4.3. HT-PEMFC fuel system characteristics

In this section section, a detailed analysis of the fuel system of a HT-PEMFC is performed. This includes a layout of the fuel system components and energy converter, specifications of components and a mass-, heat- and electrical balance.

The methanol fuel system of a high temperature PEMFC is relatively complicated compared to the internal combustion engine version. Additional system components such as a reformer, vaporiser, catalytic burner and air compressor are needed for the operation of the power plant as shown in figure 4.18

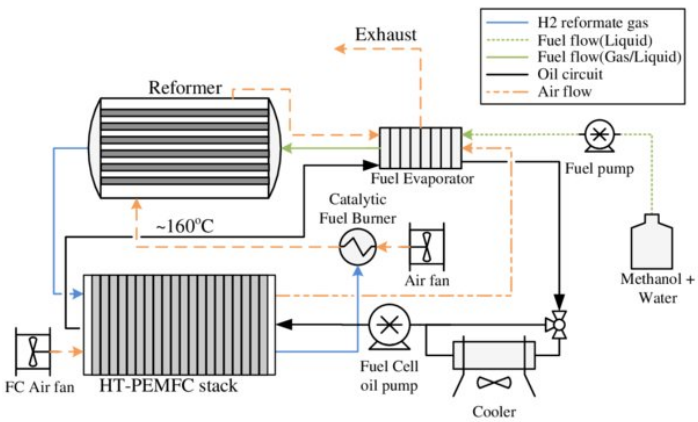


Figure 4.18: Schematic representation of a methanol HT-PEMFC power plant [86]

Analysis of fuel system specific components, such as the reformer and evaporator is out of the scope of this research. Hence, the reformer, catalytic burner, evaporator and compressor will be integrated into one fuel cell unit.
The layout of the integrated fuel system of a 60%/40% methanol-water HT-PEMFC is visualised in figure 4.19. The fuel diagram is based on an integrated fuel cell system named Advent H3 5000 with the technical data sheet shown in appendix E.1. In this report, the storage of water is not taken into account, because it is assumed that water can be created by a watermaker and therefore minimal storage is needed.

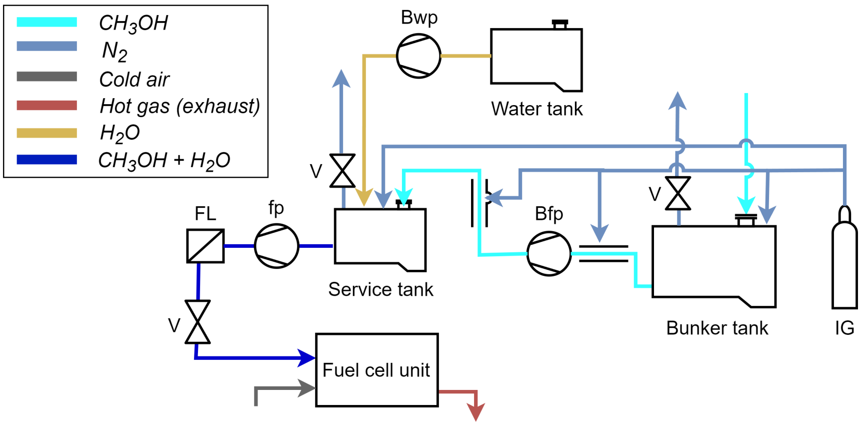


Figure 4.19: Layout of a methanol fuel system with a HT-PEMFC unit

In the fuel system several supporting components/systems can be identified, namely:

- Bunker water pump (Bwp)
- Bunker fuel pump (Bfp)
- Fuel pump (fp)
- Inert generator (IG)
- Filter (FL)
- Safety valve (V)

The HT-PEMFC have certain specifications which are mentioned in table 4.13

Table 4.13: Fuel system specifications

	Advent H3 5000
Fuel composition	60 %vol CH_3OH, 40 %vol H_2O
Rated electrical power	5 kW
Net electrical efficiency	41 %
Operating temperature	150-180 °C

A fuel system with an integrated fuel cell unit is less complex than a fuel systems with external fuel systems/components that support the fuel cell. The layout is comparable to the SI-ICE fuel system, but the HT-PEMFC fuel systems contains an extra water tank with bunker water pump to create the methanol/water mixture in the service tanks. This tank can be large or small depending on the possibility to make purified water which can be used by the methanol reformer in the fuel cell unit. For this analysis, it is assumed that water can be purified and used for the steam reforming process.

An inert generator is still needed to keep the oxygen levels low in fuel tanks and double fuel pipes when ventilation is not possible.
A filter is placed between the service tank and fuel cell unit to prevent contamination of the fuel cell with small particles.
In emergency situations the valve between the fuel cell unit and service tank can be closed.
Two bunker pumps are necessary to transfer methanol and water to the service tank where it can be mixed with a fuel composition mentioned in table 4.13. From the service tank, again a fuel pump is needed to pump the fuel mixture to the fuel cell unit. HT-PEMFC's operates at atmospheric pressure, so the power consumption of the fuel pump will be lower than the fuel pump of the SI-ICE [86]. However, a higher volume flow will be expected due to a

lower energy content in the fuel mixture. Hence, the power of the fuel pump will be assumed to be in the same range as the low pressure fuel pump of the SI-ICE.

The fuel cell unit has a certain efficiency to convert chemical energy stored in methanol into electrical energy. The losses of the fuel cell unit are in the range of 59% which means the efficiency is approximately 5.1 percentage point higher (+14.2%) than the SI-ICE. In figure 4.21 an energy balance of a set of HT-PEMFC units with a total power output of 400 kW is made. This means the power plant consist of four sets of eighty 5 kW HT-PEMFC units connected to each other in cabinets, as shown in figure 4.20.
Certain assumptions are made when analysing the process within the HT-PEMFC unit. First, the reaction of hydrogen is complete and no other gases are formed afterwards due to incomplete combustion. Reforming methanol into syngas is also complete and only hydrogen (H_2) and carbon dioxide (CO_2) is formed.

Figure 4.20: HT-PEMFC units on board of MS Innogy (35 kW) [89]

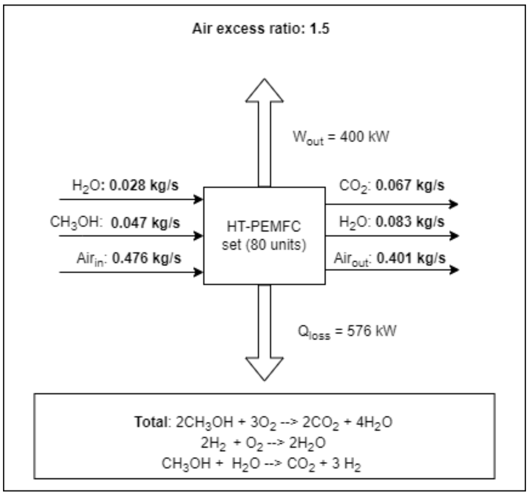


Figure 4.21: Energy flow balance of a 400 kW methanol HT-PEMFC set

The methanol mass flow is equal to 0.047 kg/s (215 L/h) for a 400 kW HT-PEMFC set. Water is fed into the unit as well for the steam reforming process (SR) which will convert methanol into hydrogen. The total methanol volume flow at maximum power (1600 kW) is equal to 860 L/h, including water 1455 L/h. It should be noted that a power output of 400 kW for fuel cell is already electrical power compared to brake power of a ICE which has to be converted to electrical power by a generator ($\sim 5\%$ loss).

The electrical power consumption needs to be sufficient to support all systems on board of the vessel including the additional fuel system that are methanol specific. To verify the electrical power balance, the power consumption of the inert generator and bunker fuel pumps (water + methanol) are analysed.
The bunker fuel pump for methanol has to pump a certain amount of energy within a certain amount of time to fill the service tanks. The energy content flow will be in the order of the methanol SI-ICE power- and energy system. Due to the higher efficiency of the fuel cell, slightly less fuel has to be transferred from the bunker tanks to the service tanks which results in a lower power consumption. The inert generator also needs less electrical power due to the decrease in fuel consumption, but will be in the range of the methanol SI-ICE power- and energy system. In table 4.14, an estimation of the electrical power consumption of additional fuel systems are given including the active power. The electrical power calculations are shown in appendix A.2.

Table 4.14: Electrical power consumption of additional fuel system components

Type	Power	Active power
Bunker fuel pump	3.7 kW (1x)	0.4 kW (10%)
Bunker water pump	1.7 kW (1x)	0.2 kW (10%)
Fuel pump	0.9 kW (1x)	0.9 kW (100%)
Inert generator	3.5 kW (1x)	3.5 kW (100%)
Total	9.8 kW	5.0 kW

So 5.0 kW electrical power is necessary to support the HT-PEMFC fuel system. The total electrical balance at conditions mentioned in table 4.9 with the new fuel systems is shown in figure 4.22

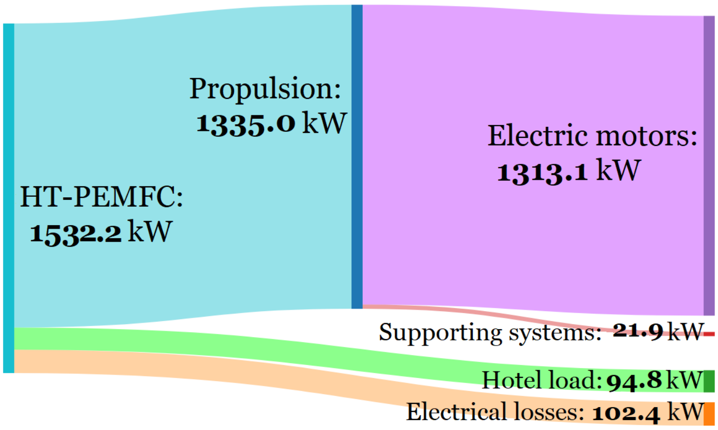


Figure 4.22: Sankey diagram of the electrical load for winter sailing for an HT-PEMFC power plant

The increase in total needed power is slightly more than the methanol SI-ICE system (~ 0.1 kW), but almost neglectable. The total active power demand of 4.9 kW (-0.1 kW MGO bunker pump) is within the boundaries of the maximum electric power that the fuel cells can deliver (1600 kWe) with a margin of approximately 67 kW. Hence, it is expected that additional power does not need to be installed.

4.4.4. Reliability and durability comparison

The reliability and durability of the fuel system and energy converters is relevant to determine readiness of the technology and feasibility of implementation on board of the LABRAX. Durability focuses on the lifetime within repairs and reliability is described as the capability to perform under defined conditions over a certain period. Important aspects that describe the reliability and durability of an energy converter are, lifespan, time between overhaul, potential failure points and power decrease in time.

HT-PEMFC's from Advent Technologies are rated to have a lifespan of approximately 10,000 hours with a total power loss of 10% over this lifespan [3]. Potential failure points of the fuel cells are degraded membranes and catalysts due to unwanted reactions with foreign elements [19]. Another possible failure could occur when one of the cell dysfunctions that results in a voltage decrease over the whole stack and accelerates stack degradation. One component could therefore cause a failure in the whole stack and increase repair costs significantly [106].

ICE's usually have a longer lifespan than fuel cells and lies in the range of 90,000 hours with major overhaul of the engine at 30,000 (piston rings and valves) and 60,000 hours (pistons and cylinder liners) as can be seen in appendix E.3. The technology has also been developed over several decades, which makes it a very reliable energy converter. The power loss over the lifetime of the ICE is mainly caused by worn piston rings that reduces the pressure inside the cylinder. Nonetheless, the reduced power output is in the range of a few percent [80].
However, SI-ICE's on 100% methanol are still in the testing phase and have certain problems due to the chemical properties of methanol. Cold start problems are common with a SI-ICE on methanol, which can be solved by preheating the engine with natural gas [9] or heating up the cooling system. The corrosive behaviour of methanol has been mentioned in section 2.4.3 and can be problematic for certain materials, especially for aluminium engine parts. Even wrongly chosen seals, usually made from rubber and fuel pipes, can be affected by methanol and fail over time.

Although HT-PEMFC's are currently less durable, they are potentially more reliable than combustion engines due to the absence of moving parts. The rapid developments of fuel cells could solve the durability and reliability issues and targets are set for fuel cell stacks that last for 24,000 hours and systems that last for 15 years long [43].

4.5. Performance indicators

All parameters of the new power- and energy systems are determined, hence the performance comparison can be established. In this section, the performance of the new situations is compared to the current situation with the aim to answer the following sub-question: *"How does a methanol power- and energy system influence design aspects and performance of the LABRAX general cargo vessel?"*.
Key performance parameters are already mentioned in section 3.3 and are used as well for this performance analysis. Before the performance indicators will be determined and compared to each other, the final weight and volume of the three power- and energy systems are determined. These values are needed to compose the new performance indicators due to change in DWT. An overview of all performance indicators can be found in appendix B.3.2.

4.5.1. Weight and volume of methanol power- and energy systems

In figure 4.23, the influence of a methanol power plant on the change in system volume and weight compared to a diesel power plant is visualised. The increase in weight is relatively limited compared to the increase of volume. The weight increase for both power plants is in the range of 10 tonnes, with a diesel system weight of 12 tonnes. The increase in volume between both system is however larger with a system volume increase of 10 m^3 for the SI-ICE and 20 m^3 compared to a system volume of 6 m^3 for diesel.
Last, the payload of the vessel is reduced by respectively 68 and 71 tonnes when fully loaded with fuel (methanol). This mainly caused by the lower gravimetric energy density of the methanol.
Exact values and additional information is shown in appendix B.3.1.

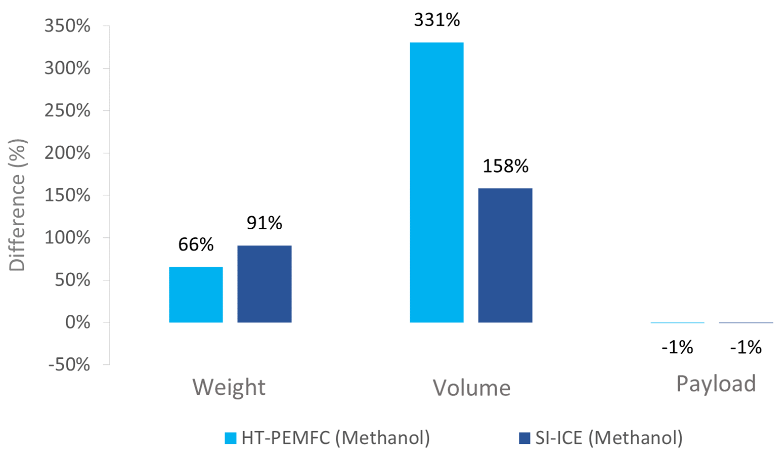


Figure 4.23: Weight and volume comparison of methanol power- and energy systems with respect to a diesel power- and energy system

With these parameters the new deadweight and payload of the vessel can be determined which are stated in table 4.15.

Table 4.15: DWT and payload specifications

System	Fuel	Dead weight	Payload
HT-PEMFC	Methanol	6992 t	6787 t
CI-ICE	Diesel	7000 t	6855 t
SI-ICE	Methanol	6988 t	6782 t

As can be seen in table 4.15, the deadweight decreases slightly. This can be explained by the fact that fuel is not included in the dead weight of vessel, but is included in the payload.

4.5.2. Energy indicators

In the performance analysis of the current LABRAX, the importance of using energy in a efficient way was already mentioned. In this section, the results of the two methanol power- and energy systems in terms of energy efficiency are presented by using the same performance indicators as in section 4.5. In this way, a comparison can be made between the energy usage in the current and new situation. In the end, the aim is to draw a conclusion which system is most efficient.

First the specific fuel consumption of energy converters on methanol is given and compared to the diesel energy converters.
The specific fuel consumption of energy converters on methanol and diesel has been mentioned in section 4.4 and 3.2, but will be compared to each other to provide a clear overview.

Table 4.16: Specific fuel consumption

	Advent H3 5000	**Volvo D13-MG**	**CAT G3508A**
Type	HT-PEMFC	CI-ICE	SI-ICE
Fuel	Methanol	Diesel (MGO)	Methanol
Engine speed	n.a.	1800 rpm	1500 rpm
Rated power	5 kW	400 kW	500 kW
SFC @ 50% load	426 g/kWh	203 g/kWh	532 g/kWh
SFC @ 75% load	426 g/kWh	197 g/kWh	481 g/kWh
SFC @ 100% load	426 g/kWh	199 g/kWh	481 g/kWh

Due to the lack of information of fuel consumption for different loads for the HT-PEMFC (H3 5000) it is assumed that the efficiency is constant over the load step from 50-100 %, which is good approximation of a fuel cell within this load range [92].

The fuel consumption of the HT-PEMFC and SI-ICE power plant on methanol per operational mode is shown in the table 4.17.

Table 4.17: Methanol consumption per operational mode

Ship speed (V_s)	**HT-PEMFC ($\dot{m}_f$)**	**SI-ICE ($\dot{m}_f$)**
8 kn (Slow steaming)	279 kg/h	364 kg/h
9.5 kn (Cruising)	488 kg/h	578 kg/h
10.4 kn (Sprint)	651 kg/h	770 kg/h

The difference in fuel consumption is already visible for both methanol energy converters. At cruising speed the increase in fuel consumption of the SI-ICE compared to the HT-PEMFC is in the order of 90 kg/h (~ 18%). This increase will be slightly less due to the higher system weight of the HT-PEMFC which will decrease the payload of the vessel and increase the specific fuel consumption (FI) (g/tonne•NM)

The **fuel index** is defined as the fuel consumption at a certain operation of which the equation is defined in section 3.3.1. In figure 4.24, the fuel index of the current power- and energy system on MGO and the new methanol power- and energy systems are visualised.

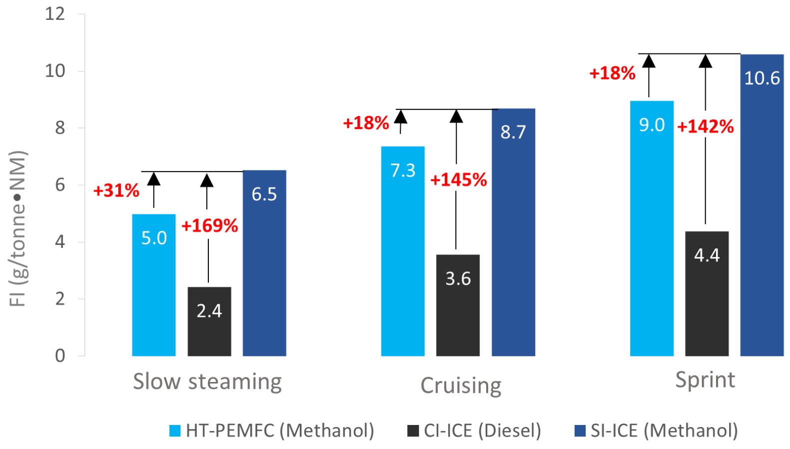


Figure 4.24: Fuel index (FI) comparison per operational mode between the current power- and energy system (CI-ICE) and future power- and energy system (HT-PEMFC and SI-ICE)

As expected from the literature research, the largest fuel consumption per tonne•NM is for a methanol fuelled power- and energy system due to the lower gravimetric energy density (LHV). The HT-PEM fuel cell is more efficient than the SI-ICE and therefore uses less fuel per tonne•NM, which has a positive effect on the total fuel that has to be stored on board of the vessel and the emitted GHG-gases per tonne•NM. The efficiency of the SI-ICE decreases rapidly below 75% MCR, as can be seen in table 4.16. The decrease in efficiency results in a larger difference in fuel index (142% vs 169%) compared the CI-ICE (Diesel) from sprint to slow steaming mode. In the end, the increase in fuel consumption per tonne•NM for a methanol power plant is still a factor 2.1 to 2.4 higher than a diesel power plant.
In the fuel index comparison, the consumption of water for the steam reforming process in the HT-PEMFC is not taken into account.

The definition of the **energy conversion effectiveness** is already provided in section 4.5.2. In short, the energy conversion effectiveness is in principle the inverse of the fuel index, but also takes into the "energy management" of vessel.
As already can be seen in 4.25, the large difference in gravimetric energy density between diesel and methanol, visible in the fuel index of figure 4.24, is taken into account. Analysis by means of energy content makes the comparison more convenient and fair.

For every operational profile the energy conversion effectiveness is determined and visualised in figure 4.25

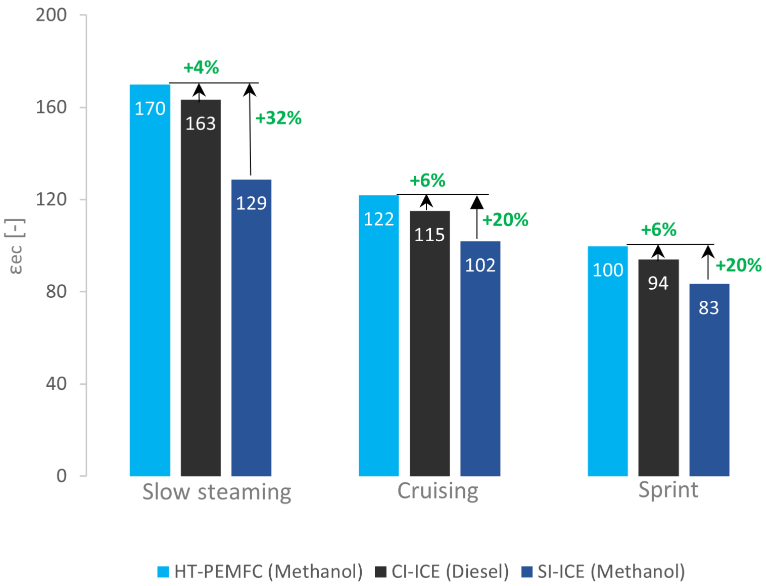


Figure 4.25: Energy conversion effectiveness ϵ_{ec} comparison per operational mode

Slow steaming is the most energy effective operational profile for all energy converters as expected from the fuel index. However, an interesting result, is the minor difference in energy effectiveness (4-6%) between HT-PEMFC and CI-ICE. This could be explained by the fact that the electrical efficiency of the HT-PEMFC (0.41) and CI-ICE (0.38) are very similar and the deadweight of the vessel decreases slightly for the HT-PEMFC.
Another notable result is the relatively low energy conversion effectiveness of the SI-ICE on methanol. This can be the results of an overall higher SFC at all operational loads and therefore lower engine efficiency. The larger difference in ϵ_{ec} at slow steaming can be clarified by a higher SFC at lower loads.

4.5.3. Emission indicator

Emissions and especially pollutant emissions need to be assessed for methanol as well. Combusting methanol is an exothermic reaction of which the chemical reaction is shown in equation 4.2. In this section, only GHG-emissions will be analysed, which is for methanol the same as diesel, namely CO_2.
In terms of emitted CO_2 per energy content (kWh), methanol and diesel do not differ much, but the combustion of methanol is much cleaner. However in order to evaluate the emissions in a correct way, the complete picture has to be taken into account. This means the efficiency of the energy converter (per operational profile) and the dead weight of the vessel needs to be integrated.

The **emission index** is a performance indicator that integrates theses factors and is defined as the amount of emitted CO_2 in gram per tonne•NM. The equation to calculate the emission index is stated in section 3.3.2.

In figure 4.26 the CO_2-emission index per operational profile and power- and energy system is visualised.

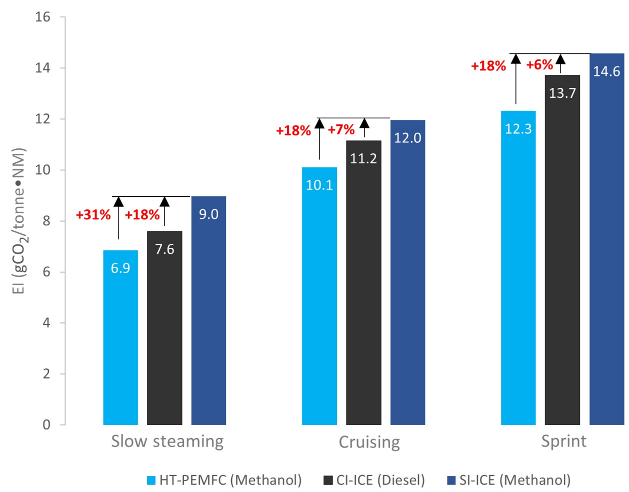


Figure 4.26: Emission index (EI) comparison per operational mode between the current diesel configuration (CI-ICE) and future methanol configurations (HT-PEMFC and SI-ICE)

As shown in figure 4.26, the CO_2 emissions from tank-to-wake per tonne•NM is currently larger for methanol with a SI-ICE than for a HT-PEMFC on methanol and CI-ICE on MGO. The increase in emission index between a SI-ICE and HT-PEMFC is approximately 18% at cruising and sprint mode and 31% at slow steaming mode. However the NO_x, SO_x and PM emissions, which are not GHG-gasses but do play a significant role for the IMO Tier III emission restrictions, are significantly lower for methanol, but was out of focus in this report.
The reduction of specific CO_2-emission from tank-to-wake for a HT-PEMFC on methanol compared to a CI-ICE on diesel is limited. Although, it is still in the order of 10%, mainly due to an increase in electrical efficiency.

$$2CH_3OH\ (l) + 3O_2\ (g) \rightarrow 2CO_2\ (g) + 4H_2O\ (l) \quad (\Delta H_C{}^{\circ} = -726.3\ kJ/mol) \tag{4.2}$$

4.5.4. Range and operation time

The range is a combination of the electrical efficiency, type of fuel, operational profile and total bunker capacity. In figure 4.27, the range in nautical mile (NM) is given for CI-ICE on diesel (MGO) with a bunker capacity of 172 m^3 and a SI-ICE and HT-PEMFC on methanol with a bunker capacity of 259 m^3.

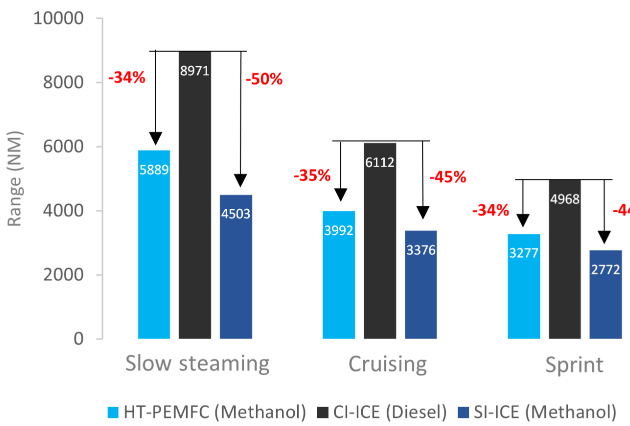


Figure 4.27: Range comparison per operational mode

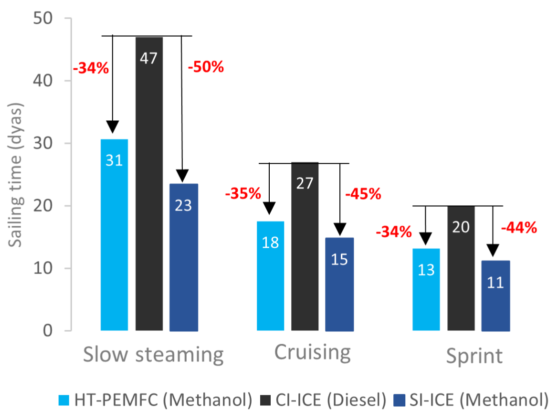


Figure 4.28: Operational time comparison per operational mode

Although an increase of bunker capacity for methanol of 50% is realised on board of the LABRAX, the range for a HT-PEMFC and SI-ICE on methanol is still significantly lower than a CI-ICE on diesel (MGO). At cruising speed, the range for a power plant with a SI-ICE on 100% methanol decreases by almost 3000 NM which is half of the original range. The HT-PEMFC has a higher efficiency than a SI-ICE, so an additional 600 nautical is added to the range of a HT-PEMFC power plant. In the literature study a minimum range of 2700 NM was defined of which all operational mode and power plant types comply with. Additional data can be seen in appendix B.8.

4.5.5. Load step response and start-up time

Table 4.18: Response time

HT-PEMFC [65] [14]	Single load	Recovery time 0-100% load	< 10 s
	Start-up	Warm-up time with pre-heater	100 - 130 min
CI-ICE	Single load	Recovery time 0-100% load	2.2 s
	Start-up	Time to stay within 0.5% of no load speed (20°C)	4.6 s
SI-ICE [35]	Single load	Recovery time 0-100% load	< 4 s
	Start-up	Time to stay within 0.5% of no load speed	< 5 s

The comparison in start-up and recovery time for the different types of energy converters is visualised in table 4.18. The difference between compression ignited and spark ignited engines is very small, but in principle spark ignited engines have a slightly larger recovery and start-up time which is in order of seconds. The HT-PEMFC needs approximately twice the time to recover than ICE's and a significantly amount of more time to start-up. The time responses are engine specific and could differ per engine type/brand, so these values give an indication of the performance in practice.

5 Capital- and operating expenditures

Technical assessment of the new power- and energy system on board of the LABRAX has been performed and performance indicators determine which gives an measure of the impact of the new system on board of a coaster. Feasibility of the system is not only dependent on technical aspects, but also on the economical viability of the new power- and energy system. Therefore a confined and indicative economical assessment is made, focused on the CapEx and OpEx of case study.

5.1. CapEx

Capital expenditures are funds that are used to acquire the needed power- and energy systems. In this economical assessment, the focus lies on costs from energy converters to capital intensive fuel systems for a designed new-build vessel. Prices are converted to Euro's with a Dollar-Euro exchange rate of 1. The propulsion system will not be of interest in the economical assessment, because it is assumed that the system will remain identical when applying new energy converters. First, the current situation is assessed and compared to the new situations with methanol as main fuel. The following components will be taken into account to calculate the CapEx.

- Energy converter
- Generator (ICE only)
- Bunker tanks
- Fuel piping
- Inert generator (Methanol only)

These components give an indication of the system cost on board of the LABRAX. Build-in costs have also been integrated in the CapEx estimations. Concerning the installed power, for the HT-PEMFC and CI-ICE 1600 kW value is used and 1613 kW for SI-ICE. In table 5.1, capital expenditures are visualised per option.

Table 5.1: CapEx estimations for different power- and energy systems

System	Fuel	Total specific cost	CapEx	Factor
HT-PEMFC	Methanol	1689 [€/kW]	€2,702,000	4.2
CI-ICE	MGO	404 [€/kW]	€646,000	1
SI-ICE	Methanol	676 [€/kW]	€1,088,000	1.7

The cost of current power- and energy system is based on fixed prices for the first LABRAX of which contracts are signed in 2020. For the cost estimation of the new power- and energy systems literature research is used. Detailed information of the capital expenditures per energy converter can be found in appendix B.4.

The cost of the methanol bunker tanks are assumed to be comparable to MGO bunker tanks, because methanol is also a fluid at STP. Additionally, methanol is stored under the waterline in steel tanks, so no cofferdam is needed.

As determined in the concept designs which is visualised in section 4.3.4, methanol is stored in existing tanks (ballast/MGO tanks), so large conversions are not necessary. The adaptation costs will be small comparable to other components and is left out in the cost analysis.

The specific cost of the HT-PEMFC including installation is estimated at €1650/kW (75% €2200/kW) [107]. The correction of 25% can be assigned to the decrease in production cost of a HT-PEMFC from 2014-2022 as can be seen in appendix E.4. A nitrogen flow larger than 200 L/min is needed which means a LF (large flow) nitrogen generator is needed which starts at €31,000 [71]. The minimum flow was estimated at 260 L/min and is in the low range of the LF nitrogen generators. Including nitrogen piping and installation, costs are estimated to be around €50,000. For both systems (SI-ICE and HT-PEMFC) the same nitrogen generator costs is applicable.
Single fuel pipes on the LABRAX is currently €46 per meter without installation and approximately 100 meters of fuel pipes are installed. Hence, total cost including installation (~ 25%) is equal to €6,000. Worst case scenario for methanol fuel pipes is that the whole length needs to be double walled. The increase in size (weight) and complexity will increase the cost and is estimated to be at least a factor 2 compared to normal fuel price. Total cost of a methanol fuel pipe including installation is equal to €12,000.

Installation costs of the energy converters is determined and equal to 150 €/kW [29].

5.2. OpEx

Operating expenditures are costs to run company and in particular for this study a vessel of which fuel is usually the largest expense. In this OpEx analysis only fuel consumption is analysed, because other factors have less influence on the OpEx and the difference between MGO and methanol is limited. In section 2.5 a minimal trip length of 5000 km has defined which will be used in analysing the OpEx. The price for MGO (Rotterdam) at 14-07-2022 is equal to $1,185.00 per metric tonne which is equal to €1,185.00 per metric ton. The price for methanol (Methanex-Europe) at 24-06-2022 is equal to €555.00 per metric ton.

In table 5.2, the fuel costs are visualised with the total consumption in metric tons. The fuel consumption is determined at design speed of the vessel (9.5 kn) with the determined minimal trip length.

Table 5.2: OpEx estimations for different power- and energy systems

System	Fuel	Fuel cons.	Fuel cost
HT-PEMFC	Methanol	175 m^3	€ 97,223
CI-ICE	MGO	80 m^3	€ 94,214
SI-ICE	Methanol	207 m^3	€ 114,948

The difference in operating expenditures in fuel costs are limited due to the lower cost of methanol per metric ton. However, prices can fluctuate heavenly when supply and demand is not matched properly. Especially for an upcoming alternative fuel, because infrastructure to support the methanol supply needs to be available. In section 2.2.2 of the literature study it became clear that still less than 1% of the methanol is produced out of renewable feedstocks and mostly out of fossil feedstock. Producing methanol out of these feedstock still contributes heavenly to global warming, so renewable sources are necessary to reduce the impact on the GHG-effect. This will increase the price even more according to the economical analysis in section 2.4.5.
The fuel price in the future is therefore dependent on the cost to produce methanol out of renewable feedstock and should be taken into consideration when choosing methanol as alternative fuel.

The OpEx includes more than only fuel costs, such as maintenance cost, crew and other ongoing company spends. It can be assumed that due to a more complex system and increased safety regulation and maintenance, OpEx would increase compared to a conventional diesel configuration. In order to verify the total increase in OpEx more detailed economic analyses should be made which is out of the scope of this research.

6 Conclusions

Reduction of GHG-emissions has become an important topic in the international shipping sector. Shipbuilders and shipping companies, such as Thecla Bodewes Shipyards and Vertom, face challenges to design, construct or overhaul vessels with the goal to reduce their GHG-emissions and comply with regulation.
This raised the question at Thecla Bodewes Shipyards, what the possibilities are to decrease the carbon-footprint of their new coaster series LABRAX and comply with future emission regulations.
The specific question resulted in the goal of this research, namely to determine the impact of an alternative fuel on the power- and energy system of a specific general cargo vessel.
The purpose of this chapter is to present conclusions that are drawn based on research performed in this report. The main question is divided into several sub-questions, which are stated in section 1.3. First conclusions of the literature research are presented, subsequently conclusions of the object of study and case study.
In the end, recommendations are offered for future research in this field of expertise.

The goal of the literature review is to determine the most suitable alternative fuel for a general cargo vessel such as the LABRAX. The following sub research question is established to provide an answer:

- *"How are alternative fuels produced, can it be implemented in vessels and what are the characteristics?"*

It can be stated that alternative fuels are mainly made out of three feedstocks, namely green electricity, biomass and natural gas. Certain feedstock prove to be more suitable for the production of specific alternative fuels than other feedstock. Although it is determined that currently almost all alternative fuels are suitable to be produced out of natural gas which is currently performed on large scale.
The disadvantage of producing alternative fuels out of natural gas is that the total energy consumption from Well-to-Wake increases by almost a factor 2 compared to conventional fuels. This results in a higher environmental impact due to an increase in emitted GHG, which is in the order of 40% to 66% more greenhouse gas emissions for ammonia and hydrogen than conventional fuels.
Using green electricity as feedstock for fuel production, can even result in an increase of 2.5 times in energy consumption from Well-to-Wake. However, the increase in energy consumption for producing e-fuels has a significantly lower environmental impact due to the carbon neutral production process.
Hence, it is not always self-evident that alternative fuels have a lower impact on the environment, in particularly the greenhouse effect. Therefore it is necessary to consider the origin of the alternative fuel.

Implementation has its challenges too, mainly due to the difference in characteristics of alternative fuels compared to diesel. In general, it can be confirmed that alternative fuels have a lower volumetric- and gravimetric energy density, which makes it complicated to store a sufficient amount of energy on board. The volumetric energy density, which is the limiting factor due to the bounded space on board of a vessel, can decrease by respectively 60% for methanol and 65% for ammonia compared to diesel.
With respect to safety, flammability and health issues seem to be dominant factors. Overall, all alternative fuels have a flash point above 65°C except for ammonia, which means almost all alternative fuels have an increased fire- or explosion risk. Health issues were mostly associated with ammonia and methanol due to the toxicity of both fuels, with ammonia as most toxic alternative fuel.

For the future, on short- and long term, characteristics such as availability, technological readiness and developments in the area of a certain alternative fuel seem to be determining factors for the selection of a suitable fuel.

Based on information gathered in this literature study, methanol appears to be the most suitable alternative fuel, with a growth potential of bio-methanol as sustainable fuel on the long term and a high level of readiness for an ICE marine application on short-term. Also, an extensive research project (MENENS) into implementation of methanol power- and energy systems where I am involved in and operational profiles of comparable vessels, contributed to this outcome.

After the literature research, the first sub-question for the object study was established as follows:

- *"What is the current design of the power- and energy system on board of the LABRAX general cargo vessel?"*

It is identified that the current power plant consist of a diesel-electric configuration, which means power- and propulsion generation are separated. This separation however has some implications, because this power configuration has significant efficiency losses in the power train due to electrical losses in the generator, electric motor and variable frequency drive. Expressed in numbers, an additional 11.2% of energy lost compared to a conventional power train which combines into a total energy loss of 13% from engine output to propeller shaft. However, it could increases the overall efficiency, because supply of power can be matched better to power demand. Also redundancy is increased compared to a conventional single engine configuration, due to four separate engines.
If looked at a possible change in energy converter due the implementation of an alternative fuel, the current configuration makes it easier to do undertake this modification without adaptation of the propulsion system. This makes the current design of the vessel already more suitable for the implementation of alternative fuels in the future.

Hence, a considerable step is made in making a future proof ship design by applying a flexible power plant and make it possible to match power demand and power supply more efficiently.

In order to asses the diesel power- and energy system, the following sub-question is raised:

- *"What is the current performance of the LABRAX general cargo vessel?"*

With help of performance indicators and three defined operational modi, the performance of the current LABRAX is determined. In terms of energy efficiency, the LABRAX has the lowest fuel index and highest energy conversion effectiveness for slow steaming. On average the vessel consumed 3.4 grams of diesel per tonne•NM, with the highest fuel index of 4.4 grams of diesel per tonne•NM in sprint mode. It could be stated that an increase in speed increases the specific fuel consumption significantly, namely an increase of 30% in speed results in an increase of 81% in fuel index (g/tonne•NM).
The environmental impact of the vessel is directly related to the fuel consumption and is presented in an emission index. On average the vessel emits 10.6 grams of CO_2 per tonne•NM, with a maximum CO_2-emission of 13.7 grams per tonne•NM in sprint mode.
In comparison to other transport modes and comparable vessels, the LABRAX performs good with an emission index of a factor 1.8 lower than general cargo vessels with DWT between 5,000 and 9.999. Road transport has even an average emission index that is a factor 10 higher. The distance the LABRAX could travel with current bunker capacity at cruising speed is 6112 NM, which means the current range is a factor 2.3 higher than the minimal range to sail from port to port (2700 NM).

The current LABRAX creates the impression to be optimised to decrease the environmental impact with a conventional fuel as main energy source. In order to take the next step to become carbon-neural, a specific case study is performed, which defined the following sub-question:

- *"Which power plant configurations can be identified for a methanol power- and energy system?"*

For the power plant, two categories of energy converters are identified, namely internal combustion engines (ICE) and fuel cells (FC). These types can be divided into several types of which the spark ignited internal combustion engine (SI-ICE) and high temperature proton exchange membrane fuel cell (HT-PEMFC) show most potential to be implemented in the LABRAX.
SI-ICE has preferable characteristics for a methanol single fuel installation and a PEMFC has a beneficial gravimetric- and volumetric energy density and a high maturity level compared to other fuel cell types.
Two power plant configurations are identified one SI-CI power plant based on a CAT G3508A engine and one HT-PEMFC based on a Advent H3 5000 with integrated methanol reformer.

It could be confirmed that the electrical balance in winter sailing conditions is maintained for both configurations with minor power increases of methanol fuel systems. Hence, no extra power needs to be installed to support these systems.
The difference of reliability and durability between the two power plants is considerable. The SI-ICE has currently a longer lifespan, which runs into 90,000 hours before mayor overhaul and is a proved technology. The HT-PEMFC however has a lifespan of approximately 10,000 hours with an additional 10% power loss and is a technology in development. Yet rapid developments can solve reliability and durability issues for fuel cells in the near future.

The future- and current power plants configurations are now defined, but the performance of the LABRAX with a methanol power- and energy system needs to be analysed which raises the following sub-question:

- *"How does a methanol power- and energy system influence design aspects and performance of the LABRAX general cargo vessel?"*

In terms of design aspects, methanol power plants require more space inside the engine room. The maximum volume increase, compared to a diesel configuration, is in the range of 331%. This increase in volume ($20m^3$) should not be a problem for the LABRAX due to the relatively large engine room (346 m^3). This especially applies for fuel cells, hence application of fuel cells should be less of an issue on the LABRAX.
As a result of the lower volumetric energy density, more space is required to store methanol. For an acceptable range, approximately 87 m^3 more storage is made available for methanol. Even with this extra storage capacity, the range decreases respectively by 35% and 45% for cruising speed.
Also placement of the fuel tanks is challenging due to safety regulation. In order to decrease the loss of tank volume due to cofferdams, certain locations need to be avoided such as category A rooms and storage spaces above the waterline.

The performance is measured in several categories, of which the payload capacity of the vessel is one. If a methanol power plant (FC or ICE) is installed, the payload capacity decreases by approximately 70 tonnes. Despite the decrease in cargo capacity, the loss is minimal and in the order of -1% of the total payload capacity. Hence, it is expected that the business model of the vessel is not effected by the cargo loss.
In terms of energy efficiency, the diesel power plant consumes less gram fuel per tonne•NM compared to both methanol power plants for all operational modi. The significant increase in FI of respectively 107 % and 145% is mainly related to a lower gravimetric energy density of methanol. A SI-ICE power plant increases the fuel consumption by 18% compared to a HT-PEMFC power plant at cruising speed.
The environmental impact in terms of GHG-emissions from Tank-to-Wake of a methanol power plant compared to diesel is limited due to the same CO_2-emission per energy content. However, for a HT-PEMFC still a reduction of 10% in specific CO_2-emission can be achieved due to a higher electrical efficiency. On the other hand, the specific CO_2-emission increases by 7% in cruising mode for the SI-ICE on methanol due to a lower engine efficiency.
In the end, it is concluded that the performance over almost all aspects decreases, but not significantly that the operationality is in dispute. Considerations such as bunkering more often and increased loss of payload should be taken into account.
Nevertheless, methanol is more suitable to become carbon neutral from Well-to-Tank as a bio- or e-fuel than diesel. E-diesel requires more energy to be produced and has still the same negative combustion characteristics.

After answering all sub-questions, it should be possible to answer the main-question. The main question of this research is formulated as follows:

- *"What is the most suitable alternative fuel power- and energy system on board of a 7000 DWT general cargo vessel?"*

Several factors are investigated and many conclusions are drawn during this research. In the end, a suitable pathway is determined concerning a future power- and energy system based on a combination of aspects.
Methanol as alternative fuel seems to be most suitable due to the high technological readiness and large potential availability of renewable methanol. This alternative fuel needs to be converted by an energy converter of which reliability and durability, vessel compatibility, environmental impact, energy efficiency and economics are the most important factors to consider.

Two types of energy converters, namely SI-ICE and HT-PEMFC show good compatibility with methanol as alternative fuel. The SI-ICE seems to be the most reliable and less capital intensive technology current day, but has disadvantages due to the increase in GHG-emissions from Tank-to-Wake. The HT-PEMFC has a higher electrical efficiency which results in a decrease in GHG-emissions from Tank-to-Wake, but seems to be much less reliable, has a higher impact on the vessel in engine room volume specifications and is significantly more capital intensive.
For the future, fuel cells have great potential to increase the energy efficiency and decrease the Tank-to-Wake emissions. For now, an SI-ICE power plant on methanol appears to be more feasible and the increase in Tank-to-Wake emissions will play a smaller role due to the increase in production of renewable methanol (bio/e-methanol) in the future.

With this new power- and energy system, is the carbon footprint of the LABRAX decreased? On the very short term probably not, but on the long term with the intended increase in renewable methanol and rapid developments in the field of energy conversion technologies definitely, yes.

7 Recommendations

Unfortunately not every aspect of the implementation of methanol on board of the LABRAX can be analysed and certain assumptions had to be made in order to make this research feasible. These assumptions created a path that resulted in the conclusion of this research, but making these assumptions will create a certain uncertainty in the end result. Hence it is of importance that more research is performed in the field of alternative fuels and especially for different types of vessels with their unique challenges. Additionally, more detailed research into the challenges of implementing methanol as alternative fuel for the LABRAX can be performed.

In the following part, multiple recommendations are given:

- In this research different loading conditions of the vessel were not taken into account. It was assumed that the vessel would always be fully loaded when sailing. To create a more detailed and fair comparison, different loading conditions should be taken into account when determining the performance of the vessel. This because every different loading condition has a different power requirement to sail at a certain speed. The loading conditions should be incorporated in the performance indices as well in order to create a more accurate operational performance of the vessel.
- Only one type of operation has been taken into account during the analysis of the performance of the vessel. Other types of operations, such as harbour operations or anchoring creates a complete view of the vessels performance. This implies more research into data of comparable vessels with the same trade routes or analysing the LABRAX series vessels when completed and under operation by the shipping company Vertom.
- The placement options for storing methanol have been only considered when cargo hold capacity is not compromised. Also large constructional changes to store methanol were not investigated which could be of interest for vessels that are not under construction yet. Investigation into placement of fuel tanks should be extended and a design iteration could be performed to realize more placement options to increase range of the vessel.
- Further research into pollutant emissions is recommended. For this research only GHG-emissions have been considered in which methanol does not particularly excels at when combusted. Emission such as NO_x, SO_x and PM are also necessary to investigate the environmental impact of the LABRAX into more detail. This implies a more detailed analysis of the energy converters that determine these emissions predominately.
- Layout of the engine configuration is recommended to be investigated in order to determine the most suitable configuration for different types of energy converters and operational modi. This would include the amount of energy converters and optimise it to maximize engine efficiency per operational mode.
- In addition to the layout, combination of energy converters should be considered as well. Power plant configurations that combine fuel cells and internal combustion engines have great potential, such as the ICE-SOFC configuration suggested in (Sapra, 2020). Also for these combinations, the power division has to be determined for the operational modi to assure maximum efficiency.
- During the literature research it could be concluded that the environmental impact of alternative fuels are dependent on method of production. Therefore to investigate the feasibility of methanol, more research should be performed in the area of production and emissions that are associated with this production. In the end, the availability of the fuel as a green fuel (bio/e-fuel) determines if the impact of vessel on the environment is really reduced.

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A
Calculations

A.1. Effective engine efficiency

A.1.1. Volvo D13-MG (CI-ICE)

$$\dot{m}_f = sfc \cdot P_b = 199\ [g/kWh] \cdot 400\ [kW] = 83600\ [g/h] = 0.0221\ [kg/s] \quad (A.1)$$

$$\dot{Q}_f \simeq \dot{m}_f \cdot h^L = 0.0221\ [kg/s] \cdot 42700\ [kJ/kg] = 944.14\ [kW] \quad (A.2)$$

$$\eta_e = \frac{P_b}{\dot{Q}_f} = \frac{400[kW]}{944.14\ [kW]} = 0.424\ [-] \quad (A.3)$$

A.2. Power estimations methanol fuel systems

A.2.1. Bunker fuel pump (SI-ICE)

$$P_{MGO-pump} = 1.3\ [kW] \quad (A.4)$$

$$Q_{MGO} = 0.38\ [m^3/h] \quad (A.5)$$

$$Q_{CH_3OH} = 0.96\ [m^3/h] \quad (A.6)$$

$$Q_{MGO-pump} = 5\ [m^3/h] \quad (A.7)$$

$$Q_{min-pump-CH_3OH} = \frac{Q_{CH_3OH}}{Q_{MGO}} \cdot P_{Pump-MGO} = \frac{0.96}{0.39} \cdot 5 = 12.3\ [m^3/h] \quad (A.8)$$

$$\nu_{CH_3OH} = 0.75\ [cSt] \quad (A.9)$$

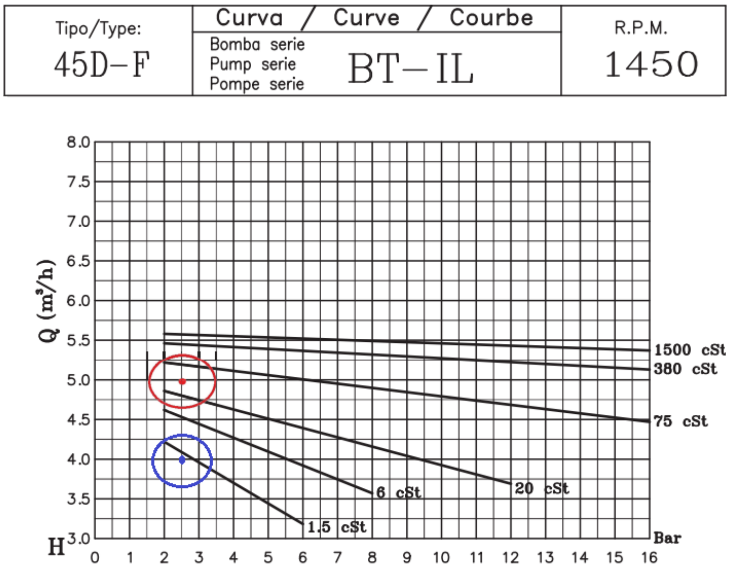


Figure A.1: Operation point (Red = MGO, Blue = Methanol)

$$Q_{pump-CH_3OH-@0.75cSt,2.5bar,1.3kW} = 4.0\ [m^3/h] \tag{A.10}$$

$$P_{pump-CH_3OH-@0.75cSt,2.5bar} = \frac{12.3}{4} \cdot 1.3 = 4.0\ [kW] \tag{A.11}$$

A.2.2. Bunker fuel pump (HT-PEMFC)

$$P_{MGO-pump} = 1.3\ [kW] \tag{A.12}$$

$$Q_{MGO} = 0.38\ [m^3/h] \tag{A.13}$$

$$Q_{CH_3OH} = 0.90\ [m^3/h] \tag{A.14}$$

$$Q_{MGO-pump} = 5\ [m^3/h] \tag{A.15}$$

$$Q_{min-pump-CH_3OH} = \frac{Q_{CH_3OH}}{Q_{MGO}} \cdot P_{Pump-MGO} = \frac{0.90}{0.39} \cdot 5 = 11.5\ [m^3/h] \tag{A.16}$$

$$\nu_{CH_3OH} = 0.75\ [cSt] \tag{A.17}$$

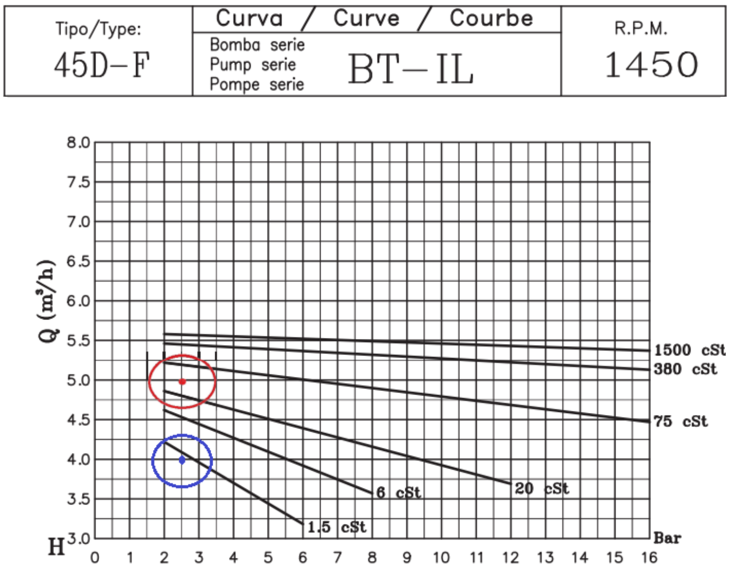


Figure A.2: Operation point (Red = MGO, Blue = Methanol)

$$Q_{pump-CH_3OH-@0.75cSt,2.5bar,1.3kW} = 4.0\ [m^3/h] \tag{A.18}$$

$$P_{pump-CH_3OH-@0.75cSt,2.5bar} = \frac{11.5}{4} \cdot 1.3 = 3.7\ [kW] \tag{A.19}$$

A.2.3. Bunker water pump (HT-PEMFC)

$$P_{MGO-pump} = 1.3\ [kW] \tag{A.20}$$

$$Q_{MGO} = 0.38\ [m^3/h] \tag{A.21}$$

$$Q_{H_2O} = 0.40\ [m^3/h] \tag{A.22}$$

$$Q_{MGO-pump} = 5\ [m^3/h] \tag{A.23}$$

$$Q_{min-pump-H_2O} = \frac{Q_{H_2O}}{Q_{MGO}} \cdot P_{Pump-MGO} = \frac{0.4}{0.39} \cdot 5 = 5.1\ [m^3/h] \tag{A.24}$$

$$\nu_{H_2O} = 1\ [cSt] \tag{A.25}$$

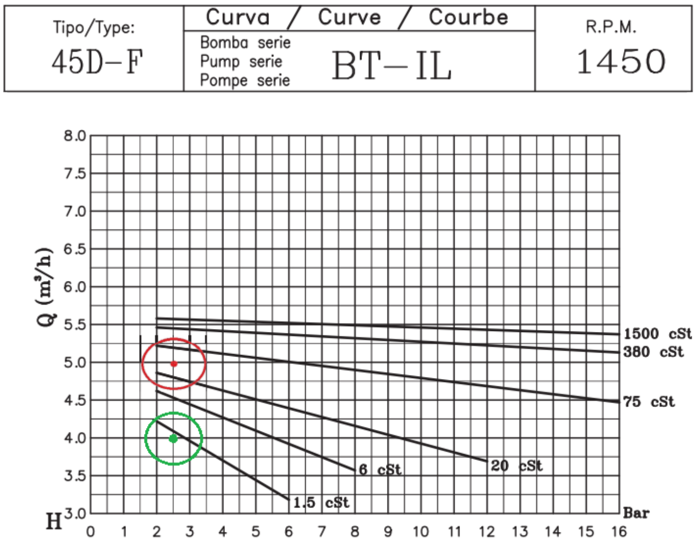


Figure A.3: Operation point (Red = MGO, Green = Water)

$$Q_{pump-H_2O-@1cSt,2.5bar,1.3kW} = 4.0\ [m^3/h] \tag{A.26}$$

$$P_{pump-H_2O-@1cSt,2.5bar} = \frac{5.1}{4} \cdot 1.3 = 1.7\ [kW] \tag{A.27}$$

A.2.4. LP fuel pump 41402-c (SI-ICE)

$$U = 13.5\ [V] \tag{A.28}$$

$$I_{@5bar} = 17.5\ [A] \tag{A.29}$$

$$P = I \cdot U = 13.5 \cdot 17.5 = 0.236\ [kW] \tag{A.30}$$

$$P_{total} = N^{\circ}{}_{engines} \cdot P = 4 \cdot 0.236 = 0.944\ [kW] \tag{A.31}$$

A.2.5. Nitrogen generator (SI-ICE)

$$P_{cons} = 0.3\ [kW/m^3/h] \tag{A.32}$$

$$Q_{fuel} = 0.96\ [m^3/h] \tag{A.33}$$

$$Q_{min-pump-CH_3OH} = 12.3\ [m^3/h] \tag{A.34}$$

$$P_{N_2gen} = Q_{min-pump-CH_3OH} \cdot P_{cons} = 12.3 \cdot 0.3 = 3.7\ [kW] \tag{A.35}$$

A.2.6. Nitrogen generator (HT-PEMFC)

$$P_{cons} = 0.3\ [kW/m^3/h] \tag{A.36}$$

$$Q_{fuel} = 0.90\ [m^3/h] \tag{A.37}$$

$$Q_{min-pump-H_2O} = 11.5\ [m^3/h] \tag{A.38}$$

$$P_{N_2gen} = Q_{min-pump-H_2O} \cdot P_{cons} = 11.5 \cdot 0.3 = 3.5\ [kW] \tag{A.39}$$

B

Tables

B.1. Diesel-electric power plant components

B.1.1. Main diesel generator

Table B.1: Main engine specifications [2]

	**Main Engine**
Engine type	Volvo Penta D13-MG (Keel cooled)
Nº cylinders	6 (In-line)
Operation type	4 stroke, direct-injection, turbocharged with air cooler
Dry weight	1480 kg
Power	360 - 400 kW
Rpm	1500 - 1800
Stroke	158 mm
Bore	131 mm
Cylinder displacement	12.78 L
Specific Fuel Consumption (SFC)	199 g/kWh (100% load)
Emission standard	IMO Tier II
Fuel	MGO (diesel)

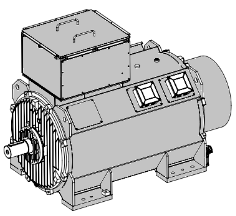
B.1.2. Generator

Table B.2: Generator specifications [15]

	**Generator**
Generator type	STAMFORD S5L1M-F4 Wdg.25
kVA base rating	565 kVA
Voltage	690 V
Alternator Weight	1685 kg
Frequency	50 Hz
Max over speed	2250 rpm (2min)
Nº phases	3

B.1.3. Electric motor

Table B.3: Electric motor specifications [23]

	**Electric motor**
Electric motor type	Electro Adda W 40 LX 6
Rated power output	650 kW
Voltage	660 V
Weight	4400 kg
Frequency	45,3 Hz
Speed	900 rpm
Rated torque	6900 Nm
Cooling	Jacket water cooled

B.1.4. Gearbox

Table B.4: Gearbox specifications [77]

	**Gearbox**
Gearbox type	RENK Single Marine Reduction Gearbox T^2RECS-630HR
M/E power	1300 kW (mech)
Electric motor	2 x 650 kW (mech), 1 on input shaft, 1 on PTI shaft
Unit weight	4900 kg
Reduction ratio	6,369:1
Input speed	900-1080 rpm
Output speed	141,3 - 169,6 rpm

B.2. Load balance

B.2.1. Total load balance in winter sailing

Table B.5: Total load balance (Sailing Winter 1300 kW propulsion power)

System	**Active power**
Propulsion power	1313.13 kW
Electrical losses (from DC-bus)	102.35 kW
Power- and energy systems	16.97 kW
Hotel load	94.84 kW
Total needed electrical power	**1527.29 kW**

B.2.2. Power- and energy system load balance in winter sailing

Table B.6: Load balance power- and energy systems (Sailing Winter 1300 kW propulsion power)

System	Nominal power	Active power
Charger - DB-ELV02 (Main supply)	2.75 kW	0.28 kW
CW Circulating pump (#1) 23-2-B008	4.00 kW	2.45 kW
Bilge water separator	3.00 kW	0.75 kW
Heater Bow thruster room	9.00 kW	2.30 kW
Fan coil with electric heater - Switchboard room	2.90 kW	0.73 kW
Supply fan S-01 engine room PS (incl. EM. CO2 exhaust)	6.10 kW	5.23 kW
Supply fan S-02 engine room SB	6.10 kW	5.23 kW
Total	**33.85 kW**	**16.97 kW**

B.3. Operational performance

B.3.1. Weight and volume comparison: diesel vs methanol

Table B.7: Weight and volume of the power- and energy system types

	Fuel	Weight	Volume	Weight difference
HT-PEMFC power plant	Methanol	20960 kg	25.8 m^3	+8300 kg
CI-ICE power plant	Diesel	12660 kg	6.0 m^3	0 kg
SI-ICE power plant	Methanol	24180 kg	15.5 m^3	+11520 kg
HT-PEMFC fuel	Methanol	205128 kg	259 m^3	+59788 kg
CI-ICE fuel	Diesel	145340 kg	172 m^3	0 kg
SI-ICE fuel	Methanol	205128 kg	259 m^3	+59788 kg
HT-PEMFC total	Methanol	226088 kg	285 m^3	+68088 kg
CI-ICE total	Diesel	158000 kg	178 m^3	0 kg
SI-ICE total	Methanol	229308 kg	275 m^3	+71308 kg

B.3.2. Performance indicators comparison: diesel vs methanol

Table B.8: Performance indicators data

	HT-PEMFC			**CI-ICE**			**SI-ICE**		
Ship speed (kn)	**8**	**9.5**	**10.4**	**8**	**9.5**	**10.4**	**8**	**9.5**	**10.4**
ϵ_{ec} (-)	169.8	121.9	99.8	163.3	115.1	94.1	144.7	101.8	83.4
FI (g/tonne*NM)	5.0	7.3	9.0	2.4	3.6	4.4	6.5	8.7	10.6
EI (g/tonne*NM)	6.8	10.1	12.3	7.6	11.2	13.7	8.9	12.0	14.6
Range (NM)	5888.6	3991.7	3277.37	8971.4	6112.3	4968.1	4503.1	3376.2	2772.0

B.4. Cost

B.4.1. Capital Expenditures: HT-PEMFC

HT-PEMFC	Specific cost	CapEx
Energy converter (incl. build-in)	1650 EUR/kW	2,640,000 EUR
Fuel piping	8 EUR/kW	12,000 EUR
Nitrogen generator	31 EUR/kW	50,000 EUR
Total	**1689 EUR/kW**	**2,702,000 EUR**

B.4.2. Capital Expenditures: CI-ICE

CI-ICE	Specific cost	CapEx
Energy converter	188 EUR/kW	300,000 EUR
Generator	62 EUR/kW	100,000 EUR
Fuel piping	4 EUR/kW	6,000 EUR
Build-in	150 EUR/kW	240,000 EUR
Total	**404 EUR/kW**	**646,000 EUR**

B.4.3. Capital Expenditures: SI-ICE

SI-ICE	Specific cost	CapEx
Energy converter (4x)	425 EUR/kW	686,000 EUR
Generator (4x)	62 EUR/kW	100,000 EUR
Fuel piping	8 EUR/kW	12,000 EUR
Build-in	150 EUR/kW	240,000 EUR
Nitrogen generator	31 EUR/kW	50,000 EUR
Total	**676 EUR/kW**	**1,088,000 EUR**

C

Regulation

C.1. Relevant Bureau Veritas classification rules

C.1.1. Section 3: Ship Design and Arrangement

- **1.2.1** Tanks containing fuel are not to be located within accommodation spaces or machinery spaces of category A
- **1.2.2** Integral fuel tanks are to be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methyl/ethyl alcohol
- **1.2.7** For single fuel installations, each fuel service tank is to have a capacity of at least 8 h at maximum continuous rating of the propulsion plant and normal operating load at sea of the generator plant
- **1.2.5** Fuel tanks located on open decks are to be protected against mechanical damage
- **1.2.10** For single fuel installations, the fuel storage is to be divided between two or more tanks so that, in the event of any one tank becoming unavailable, the remaining tank(s) will provide sufficient fuel to enable the ship to operate within its service. These tanks are to be located in separate spaces. If those spaces are adjacent, the insulation between both spaces is to be at least A-60
- **1.3.1** Independent tanks may be accepted on open decks or in a fuel storage hold space protected against mechanical damage.
- **1.3.2** Independent tanks are to be fitted with: mechanical protection of the tanks depending on location and cargo operation
- **1.4.1** Portable fuel tanks are to be located in dedicated areas fitted with: mechanical protection of the tanks depending on location and cargo operations
- **1.4.3** Consideration is to be given to the ship's strength and the effect of the portable fuel tanks on the ship's stability
- **1.4.4** Connections to the ship's fuel piping systems are to be made by means of approved flexible hoses suitable for methyl/ethyl alcohol or other suitable means designed to provide sufficient flexibility
- **1.4.6** The pressure relief system of portable tanks is to be connected to a fixed venting system
- **1.4.8** Safe access to tank connections for the purpose of inspection and maintenance is to be ensured
- **1.4.9** When connected to the ship's fuel piping system:

  a.) each portable tank is to be capable of being isolated at any time

  b.) isolation of one tank is not to impair the availability of the remaining portable tanks
- **1.6.1** Fuel pipes are not to be located less than 800 mm from the ship's side
- **1.6.2** Fuel piping are not to be led directly through accommodation spaces, service spaces, electrical equipment rooms or control stations.

- **2.3.3** Fuel tanks and surrounding cofferdams are to have access from the open deck, where practicable, for gas freeing, cleaning, maintenance and inspection
- **2.3.4** Where direct access from the open deck is not practicable an entry space to fuel tanks or surrounding cofferdams is to be provided and is to comply with the following:

  a) be fitted with an independent mechanical extraction ventilation system, providing a minimum of six air changes per hour; a low oxygen alarm and a gas detection alarm are to be fitted

  b) have sufficient open area around the fuel tank hatch for efficient evacuation and rescue operation

  c) not be an accommodation space, service space, control station or machinery space of category A and

  d) a cargo space may be accepted as an entry space, depending upon the type of cargo, if the area is cleared of cargo and no cargo operation is undertaken during entry to the space
- **2.3.5** Where the surveyor requires to pass between the surface to be inspected, flat or curved, and structural elements such as deck beams, stiffeners, frames, girders etc., the distance between that surface and the free edge of the structural elements is to be at least 380 mm. The distance between the surface to be inspected and the surface to which the above structural elements are fitted, e.g. deck, bulkhead or shell, is to be at least 450 mm in case of a curved tank surface or 600 mm in case of a flat tank surface
- **2.4** The fuel containment system is to be abaft of the collision bulkhead and forward of the aft peak bulkhead

C.1.2. Section 4: Fuel Containment System

- **2.1.1** The fuel tanks are to be fitted with a controlled tank venting system
- **2.1.3** A fixed piping system is to be arranged to enable each fuel tank to be safely gas freed, and to be safely filled with fuel from a gas-free condition
- **2.1.4** The arrangement of internal tank structure and location of gas freeing inlets and outlets are to be such as to avoid the formation of gas pockets during the gas freeing operation
- **2.1.5** Pressure and vacuum relief valves are to be fitted to each fuel tank to limit the pressure or vacuum in the fuel tank. The tank venting system may consist of individual vents from each fuel tank or the vents from each individual fuel tank may be connected to a common header
- **2.1.11** The fuel tank vent system is to be connected to the highest point of each tank and vent lines are to be self-draining under all normal operating conditions.
- **2.1.12** Fuel tank vent outlets are to be situated normally not less than 3 m above the deck or gangway if located within 4 m from such gangways. The vent outlets are also to be arranged at a distance of at least 10 m from the nearest air intake or opening to accommodation and service spaces and ignition sources. The vapour discharge is to be directed upwards in the form of unimpeded jets
- **2.1.14** The vent outlets are to be arranged in one of the following ways:

  1.) outlets located at least 3 m above the deck level with a vertical efflux velocity of at least 30 m/s

  2.) outlets located at least 3 m above the deck level with a vertical efflux velocity of at least 20 m/s which are protected by suitable devices to prevent the passage of flame

  3.) underwater outlets.
- **3.1.1** The system is to be sized to be able keep the tanks inerted under during normal operation, gas freeing or inerting by utilizing an inerting medium.
- **4.1.1 I**nert gas should be available permanently on board in order to achieve at least one trip from port to port considering maximum consumption of fuel expected and maximum length of trip expected and to keep tanks inerted during two weeks in harbour with minimum port consumption

C.1.3. Section 6: Bunkering Equipment

- **1.1.1** The bunkering station should be located on open deck so that sufficient natural ventilation is provided.
- **1.2.5** Fuel piping system is to be double walled. The efficiency of the inerting or ventilation arrangement of the double walled space is to be verified

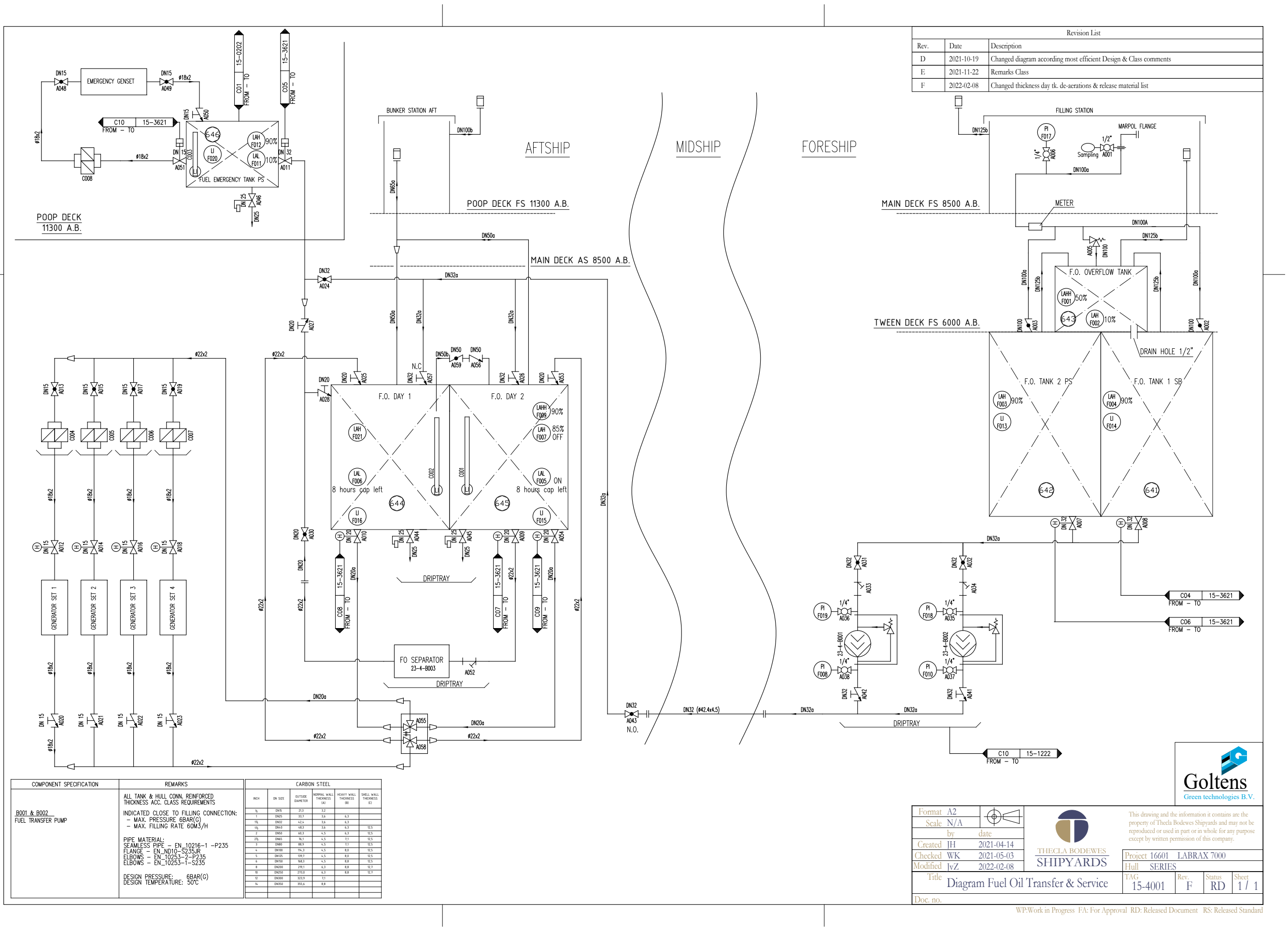
C.1.4. Section 9: Safety

- **1.2.2** For fire integrity, the fuel tank boundaries are to be separated from the machinery spaces of category A and other rooms with high fire risks by a cofferdam of at least 600 mm, with insulation of not less than A-60 class
- **4.1.1** Where fuel tanks are located on open deck, there is to be a fixed fire-fighting system of alcohol-resistant foam type, as set out in chapter 17 of the IBC Code and, where appropriate, chapter NR467 Pat D, Ch 7, Sec 6, [3]. The system is to be operable from a safe position

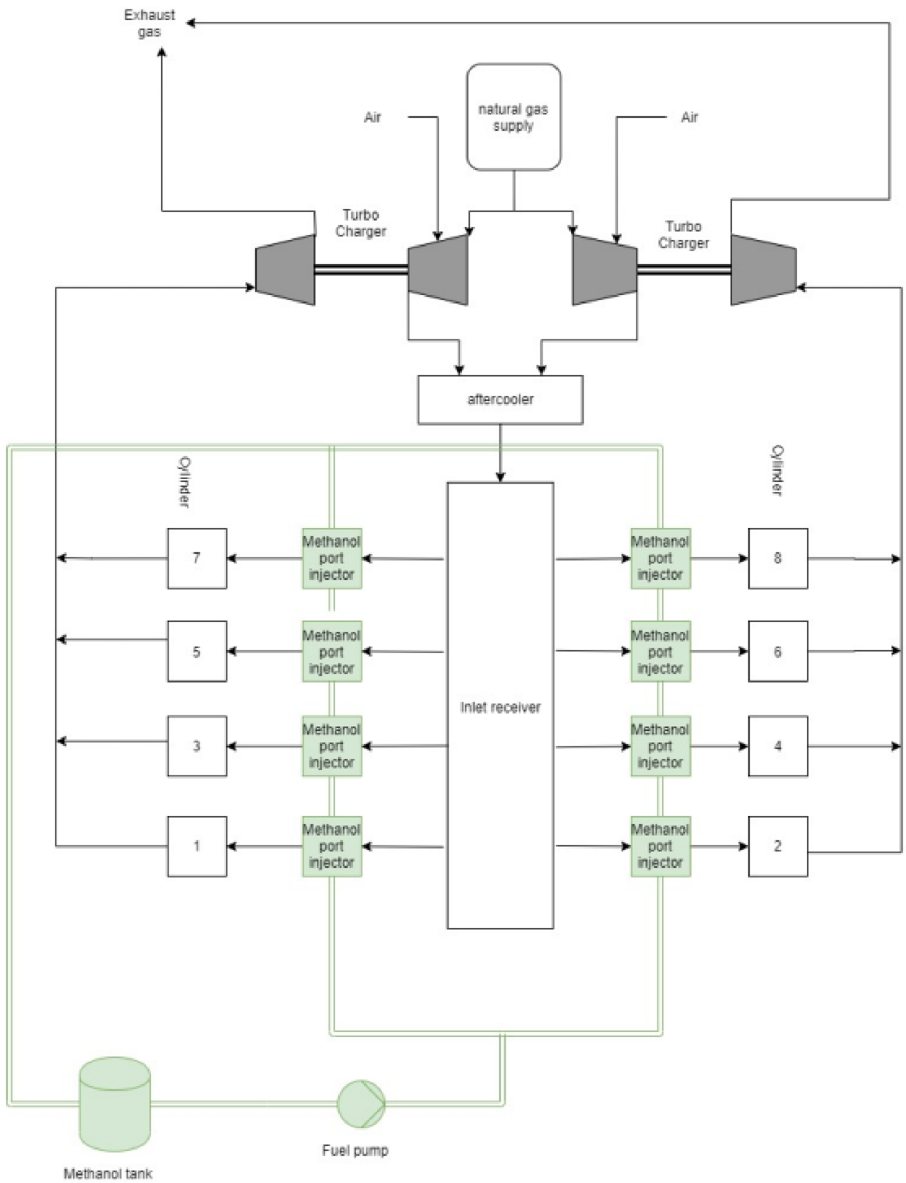
D

Diagrams

D.1. fuel oil transfer and service diagram



D.2. Fuel system diagram (CAT 3508A)



E.1. HT-PEMFC: Advent H3 5000

ADVENT

HT-PEM FUEL CELL TECHNOLOGY

H3 5000
High Voltage Variants

- Low noise and no harmfull emission
- Compact and light footprint
- High efficiency and lower fuel costs
- Flexible installation in- and outdoor
- Reduction of CO2 footprint
- Elimination of fuel and equipment theft

CLEAN, SIMPLE AND SUSTAINABLE POWER

The H3 5000 fuel cell systems offer a simple, powerful and reliable solution for on-demand power generation. On top of that, it is uniquely designed in a way where methanol is reformed on site to hydrogen. This means that the fuel for the systems is liquid and is not only easily distributed but also available all around the world. The system produces up to 5kW and as the system is modular, multiple systems can be interconnected.

The system delivers DC power directly, meaning that it is a highly efficient solution. There is no need for additional converters that have high power losses as a result. This reduces complexity and fuel consumption on site.

The system has built-in energy management system to combine with hybrid systems such as wind or solar power.

As a low maintenance power solution the system is ideal for critical backup power, temporary or continuous 24/7. This means that the system can work in off-grid applications as well as backup power in grid applications.

The system uses HT-PEM technology which is unique and offers many advantages.

www.advent.energy | sales.dk@advent.energy |

Methanol fuel cell unit

HIGH VOLTAGE VARIANTS	
190 [Vdc]	144-237
250 [Vdc]	200-312
380 [Vdc]	288-474
500 [Vdc]	400-624
760 [Vdc]	576-948
1000 [Vdc]	800-1248

PERFORMANCE	
Max power output[1] [kW]	5
Nominal output [kW]	3.75
Turn down [%]	0 - 100
IP rating	IP-20

1. Max power at beginning of life.

OPERATIONS	
Fuel mix	60% vol methanol, 40% vol deionized water
Fuel consumption[2] [l/kWh]	0,897
Net electric efficiency[2] [%]	41
Ambient temperature[3] [oC]	-20°C and up to 50°C
Interfaces	AUX, HTTP/SNMP/Ethernet IP, CAN open, Remote monitoring and USB

2. At beginning of life and rated load.
3. Options for lower temperatures.

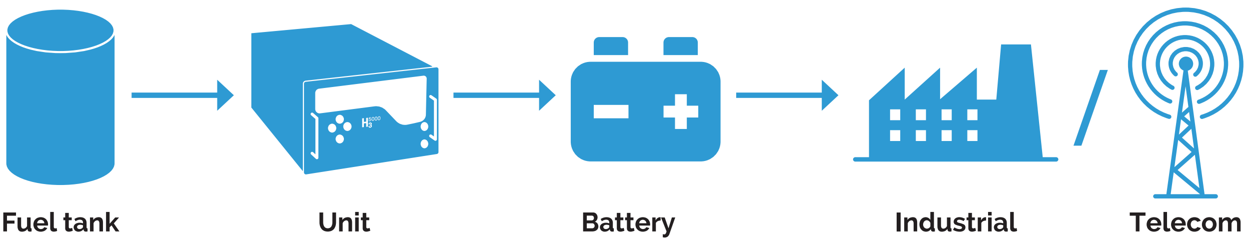
WEIGHT & DIMENSIONS	
Hight [mm] / Rack units [U]	267 / 6
Width [mm] / Rack size [in]	430 / 19
Length[4] [mm]	702
Weight [kg]	65,5
Volume [l]	80,6

4. Length excluding handles, connectors on front and exhaust pipes on rear.

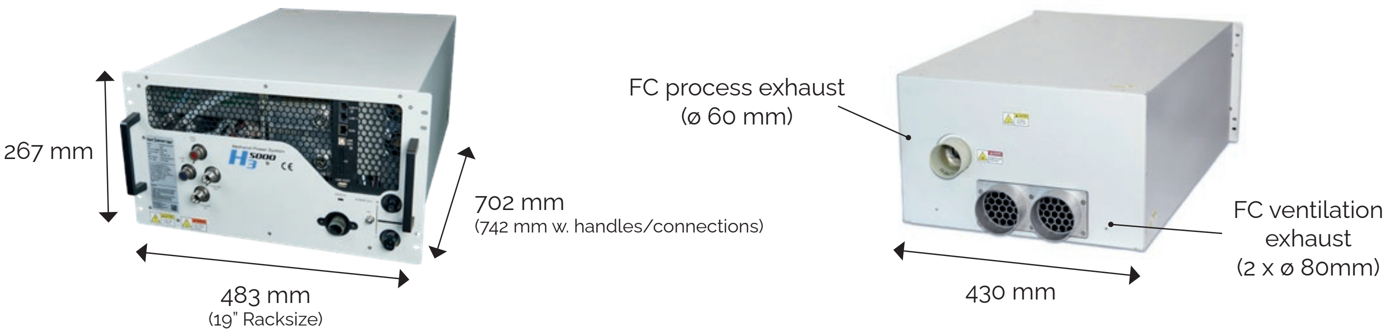
All numbers related to kW or kWh is electrical power / Energy delivered at module terminals (kWe / kWhe)

Contact Advent for other voltage variants.

Typical set-up

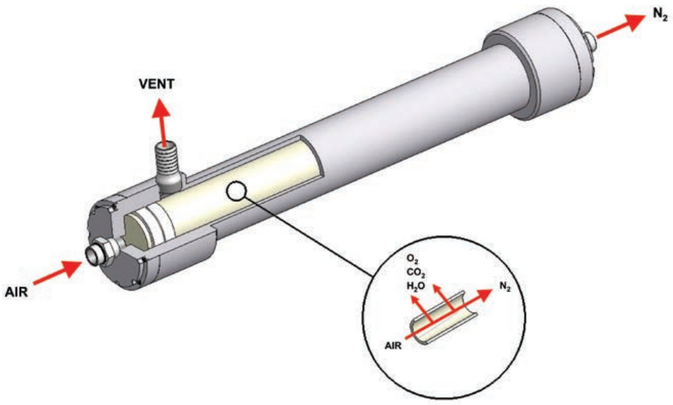


Dimensions



E.2. Nitrogen generator: Mos

MEMBRANE SEPARATION PRINCIPLE
Each membrane separator module contains thousands of polymer hollow fibres bundled together. Air fed at specified optimal pressure and temperature to one side of the membrane, dissolves and diffuses across the fibre material and desorbs as permeate at the low-pressure side of the membrane. As the air comprises different constituents, each component dissolves in the matrix to a different extent and permeates at a different rate. The more rapidly permeating components such as oxygen, carbon dioxide and water vapor are enriched in the low-pressure stream, which is safely vented to the atmosphere. The slower permeating components like nitrogen and argon are retained in the high-pressure stream and further removed from the membrane module as the nitrogen gas product.



PERFORMANCE DATA

Produced Nitrogen purity:
Up to 99.9%.

Product capacity:
10 to 6 000 Nm³/h or more.

Ambient temperature:
+2 to +45°C (possible +55°C, special design).

Product dew point:
Down to -70°C (Atmospheric pressure) depending on application and capacity.

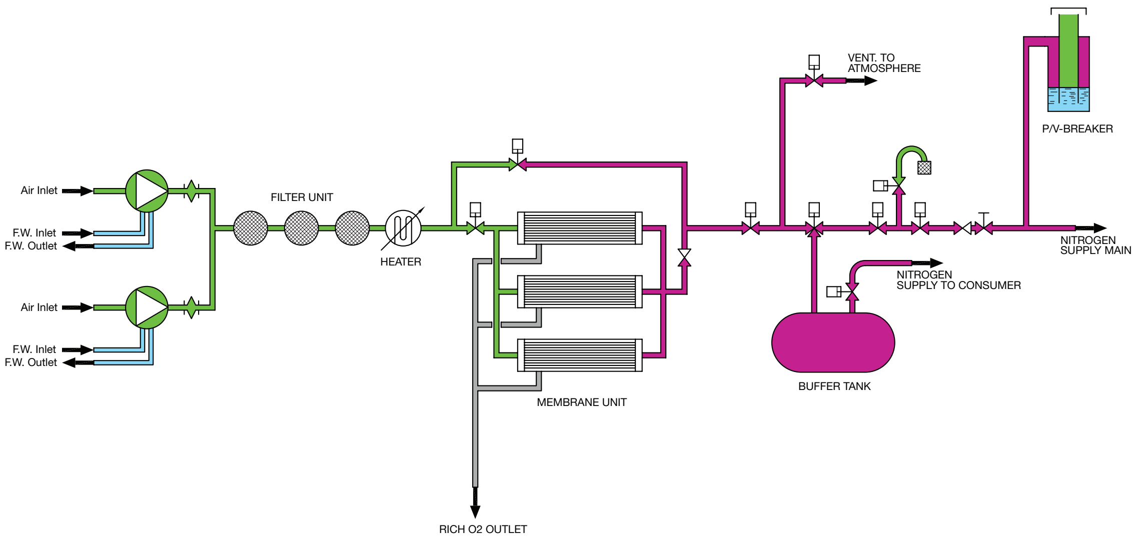
Product CO_2:
Less than 5 ppm.

Delivery pressure:
Up to 11.5 bar g, using 13barg compressor(s).

Nominal el. power consumption:
Approx. 0.3 kW/Nm³/h gas at 95% N_2 (excluding water pump).

Nominal sea/fresh water consumption:
11.5 l/Nm³ gas at 95% N_2.

Typical schematic of a Wärtsilä Moss nitrogen generator system



E.3. Engine durability: MaK M 20 C

M 20 C • Safety First

Engine with high safety level

The M 20 C is an engine with a high safety level. This applies not only to those special internal design features which guarantee long component life and high availability but also to safety in the area around the engine. As a result, SOLAS regulations are strictly and consistently observed. Explosion protection cover for the cylinder/crankcase housing and cladding of the complete fuel and exhaust gas system in stainless steel are part of an overall SOLAS safety concept.

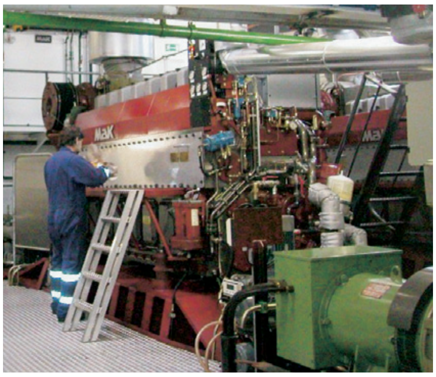
HFO/MDO – Long TBO and lifetime

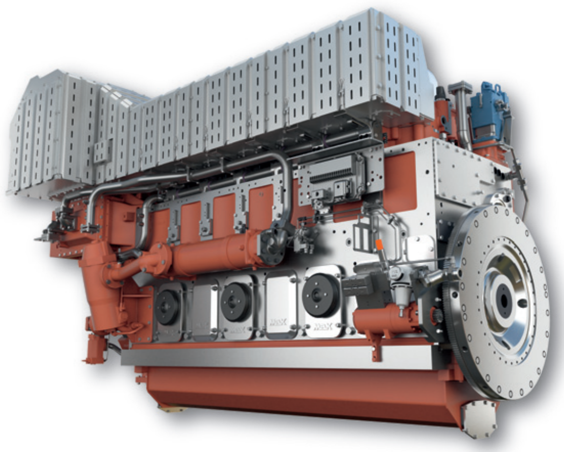
Long maintenance intervals and the life of components are the basis for low operating costs.

	Lifetime x 1000 h
Piston	60
Piston rings	30
Cylinder liner	60 / 90*
Cylinder head	90
Inlet valve	30
Exhaust valve	30
Nozzle element	5 / 7.5*
Pump element	15
Main bearing	30
Big-end bearing	30

*MDO Operation

The above mentioned data are not binding. They only serve as standard values. These standard values can be attained if the MaK operating and maintenance specifications are strictly observed and only MaK spare parts are used. Please consider as well the negative effect of bad fuel qualities.





E.4. HT-PEMFC: Cost Advent Fuel Cell