

A conceptual design study to prepare a general cargo ship for a refit towards alternative fuels

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Abstract

The shipping industry needs to reduce greenhouse gas emissions and other pollutants. In order to achieve this reduction, the shipping industry will be faced with stricter regulations that are currently unclear.

The lifetime of a ship is about 25 years. As a result, it can be interesting to already take a possible refit to an alternative fuel into account, when designing a new ship. This study investigates which aspects of the ship's design can be prepared for a refit to an alternative fuel, regarding a general cargo ship that starts sailing on LSFO and MGO. Due to the uncertainty in the future regulations, two possible scenarios are described. These scenarios are based on current regulations, known future regulations, the goals of the International Maritime Organization (IMO) greenhouse gas (GHG) strategy and a well-to-tank (WTT) analysis. The first scenario allows carbon-neutral fuels and the second scenario only allows carbon-free fuels.

Hereafter, different fuels are identified to be applicable in these scenarios. Then the most relevant aspects of the fuels that have an impact on the design of a ship are identified. These are the way the fuel should be stored, the volumetric and gravimetric energy density of the fuel, including the system and finally the applicability of the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF code). Based on these aspects, the fuels are compared with each other and a qualitative matrix is formed which shows how difficult it is to refit a ship from one fuel to another. The three most promising fuel refits are selected for a further conceptual design. The most manageable fuel switch in the carbon-neutral scenario is a switch towards hydrotreated vegetable oil (HVO), and the easiest in the carbon-free scenario is a switch to ammonia. Methanol is also selected, because, in the carbon-neutral scenario, it is relatively easy to refit to, and in terms of emissions, it does better than HVO.

To evaluate the possible design options for an easier refit, a reference ship is used as a starting point. The properties of this ship are also used to define the starting requirements for sailing on LSFO and MGO. Subsequently, a design spiral is used to adjust the design of the reference ship, to prepare it as far as possible for the selected refits. It has been concluded that it is relatively easy to prepare the ship sailing on LSFO and MGO for HVO. Due to the lower energy density of HVO, it is recommended to decrease the sailing range after the refit, so that no further adjustments have to be made to the design of the ship. The ship's range will be reduced by 8.6%. Because the ship has overcapacity, this has no impact on the sailing profile.

For methanol, cofferdams could already be placed in relevant tanks. Double pipes can be laid to these tanks or a double duct can be installed. Unlike MGO and LSFO, methanol can be stored in double bottom ballast water tanks, so for example, cofferdams can also be placed in ballast water tanks. By preparing the ship, space will be lost due to the preparations, in order to meet the initial requirements, the ship must be 2.3 [m] longer. If there is refit in the future, the ship will not yet meet the requirements for methanol. In order to meet the refit requirements, the ship will have to surrender 40% of its range. Furthermore, 1.4% of the cargo capacity will have to be surrendered.

It was concluded that, starting from LSFO and MGO, there was no point in preparing the ship for ammonia, because there are too many differences between the fuels. It could be interesting to build a ship for LNG in the coming years and then see if it can be prepared in the design for a refit to ammonia or hydrogen.

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List of Abbreviations and Acronyms

% m/m	% mass/mass
B	breadth
BAU	business as usual
C ₂ H ₆	ethane
C ₃ H ₈	propane
C ₄ H ₁₀	butane
CCS	carbon capture and storage
CH ₄	methane
CI	compressed ignition
CO	carbon monoxide
CO ₂	carbon dioxide
CO ₂ e	carbon dioxide equivalent
D	depth
DCS	data collection system
DF	dual fuel
DME	dimethyl ether
DNV-GL	Det Norske Veritas Germanische Lloyd
DWCC	deadweight cargo capacity
DWT	deadweight tonnage
ECA	emission control area
ECAs	emission control areas
EEDI	energy efficiency design index
EEZ	exclusive economic zone
EF	emission factor
EGR	exhaust gas re-circulation
ER	engine room
EtOH	ethanol
EU	European Union
FAME	fatty acid methyl ester
FT	Fischer-Tropsch
GCV	gross calorific value
GHG	greenhouse gas
GHS	globally harmonized system of classification and labelling chemicals
GWP	global warming potential
H ₂	hydrogen
HCV	higher calorific value
HFC	hydrofluorocarbons
HFO	heavy fuel oil
HHV	higher heating value

HVO	hydrotreated vegetable oil
IBC	International Code for the Construction of Equipment of Ships Carrying Dangerous Chemicals in Bulk
ICE	internal combustion engine
IGC	International Code for Ships Carrying Liquefied Gases in Bulk
IGF code	International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels
IMO	International Maritime Organization
IPPC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
kn	knot
kWh	kilowatt hour
LCA	lifecycle assessment
LCV	lower calorific value
LDO	lingnin diesel oil
LEL	lower explosive limit
LFO	light fuel oil
LHV	lower heating value
LNG	liquefied natural gas
Loa	length over all
LPG	liquefied petroleum gas
Lpp	length between perpendicular
LSFO	low-sulphur fuel oil
m	meter
m ³	cubic Meter
MDO	marine diesel oil
MeOH	methanol
MEPC	Marine Environment Protection Committee
MGO	marine gasoil
MRV	monitoring, reporting and verification
mt	metric tonnes
N ₂ O	dinitrogen monoxide
n/a	not applicable
NCV	net calorific value
NG	natural gas
NH ₃	ammonia
nm	nautical mile
NMVOC	non-methane volatile organic compound
NO	nitric oxide
NO ₂	nitrogen dioxide
NO _x	nitrogen oxide
PFC	perfluorocarbons
PM	particulate matter
PPO	pure plant oil
PS	port side

rpm	revolution per minute
SATP	standard ambient temperature and pressure
SB	starboard
SCR	selective catalytic reduction
SECA	sulphur emission control area
SECAs	sulphur emission control areas
SEEMP	ship energy efficiency management plan
SF ₆	hexafluoride
sfc	specific fuel consumption
SI	spark ignition
SO ₂	sulphur dioxide
SO _x	sulphur oxide
SOLAS	safety of life at sea
SVO	straight vegetable oil
T	draught
t	tonnes
TRL	technology readiness level
TTP	tank-to-propeller
UEL	upper explosive limit
UN	United Nations
US	United States
VOC	volatile organic compounds
WTP	well-to-propeller
WTT	well-to-tank
WTW	well-to-wake

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1

Introduction

Temperatures on earth are rising as a result of the release of greenhouse gases (GHGs) produced by human activities [65, 93]. Global warming changes the natural environment, ecosystems and human societies, causing extreme weather events, droughts and floods [119]. Climate change makes food insecurity worse in many places and puts pressure on freshwater supply [82]. Carbon dioxide (CO₂) emissions from fossil fuel combustion are one of the largest contributors to the total GHG emission increase [72].

Seaborne transport, representing over 80% of international trade by volume, predominantly uses fossil fuels [112]. Ship-source pollutants, most closely linked to climate change and to the negative impact on public health, include carbon dioxide (CO₂), nitrogen oxide (NO_x), sulphur oxide (SO_x) and particulate matter (PM) [41]. Shipping-related air emissions strongly depend on fuel type and engine type characteristics [58]. On a global scale, the marine shipping industry's share of total emissions coming from human sources is 2.2% for CO₂, 15% is NO_x, and 13% for SO_x [106].

The shipping industry is regulated by the International Maritime Organization (IMO), the United Nations (UN) agency responsible for the safety of life at sea and the protection of the marine environment [15]. On April 13, 2018, the Marine Environment Protection Committee (MEPC), the committee addressing environmental problems under the IMO mandate [25] adopted a strategy to decarbonise international shipping and reduce ship emissions [27]. The IMO GHG strategy's three main goals are first lowering the CO₂ emissions of the shipping industry by 40% in 2030 compared to 2008; secondly, lowering the CO₂ emissions of the shipping industry by 70% in 2050 compared to 2008; and thirdly, reducing all GHG emissions by 50% in 2050 compared to 2008, whilst at the same time, pursuing efforts towards phasing them out entirely [17, 21]. IMO's initial GHG strategy also includes a list of procedures which could be implemented to meet the emission targets. Measures are distinguished as either short-, mid-, or long term, meaning they would be finalised and implemented from 2018 to 2023, 2023 to 2030, and 2030 or after. These measures must be made mandatory under an IMO convention before they become legally binding. Whilst the direction of the strategy is clear, the path towards implementation remains uncertain. The shipping industry will, therefore, face new regulations in the future, but the specifics of these regulations are not yet certain [27].

A single technical or operational efficiency improvement measure may reduce emissions between 5% and 30% [55]. A combination of multiple different measures could therefore be enough to reach the IMO target of 2030. Where these efficiency improvements are likely to be enough to reach the 2030 goals, achieving those set for 2050 will require an uptake of lower and zero-carbon fuels which can diminish GHGs entirely. These are referred to as alternative fuels [17, 45, 55, 59, 60, 103, 106].

Given the long lifetime of oceangoing ships, typically 25 to 30 years, and the current firm reliance of the sector on fossil fuels, a rapid introduction of alternative fuels is required to meet the IMO's ambitions [11]. Currently, many hurdles must be overcome to use these fuels. Examples of such obstacles include the technology readiness level (TRL) and the availability of the fuel [60]. There is no one-size-fits-all solution, and there is no single route to fully decarbonise the maritime industry, so a multifaceted response is required [55].

Shipping companies anticipate building their strategy upon these new uncertain, expected regulations to the best of their knowledge. However, in addition to the barriers of TRL and fuel availability, strong price competition makes the early adoption of solutions unfeasible.

One such shipping company is Royal Wagenborg. Wagenborg offers a variety of maritime services concerning shipping, ports and terminals, and offshore services and operates a fleet of around 180 general cargo vessels to provide logistic solutions to international exporting industries. Due to uncertain future regulations, Wagenborg aims to investigate various levels of fuel flexibility and multiple approaches to fuel flexibility for new vessels, to respond to the IMO GHG strategy. These yet-to-be-built ships that will add to the Wagenborg fleet will most likely still be in operation in 2050. However, GHG reduction measures might require these vessels to be retrofitted to sail on an alternative fuel. Wagenborg wants to build its strategy upon these future uncertain regulations to the best of its ability.

Nonetheless, rules are not the only reason, for Wagenborg to investigate various fuel flexibility levels and different fuel flexibility approaches. Another reason is the demand from freight owners, as well as the aim of Wagenborg itself, to reduce the negative impact which conventional fuels now have on the environment [29].

1.1. Problem Statement

As discussed above, the specific future emission regulations are still unknown. Given the lifetime of ships and the IMO GHG goals for 2050, it could be possible that new-build ships may have to be converted to a more sustainable fuel during their lifetimes. Therefore, the following problem statement is defined:

General cargo shipowners are uncertain about which actions to take for new-build vessels to address the expected changes in emission legislation towards 2050.

1.2. Objective

The primary objective of this research is to identify the key aspects of a fuel change for a general cargo ship during its lifetime, with regards to fuel supply and fuel storage, and to evaluate the ship design regarding these aspects. This objective leads to the following main research question:

How can a shipowner prepare a new general cargo ship for uncertain future emissions regulations with respect to its design for onboard fuel storage and fuel supply?

The main research question is answered systematically with three sub-questions, first by elaborating on the uncertainty by defining possible fuel transitions; secondly, by identifying the key aspects of a general cargo vessel design regarding fuel storage and fuel supply systems; and, lastly, by evaluating the ship design regarding these key aspects. These steps can be translated into the following research sub questions:

1. *What are realistic possible fuel transitions towards 2050 starting with conventional fuels?*
2. *What are the key aspects of a fuel that have a significant impact on the design of a general cargo vessel?*
3. *How can a shipowner prepare a new general cargo ship for a fuel change with respect to its design for onboard fuel storage and fuel supply?*

1.3. Methodology

This section describes how the main research question is answered by the three sub questions defined in Section 1.2. It also describes which methods have been used.

To answer the main research question, this research is divided into the following five parts: background, analysis, design, evaluation and synthesis. An overview of the structure of this research and the methods used is shown in 1.1.

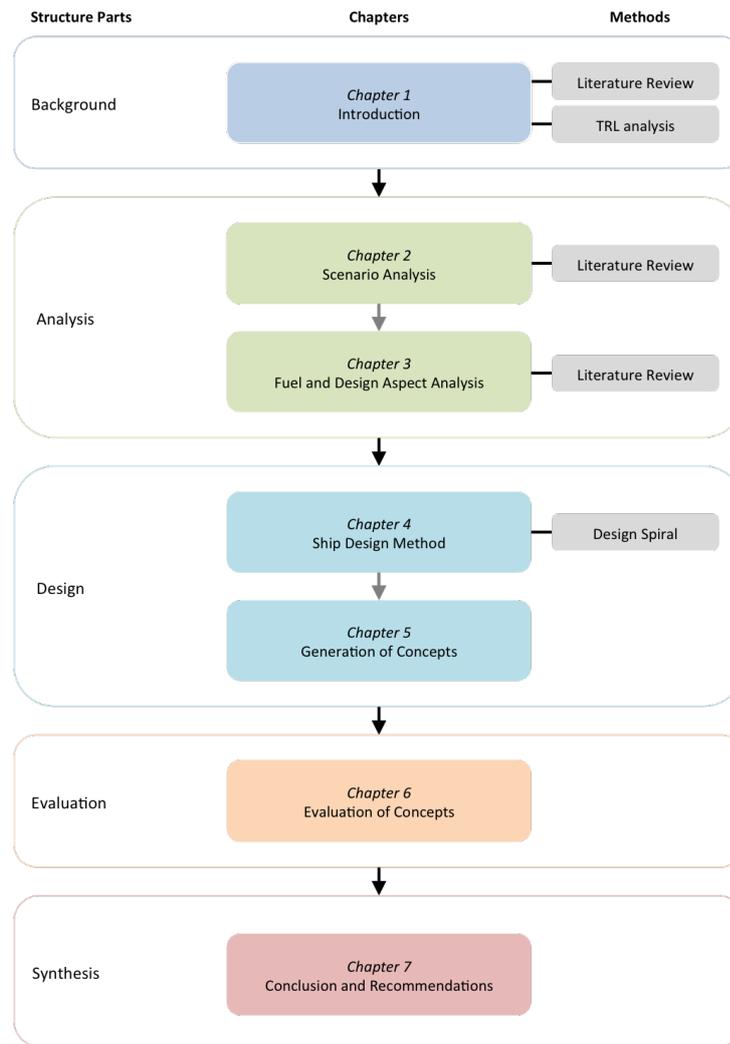


Figure 1.1: Methodology outline of this research. Technology readiness level (TRL)

Before starting a literature review to answer sub question 1, a literature study is performed to make a selection of fuels based on their technical maturity and availability. The assessment of maturity is based on TRLs, a measurement system for the maturity of particular technology whereby this maturity is divided into nine levels [90]. The selection of these fuels is given in the scope of this research in Section 1.4.

The first sub question addresses the uncertainty of the problem. In studies regarding significant uncertainty, particularly in fields with long-term planning horizons, such as energy policies, scenarios are used as a tool for considering possible energy transition paths [94]. Because this research also involves significant uncertainty and a long-term planning, two different scenarios are presented. First, a literature study is performed to create an overview of the relevant regulations and IMO goals, followed by a literature review to gain insight into the emissions of fuels and finally formulate scenarios. This provides the answer to sub question 1 (in Chapter 2).

The second sub question is answered by a literature review. The key design criteria are formulated which state the important characteristics for this design problem [34], and the answer is provided in chapter 3.

The third sub question is answered by applying the analyses in chapters 2 and 3 and generating concepts based on the key requirements selected in chapter 3 and the scenarios formulated in chapter 2. The generated concepts (in chapter 5) are then evaluated, whereby the best approach is selected (chapter 6).

1.4. Scope

Because of the many directions which can be taken with the subject of this research, and in to fulfil the objective of this study and ensure the quality, and reliability of the findings within the limited time available,

the scope is extensively defined and divided into four categories. First, items which cannot be classified in a particular category are discussed. This is followed by defining the scopes of the ship type with the associated aspects, the alternative fuels and the emissions.

1.4.1. General

General aspects within or outside the scope of this project include:

- **Timeframe**

- This thesis studies is focused on the medium to long term (2030-2050). This refers to the fact that a refit of a vessel, switching to an alternative fuel will occur during this period.
- Due to the high investment costs of a refit, it is assumed that only one refit will occur during the lifetime of a ship to switch from conventional fuel to an alternative fuel.

- **Abatement Technologies**

- As mentioned in the introductory text, it is unlikely that emission abatement technologies other than alternative fuels will be sufficient in 2050; therefore, emission abatement technologies such as selective catalytic reduction (SCR), exhaust gas re-circulation (EGR), open-loop scrubber and closed-loop scrubber are beyond the scope of this study.

1.4.2. Vessel

Aspects related to the vessel within the scope of this research include:

- **Type**

- The vessel type directly related to the company Royal Wagenborg, where the research is performed, is a general cargo vessel.
- The study focusses on general cargo vessels with a deadweight cargo capacity (DWCC) between 10,000 and 25,000 [tonnes].
- The focus is on the current ship design.

- **Driveline**

- The current driveline is examined, which is a diesel direct driveline. This is mainly done because other efficiencies are involved in other driveline technologies. Furthermore, the focus is on the fuel storage and fuel supply; therefore, no in depth research is done on the subject of driveline technologies.

- **Fuel Storage**

- A flexible engine is of little use if the onboard storage and supply systems cannot manage the appropriate fuels. Fuel-flexible storage tanks and onboard fuel supply systems are thus necessary for changing fuel [75].
- Only physical-based storage methods are studied as they are the most mature method applicable for all fuels. The other storage type is material-based, which includes liquids, solids and surface (especially applying to hydrogen) and is not covered in this research [92, 104].

- **Reference Fuel**

- Marine gasoil (MGO) and low-sulphur fuel oil (LSFO).

1.4.3. Fuels

Researchers and those in the maritime industry are currently discussing a wide variety of fuels. The preference of a fuel also strongly depends on the type of ship, especially the amount of fuel needed, which relates to the bunker intervals; for instance, deep-sea vessels have fewer options compared to the short-sea segment [23, 70]. Many more criteria can be of importance when considering alternative fuels [49, 60].

For this research, an initial selection is made based on two criteria: TRL onboard general cargo ships, which includes the fuel compatibility with the engine, the TRL of the engine itself and other systems, and the availability of the fuel, which includes the production TRL, scalability of the fuel and infrastructure.

As mentioned, the TRL estimates the maturity of technologies [56]. TRL 1 and 2 indicates the starting phase whereby basic technology research is done, and TRL 2 and 3 indicate the research phase to prove feasibility. TRL 3 to 5 refer to technology development, and TRL 5 and 6 stipulate technology demonstration. TRL 6 to 8 indicate system development, and TRL 8 and 9, the phase of system testing, launching and operations [56]. The TRLs are shown in Figure 1.2.

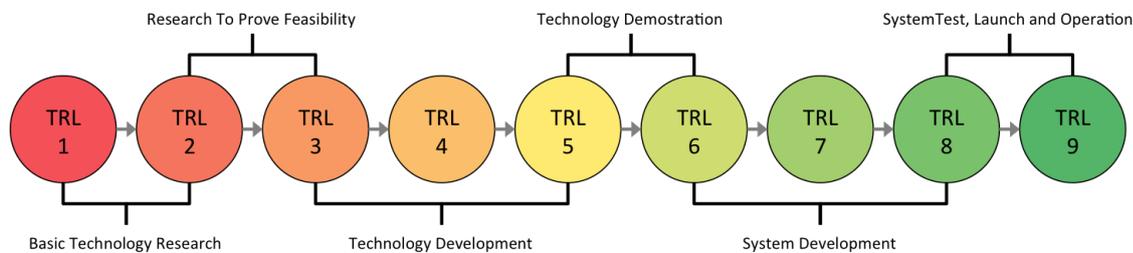


Figure 1.2: Technology readiness levels (TRLs). Figure inspired by [51].

Fuels within the Scope

The following fuels are in the scope of this research and could meet the requirements for general cargo ships for the next 30 years related to availability and TRL [70]:

- **Hydrotreated vegetable oil (HVO)**

- HVO, also called renewable diesel, can be made from oil crops or used oil. The TRL for fuel production for both feedstocks is 9.
- HVO is compatible with existing onboard fuel infrastructure and engine systems and can be used in diesel engines. This can be done as pure fuel or as a blend. Currently, there is limited operational experience with the use of HVO as a fuel in the shipping industry. However, it is currently used onboard several ferries operating in Norway without reported negative effects [48, 49].

- **Liquefied natural gas (LNG)**

- The infrastructure for LNG and its availability are limited but improving. Increasingly more ships are being added which run on LNG, and as a result, the infrastructure will also grow.
- The technology required for employing LNG as ship fuel is readily available [42, 49].

- **Liquefied petroleum gas (LPG)**

- LPG can be produced as by-product of oil or gas production. It is also possible to produce LPG from renewable sources, for example, as a by-product of renewable diesel production. Infrastructure already exists, but bunkering facilities must grow. There is an extensive network available, so it is relatively easy to develop bunkering infrastructure at existing LPG storage locations or terminals by simply adding distribution installations.
- LPG is already used in four-stroke diesel engines but is currently limitedly used [42, 49, 96].

- **Ethanol (EtOH)**

- First-generation ethanol competes with food. First-generation biofuels appear unsustainable because of the potential stress which their production places on food commodities. Second-generation biofuels are produced from biomass in a more sustainable fashion, which is truly carbon neutral or even carbon negative in terms of its impact on CO₂ concentrations.
- Ethanol has been shown to work well in diesel engines for road transport [60, 113].

- **Methanol (MeOH)**

- Methanol can be produced from various sources such as natural gas, coal, black liquor, forest thinning, agricultural waste, CO₂ and hydrogen. The main source of methanol is currently natural gas. Methanol produced from gasification of coal relies on a cheap, widely available resource, but the GHG emissions are about twice as high as from natural gas.
- There are two main options for using methanol as fuel in conventional ship engines. Wärtsilä four-stroke engines are in operation onboard the passenger ferry Stena Germanica, so these are already available [49, 91, 96].

- **Dimethyl ether (DME)**

- DME can be produced by dehydration of methanol or from synthetic materials.
- DME has been tested on small engines, but this is no guarantee of its suitability for use in larger engines [56, 60, 116].

- **Hydrogen (H₂)**

- Hydrogen can be produced employing various energy sources, such as by electrolysis of renewables, or by reforming natural gas. Today, nearly all hydrogen is produced from natural gas. If hydrogen is produced from renewable energy sources, or from natural gas with carbon capture and storage (CCS). Can be produced by electrolysis of water, reforming of natural gas or by reforming of other hydrogen carriers.
- Currently limited experience with marine storage and use of hydrogen [49]. Storage technologies are available from land-based applications.

- **Ammonia (NH₃)**

- Ammonia as a ship fuel has quickly gained interest amongst many stakeholders over the last several years, provided that the production is carbon-free. Since there is already widespread demand for ammonia in land-based industries (for example, in the use of synthesis of fertilizers or for house-cleaning products), the infrastructure for transport and handling of ammonia is in place. However, bunkering infrastructure must grow for marine application.
- Internal combustion engines (ICEs) running on ammonia are promising. However, the disadvantages of Ammonia for ICEs are that it has a very high auto-ignition temperature, low flame speed, high heat of vaporisation, narrow flammability limits and toxicity [49].

A summary of the availability and TRLs is shown in Table 1.1. For the availability, a relative scale of red to green is used, whereby red is not available and green means widely available, which is similar to the coloured TRL scale shown in Figure 1.2.

Table 1.1: TRLs onboard general cargo vessels and availability of alternative fuels in 2030 and 2040.

Fuel	2030		2040	
	TRL	Availability	TRL	Availability
Hydrotreated vegetable oil (HVO)	9	Orange	9	Yellow
Liquefied natural gas (LNG)	9	Green	9	Green
Liquefied petroleum gas (LPG)	8	Yellow	9	Green
Ethanol (EtOH)	8	Yellow	9	Green
Methanol (MeOH)	8	Yellow	9	Green
Dimethyl ether (DME)	8	Yellow	9	Green
Hydrogen (H ₂)	7	Yellow	9	Green
Ammonia (NH ₃)	7	Yellow	9	Green

Fuels and Technologies outside the Scope

The following fuels are not covered in this research and are outside the scope:

- **Electric propulsion/batteries**

- With the scope of current powertrain technology, battery technology is excluded. Furthermore, the TRL of batteries is 9, but to store enough energy to use these batteries on general cargo vessels which are sailing for several days to weeks is not possible because of the number of batteries needed [23, 70].

- **Nuclear fuels**

- The scope of current powertrain technology also excludes nuclear propulsion. Furthermore, nuclear fuels are not relevant due to high investment costs and negative public opinion [116].

Comments

Because this thesis focusses on the technical aspects, fuels which are not specifically mentioned can be compared with the properties of the fuels which are included in the scope. Examples include bioliquid fuels such as Fischer-Tropsch (FT) diesel, biodiesel/fatty acid methyl ester (FAME), straight vegetable oil (SVO)/pure plant oil (PPO) and lignin diesel oil (LDO), which are comparable to HVO in their physical properties, as well as butanol which is comparable to methanol and ethanol but less promising.

2

Scenario Analysis

The aim of this chapter is to formulate scenarios to provide insight into which fuels will comply with future regulations so that ships can switch to using them.

In studies with significant uncertainty and long-term planning horizons, such as with energy policies, scenarios are used as a tool (e.g. for considering possible energy transition paths) [94]. This research, which also involves significant uncertainty and a long-term planning, presents two different fuel scenarios, as a possibility of alternative fuels to meet uncertain regulations.

To arrive at these different fuel scenarios (presented in section 2.4), the current regulations are first described in section 2.1. After that, the future regulations are discussed in section 2.2. Lastly, in section 2.3 the extent to which these fuels comply with regulations is examined.

2.1. Current Emission Regulations

This section discusses the current emission regulations so that these can later be evaluated against alternative fuels. The current regulations consist of two main rules; the emission control areas (ECAs) and the energy efficiency design index (EEDI).

2.1.1. Emission Control Areas

ECAs are areas subject to emission limits. The ECAs regulated by the IMO can be divided into two types; areas subjected to nitrogen oxide (NO_x) limits (nitrogen emission control areas [NECAs]) and areas subjected to SO_x limits (sulphur emission control areas [SECAs]). By limiting the SO_x , particulate matter (PM) emissions are also reduced.

Nitrogen oxide (NO_x) is a generic term for different gases, of which nitric oxide (NO) and nitrogen dioxide (NO_2) are the most relevant for air pollution. These gases contribute to the formation of smog and acid rain, amongst other conditions [60].

Sulphur oxide (SO_x) is a generic term for different gases, of which SO_2 is the most pollutant [60]. These gases are emitted by burning fossil fuels. SO_x is mainly bad for human health and can contribute to respiratory illness, as well as smog formation [60].

Particulate matter (PM) is a generic term to describe solid particles and liquid droplets found in air. The composition and size of these airborne particles and droplets vary. PM is mainly bad for human health.

North America and the Caribbean are full ECAs where both the limits for NO_x and SO_x are enforced. The Baltic Sea and North Seas are SECAs. An overview of the IMO-regulated ECAs is shown in Figure 2.1. Furthermore, there are local ECAs regulated by each country's national law. These include all EU ports and all Turkish ports, with a limit of 0.1 [% m/m] sulphur and Iceland, with a sulphur limit of 0.1 [% m/m] at berth and a sulphur limit of 2.0 [% m/m] in Icelandic exclusive economic zones (EEZs). China coastal and inland waters and seven Taiwanese ports have a SO_x limit of 0.5 [% m/m].



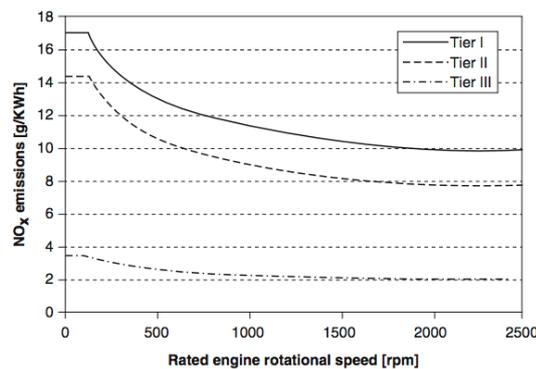
Figure 2.1: Current ECAs [16].

Nitrogen Legislation

The nitrogen oxide emissions are related to the engine. NO_x emission limits set for diesel engines depend on the engine's maximum operating speed. NO_x emission limits for shipping are set according to three different levels (tiers) based on the ship's construction date. The different tiers are shown in Table 2.1. Tiers I and II currently apply worldwide. Tier III presently applies only in North America and the Caribbean. The data from Table 2.1 is plotted in Figure 2.2.

Table 2.1: Different levels (tiers) of control applied based on the ship's construction date [102].

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm - 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.2)}$ e.g., 720 rpm - 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm - 2.4	2.0

Figure 2.2: Nitrogen oxide (NO_x) Tiers I, II, and III regulations [78].

Sulphur Legislation

The sulphur oxide limits are related to the fuel (and are shown in Figure 2.3). The current global sulphur limit is 0.5 [% m/m], which has applied since 1 January 2020. There are basically three main options to comply with this limit. The first, most commonly used option is to use a fuel oil with low sulphur content. The second option is to use an alternative fuel, and the third is an option whereby a fuel with a higher sulphur content may still be used, by employing an exhaust gas cleaning system, also known as a scrubber.

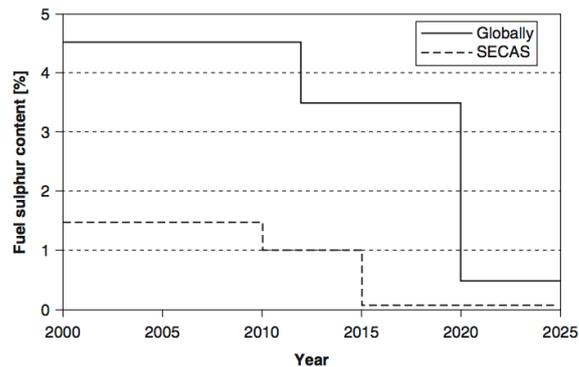


Figure 2.3: Current and projected restrictions on fuel sulphur content according to IMO [78].

2.1.2. Energy Efficiency Design Index

The energy efficiency design index (EEDI) is meant to drive ship technologies to become more energy-efficient over time by imposing limits on this index. The EEDI is a global-based technical standard that applies to new ships.

The EEDI indicates the energy efficiency of a ship in grams of CO₂ produced for every mile which is travelled per tonne cargo (gCO₂/tonne-mile). The EEDI is calculated for a specific reference ship's operational condition.

Ship designers and builders are free to choose the technologies to satisfy the EEDI requirements in a specific ship design. The reference lines are established for each ship type to which the required EEDI is applicable. The values for the EEDI for five different ship types are shown in Table 2.2. The purposes of the EEDI are to provide a fair basis for comparison, to stimulate the development of less polluting ships in general and to establish the minimum efficiency of new ships depending on ship type and size [39]. Smaller size vessels are excluded from having a required EEDI because of the limited possibility for energy-efficiency measures.

Table 2.2: Reduction factors in [%] for the EEDI relative to the EEDI reference line for different ship types [37].

Ship Type	Size	Phase 0	Phase 1	Phase 2	Phase 3
		1 January 2013 - 31 December 2014	1 January 2015 - 31 December 2019	1 January 2020 - 31 December 2021	1 January 2025 and onwards
Bulk carrier	20,000 DWT and above	0	10	20	30
	10,000 - 20,000 DWT	n/a	0-10*	0-20*	0-30*
Gas carrier	10,000 DWT and above	0	10	20	30
	2,000 - 10,000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20,000 DWT and above	0	10	20	30
	4,000 - 20,000 DWT	n/a	0-10*	0-20*	0-30*
Container ship	15,000 DWT and above	0	10	20	30
	10,000 - 15,000 DWT	n/a	0-10*	0-20*	0-30*
General cargo ships	15,000 DWT and above	0	10	15	30
	3,000 - 15,000 DWT	n/a	0-10*	0-15*	0-30*

Note: n/a means that no required EEDI applies.

* Reduction factor to be linearly interpolated between the two values dependent upon ship size. The lower value of the reduction factor is to be applied to the smaller ship size.

The EEDI for general cargo ships is displayed in Figure 2.4.

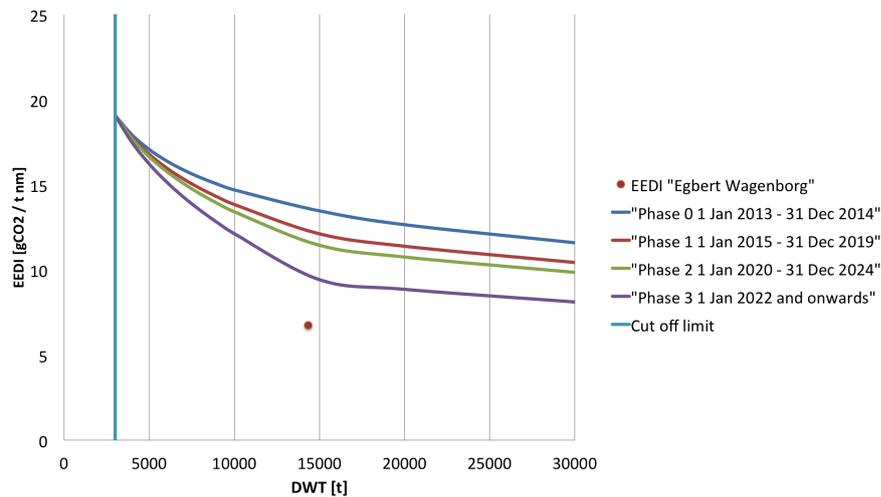


Figure 2.4: EEDI phases for general cargo ships [78].

2.2. Future Emission Regulations

In this section, the future regulations are divided into known future regulations and part of the IMO GHG strategy. The known future regulations are needed to examine the alternative fuels to determine if they comply and the IMO GHG strategy is necessary because it forms the basis for future regulations. To evaluate alternative fuels against this strategy, its main goals are first discussed, followed by elements of this strategy explained in more detail. Lastly, two different scenarios are formulated based on this information.

2.2.1. Known Future Emission Regulations

The known future emission regulations are stricter measures of the current nitrogen Tier III legislation discussed in subsection 2.1.1 and the EEDI discussed in subsection 2.1.2. Tier III will also affect the Baltic and North Seas for ships constructed (keel-laying) on or after 1 January 2021 or for existing vessels which replace an engine [102].

Discussions are ongoing to bring forward the EEDI phase 3 from 2025 to 2022 because the ships which are now being built can easily meet a lower EEDI. This is also the case for the last commissioned vessel of Wagenborg, which has an EEDI of 6.76 [28]. already more than 30% better than phase 3. The MEPC also agreed with terms of reference for the introduction of a possible phase 4 of EEDI requirements.

Current regulations and known future regulations are aimed at reducing nitrogen oxide (NO_x) emissions and sulphur oxide (SO_x) emissions. The EEDI, is intended to improve the ship's overall efficiency, whereby all emissions will be reduced. An overview of the current and future known regulations is displayed in Figure 2.5.

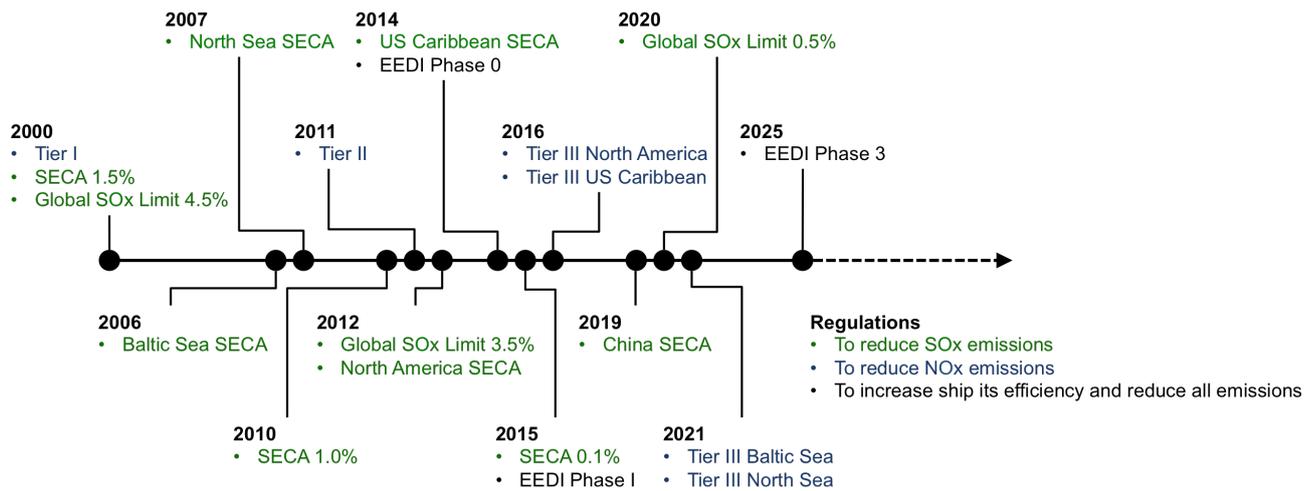


Figure 2.5: Past, current and known future regulations.

In the future, more regulations (which are not known at this time) will be formulated to reduce other harmful emissions based on the IMO GHG strategy.

2.2.2. IMO GHG Strategy

The strategy of the IMO envisages a reduction of the total GHG emissions from international shipping [25]. The three main goals of this strategy are [17]:

1. Lowering the CO₂ emissions per transport work of the shipping industry by at least 40% in 2030 compared to 2008.
2. Lowering the CO₂ emissions per transport work of the shipping industry by 70% in 2050 compared to 2008.
3. Reduction of all GHGs by 50% in 2050 compared to 2008.

These goals are aimed at the entire shipping industry. The first two are to reduce CO₂ emissions per transport work, which means that the total CO₂ emissions can still increase if the transported goods increase. The third goal is to reduce all GHG emissions from the shipping industry and is not explicitly focussed per transport work, which means that the total GHGs must be reduced and should not increase.

A GHG is a different emission than what current and known future regulations are now focussing on. GHGs absorb and emit radiant energy and cause the greenhouse effect on planets. Many GHGs occur naturally in the atmosphere, and without these, earth's average temperature would be -18 °C rather than 14 °C [36, 98, 100].

The most significant GHG emissions caused by humans and identified in the Kyoto Protocol are carbon dioxide (CO₂), methane (CH₄), dinitrogen monoxide (N₂O), hydrofluorocarbons (HFC), perfluorocarbons (PFC) and hexafluoride (SF₆). HFCs, PFCs and SF₆s are not the result of fuel combustion and are therefore not further discussed in this research.

CO₂ is by far the most prevalent GHG; thus, it is considered separately in the first two IMO goals. According to the IMO, CO₂ emissions will increase between 50 and 250% by 2050 depending on future economic growth [102].

CO₂ emissions from shipping under the IMO GHG strategy are shown in Figure 2.6 and compared to one possible business as usual (BAU) pathway [17, 59, 68, 102]. The blue dashed line in the figure represents the minimum ambition of CO₂ reductions in the strategy and the green dashed line in the figure is the maximum ambition. However, because these goals are aimed at the entire shipping industry, it is uncertain to what extent the current fleet should contribute to the IMO strategy compared to new-build vessels [17, 59, 68].

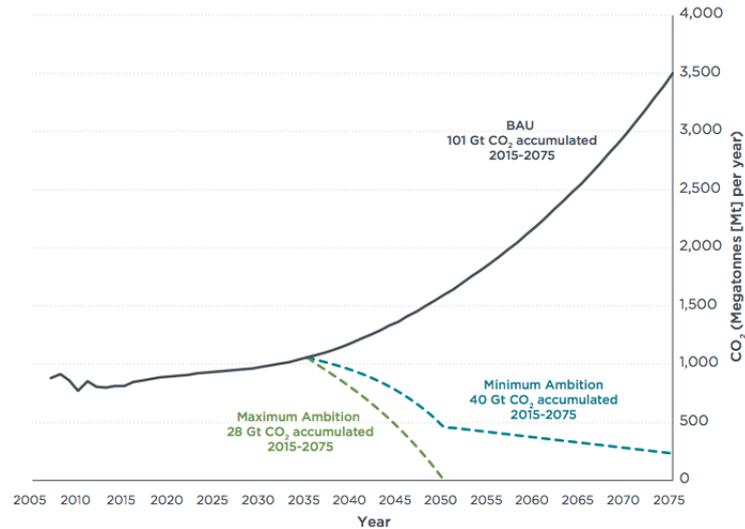


Figure 2.6: CO₂ emissions from international shipping under IMO's initial GHG strategy (blue and green) versus BAU (black), with cumulative emissions 2015 through 2075 [102].

To meet the targets, the IMO GHG strategy includes a list of measures which could be implemented (shown in Table 2.3). This contains short-, mid-, and long-term measures, meaning they would be finalised and implemented from 2018 to 2023, 2023 to 2030, and 2030 or after, respectively.

The table contains measures to stimulate the efficiency of ships, such as the previously mentioned already existing EEDI and also the ship energy efficiency management plan (SEEMP), which is a system for shipowners to measure the efficiency of their ships by collecting voyage data. SEEMP is the major part of the data collection system (DCS) to collect emission information from shipping companies globally. Since January 2019, all shipping companies must use this system.

Table 2.3 also contains measures to better map ship emissions, namely methane and VOC emissions but SEEMP provides better insight in the emissions. Furthermore, there are measures in the form of programmes to help the shipping industry develop and improve ships and introduce alternative fuels.

Table 2.3: Candidate measures included in IMO's initial GHG strategy [37].

Type	Years	Measures	Target	Current status
Shortterm	2018-2023	New Energy Efficiency Design Index (EEDI) phases	New vessels	-10% in 2015 -20% in 2020 -30% in 2025
		Operational efficiency measures (e.g. SEEMP, operational efficiency standard)	In-service vessels	SEEMP planning required
		Existing fleet improvement programme	In-service vessels	-
		Speed reduction	In-service vessels	-
		Measures to address methane and VOC emissions	Engines and fugitive emissions	-
Midterm	2023-2030	Alternative low-carbon and zero-carbon fuels implementation programme	Fuels/new and in-service vessels	-
		Further operational efficiency measures (e.g. SEEMP, operational efficiency standard)	In-service vessels	SEEMP planning required
		Market-based measures (MBMs)	In-service vessels/fuels	-
Longterm	2030+	Development and provision of zero-carbon or fossil-free fuels	Fuels/new and in-service vessels	-

Ship energy efficiency management plan (SEEMP), volatile organic compounds (VOC).

The IMO GHG strategy is currently not focussed on the total lifecycle emissions but only on the emissions involved in shipping. With the introduction of alternative fuels, however, the IMO is considering examining total life cycle emissions [44].

2.2.3. Lifecycle Emissions

The total lifecycle emissions are known as well-to-propeller (WTP) emissions. The WTP emission performance can be subdivided by well-to-tank (WTT) and tank-to-propeller (TTP) emissions. A fuel is produced from an energy source by a processing technology. The route from energy source to fuel will determine the WTT emissions, which includes extracting the energy source, the production from the energy source to a fuel and all transportation and distribution involved (shown in Figure 2.7).

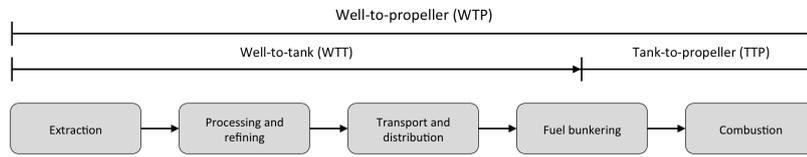


Figure 2.7: Generic well-to-propeller supply chain to illustrate the terms WTP, WTT and TTP. This simplified chart was inspired by [44, 61].

For every fuel, the WTT emissions strongly depend on the primary energy source; therefore, the WTP emissions can also vary significantly [60].

The determination of the required energy for production of a fuel is a complex task [85]. WTT emissions may differ based on what is and is not included, for example whether or not construction or decommissioning of fuel production and transportation facilities is included [73]. Emissions can also differ based on fuel sources, refineries and per country [60].

Environmental performance in shipping, which includes analysing WTP and therefore also WTT emissions, has been studied by many researchers using lifecycle assessment (LCA) [60, 63, 76, 77] of fuels for vehicles (aviation as well as shipping). LCA allows for a comparison between various pathways along the energy value chain, and therefore for the assessment of the potential impact compared to marine diesel fuels [70].

Examples of fuel chains from energy source to fuel are shown in Figure 2.8. However, there are many more ways to produce fuels.

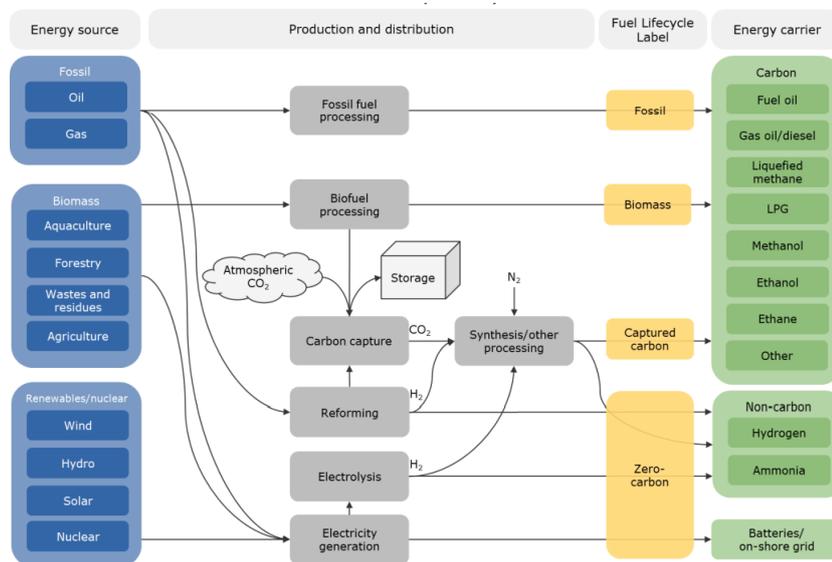


Figure 2.8: Fuel pathways [44].

The TTP emissions vary less and depend on the composition of the fuel. Moreover, the well-to-propeller (WTP) is sometimes called the well-to-wake (WTW), although this is used more often to describe the life cycle GHG inventory of aviation fuels [110]. Based on the findings from regulations and the lifecycle emissions, two scenarios have been formulated.

2.2.4. Fuel Scenarios

The first scenario represents a decrease in GHGs in the shipping industry by evaluating the emissions on the WTP LCA. In this scenario, it is assumed that all ships in the fleet should be able to sail carbon neutral.

The second scenario represents reaching the highest goals of the IMO GHG strategy. In this scenario all the ships of the fleet, new-builds and old vessels, should become carbon-free regardless of the resource.

The fuels are examined against these scenarios and the extent to which they comply with the known regulations.

2.3. Fuels

In this section, the current regulations, known future regulations and IMO GHG strategy discussed in the previous section are linked to the fuels. For the IMO GHG strategy, the CO₂ emissions are examined.

The non-CO₂ GHG are not coupled because there is little literature on this subject, and it is assumed that these are combined with a CO₂ reduction. However, it should be noted that other GHGs can have a more negative effect on the climate than CO₂.

Some GHGs make the planet warmer than others. Therefore carbon dioxide equivalents allow other GHG emissions to be expressed in terms of CO₂, based on their relative global warming potential (GWP) [57]. This is also done in the IMO study which gives an overview of CO₂ emissions and carbon dioxide equivalents (CO₂e). The GWP has been developed as a metric to compare the ability of each GHG to trap heat in the atmosphere relative to another gas; CO₂ has a GWP of 1. A GWP is calculated over a specific time horizon, commonly 20, 100 or 500 years, which can strongly affect the numerical values. The GWP is a physical characteristic of GHGs, representing their impact on the greenhouse effect. The CO₂e values for a selection of GHG emissions in the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) for a 100-year time horizon are shown in Table 2.4 [98]. As can be seen, in the table, methane (CH₄) is much worse than CO₂, and N₂O even more.

Table 2.4: A selection of different CO₂e values.

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon
Carbon dioxide	CO ₂	1
Methane	CH ₄	28
Nitrous oxide	N ₂ O	265

To compare fuels with these emissions, this study employs the emission factors used by the IMO in the data collection system (DCS), which is part of the candidate measures described by the IMO GHG strategy described in subsection 2.2.2.

The IMO has developed EFs per gram of fuel for the following GHGs and pollutants: CO₂, NO_x, SO_x, CO, CH₄, N₂O and NMVOC. The values for the CO₂ factor of the fuels in this research, which is directly related to the carbon content in the fuel and used in the MRV plan, is shown in Table 2.5.

The factor in the MRV plan is called C_F, which is a nondimensional conversion factor between fuel consumption measured in tonnes and CO₂ emission, which is also measured in tonnes based on carbon content.

Table 2.5: MRV values for CO₂ emissions [43, 44].

Type of fuel	Reference	Carbon content	C _F (t-CO ₂ /t-fuel)
Diesel/gas oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
Light fuel oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
Heavy fuel oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
Liquefied petroleum gas (LPG)	Propane (C ₃ H ₈)	0.8182	3.000
	Butane (C ₄ H ₁₀)	0.8264	3.030
Liquefied natural gas (LNG)	n/a	0.7500	2.750
Methanol (MeOH)	n/a	0.3750	1.375
Ethanol (EtOH)	n/a	0.5217	1.913
Hydrotreated vegetable oil (HVO)	n/a	n/a	n/a
Dimethyl ether (DME)	n/a	n/a	n/a
Ammonia (NH ₃)	n/a	0	0
Hydrogen (H ₂)	n/a	0	0

In accordance with the International Standards Organization (ISO) 8217, residue fuels are divided into the following six fuel types: RMA, RMB, RMD, RME, RMG and RMK. This distribution is made on the basis of their kinematic viscosity [24].

The fuels are discussed in the following uniform way:

1. Current and Known Future Emission Legislation

- (a) NO_x emissions and compliance with the strictest regulations (Tier III)
- (b) SO_x emissions, sometimes also PM emissions and compliance with SO_x emission regulations (global sulphur limit [0.5%] and SECA limit [0.1%])

2. IMO GHG Strategy

- (a) Chemical structure: used to determine whether a fuel is carbon free
- (b) CO₂ emissions and other GHG emissions
- (c) Primary energy source and potential to become carbon neutral

• Hydrotreated vegetable oil

- (1a) HVO combustion does not lead to less NO_x emission than conventional fuels. To meet the Tier III regulation HVO must be used in combination with a NO_x reduction system.
- (1b) HVO is free of sulphur, and therefore it meets with the strictest SO_x regulations.
- (2a) HVOs are straight-chain paraffinic hydrocarbons with the chemical structure C_nH_{2n+2}.
- (2b) HVO causes CO₂ emissions because it is a hydrocarbon. HVO can offer a reduction of WTP CO₂ emissions up to 90% depending on the feedstock.
- (2c) HVO can be made from oil crops or used oil and is carbon neutral [47, 60].

• Liquefied natural gas

- (1a) LNG combustion can yield a NO_x reduction of up to 85%. LNG does not comply with Tier III with a diesel cycle engine but might comply in an Otto cycle engine.
- (1b) LNG can offer a reduction of SO_x up to 100% and therefore meets the strictest SO_x emission legislation.
- (2a) LNG on average contains 80 to 90% methane (CH₄), 6 to 9% ethane (C₂H₆), and 2 to 5% propane (C₃H₈). It also contains non-combustible substances which present in minor quantities in natural gases, such as nitrogen (0.5 to 2.0%) and carbon dioxide (0.1 to 1.0%).
- (2b) LNG can offer a reduction of CO₂ up to 30%. Potential unburned methane, which is called methane slip, must be considered, but in the future this will be eliminated by better engine technology.
- (2c) LNG has the possibility to become carbon neutral with liquefied biogas (LBG; called bio-LNG), and synthetic LNG (from power-to-gas process) [9, 10, 42, 49, 60, 89, 112].

• Liquefied petroleum gas

- (1a) LPG has lower NO_x emissions than conventional fuels. To meet the Tier III regulation, LPG must be used in combination with NO_x reduction technology.
- (1b) LPG contains no SO_x, and the combustion of LPG results in lower PM emissions; therefore, it meets the strictest SO_x legislation.
- (2a) LPG is composed of propane (C₃H₈) and butane (C₄H₁₀). Small concentrations of other hydrocarbons may also be present.
- (2b) LPG combustion results in lower CO₂ emissions. Potential LPG slip must be considered because propane (C₃H₈) and butane (C₄H₁₀), have three to four times higher GWP than CO₂ emissions.
- (2c) LPG can be produced as a by-product of oil or gas production. GHG benefits for LPG will increase proportionally with the fraction of corresponding bio or synthetic energy carrier used as a drop-in fuel. It is possible to produce LPG from renewable sources, for example, as a by product of renewable diesel production [20, 49, 96].

• Ethanol

- (1a) Ethanol has the potential to reduce NO_x emissions, but to meet Tier III, it must be used in combination with NO_x reduction technology.

- (1b) Ethanol combustion results in lower emissions and meets the SECA regulation and therefore also the global sulphur limit.
- (2a) Ethanol's chemical structure is C_2H_5OH .
- (2b) Ethanol combustion results in lower CO_2 emissions.
- (2c) Ethanol can be sustainably produced from waste and lignocellulosic feedstocks, which is then called bio-ethanol. A downside is that first-generation ethanol competes with the food supply. Second-generation biofuels are produced from biomass in a more sustainable fashion, which is truly carbon neutral or even carbon negative in terms of its impact on CO_2 concentrations [113].

- **Methanol**

- (1a) Methanol has the potential to reduce NO_x emissions by 80%. Methanol may comply with Tier III regulations but should probably still be used with a NO_x reduction system to meet the Tier III emission regulation.
- (1b) Methanol has the potential to reduce SO_x emissions by 99% and PM emissions by 95%. Methanol complies with the global SO_x limit of 0.5% and the SECA limit of 0.1%.
- (2a) Methanol's chemical structure is CH_3OH .
- (2b) Methanol combustion results in fewer CO_2 emissions compared to conventional fuels.
- (2c) Methanol can be produced from various sources such as natural gas, coal, biomass, agricultural waste, CO_2 and hydrogen. Currently, the main source of methanol is natural gas. GHG benefits for methanol will increase proportionally with the fraction of corresponding bio or synthetic energy carrier used as a drop-in fuel. Bio-methanol has the possibility to become carbon neutral. It requires, however, that all input energy streams are carbon neutral and that harvested biomass is replaced and cultivated in a way that does not release carbon from the soil [50, 91, 96].

- **Dimethyl ether**

- (1a) DME combustion still causes NO_x emissions, which must be reduced using a NO_x reduction system to meet the Tier III regulation.
- (1b) DME is sulphur free and therefore meets the global sulphur limit and the SECA regulation. Burning DME also leads to very low emissions of PM.
- (2a) DME's chemical structure is CH_3OCH_3 .
- (2b) DME is a hydrocarbon, and therefore combustion of DME still causes CO_2 emissions.
- (2c) DME can be produced by dehydration of methanol or from syngas, the fuel is carbon neutral. When capturing and storing CO_2 from the syngas production, it can have a negative greenhouse effect [7, 64, 70, 116].

- **Hydrogen**

- (1a) Hydrogen emits only negligible amounts of NO_x , if it is used in an internal combustion engine (ICE); to meet Tier III, it needs a NO_x reduction system.
- (1b) Hydrogen emits zero sulphur oxides (SO_x s) and therefore meets the global sulphur limit and SECA limit.
- (2a) Hydrogen consists of two hydrogen (H) atoms.
- (2b) Hydrogen contains no carbon; therefore, it has no CO_2 emissions and is thus carbon free.
- (2c) Hydrogen can be produced employing various energy sources, such as by electrolysis of renewables or by reforming natural gas. Today, nearly all hydrogen is produced from natural gas. If hydrogen is produced from renewable energy sources, it is truly carbon free [6, 49, 76].

- **Ammonia**

- (1a) Ammonia emits close to zero NO_x , but to meet the Tier III regulation, it must be used in combination with a NO_x reduction system.
- (1b) Ammonia emits zero SO_x .

- (2a) Ammonia is made out of one nitrogen (N) and three hydrogen (H) atoms.
- (2b) Ammonia contains no carbon; therefore, it has no CO₂ emissions and is thus carbon free.
- (2c) Ammonia's WTT GHGs remain high with the current production from fossil energy sources without CCS. To achieve 100% renewable ammonia, synthesis gases are generated using electricity alone, and therefore hydrogen is produced via water electrolysis [6, 49, 63].

As seen in Table 2.7, no fuel complies with the NO_x Tier III regulation. The solution is a NO_x reduction system to reduce NO_x emissions in a diesel engine to meet the Tier III regulations. All fuels except from LSFO meet the stringent SO_x limits. The table also shows how the fuels relate to each other in terms of emissions. This has been done in a qualitative way, because there is too much variation and conflicting information in the literature, depending on energy source, country and emissions which are included and excluded.

The colour scale in Table 2.6 is used to compare these emissions.

Table 2.6: Colour scale

Sign	Meaning
	Zero
	Low
	High
	Very High

Furthermore, the table also shows the relative CO₂ emissions based on the carbon factor formulated by the IMO. Lastly, the table depicts whether a fuel is fossil, can become carbon neutral, or is carbon free. Although no fuels meet the Tier III regulations for a diesel engine, all fuels, comply with the strictest SO_x regulations. The focus is on the IMO GHG strategy.

Table 2.7: Fuels, their emissions and compliance with current maritime legislation plus the possibility to become carbon neutral or carbon free.

Fuel		Tank-to-propeller (TTP)				Well-to-propeller (WTP)		
Name	Chemical Structure	Nitrogen oxide (NO _x)		Sulphur oxide (SO _x)		Carbon dioxide (CO ₂) Relative Emissions	Carbon neutral/ carbon free	Relative
		Relative* Emissions	Legislation Tier III	Relative Emissions	Legislation SECA 0.1%			
Low-sulphur fuel oil (LSFO)	C _x H _y O _z	Red	Does not comply	Red	Does not comply	Red	Fossil	Red
Marine gasoil (MGO)	C _x H _y O _z	Red	Does not comply	Orange	Comply	Red	Fossil	Red
Hydrotreated vegetable oil (HVO)	C _n H _{2n+2}	Red	Does not comply	Green	Comply	Red	Neutral	Green
Liquefied natural gas (LNG)	CH ₄	Green	Does not comply	Green	Comply	Orange	Neutral	Green
Liquefied petroleum gas (LPG)	C ₃ H ₈ and C ₄ H ₁₀	Green	Does not comply	Green	Comply	Red	Neutral	Green
Ethanol (EtOH)	C ₂ H ₅ OH	Orange	Does not comply	Green	Comply	Green	Neutral	Green
Methanol (MeOH)	CH ₃ OH	Orange	Does not comply	Green	Comply	Green	Neutral	Green
Dimethyl ether (DME)	CH ₃ OCH ₃	Green	Does not comply	Green	Comply	Orange	Neutral	Green
Hydrogen (H ₂)	H ₂	Green	Does not comply	Green	Comply	Green	Free	Green
Ammonia (NH ₃)	NH ₃	Green	Does not comply	Green	Comply	Green	Free	Green

*NO_x emissions are related to fuel and engine technology. The scope of this table is a diesel cycle; therefore, the NO_x emissions in this table are related to a diesel cycle. If, for example, an ICE with Otto cycle is used for the combustion of LNG, hydrogen, LPG or ammonia, the fuels may comply with Tier III regulations. **Possible if produced from bio resources. Perhaps confusing given the fuel names because often in the literature, bio-LPG or bio-LNG is used, whilst petroleum gas and natural gas are fossil.

2.4. Scenarios

As started at the beginning of this chapter, in studies with significant uncertainty, scenarios are used. In this research, the two scenarios described at the end of section 2.2 are used to ultimately evaluate the ship design.

1. What are realistic possible fuel transitions towards 2050 starting with conventional fuels?

Conventional fuels are not sustainable in the long term. Furthermore, in addition to the fossil fuels, HVO, LNG, LPG, methanol and DME can become carbon-neutral fuels, which, very simply put means that the emissions during the combustion of the fuel are collected again as the fuel grows. Hydrogen and ammonia are the only carbon-free fuels.

Scenario 1: Carbon neutral

The carbon-neutral scenario assumes that LNG, LPG, methanol, ethanol, and DME are all produced from biomass. Thus, this scenario contains the following fuels:

- Hydrotreated vegetable oil (HVO)
- Liquefied natural gas (LNG)
- Liquefied petroleum gas (LPG)
- Methanol (MeOH)
- Ethanol (EtOH)
- Dimethyl ether (DME)

Scenario 2: Carbon free

The carbon-free scenario means that the fuel must not contain any carbon. Therefore, ships are only allowed to sail with the following fuels:

- Ammonia (NH₃)
- Hydrogen (H₂)

3

Fuel and Design Aspect Analysis

The purpose of this chapter is to describe and evaluate the key properties of the alternative fuels that will have an impact on the ship's design. Based on the differences between the fuel's properties, this chapter identifies the fuel switches that are the most realistic and therefore that have the most potential.

In section 3.1, the most important fuel properties are described. Next, in section 3.2, the properties per fuel are discussed. Section 3.3 then discusses the connection between these properties and a ship's systems and design. In section 3.5, the fuels and their systems are compared so that the switch from one fuel to another can be qualitatively analysed. In section 3.5.4, the most realistic fuel switch scenario is discussed a selection is made for the most realistic scenarios for a fuel switch from LSFO and MGO.

3.1. Physical Fuel Properties

The applicability of a fuel on a ship is determined by the properties of the fuel. Fuel properties depend on the chemical composition of the fuel. Alternative fuels may be particularly pure, such as hydrogen and ammonia, whereas others can be of a variable composition, such as LSFO, MGO, HVO, LNG, LPG, ethanol, methanol and DME. Clearly, any alternative fuel supply must be reasonably consistent, so that the combustion equipment can be designed to suit its particular combustion characteristics [52].

Many fuel aspects have been discussed in the literature when considering alternative fuels [49, 52, 60, 91, 108]. In order for a fuel to ignite, it must be mixed with an oxidant to make flammable atmosphere, and there must be a source of ignition present [52, 108]. These properties are important for the combustion in the engine. However, properties that are useful for combustion can be inconvenient for storage and supply.

Many aspects relate to the storage and supply of alternative fuels on ships. In section 3.1.1, the general physical properties relevant for the storage design are described. In section 3.1.2, the key inherent properties of the fuels which influence safety are analysed.

3.1.1. General Fuel Properties

The calorific value and boiling point are identified in the literature as important for the technical application of fuel storage [49, 52, 60]. The calorific value and boiling point have a direct impact on the technical design of the fuel supply, storage and other systems. The flash point, auto-ignition temperature, flammability limits, vapour density and toxicity, have an indirect impact on the design of the ship [83].

Calorific Value

The calorific value represents the energy contained in a fuel or other substance. Synonyms for calorific value are energy value, heating value, or energy density [9, 10]. The calorific value is determined by measuring the heat produced by the complete combustion of a specified quantity. A distinction is often made between two heating values. The lower heating value (LHV) (or net calorific value (NCV) or lower calorific value (LCV)) and the higher heating value (HHV) (or gross calorific value (GCV) or upper heating value, or higher calorific value (HCV)) [10, 12, 52]. The difference between the LHV and HHV of a fuel is roughly equivalent to the amount of latent heat of vaporization. Practically, this heat can be recovered in a secondary condenser per unit of fuel burned. When internal combustion engines (ICEs) or boilers with no secondary condenser are designed, the appropriate fuel value to use in the design process is the LHV, which assumes that the water

vapor generated when the fuel is burned goes out in the exhaust stream. When advanced combustion units having secondary or tertiary condensers are designed, the appropriate fuel value to use in the design process is the HHV [9, 52]. This value is often shown in two forms - namely, the calorific value in terms of MJ kg^{-1} (gravimetric energy density) and MJ m^{-3} (volumetric energy density) [52]. The volumetric energy density is particularly relevant to the storage and distribution of gaseous fuels, where a high pressure may be required for a reasonable storage volume [52].

In this research, the LHV is used to compare all the fuels assuming an Internal combustion engine is used without a secondary condenser. Figure 3.4 shows the fuels with their gravimetric and volumetric energy density.

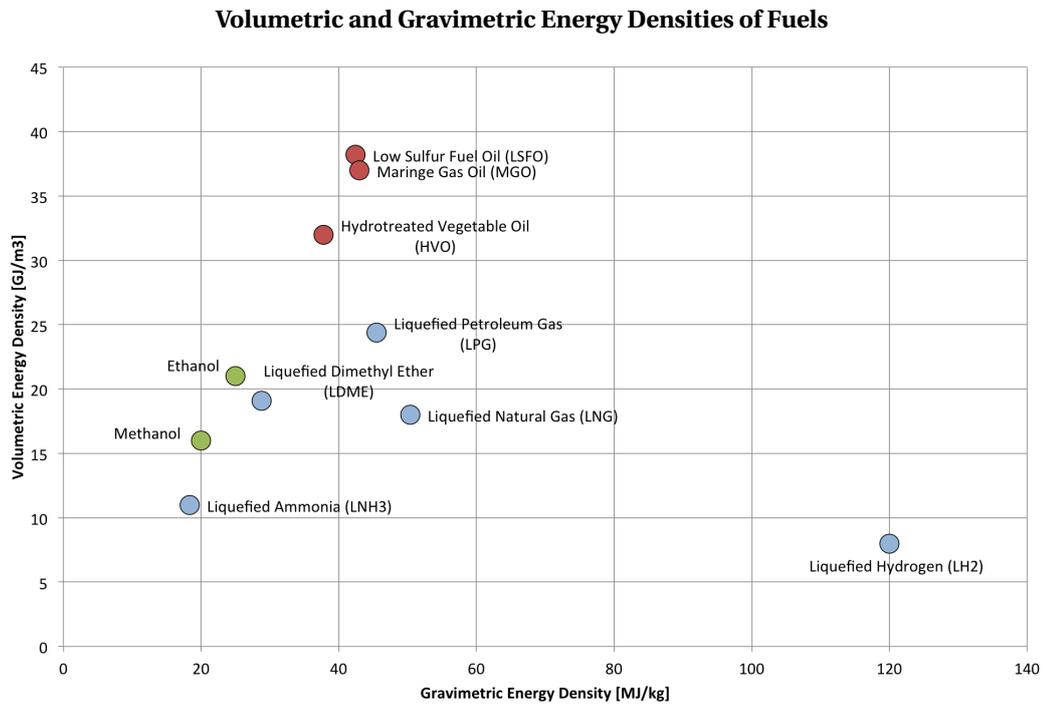


Figure 3.1: Light blue/grey: gases, green: alcohols, red: liquid fuels. Figure inspired by [75, 80, 92, 113].

The ideal storage medium should allow high volumetric and gravimetric energy densities.

Boiling Point

The boiling point is directly related to the volatility of a fuel. The normal boiling point (also called the atmospheric boiling point or the atmospheric pressure boiling point) of a liquid is a special case in which the vapor pressure of the liquid equals the defined atmospheric pressure at sea level, one atmosphere [26, 53]. At that temperature, the vapor pressure of the liquid becomes sufficient to overcome atmospheric pressure and allows bubbles of vapor to form inside the bulk of the liquid [66]. The IMO defines gas as being "liquids having a vapour pressure exceeding 2.8 bar at a temperature of 37.8 °C".

The boiling point of a fuel is often given at ambient pressure. A low boiling (below 0 °C) means that at ambient temperature and pressure the fuel is in gaseous state. The lower the boiling point, the more pressure must be applied to make it a liquid at ambient temperature.

As an example the relation of the energy density is shown for hydrogen, methane and ammonia in Figure 3.2. This energy density varies with temperature and pressure, determining whether it is a gas, liquid or solid. The phase diagrams of the other fuels are not shown because they also depend on the composition of the fuel, and these are shown for example purposes.

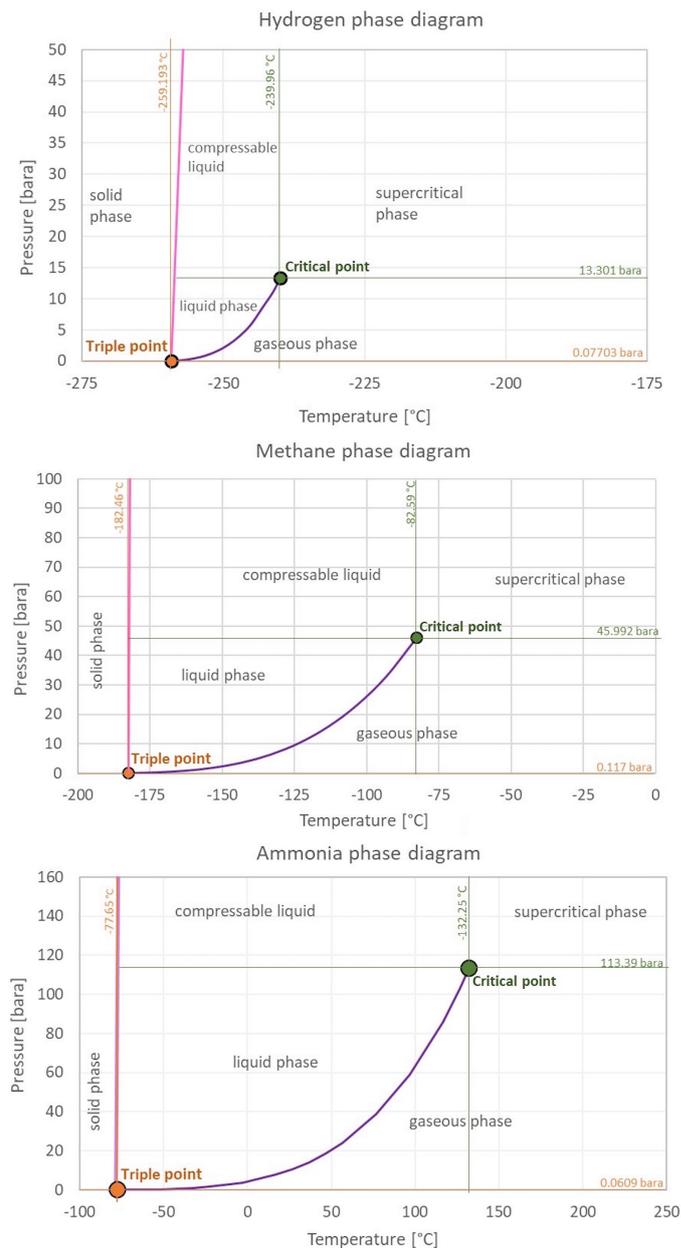


Figure 3.2: Critical temperature: the temperature above which a substance cannot exist as a liquid, no matter how much pressure is applied; critical pressure: the pressure required to liquefy a substance vapor at its critical temperature; critical point: the end point of the pressure-temperature curve that designates conditions under which a liquid and its vapor can coexist; triple point: the temperature and pressure at which the three phases (gas, liquid and solid) of a substance coexist in thermodynamic equilibrium. [13]

In order to be able to transport large amounts of fuel in an efficient manner, it is preferable to transport this fuel as liquid. The boiling point is the temperature of a fuel at which it changes from a liquid state to a gas state. This point is between the critical point and the triple point. This can be seen on the purple line in Figure 3.2 [52].

3.1.2. Safety-Relevant Fuel Properties

For safe application, the flashpoint, auto-ignition temperature, flammability limits, vapour density and toxicity are identified as the most important fuel properties [49, 52, 60].

Flammability

One of the primary safety hazards associated with alternative fuels is that these fuels are flammable. The flashpoint, auto-ignition temperature and the flammability limits play a major role in flammability properties

of alternative fuels [49].

- **Flashpoint**

- The lower the flashpoint, the easier it is to ignite the fuel. The flash point of a liquid is the temperature at which the vapour pressure is sufficient to form a flammable concentration with air above the liquid. If a liquid fuel is stored above its flash point, then a flammable vapour is always liable to form above the liquid. Hence spillages of fuels above their flash point will always form flammable vapours which are likely to explode if ignited. Liquids below their flash point do not form flammable concentrations of vapours, but mists of such fuels may be flammable [52].

Both methanol and ethanol have a low flashpoint. For the other liquid fuels and gases in this research, flashpoint does not play a role [88].

- **Auto-Ignition Temperature**

- The auto-ignition temperature is the minimum temperature required to ignite a gas or vapor in air without a spark or flame being present [49]. Leakage of gases and vapours can accumulate in spaces and a hot surface can act as a source of ignition. A second effect is turbulence, with increases in turbulence increasing the auto-ignition temperature.

The auto-ignition temperatures for all fuels discussed in this research are high [52].

- **Flammability Limits**

- The flammability limits show the range of vapour concentrations of a certain chemical, expressed in volume percent, over which a flammable mixture of gas or vapour in air can be ignited at 25 °C and at atmospheric pressure. A wide range indicates that a fuel is flammable under several conditions, and in the absence of additional safety measures, this range indicate higher risk [49, 52]. Before a fire or explosion can occur, the following condition must be met: a fuel and oxygen (air) must exist in certain proportions, along with an ignition source, such as a spark or flame. The ratio of fuel and oxygen that is required varies with each combustible gas or vapor [22]. The minimum concentration of a particular combustible gas or vapor necessary to support its combustion in air is defined as the lower explosive limit (LEL) for that gas. Below this level, the mixture is too "lean" to burn. The maximum concentration of a gas or vapor that will burn in air is defined as the upper explosive limit (UEL). Above this level, the mixture is too "rich" to burn [22]. The flammability limits are shown in Figure 3.3. As can be seen hydrogen has a wide range, followed by methanol, DME and ethanol [49].

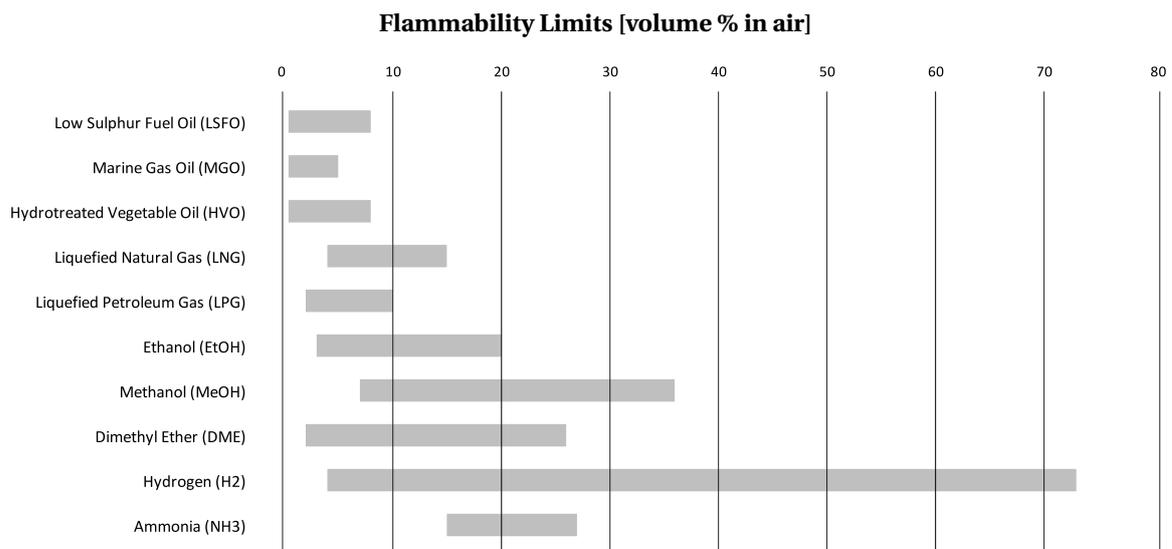


Figure 3.3: Flammability limits of different fuels. This figure is inspired by Anders [49] and the values are derived from [47, 49, 52, 91].

Vapour Density

Vapour density is a measure of how buoyant the vapour is compared with air. Light gases and vapour tend to rise and disperse readily in the open air, whereas heavy vapour tends to creep along the ground and spread downwind [52].

Toxicity

Toxicity is the degree to which a chemical substance or a particular mixture of substances can damage an organism. Some fuels are toxic and thus require extra safety measure and different materials.

In order to make it easier to compare fuels with their potential hazards, below the fuels are compared with the globally harmonized system of classification and labelling chemicals (GHS).

3.1.3. Globally Harmonized System of Classification and Labelling Chemicals

This section uses the GHS to navigate through the different properties that characterize a fuel.

The GHS is used to navigate through the different properties that characterize a fuel. The GHS is appropriate because of its broad applicability and detailed information and because it is used worldwide. The hazard statements are shown in Table 3.1, in which a distinction is made between physical, health and environmental hazards. Precautionary statements also can be found in this table.

Table 3.1: Hazard statements for the selection of fuels covered in this research from the globally harmonized system of classification and labelling chemicals (GHS).

Hazard (H) / Precautionary (P)			Fuel									
Number	Statement		LSFO [40]	MGO [33]	HVO [74]	LNG [32]	LPG [19]	Ethanol [101]	Methanol [101]	DME [38]	Hydrogen [105]	Ammonia [31]
Physical Hazards												
H 220	Extremely flammable gas.					X	X			X	X	
H 221	Flammable gas.											X
H 225	Highly flammable liquid and vapour.							X	X			
H 226	Flammable liquid and vapour.			X								
H 227	Combustible liquid.		X		X							
H 280	Contains gas under pressure; may explode if heated.						X			X	X	X
H 281	Contains refrigerated gas; may cause cryogenic burn or injury.					X						
Health Hazards												
H 301	Toxic if swallowed.				X				X			
H 304	May be fatal if swallowed and enters airways.			X	X							
H 311	Toxic in contact with skin.								X			
H 314	Causes severe skin burns and eye damage.											X
H 315	Causes skin irritation.			X	X							
H 318	Serious eye damage/eye irritation.											X
H 319	Causes serious eye irritation.							X				
H 331	Toxic if inhaled.					X			X			X
H 332	Harmful if inhaled.		X	X								
H 336	May cause drowsiness or dizziness.			X						X		
H 350	May cause cancer.		X									
H 351	Suspected of causing cancer.			X	X							
H 361	Suspected of damaging fertility of the unborn child.		X									
H 370	Causes damage to organs (liver, kidneys, central nervous system, optic nerve).								X			
H 373	May cause damage to organs through prolonged or repeated exposure.		X	X	X							
Environmental Hazards												
H 400	Hazardous to the aquatic environment - acute hazard.			X	X							X
H 410	Very toxic to aquatic life with long lasting effects.		X									X
H 411	Toxic to aquatic life with long lasting effects.			X	X							X
Prevention												
P 201	Obtain special instructions before use.		X									
P 202	Do not handle until all safety precautions have been read and understood.		X			X						
P 210	Keep away from heat/sparks/open flames/hot-surfaces - no smoking.		X			X	X	X	X	X	X	X
P 233	Keep container tightly closed.					X		X				X
P 235	Keep cool.			X	X							
P 240	Ground/bond container and receiving equipment.											
P 241	Use explosion-proof electrical/ventilating/lighting equipment.					X						
P 242	Use only non-sparking tool.					X						
P 243	Take precautionary measures against static discharge.					X	X					
P 260	Do not breathe gas, vapours.		X	X	X							X
P 261	Avoid breathing gas.		X							X		X
P 262	Do not get in eyes, on skin, or on clothing.									X		X
P 264	Wash exposed skin thoroughly after handling.									X		X
P 270	Do not eat, drink or smoke when using this product.								X			
P 271	Use only outdoors or in a well-ventilated area.		X							X	X	X
P 273	Avoid release to the environment.		X	X	X							X
P 280	Wear protective gloves, protective clothing, eye protection, face protection.		X	X	X					X		X
P 282	Wear cold insulation gloves, a cold insulation apron, eye protection, and face shield.				X						X	
Response												
P 303	If on skin (or hair): take off immediately all contaminated clothing. Rinse skin with water (or shower).								X			
P 304	IF INHALED: Remove person to fresh air and keep comfortable for breathing.		X						X			X
P 305	IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses if present and easy to do. Continue rinsing.							X				X
P 308	IF exposed or concerned: Get medical advice/attention.		X						X			
P 310	IF INHALED: Remove person to fresh air and keep comfortable for breathing. Immediately call a POISON CENTER/doctor.			X	X							X
P 312	Call a POISON CENTER or doctor/physician if you feel unwell.		X									
P 313	IF exposed or concerned: Get medical advice/attention.		X									
P 314	Get medical advice/attention if you feel unwell.		X									
P 315	If exposed to liquid, immediately seek medical attention.					X						
P 331	Do NOT induce vomiting.			X	X							
P 336	Limbs affected by frostbite may be thawed with lukewarm water. Do not rub affected area. Seek immediate medical attention.					X						
P 338	IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.							X				X
P 340	IF INHALED: Remove person to fresh air and keep comfortable for breathing.		X						X			X
P 351	IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.							X				X
P 370	In case of fire: Use appropriate media to extinguish.		X									
P 377	Leaking gas fire: Do not extinguish unless leak can be stopped safely.					X				X	X	X
P 378	In case of fire: Use appropriate media to extinguish.		X									
P 381	Eliminate all ignition sources if safe to do so.					X	X			X	X	
P 391	Collect spillage.		X									
Storage												
P 403	Store in well-ventilated place; keep cool.		X	X	X	X	X	X	X	X	X	X
P 405	Store locked up.		X					X	X			X
P 410	Protect from sunlight.						X			X	X	

Low-sulphur fuel oil (LSFO), marine gasoil (MGO), hydrotreated vegetable oil (HVO), liquefied natural gas (LNG), liquefied petroleum gas (LPG), ethanol (EtOH), methanol (MeOH), dimethyl ether (DME), hydrogen (H₂) and ammonia (NH₃). Inspired by [69]

3.2. Fuels

This section describes the considered fuels based on discussed fuel properties. The fuels are described in a uniform way and the following aspects are described in more detail:

1. General Fuel Properties

(a) Calorific Value

- i. Volumetric Energy Density
- ii. Gravimetric Energy Density

(b) Boiling Point

2. Relevant Safety Properties

(a) Flammability

- i. Flashpoint
- ii. Auto-Ignition Temperature
- iii. Flammability Limits

(b) Vapour Density

(c) Toxicity

• Hydrotreated vegetable oil

(1ai) HVO's volumetric energy density is 34.8 [GJ/m³], which is slightly lower than the volumetric density of conventional fuels.

(1aii) HVO's gravimetric energy density is 37.8 [GJ/m³], which is slightly lower than the gravimetric density of conventional fuels.

(1b) HVO's boiling point is around 313 [°C].

(2ai) HVO's flashpoint is higher than 61 [°C].

(2aii) HVO's auto-ignition temperature is 204 [°C].

(2aiii) HVO has a small flammability range. The LEL of HVO is 0.6 [% v/v], and the UEL is 7.5 [% v/v].

(2b) HVO vapour density is not relevant.

(2c) HVO is not toxic [49, 74].

• Liquefied natural gas

(1ai) LNG's volumetric density ranges between 26.1 and 55.9 MJ/m³, the majority averaging 37.3 MJ/m³. The range depends on calorific values of the separate substances of the composition. Natural gas on average contains 80-90% methane, 6-9% ethane, and 2-5% propane. It also contains non-combustible substances which are present in minor quantities in natural gases, such as are nitrogen (0.5 - 2.0%) and carbon dioxide (0.1 - 1.0%).

(1aii) LNG's gravimetric density is 48.6 [MJ/kg].

(1b) LNG's boilingpoint at ambient pressure is -162 [°C].

(2ai) LNG's flash point is -188 [°C].

(2aii) LNG's auto-ignition temperature is 537 [°C].

(2aiii) LNG has a small flammability range. The LEL of LNG is 4 [% v/v], and the UEL is 15 [% v/v].

(2b) LNG's is lighter than air and has a density of about 0.68 [kg/m³] at atmospheric pressure and temperature.

(2c) LNG is not toxic [9, 10, 32, 49].

• Liquefied petroleum gas

(1ai) LPG's volumetric energy density is on average 24.4 [GJ/m³].

(1aii) LPG's gravimetric energy density is on average 45.5 [MJ/kg].

(1b) LPG's boiling point is -43 [°C].

(2ai) LPG's flashpoint is -104 [°C].

(2aii) LPG's auto-ignition temperature ranges from 410 to 580 [°C].

(2aiii) LPG has a small flammability range. The LEL of LPG is 1.8 [% v/v] and the UEL is 10.1 [% v/v].

(2b) LPG has a density of 1.898 [kg/m³] at 15 [°C]. Thus, it is heavier than air.

(2c) LPG is not toxic [19, 49].

• Ethanol

(1ai) Ethanol's volumetric energy density is approximately on average 22.7 [GJ/m³].

(1aii) Ethanol's gravimetric energy density is approximately on average 28.8 [MJ/kg].

(1b) Ethanol's boiling point is 78 [°C].

(2ai) Ethanol's flashpoint is 13 [°C].

(2aii) Ethanol's auto-ignition temperature is about 363 [°C].

(2aiii) Ethanol has a LEL of 3.3 [% v/v] and the UEL is 19 [% v/v].

(2b) Ethanol's vapour density is not relevant.

(2c) Ethanol is not toxic [49, 101].

• Methanol

(1ai) Methanol volumetric energy density is approximately on average 15.8 [GJ/m³].

(1aii) Methanol gravimetric energy density is approximately on average 19.9 [MJ/kg].

(1b) Methanol's boiling point is 64 [°C].

(2ai) Methanol's flashpoint is about 11 to 12 [°C].

(2aii) Methanol's auto-ignition temperature is about 470 [°C].

(2aiii) Methanol has a relative large flammable range, with an LEL of 6.7 [% v/v] and a UEL of 36 [% v/v].

(2b) Methanol's vapour density is not relevant.

(2c) Methanol has low acute toxicity, which is dangerous for humans [49, 101].

• Dimethyl ether

(1ai) DME's volumetric energy density is approximately on average 19.2 [GJ/m³].

(1aii) DME's gravimetric energy density is approximately 28.9 [MJ/kg].

(1b) DME's boiling point is -23.6 [°C].

(2ai) DME's flashpoint is about -42 [°C].

(2aii) DME's auto-ignition temperature is about 350 [°C].

(2aiii) DME also has a relative large flammable range. The LEL is 2 [% v/v] and the UEL is 27 [°C].

(2b) DME's vapour density at 15 [°C] is 1.993 [kg/m³]. Thus, it is heavier than air.

(2c) DME is not toxic [38, 49].

• Hydrogen

(1ai) Hydrogen's volumetric energy density is about 0.012 [GJ/m³] at 25 [°C] at atmospheric pressure.

(1aii) Hydrogen's gravimetric energy density is 120 [MJ/kg].

(1b) Hydrogen its boiling point is -253 °C.

(2ai) Hydrogen's flashpoint is 132 [°C].

(2aii) Hydrogen's auto-ignition temperature is 577 [°C].

(2aiii) Hydrogen has a large flammability range. The LEL is 4 [% v/v], and the UEL is 74.2 [% v/v].

(2b) Hydrogen's vapour density is 0.1 [kg/m³]. Thus, it is lighter than air.

(2c) Hydrogen is not toxic [49, 105].

- **Ammonia**

(1ai) Ammonia's volumetric energy density is about 6.8 [GJ/m³] at ambient pressure and -3 [°C].

(1aii) Ammonia's gravimetric energy density is about 18.6 [MJ/kg].

(1b) Ammonia's boiling point is -33.34 [°C].

(2ai) Ammonia's flashpoint is 132 [°C].

(2aii) Ammonia's auto-ignition temperature is 630 [°C].

(2aiii) Ammonia's LEL is 15 [% v/v] ,and itsUEL is 28 [% v/v].

(2b) Ammonia's vapour density is 0.73 [kg/m³] at 15 [°C] and 1 [bar]. However, in air it reacts immediately with the humidity and may remain close to the ground.

(2c) Ammonia is very toxic [31, 49, 60].

A summary of the fuels is shown in Table 3.3 with a qualitatively representation to make these fuels, the colours are linked in Table ???. A detailed table is shown in Appendix A

The colour scale shown in Table 3.2 is used to compare the fuels.

Table 3.2: Colour scale

Sign	Meaning
	n/a
	Excellent
	Good
	Fair
	Poor
	Bad

3.3. Onboard Fuel Systems

Based on the fuel properties described above, this section evaluates the onboard safety and the storage type. One of the new codes under the SOLAS convention is the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF code) code. This code provides mandatory rules for the ship's design and is described in section 3.3.1.

3.3.1. International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels

The IGF code contains operational and technical measures. The basic philosophy of the IGF code code is to provide mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuel to minimize the risk to the ship, its crew and the environment, having regard to the nature of the fuels involved [2].

The International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF code) was initially designed for LNG but also contains requirements for methanol and ethanol which have been finalized by the IMO and are awaiting final approval [2, 113]. The International Code for Ships Carrying Liquefied Gases in Bulk (IGC) and the International Code for the Construction of Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC) formed the basis for the IGF code [1]. These codes follow from the demand for the transport of these substances and from the nature of these substances.

However, this code does not yet apply to all fuels described. The IGF code addresses three main groups of fuels namely: gases lighter than air such as LNG, hydrogen, DME and ammonia; gases heavier than air such as LPG; and low-flashpoint liquid fuels such as methanol and ethanol) [1]. Which means that LSFO, MGO and HVO do not have to comply with the IGF code.

3.3.2. Storage Design

Fuel storage can be divided into physical-based and material-based types. Physical-based storage comprises compressed storage, liquid storage and cryogenic storage [2, 92]. Material-based storage is primarily used for hydrogen, which suffers more from its properties and is more difficult to store than other fuel types. Material-based storage types for hydrogen include liquids, solids and surfaces [92, 104]. Physical storage methods are the most mature applicable for all fuels; therefore, material-based storage is not further covered in this research which was also stated in the scope of this research in Section 1.4.

As discussed in section 3.1 a fuel's numerous physical properties determine properties determine the storage preference of a certain fuel. The boiling point and the LHV are of importance. These fuel properties resulting in a system on board of the ship. But a system is required to store the fuel. A system is required to store the fuel which result in a lower 'effective density'. [23, 49, 60, 75]. van Biert et al. [113] takes into account systems that scale linearly with volume such as the tank, pumps, insulation, safety systems, and loss of space due to a cylindrical tank.

To substantiate that hydrogen and LNG should be stored as liquid. A simple calculation is executed with an example ship: the Eemsborg is a 10,200-ton general cargo ship with a HFO capacity of 881 m³ and a MGO capacity of 72.3 m³ [8]. Based on the LHV for LSFO and MGO, the Eemsborg has a capacity of 36,300 [GJ]. The calculation is shown in Equation 3.1.

$$881[m^3] * 38.2[GJ/m^3] + 72.3[m^3] * 36.6[GJ/m^3] = 36300[GJ] \quad (3.1)$$

Thus hydrogen stored at 350 [bar] pressure will result in a required space of 25,384 [m³]. The calculation is shown in Equation 3.2. This is about 26 times the amount of space required for LSFO and MGO. The storage system has not even been included in this. This is not even possible compared to the hold capacity of 14,260 m³ [8].

$$36300[GJ]/1.43[GJ/m^3] = 25384[m^3] \quad (3.2)$$

A fuel containment system is physically limited to a certain pressure. Therefore, large quantities of fuel with an extremely low boiling point at ambient pressure are cryogenically stored. Gaseous fuels with a relatively high boiling point are preferably stored as liquids under pressure [23, 49, 60, 75]. Therefore, the final storage techniques are as follows:

- **Liquid:** Regular storage is for conventional fuels and bioliquids.
LSFO, MGO, HVO and methanol are stored conventionally as liquid.

- **Pressurized:** Pressurized tanks are used for liquids that need to be stabilized and stored under pressure. Compared to cryogenic storage, the system is relatively simple because there is no refrigeration system needed, resulting in higher reliability. The high pressure, though, results in a safety issue as well as a high storage volume and a large mass of storage tanks.

LPG, DME and ammonia are stored pressurized. Storage for LPG can be done in a semi-refrigerated tank made of cheaper steel than is possible for LNG, but in order for such an arrangement to be sufficiently reliable, special systems must be in place to ensure a low temperature in the tank [88]. The spatial distribution of LPG storage facilities favours LPG over LNG as a fuel. At room temperature and at atmospheric pressure, ammonia is a gas. Ammonia must be stored either below $-33\text{ }^{\circ}\text{C}$ or under pressure (10 - 17 [bar]). The preferred way of storing LPG for use as propulsion fuel is in a pressurized tank at ambient temperature [88].

- **Cryogenic:** Cryogenic storage reduces storage size. Cryogenic storage is a complex system because of the refrigerator, which requires extra electrical power which increases the size of the system [88].

Large quantities of LNG and hydrogen are stored in a cryogenic manner.

Not all system densities of the fuels described in this thesis could be found in literature [23, 49, 60, 75]. Therefore, such densities were derived from the densities that could be found in the literature. LSFO and HVO were derived from MGO because these are both comparable fuels. Ethanol was derived from methanol, both of which are alcohols. LPG was derived from ammonia because both fuels are stored under 10 [bar] pressure.

Volumetric and Gravimetric Energy Densities of Fuels + Systems

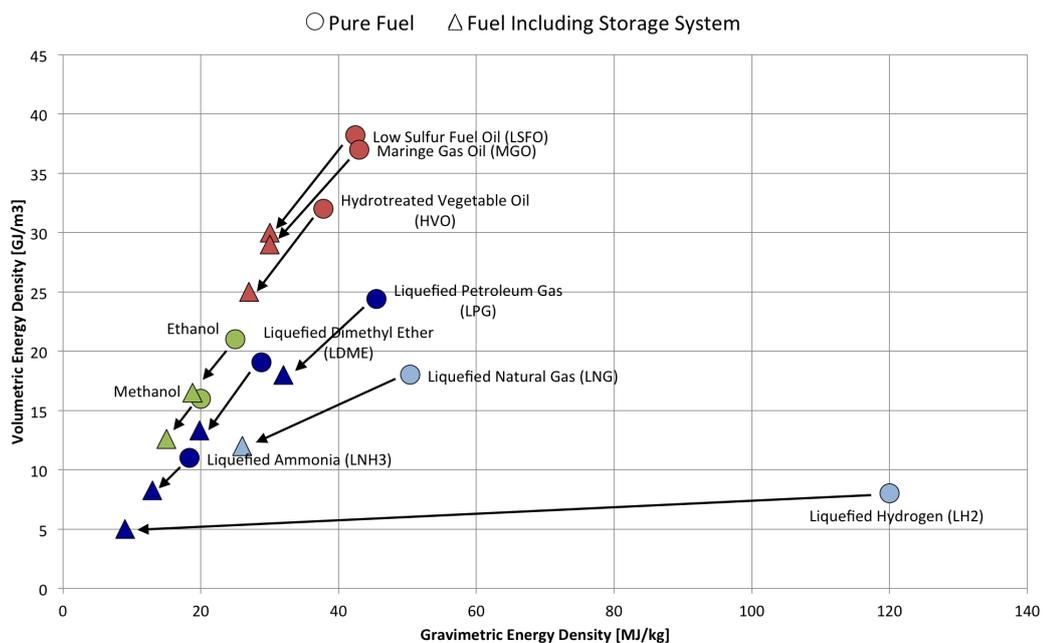


Figure 3.4: Navy blue: gases which will be stored pressurized; light blue/grey: gases which will be stored cryogenically; green: alcohols; red: liquid fuels. Inspired by [75, 80, 92, 113].

The 'effective density' remains arbitrary. The sources used have made simplified considerations. Among others, van Biert et al. [113] corrects roughly for the shape factor, insulation and pressure vessel. In practice, it is not this simple, and every case has to be evaluated separately. To give a simple example, the larger the fuel tank, the closer the system gets to the energy density of the pure fuel. Scale matters a lot.

Of course, the system of a cryogenic tank - for instance, for hydrogen - will always use more weight or space than a general comparable tank for MGO. Therefore, these tanks scale differently. For all the liquid fuels, van Biert et al. [113] used the same correction factor. This approach, though, could be questioned, since additional requirements, such as more space and weight. However, space should also be made available for the general facilities necessary for of, such as separators, fuel pumps, valves, regulators and air vents.

Moreover, fuel tanks are not filled to their full capacity. Because the densities from the figure are used for a first selection of the fuels, it is assumed that these simplified values can be used. Below, in the specific designs, the densities of the fuels and the systems are considered separately and in more detail.

Table 3.4: Fuels and their systems.

Fuel	Boiling point [°C]	Energy density [GJ]	Storage Technique		Energy density at preferred storage			Must comply with IGF		Group	
			Liquid/pressurized/ Cryogenic	Cryogenic	Volumetric [GJ/m ³] Pure fuel	Gravimetric [MJ/kg] Incl. system	Incl. system	No/Yes	No IGF code/lighter than air/ low flashpoint fuels/heavier than air		
Low-sulphur fuel oil (LSFO)	160 - 366	38.2	Liquid		38.2	42.44	30	No	No	No IGF	
Marine gasoil (MGO)	260 - 371	36.6	Liquid		36.6	43	29	No	No	No IGF	
Hydrotreated vegetable oil (HVO)	313	34.8	Liquid		34.8	37.8	25	No	No	No IGF	
Liquefied natural gas (LNG)	-162	0.035	Cryogenic (-162)		20.8	50.4	12	Yes	Yes	Lighter than air	
Liquefied petroleum gas (LPG)	-43	0.088	Pressurized (10 bar)		24.4	45.5	18	Yes	Yes	Heavier than air	
Ethanol (EtOH)	78	22.7	Liquid		22.7	25	16.5	Yes	Yes	Low flashpoint fuels	
Methanol (MeOH)	64	15.8	Liquid		15.8	20	12.6	Yes	Yes	Low flashpoint fuels	
Dimethyl ether (DME)	-23.6	12.5	Pressurized (5 bar)		19.2	28.8	13.32	Yes	Yes	Heavier than air	
Hydrogen (H ₂)	-252	0.012	Cryogenic (-252)		8	120	5	Yes	Yes	Lighter than air	
Ammonia (NH ₃)	-33.34	0.013	pressurized (10 bar)		11	18.36	8.28	Yes	Yes	Lighter than air*	

Table 3.5: * Lighter than air but will react with air and becomes heavier, therefore, a red sign is called for.

3.4. Key Design Aspects

From the previous sections, sub-question 2 can be answered.

2. What are the key aspects of a fuel that have a significant impact on the design of a general cargo vessel?

The most important aspects of a fuel are the ones that determine how the fuel must be stored. The volumetric and gravimetric energy density of the whole system are also important. Furthermore, the IGF code is an important aspect to take into account.

Figure D.9 shows a combination of the different categories of fuel types which are relevant for determining the appropriate storage method.

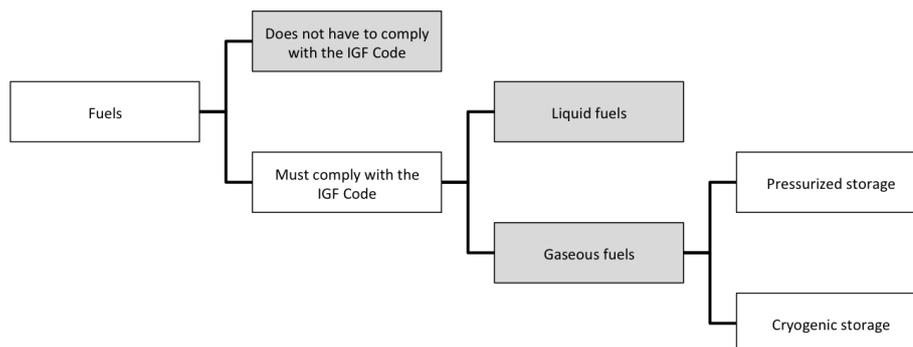


Figure 3.5: Overview of the fuel categorization

In this report the starting situation of LSFO and MGO is assumed, but In this chapter a more general approach is chosen, to evaluate possible fuel transitions, to have extra insight in situations that might be relevant for the future.

3.5. Fuel Transition

The purpose of this section is to describe the difficulty of switching to another fuel. This description is done using the aspects in the previous section. A qualitative transition matrix was made which represents the transition from one fuel to another. A colour scale is assigned to indicate whether changing is easy or not. To arrive at an end matrix, the matrix is divided into three different parts: the energy conversion, fuel containment system and other aspects.

3.5.1. Energy conversion

Alternative energy conversion systems for shipping include pure gas, dual-fuel engine, multi-fuel engines, marine fuel cells, battery-electric propulsion systems, and gas and steam turbines [70]. In this study only the ICE is considered as an energy converter. Other fuel converters are not covered in this research, as discussed in the scope of this research (section 1.4). As further explained below, ICEs can operate on a wide range of different marine fuels [115] and can be subdivided into the following three main types: diesel engine, dual fuel engine and the pure gas engine.

Diesel Engine

Also known as compressed ignition (CI) engine is the most common engine in shipping [70]. Diesel engines have a relatively high efficiency and high power compared to other energy systems [70]. A diesel engine can only be used for diesel fuels. A single four-stroke diesel engine is the 'standard' propulsion system for a general cargo ship [71].

Dual Fuel Engine

Dual fuel engines, also called multi-fuel engines, can use two or more different fuels that are separate from each other. The low-Pressure dual fuel engine (LPDF) is the standard dual fuel engine used in gas-fueled ships [109].

Gas Engine

A gas-only engine is only capable of operating on gas is not able to switch over to operation on any other type of fuel. Engines running only on gas use a spark plug to initiate the combustion process; therefore these gas only engines are also known as spark-ignition engines [120]. The lean burn spark ignition gas engine (LBSI) is the standard gas engine currently available for ships. A gas engine is an Otto cycle engine and is compliant with NO_x Tier III.

Certain fuels can be used with certain engines; liqued biofuels such as HVO can directly be used in existing installations without major technical modifications [70]. There are three main options for using LPG as ship fuel: in a two-stroke diesel-cycle engine; in a four-stroke, lean-burn Otto-cycle engine; or in a gas turbine [70]. There are two main options for using methanol as fuel in conventional ship engines: in a two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine [70]. Although not all fuels have yet been proven workable, they can be distributed per engine on the basis of their properties. This results in the compatibility table shown in Table 3.6.

Table 3.6: Fuel compatibility with engines.

	Diesel Engine (CI)	Dual Fuel Engine (DF)	Gas Engine (SI)
Low-sulphur fuel oil (LSFO)/marine gasoil (MGO)	X	X	
Hydrotreated vegetable oil (HVO)	X	X	
Liquefied petroleum gas (LPG)		X	X
Methanol (MeOH)		X	X
Ethanol (EtOH)		X	X
Dimethyl ether (DME)		X	X
Hydrogen (H ₂)		X	X
Ammonia (NH ₃)		X	X

According to Bakas [54], it is not suitable to convert from an existing diesel engine to a gas-only engine. For that reason it is assumed that it is also not possible to convert to a gas engine from a diesel engine. It is possible to change from a diesel to a dual fuel engine, although doing so requires an extensive retrofit [54]. Therefore, it is assumed that the other way around from a dual fuel engine is also possible, although this change may never be done. Changing from a diesel engine to a diesel engine or from a dual fuel engine is referred to as changing but will not be a change. The matrix that shows if it is relatively easy or difficult to change from one fuel to another, base on the engine. This is shown in Figure 3.6. In this figure only the relevant fuel changes are considered from a fossil fuel to a carbon-neutral fuel or a carbon free fuel and from a carbon neutral fuel to a carbon-free fuel.

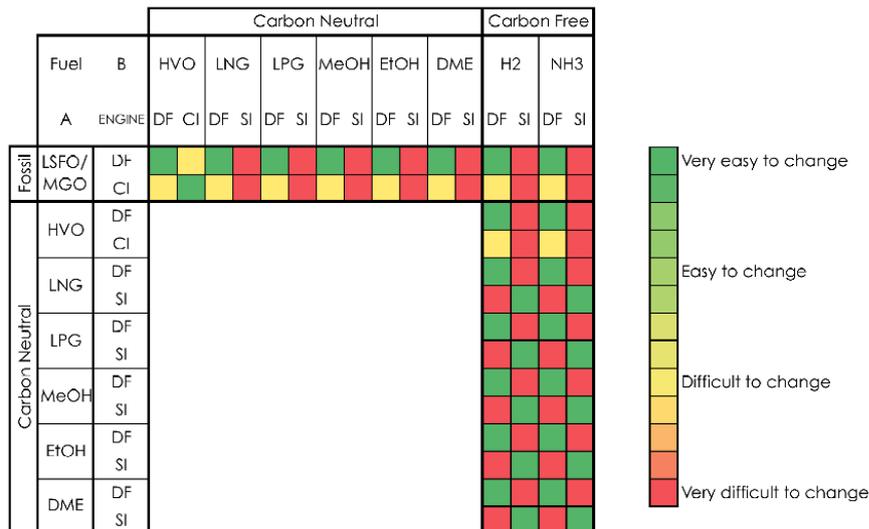


Figure 3.6: Transition matrix for the engine. Ammonia (NH₃), hydrogen (H₂), dimethyl ether (DME), ethanol (EtOH), methanol (MeOH), liquefied petroleum gas (LPG), liquefied natural gas (LNG), hydrotreated vegetable oil (HVO), low-sulphur fuel oil (LSFO), marine gasoil (MGO), Spark ignition (SI), dual fuel (DF), compressed ignition (CI)

3.5.2. Fuel Containment System

For fuel containment system, volumetric energy density, gravimetric density and method of storage are taken into account. The results are in the matrix shown in Figure 3.5.2.

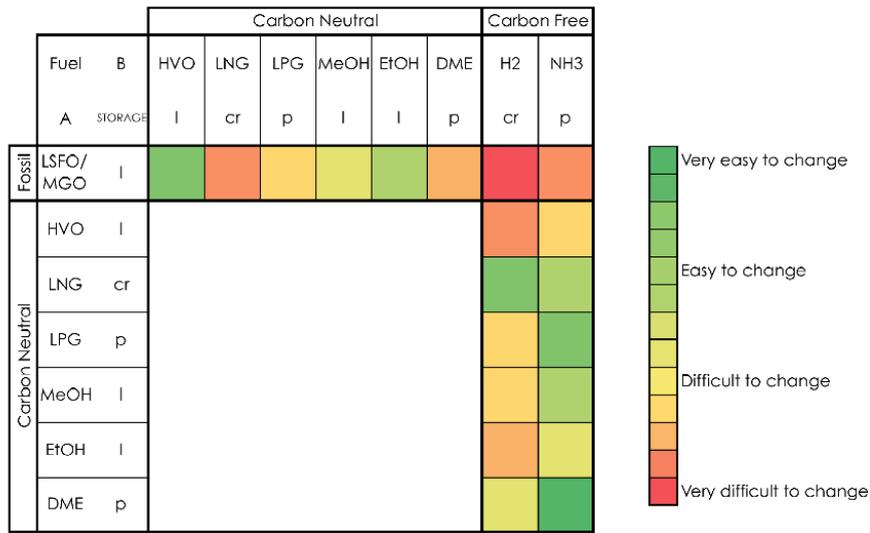


Figure 3.7: Transition matrix for fuel storage. Ammonia (NH₃), hydrogen (H₂), dimethyl ether (DME), ethanol (EtOH), methanol (MeOH), liquefied petroleum gas (LPG), liquefied natural gas (LNG), hydrotreated vegetable oil (HVO), low-sulphur fuel oil (LSFO), marine gasoil (MGO), spark ignition (SI), dual fuel (DF), compressed ignition (CI).

3.5.3. Other Aspects

The IGF code is a large contributor to the aspects that have an impact on the design of the ship next to the engine and storage. Therefore, this matrix considers the IGF code as well as which category of fuel (gas lighter than air, gas heavier than air, low flashpoint, no IGF code fuel) the fuel belongs. This approach in the transition matrix shown in Figure 3.8. The matrices used to maintain this matrix can be found in Appendix D.

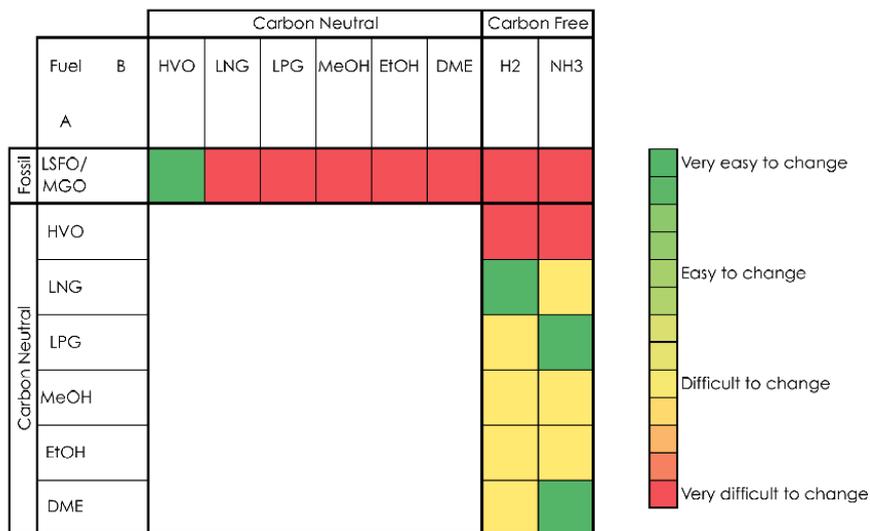


Figure 3.8: Transition matrix for the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF code). Ammonia (NH₃), hydrogen (H₂), dimethyl ether (DME), ethanol (EtOH), methanol (MeOH), liquefied petroleum gas (LPG), liquefied natural gas (LNG), hydrotreated vegetable oil (HVO), low-sulphur fuel oil (LSFO), marine gasoil (MGO).

The total ease of transition to another fuel is determined by the sum of the individual parts (engine, fuel containment system and other aspects). An equal weight has been assumed for the different parts because it

is a first estimation; it is a qualitative representation, and given the magnitude of the impact of the individual parts, it is expected to have the same impact.

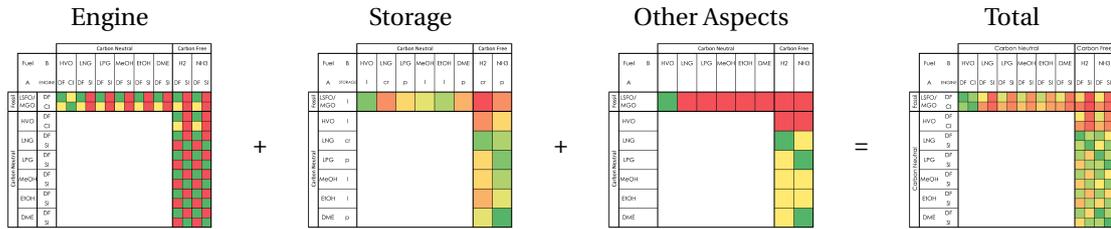


Figure 3.9: Summation of transition matrices.

3.5.4. Best Possible Fuel Transitions

The two scenarios discussed in section 2.4 are the carbon-neutral scenario and carbon-free scenario. In this section, the best possible fuel transitions are considered. Although this research is based on a starting point of LSFO and MGO, it is useful to use this knowledge to consider how other choices would work in the future, when there is more clarity about the various fuels. Because it might be interesting to start from a different fuel and then switch to a carbon-free fuel, this possibility is briefly discussed below.

Starting From Low Sulphur Fuel Oil and Marine Gasoil Fuel System

The technical aspects of the fuels described in chapter 2, are relevant for the two possible scenarios and are investigated in more detail in this section. Many different techniques are needed for the storage and supply systems of the different fuels. There are fuels that are more similar to the LSFO and MGO than others. It is expected that a fuel change towards a more similar fuel will be easier. Therefore it is relevant to consider how new-build vessels can be prepared with a possible future transition to these fuels.

For a carbon-neutral scenario, a fuel change from LSFO and MGO to HVO, seems to be the most convenient, as shown in Figure 3.10. This option is therefore investigated in more detail further in this report.

A fuel change to methanol also seems to be relatively easy. Because methanol is the most sustainable option out of the fuels in scenario 1, it could also be a promising fuel.

For a carbon-free scenario, ammonia seems to be the most convenient as shown in Figure 3.10, therefore also selected as a possible option for a fuel change to be investigated further.

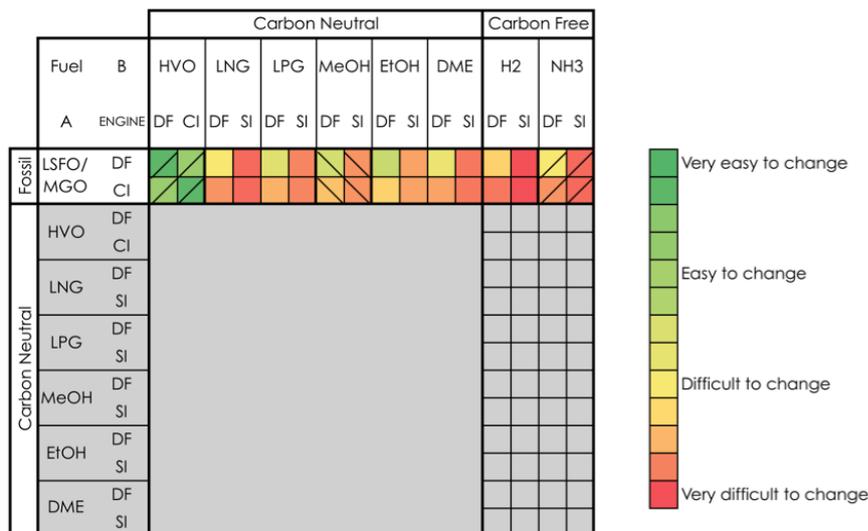


Figure 3.10: Total fuel transition matrix. Ammonia (NH₃), hydrogen (H₂), dimethyl ether (DME), ethanol (EtOH), methanol (MeOH), liquefied petroleum gas (LPG), liquefied natural gas (LNG), hydrotreated vegetable oil (HVO), low-sulphur fuel oil (LSFO), marine gasoil (MGO), spark ignition (SI), dual fuel (DF), compressed ignition (CI).

Different Starting Fuel

It may be relevant in the future to look into other possible fuel refits, than the options discussed above, starting from LSFO and MGO. For instance, if the regulations are known that general cargo ships must become carbon-free in 2060, it might be relevant to know which carbon-neutral fuels are best to start sailing on with a design for a relatively easy refit towards the carbon-free fuel. In Figure 3.11, it can be seen that a switch to hydrogen from LNG is the easiest. To switch to ammonia, LPG or DME would be the preferable starting points.

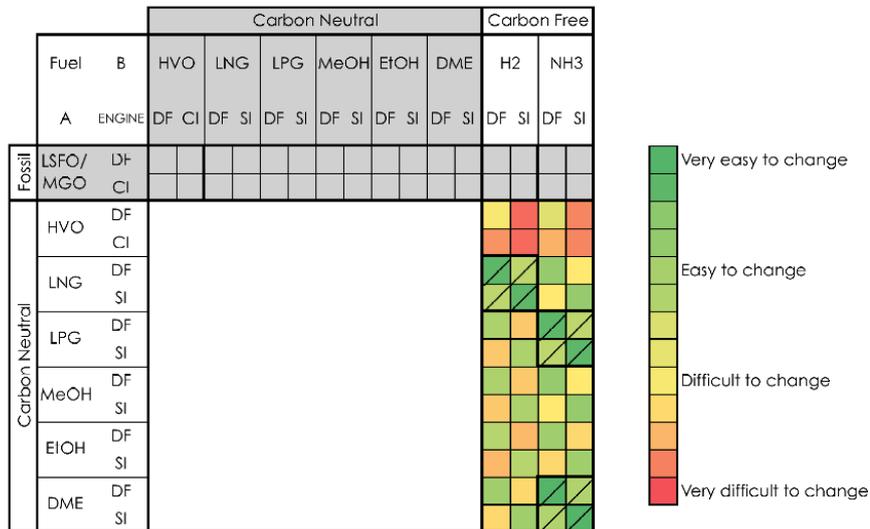


Figure 3.11: Fuel transition matrix with a focus on switching to hydrogen (H₂) or ammonia (NH₃) in the future. Dimethyl ether (DME), ethanol (EtOH), methanol (MeOH), liquefied petroleum gas (LPG), liquefied natural gas (LNG), hydrotreated vegetable oil (HVO), low-sulphur fuel oil (LSFO), marine gasoil (MGO), spark ignition (SI), dual fuel (DF), compressed ignition (CI).

DNV-GL [23] also lists the options for switching to ammonia from LPG and identifies a switch to hydrogen, from LNG as best choice. DNV-GL does not discuss DME as fuel, so they do not name it as an option.

4

Ship Design Method

The purpose of this chapter is to describe the method for designing a ship that starts sailing on MGO and LSFO, so that it can be prepared to switch to the alternative fuels selected in chapter 3. For this specific problem, a design spiral was developed based on the aspects found in chapter 3.

In section 4.1, different design phases are discussed. The first phase represents the starting point, which is based on the used reference vessel. By using the design spiral, derived from the design spiral of Evans, the second phase is discussed. This phase represents the new design of the vessel, where it is adjusted as much as possible to be able to switch to an alternative fuel more easily during a refit. This refit is then represented by the third phase.

In section 4.2, details about the reference vessel are given. In section 4.3, the elements of the design spiral are discussed. In section 4.4, the new design phase will be discussed and in section 4.5, the refit phase will be discussed. Finally, costs are considered in section 4.6.

4.1. Design Phases

The design process takes place in three different phases, which are shown in Figure 4.1.

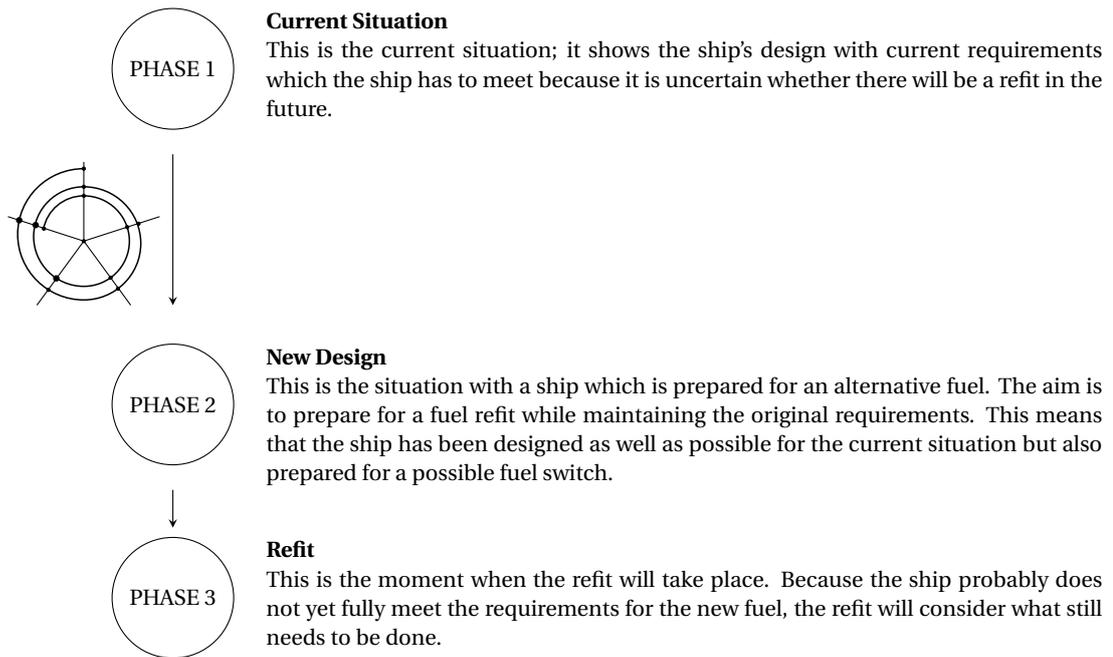


Figure 4.1: Design phases.

The design spiral of Evans is a model of a rational design procedure as applied to a "typical surface cargo ship problem" [81]. As a starting point, the owner requirements are used.

In the field of ship design, the design process of Evans, is still often used. In 1959, Evans created the design spiral which is illustrated in Figure 4.2.

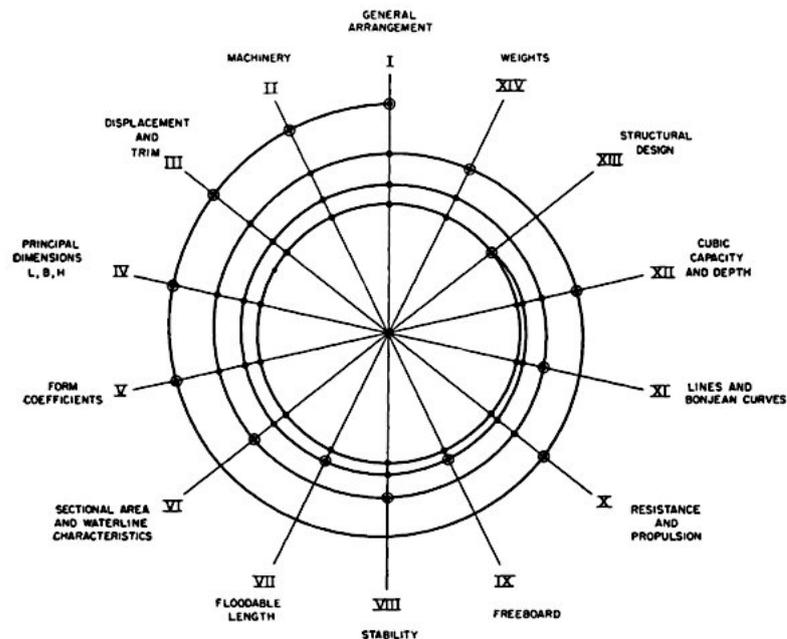


Figure 4.2: The Evans design spiral [86].

The spiral-shaped timeline illustrates the iterative characterisation of the design process of a ship. The spiral leads to different phases of design, where different types of aspects and subsystems are designed. After

completing the first round in the spiral, the ship design is likely not yet meeting mission requirements. For example, when the ship length is increased, consequently the installed propulsion power has to be increased. In the preliminary phases of ship design, mostly simple calculations and assumptions are being used. In later stages, more accurate results can lead to adjustments in the first preliminary design. With this information, new design iterations can be made until the mission requirements are met.

The advantage of the spiral design is that it shows clearly the iterative nature of design; it is a flexible concept, and it is most effective when applied to variants of existing ships [81]. A disadvantage is that it only deals with synthesis and not with optimization.

This design spiral contains many aspects that are not discussed in this research. Therefore, a simplified design spiral has been developed, as shown in Figure 4.3. The iteration of the design for a general cargo ship can be performed for each selected fuel requiring a specific design. First, the requirements of the reference vessel are determined. These requirements are based on the assumption that the ship will switch to a different fuel, thus necessitating that the ship is as prepared for this change as possible. For this purpose, the ship must meet the current design requirements, after which the ship size will be checked. Thus, the first iteration simply follows from the requirements, ship size, and thereafter changes will be made. So after adjustments have been made to the elements relating to the tanks and fuel supply, the ship size can be changed.

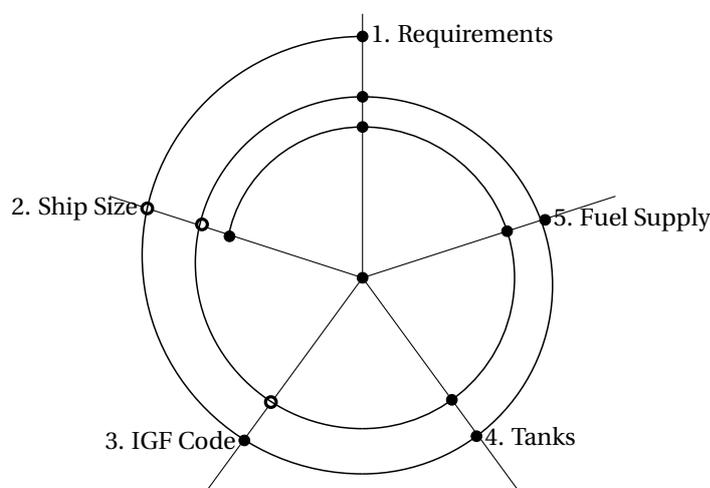


Figure 4.3: Design Spiral for this research.

For the design spiral and the process a reference ship will be used as starting point.

4.2. Reference Vessel

For this research, a ship supplied by Wagenborg was chosen as a reference vessel. The reference vessel is the Eemsborg, an 10,200 DWT general cargo vessel. A picture of the Eemsborg is shown in Figure 4.4.



Figure 4.4: Reference Vessel Eemsborg [8].

The vessel has two holds, 13.2 meters wide and 11.23 meters high. The aft hold (hold 2) has a length of 54.76 meters and the forward hold (hold 1) has a length of 41.44 meters [8]. The vessel was built by Royal Niestern Sander, which is located on the old Eems canal (Dutch: Oude Eemskanaal). The vessel has a HFO fuel capacity of 881 [m³] and an MGO fuel capacity of 72.3 [m³] [8]. The main particulars of the vessel are shown in Table 4.1.

Table 4.1: Main particulars of the reference vessel [8].

Quantity	Amount	Unit
Length over all (Loa)	137.9	[m]
Length between perpendiculars (Lpps)	131.5	[m]
Breadth (B)	15.87	[m]
Depth (D)	11.00	[m]
Draught (T)	7.7	[m]
Deadweight cargo capacity (DWCC)	10,200	[tonnes]
Design speed	14	[knots]
Main engine	4500	[kW]

4.3. Design Spiral Elements

In this section, the aspects of the design spiral are discussed. An overview of the different aspects is shown below:

1. Requirements

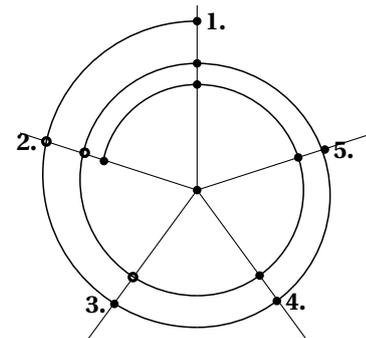
- (a) Cargo Capacity
 - Deadweight cargo capacity (DWCC)
 - Grain Capacity
- (b) Energy Capacity
- (c) Beam
- (d) Adapted as far as possible for a transition to an alternative fuel regarding tanks and supply.
- (e) Ballast water capacity

2. Ship Size

3. International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels

4. Tanks

5. Fuel Supply



4.3.1. Requirements of Current Vessel

There are four requirements. The first requirement is the cargo capacity, which is divided into carrying weight and carrying volume. The second requirement is the energy capacity. The third requirement is the beam limitation, and the fourth requirement is the fuel that is being switched to. Sometimes an extra requirement is needed; for example, methanol can also be stored in the double-bottom ballast water tank. This ballast water tank must then meet a number of requirements.

Cargo Capacity

The cargo capacity can be described in deadweight cargo capacity (DWCC) and the grain capacity. General cargo ships are designed to transport different types of cargo. As with fuels, cargo can take up volume and weight. The amount of weight a ship can carry is described by the deadweight tonnage (DWT), and the amount of volume a general cargo ship can carry is represented by the grain capacity.

Deadweight Tonnage

The deadweight tonnage (DWT) is a measure of how much total weight a ship can carry. The reference vessel has a DWT of 10,723 [tonnes], which is the sum of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers and crew. A vessel's DWT and can be expressed by Equation 4.1 [8, 111].

$$DWT = W_{cargo} + W_{fuel} + W_{freshwater} + W_{ballastwater} + W_{provisions} + W_{passengers} + W_{crew} \quad (4.1)$$

Where:	DWT	deadweight tonnage	[ton]
	W_{cargo}	cargo weight	[ton]
	W_{fuel}	fuel weight	[ton]
	$W_{freshwater}$	fresh water weight	[ton]
	$W_{ballastwater}$	ballast water weight	[ton]
	$W_{provisions}$	provisions weight	[ton]
	$W_{passengers}$	passengers weight	[ton]
	W_{crew}	crew weight	[ton]

Because the interest often lies in how much cargo the ship can carry, the cargo capacity is often expressed in deadweight cargo capacity (DWCC), shown by Equation 4.2.

$$DWCC = W_{cargo} \quad (4.2)$$

Where:	DWCC	deadweight cargo capacity	[ton]
	W_{cargo}	cargo weight	[ton]

The DWCC of the reference ship is 10,200 [tonnes] [8]. Other weights shown in the DWT formula in Equation 4.1 have a total weight of 523 [tonnes]. This study is focused on the weight of the fuel and of the cargo. Therefore, the other weights in Equation 4.1 are kept the same. Thus, given the same DWT, extra fuel weight will have a direct effect on the DWCC.

Grain Capacity

The grain capacity is a measure that is used for general cargo vessel to indicate the space that is available for cargo, like bulk grain, which can flow into every corner. The vessel has a grain capacity of 13,644 [m³] [8].

Whether a ship is deadweight critical when it still has cargo space available after it has been loaded onto its maximum DWCC. On the other hand, if a ship's hold is filled before the maximum DWCC is reached. the vessel is volume critical.

General cargo ships cannot simply be classified as either deadweight critical or volume critical. The classification depends on the specific weight of the cargo. For example, when a ship is loaded with copper concentrate (which is a heavy material with a density of 896 [kg/m³] [5]), given the DWCC of the reference vessel, the ship is able to carry 11400 [m³] of copper concentrate. Thus, for copper concentrate, the deadweight will be the limiting factor, so the ship is deadweight critical. On the other hand, when the ship is loaded with barley grain with a density of 620 [kg/m³] [4]. The cargo weight of the reference ship fully filled with barley grain is rounded 8500 [tonnes], which means that volume is the limiting factor. Thus, whether the ship is deadweight critical or volume critical thus depends on the specific weight of the cargo.

The gravimetric energy density of a fuel will be used to evaluate the impact on the deadweight and the volumetric energy density for the impact on the grain capacity. These two aspects will both be considered. In addition to the fuel, the system that contains the fuel belongs to a ship's lightweight. Because the system that belongs to a fuel can make the lightweight much heavier, the lightweight is also effected by using different fuels. Therefore, the lightweight is also discussed.

Lightweight

The lightweight of the ship, is the weight of the ship excluding cargo, fuel, ballast water, provisions, passengers, and crew. Thus, the lightweight is the ship weight minus the DWT. This weight also directly results in the displacement of the ship, which is equivalent to the lightweight plus deadweight. The displacement (Δ) is given by Equation 4.3

$$\Delta = DWT + Lightweight \quad (4.3)$$

Where:	Δ	displacement	[ton]
	DWT	deadweight tonnage	[ton]
	Lightweight	" "	[ton]

The relation of the cargo capacity displacement, lightweight components and deadweight components is shown in Figure 4.5.

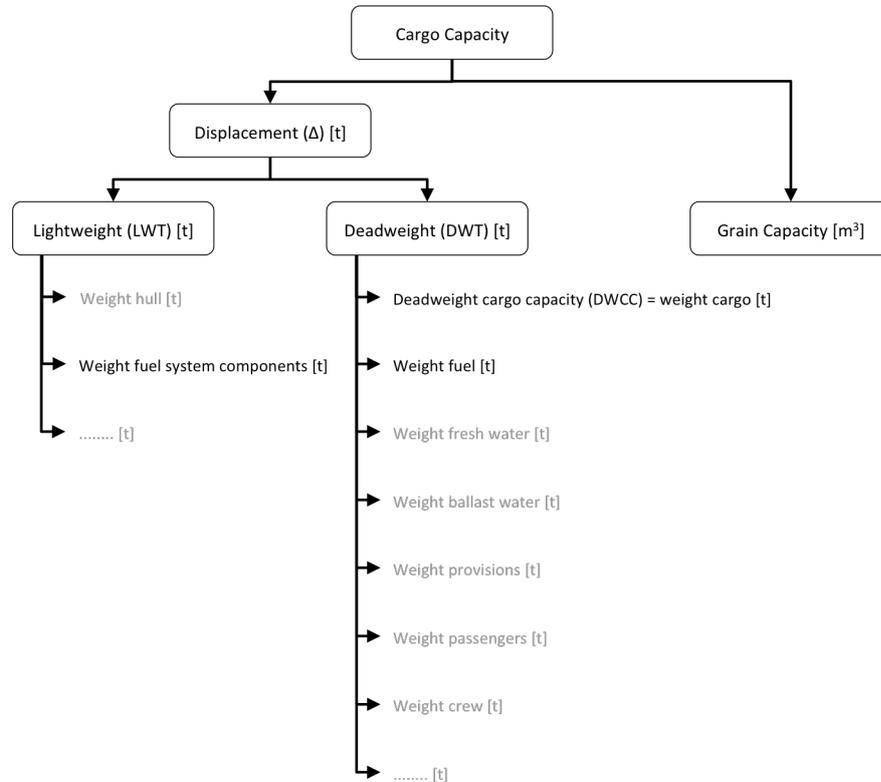


Figure 4.5: Relation between displacement, lightweight components and deadweight components. must show that these concepts may not be complete.

4.3.2. Energy Capacity

The energy capacity is the amount of energy the vessel is carrying. The energy capacity of the reference vessel is assumed to be 36,329 [GJ]. The fuel consumption of the vessel at 12 [knot] is 14 [mt] per day. This fuel consumption is based on ballast condition at a draft of 5.50 [m], deep and currentless water, a calm sea and max wind force, Beaufort 2 [8]. Under these conditions, the vessel is able to sail approximately 17,568 [nm] in 61 days. The formula for fuel consumption is shown by Equation 4.4 [87].

$$sfc = \frac{3600000}{\eta_E * LHV} \quad (4.4)$$

Where:	sfc	specific fuel consumption	[g/kWh] or [m ³ /kWh]
	η_E	prime mover efficiency	[-]
	LHV	lower heating value	[kJ/kg] or [kJ/m ³]

The prime mover efficiency for all fuels is assumed to be the same, so that the energy required from alternative fuels can be directly compared with the current energy capacity. As a result, the energy capacity is directly related to the sailing range

Beam

As mentioned in section 2.4 the vessel is built at a yard located on the old Eems canal (Dutch: Oude Eemskanaal). Because of the dimensions of the bridges on the canal, the beam of the ship is limited to 16 meters. This has the consequence that the ship can only be lengthened.

Transition To Other Fuel

The final requirement is to make the transition to another fuel easier.

Ballast Water Capacity

The ballast water capacity only plays a role in alcoholic fuels, because these fuels may be stored at the location of ballast water tanks.

4.3.3. Ship Size

As described in section 4.2 the vessel's beam is limited. Therefore, extra space requires that the vessel must be lengthened. For lengthening the ship it is assumed that only the part of the cargo hold provides extra volume. Thus, the extra required length of the ship can be calculated with Equation 4.5.

$$L_e = \frac{V_e}{H_{ch} * B_{ch}} \quad (4.5)$$

Where	L_e	extra vessel length	[m]
	V_e	extra volume required	[m ³]
	H_{ch}	height cargo hold	[m]
	B_{ch}	breadth cargo hold	[m]

4.3.4. International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels

An important aspect is the IGF code. If a fuel has to comply with the IGF code, it will be included in the tanks and in the fuel supply. This must then be taken into account in the elements that follow.

4.3.5. Tanks

The fuel tanks of a fuel can have a major impact on the ship. As discussed in Chapter 3, there are roughly three types of tanks. Regular storage tanks, cryogenic storage tanks and pressurized storage tanks. Ideally, if there is a transition to a different fuel, you want these tanks to be used in the best possible way and that this space is not lost. There are different limits for a fuel tank. First of all, the tank size is limited for some tanks and secondly, the location of the tank is limited by various aspect.

Size

The size of type C tanks is, the values are shown below.

- Type C tank minimum size of 30 [m³]
- Type C tank maximum size of 1000 [m³]

Location

The location of the fuel tank is limited mainly by The IGF code. The boundaries found in are shown below with the specific values for the reference vessel in this chapter.

1. Minimum distance of $B/5 = 3.17$ [m] of the shell.
2. Aft of the collision bulkhead.
3. Forward of the aft peak bulkhead.
4. Lowermost boundary of the fuel tank(s) above the minimum distance of $B/15 = 1.06$ [m].

Tanks can also be placed at other locations, therefore two different general cargo ships were briefly reviewed. One design shown in Figure 4.6 with the deckhouse located on the stern, and one design shown in Figure 4.7 with the deckhouse located on the forepeak. In current ship designs, conventional fuels are located in the engine room (2), in the aft cargo hold (3) and in the cross section (4). Alternative fuels have other storage requirements. Therefore three extra locations for fuel storage have been identified. The locations have been chosen so that they do not affect the gantry crane and that the cargo hold is freely accessible these locations are chosen discussed with several naval architects and literature. The pros and cons are summarized and shown in Table 4.2.

1. Deck Aft
2. Engine Room
3. Cargo Hold Aft
4. Cross Section
5. Cargo Hold Fore
6. Deck Fore

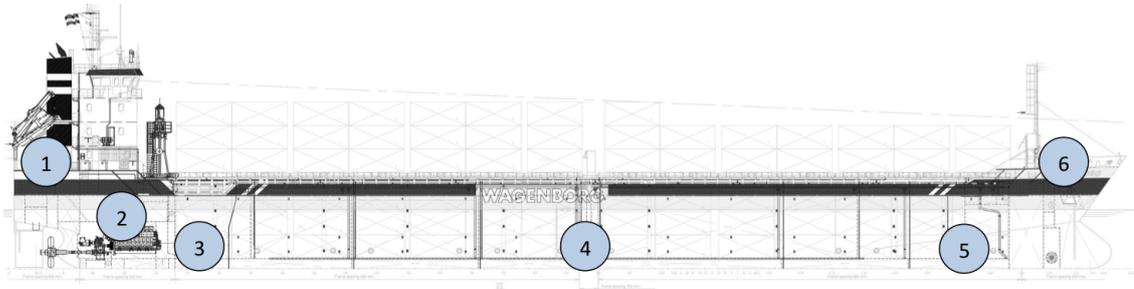


Figure 4.6: Type 1 general cargo ship design with deckhouse on the aft with current and possibly new fuel positions. 1. Deck Aft, 2. Engine Room, 3. Cargo Hold Aft, 4. Cross Section, 5. Cargo Hold Fore, 6. Deck Fore.

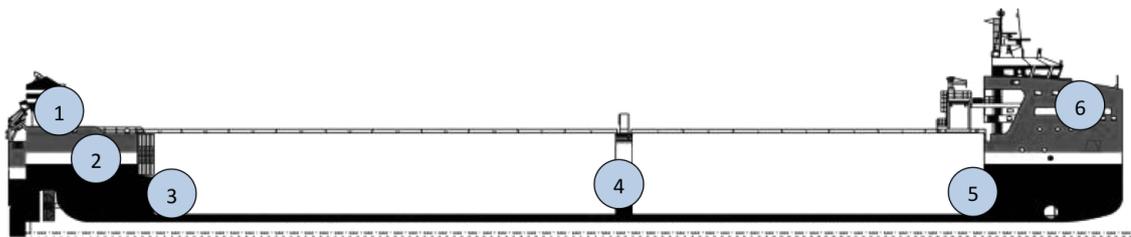


Figure 4.7: Type 2 general cargo ship design with deckhouse on the forepeak with current and possibly new fuel positions. 1. Deck Aft, 2. Engine Room, 3. Cargo Hold Aft, 4. Cross Section, 5. Cargo Hold Fore, 6. Deck Fore.

Table 4.2: Pros and cons of the storage locations.

	1. Deck Aft	2. Engine Room	3. Cargo Hold Aft	4. Cross Section	5. Cargo Hold Fore	6. Deck Fore
Cargo Volume	++	++	-	-	-	++
Stability	-	++	++	+	++	-
Pipe Length	+	++	+	-	-	-
Available Space	Type 1: - Type 2: -	-	++	+	++	Type 1: - Type 2: -
Line of Sight	Type 1: - Type 2: -	N/A	N/A	N/A	N/A	Type 1: - Type 2: -

N/A: Not applicable.

Type 1: Refers to a general cargo ship with the deckhouse at the aft.

Type 2: Refers to a general cargo ship with the deckhouse on the forepeak.

4.3.6. Fuel Supply

The location of the fuel tank also determines where the fuel pipes should run to and come from. The IGF code also prescribes rules for fuel pipes. The main rules are described below.

1. Fuel pipes shall not be located less than 800 mm from the ship its side.
2. Fuel piping should not be led directly through accommodation spaces, service spaces, electrical equipment rooms or control stations as defined in the SOLAS Convention

Because only one tank meets the requirements, it is checked whether the fuel line to this tank also complies. The piping are placed in the pipe duct. This duct satisfies and double walled piping can be placed.

4.4. New Design

After the design spiral has been applied the final design is obtained. This design meets the requirements to sail on the current fuel and is also prepared for a transition to another fuel. The adjustments needed when the ship will actually change to a different fuel will be discussed during the refit.

4.5. The Refit

When the refit takes place, the ship does not yet meet all the requirements for the new fuel. Therefore, a number of considerations are still necessary, as discussed in this section.

Because most alternative fuels will take up more space and weight onboard a ship, compromises have to be made. The following three options are considered:

1. *Reducing energy capacity*
2. *Reducing cargo capacity*
3. *Increasing ship size*

For a first clear evaluation of these specific options, the other variables are kept the same, as shown in Table 4.3.

Table 4.3: Dilemmas for alternative fuels, formulated in options.

Option	Energy Capacity	Cargo Capacity	Ship Size
1	<	=	=
2	=	<	=
3	=	=	>

For all options it is assumed that the vessel is optimally designed so that the vessel has nowhere else room for extra fuel than in the given options.

The first option is to keep the cargo capacity equal and to keep the ship size the same. This means taking into account the assumption above that the energy capacity must be reduced, which reduces the sailing range.

The second option is that the ship should keep the same energy capacity and the same ship size. The consequence is that the cargo capacity must be reduced.

The third and last option is to keep the cargo capacity and sailing range equal. This results in requirement to increase the ship size. As described in Section 4.2 the beam of the ship can have a maximum width of 16 [m] which means that the ship must be lengthened [114].

As has often been mentioned, the weight and volume of an alternative fuel system can have a major impact on the ship. These concepts have been dealt with separately and are now applied to the ship in Section 4.5.1.

4.5.1. Weights and Volumes

This section compares the volume and weight of the current conventional fuel system with that of the alternative fuels. Because it is not yet possible to estimate how much space and weight of the current fuel system can be used by an alternative fuel system, two situations are used to indicate the upper and lower limits for the alternative fuels.

In the first situation, which is the lower limit, it is assumed that the space and weight of the current fuel system can be completely replaced by that of an alternative fuel. This means that the full capacities of the current ship tanks for HFO and MGO can be used. The current ship tank capacity for HFO is 881 m³ and for MGO is 72.3 m³ [8]. The energy capacity is calculated on the basis of this tank capacity and the LHV for LSFO and MGO. The values that were found in Chapter 3 and shown in Figure 3.4 are used to make this estimation.

For the LSFO the volumetric and gravimetric density values of 38.2 [GJ/m³] and 42.44 [GJ/kg] are used. For MGO the volumetric energy density of 37 [GJ/m³] is used and the gravimetric value of 43 [GJ/kg] is used. This results in a required energy capacity of 36329.3 [GJ] which is the sum of the capacities for MGO and LSFO. The amount of volume or weight needed are subdivided in pure fuel, the system, and fuel including system.

For this calculation the interest lies in the difference between the alternative fuels and the fuels used in the current situation. These values are shown in Table 4.4. So based on the same amount of energy that is needed for example for HVO a total extra volume of 239 [m³] (including system) is needed to store this fuel.

Table 4.4: Required extra capacities per fuel.

Fuel	Pure Fuel		System Only		Including System	
	Δ Volume [m ³]	Δ Weight [kg]	Δ Volume [m ³]	Δ Weight [kg]	Δ Volume [m ³]	Δ Weight [kg]
LSFO/MGO	0	0	0	0	0	0
HVO	182	106	57	29	239	135
Methanol	1317	961	352	250	1669	1211
Ammonia	2349	1124	824	469	3174	1592

The second situation which will represent the upper limit is that the weight of the current fuel system and space of the current fuel including system cannot be replaced at all. So therefore the weight and volume of the alternative fuel including system is added. The absolute values are shown in Table 4.5. The actual extra capacity needed will be somewhere between these upper and lower limits.

Table 4.5: Required capacities per fuel.

Fuel	Pure Fuel		System Only		Including System	
	Δ Volume [m ³]	Δ Weight [kg]	Δ Volume [m ³]	Δ Weight [kg]	Δ Volume [m ³]	Δ Weight [kg]
LSFO/MGO	0	0	0	0	0	0
HVO	1135	961	318	384	1453	1346
Methanol	2270	1816	613	605	2883	2422
Ammonia	3302	1978	1085	824	4388	2803

In all cases the impact of the volume is the bigger than the impact of the weight. Therefore it is assumed that the volume will be the limiting factor in this study. This will have to be verified after the actual new designs.

Option 1: equal cargo capacity, equal ship size, reduced energy capacity,

For option 1, as seen in Table 4.4 the required volume of the systems associated with alternative fuels and the alternative fuels themselves will be bigger, to keep the same grain capacity and not making the ship bigger, the energy capacity must decrease.

Table 4.6: Option 1

Fuel	System	Fuel	Fuel + System	Energy Capacity [MJ]	Difference [MJ]
	Volume [m3]	Volume [m3]	Volume [m3]		
LSFO/MGO	261	953	1214	36329300	-
HVO	266	948	1214	30351287.36	-5978012.644
Methanol	258	956	1214	15297048.83	-21032251.17
Ammonia	300	914	1214	10052346.37	-26276953.63

The system will be limited by the volume of the alternative fuel. At eco speed the reference vessel can sail around 61 days [8], limited by the volume of the fuel system. The sailing time will be decreased for alternative fuels as follows: HVO with ≈ 10 days, LNG with ≈ 37 days; LPG with ≈ 24 days; ethanol with ≈ 27 days; methanol with ≈ 35 days; DME with ≈ 34 days; LH₂ with ≈ 51 days; and ammonia with ≈ 44 days. Because the ship will be limited by volume, the ship will become lighter, and therefore the DWCC will increase.

The sailing range for a selection of general cargo vessels is plotted against the DWT of these vessels. In the past, ships were more often made with a larger fuel capacity, making it possible to speculate with fuel prices but also saves time. A larger fuel capacity gives more flexibility. The sailing range must be determined on the basis of an operational profile. As seen in Figure 4.8, the reference vessel has a significant energy capacity and falls on the high side compared to other general cargo ships.

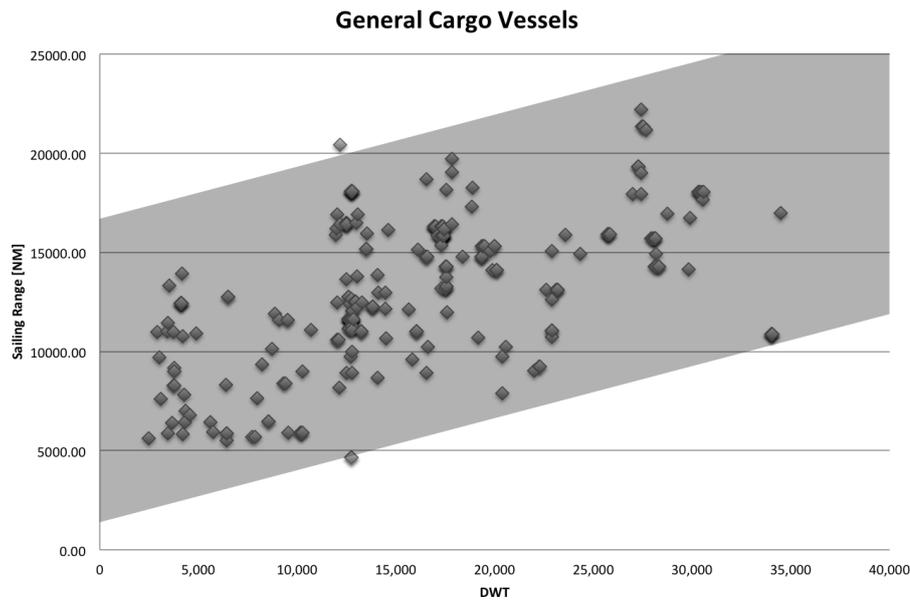


Figure 4.8: Sailing range of general cargo vessels. The data was obtained from Clarksons Fleet Register.

Option 2: reduced cargo capacity, equal energy capacity, equal ship size

For option 2, as seen in Table 4.4 the required volume of the systems associated with alternative fuels and the alternative fuels themselves will be bigger, therefore the grain capacity will decrease. The vessel has a grain capacity of 13644 [m³].

Table 4.7: Option 2

Fuel	System	Fuel	Fuel + System	Energy Capacity [MJ]	Difference [m3]	Grain Capacity [m3]			
	Volume [m ³]	Volume [m ³]	Volume [m ³]			Scenario 1	Scenario 2	Difference	%
LSFO/MGO	261	953	1214	36329300	-	13644	-	13644	-
HVO	318	1135	1453	36329300	239	13405	-2%	12191	-11%
Methanol	613	2271	2883	36329300	1669	11975	-12%	10761	-21%
NH ₃	1085	3303	4388	36329300	3174	10470	-23%	9256	-32%

Option 3: equal cargo capacity, equal energy capacity, bigger ship size

For option 3, as seen in Table 4.4 the required volume of the systems associated with alternative fuels and the alternative fuels themselves will be bigger, to keep the same grain capacity, the ship must be enlarged.

Table 4.8: Option 1

Fuel	System	Fuel	Fuel + System	Energy Capacity [MJ]	Difference [m ³]	Lengthening Ship [m]					
	Volume [m ³]	Volume [m ³]	Volume [m ³]			Scenario 1	Difference	Scenario 2	Difference		
LSFO/MGO	261	953	1214	36329300	-	137.9	-	137.9	-		
HVO	318	1135	1453	36329300	239	140	2	1%	148	10	7%
Methanol	613	2271	2883	36329300	1669	149	11	8%	157	19	14%
Ammonia	1085	3303	4388	36329300	3174	159	21	16%	167	30	21%

4.5.2. Conclusion of the Consideration

From the information described in this chapter the order that is followed is:

1. Reducing energy capacity
2. Reducing cargo capacity
3. Increasing ship size

Of course a combination of the options are also possible. It assumed that it is most realistic to first reduce the energy capacity until a certain critical amount. This because there is not extra refit needed for this and

the shipowner will not lose income. This critical amount relies on the sailing profile of the ship. For the used reference vessel this will be discussed in the next chapter. Secondly it is assumed that reducing the cargo capacity with a small amount of cargo volume or cargo weight loss may not matter much. Only in times of very profitable markets might it matter [84]. In the study from Kana et al. [84] 2% of cargo loss had no impact on ship income. Therefore, 2% cargo loss is accepted and forms the lower limit. When this limit is reached, it will be necessary to consider enlarging the ship. The selection order of the consideration made in this section is shown in Table 4.9.

Table 4.9: Sequence of the refit

Option	Energy Capacity	Cargo Capacity	Ship Size
1	<	=	=
2	<	<	=
3	<	<	>

4.6. Costs

As described in the introduction of this thesis, strong price competition makes early adaption solutions unfeasible. Therefore, this section makes an economic analysis. A number of cost functions from the literature, were used for this purpose.

4.6.1. Total Ship Costs

The cost of the ship itself is estimated using the work of Aalbers. In the work of Aalbers, a number of cost functions are derived for a ship's systems by means of a statistical analysis of 30 vessels. Those vessels are assumed to have the form shown in Equation 4.6. In this thesis, only the cost of capital is taken into account. Capital costs primarily comprise the cost for the converter, storage system and process system. It was found that cost for the process system is in general not given in available literature, so in the following, only the cost for the converter and storage system are included.

$$K = c * a * W^b \quad (4.6)$$

With: K costs/manhours
W weight/size
a factor for local conditions
b factor in the range 0.5 to 1.0
c factor for complexity of specific equipment

Where K is either the material cost or the number or man hours, W is a weight or size parameter. For the purpose of this thesis, c (a factor to account for local conditions) is assumed to be 1. The derived cost functions are shown in Table 4.10.

Table 4.10: Cost functions for each system of the ship. Obtained from Aalbers [46].

System	Materials				Manhours			
	Wm	unit	am	bm	Wh	unit	ah	bh
1 General & Engineering	Wsm	[kg]	5000	0.72	Wsm	[kg]	27	0.9
2 Hull & Conservation	Wsteel	[kg]	1900	1	Wsteel	[kg]	k based on LBD and Cb see Equation 5	
3 Ships Equipment	W_equip	[kg]	15000	0.8	W_equip	[kg]	8.5	0.86
4 Accommodation	Area_acc	[m ²]	1500	1	Area_acc	[m ²]	250	0.55
5 Electrical Systems	P_gen	[kW]	18500	0.62	P_gen	[kW]	20	0.55
6 Propulsion & Power System	P_b	[kW]	4100	0.84	nr_p_b	[kW]	6	0.75
7 Systems for Prop & Power	P_b	[kW]	3000	0.70	nr_p_b	[-]	35	0.70
8 Bilge, Ballast San. Systems	hullnr	[m ²]	300	0.93	hullnr	[m ²]	2.75	1

The formula of Watson was used to estimate the lightweight (W_{sm}), which is shown in Equation 4.7.

$$E = L(B + T) + 0.85L(D - T) + 0.85(l_1 * h_1) + 0.75(l_2 * h_2) \quad (4.7)$$

With: E Lloyd's equipment numeral
 L length
 B breadth
 D depth
 T draft
 l_1 length of full width erections
 h_1 height of full width erections
 l_2 length of houses
 h_2 length of houses

$$k = C * f * (45.36 * (LBD/1000))^{-0.115} + 3.5 \quad (4.8)$$

Where: k Weight hull [t]
 C Constant factor used to take into account the local situation at the yard [-]
 f see Equation 4.9 [-]
 L Length [m]
 B Breadth [m]
 D Depth [m]

$$f = 0.866 * Cb^{-1/3} \quad (4.9)$$

Where: f Weight hull [ton]
 Cb Block coefficient [-]

The formula of D'Almeida was used to estimate the steel weight, which is shown in Equation 4.10. The steel weight of a vessel can depend on many factors such as the type of vessel, the country where the ship was built and the shipyard. Although this formula is from 2009, it has been tested and gave a fair result for the original steel weight. This accuracy, though, does not ensure that the weight of a longer ship is also correctly estimated. Nevertheless, in the end, it is all about the difference, which is hereby correctly estimated. D'Almeida provides different k-factors. The k-factors for a general cargo ship are used.

$$W_H = k_1 * L_s^{k_2} * B^{k_3} * D^{k_4} \quad (4.10)$$

Where: W_H Weight hull [ton]
 L_s Length ship (length between perpendicular (Lpp)) [m]
 B Breadth ship [m]
 D Depth ship [m]
 k1 0.0313 [-]
 k2 1.675 [-]
 k3 0.850 [-]
 k4 0.280 [-]

Table 4.11: Values used for input

	W	Benchmark
Lightship weight	Wsm	3102
Steel weight total nett	W_steel	2274
Length (L) * Breadth (B) * Depth (D)	LBD	22955
Block coefficient	Cb	0.8469
Equipment weight	W_equip	713
Accommodation area	Area_acc	565
Installed generator power	Pgen	750
Prime power per independent system	P_b	3000
Nr of independent power systems	nr_p_b	1
Hull numeral Length (L)*(Breadth (B) + Depth (D))	hullnr	3533

4.6.2. Fuel Storage Costs

The investment costs for the different storage systems are derived from Brynolf [60] and Hansson et al. [79] and shown in Table 4.12. The short sea vessel has a fuel capacity of 3500 GJ, and the deep sea ship is equipped with a storage capacity of 71,300 GJ [60].

Table 4.12: Detailed cost for different fuels and vessel types and the associated volumetric energy densities per fuel.

Fuel ^a	Costs per ship type [USD/GJ]		Volumetric energy density [GJ/m ³]	
	Short sea	Deep sea	Pure fuel	Including system
Fuel oil	30	25	35	29.5
liquefied natural gas (LNG)	110	80	18.4	12.4
ammonia (NH ₃)	55	45	12.3	8.8
liquefied petroleum gas (LPG)	55	45	19	20.7
dimethyl ether (DME)	55	45	18.9	13.3
hydrogen (H ₂)	300	225	7.8	4.32
methanol (MeOH)	50	40	15.7	12.6
ethanol (EtOH)	50	40	21.1	17.8

^aFO: Fuel oil representing heavy fuel oil (HFO), marine diesel oil (MDO), marine gasoil (MGO) and biodiesels such as hydrotreated vegetable oil (HVO) [79][60].

5

Generation of Concepts

In this chapter, the design spiral described in Chapter 4 is followed for the different possible fuel transitions. Therefore, in Section 5.1, more details of the reference vessel that was introduced in Section 4.2 are described. This is needed to explain the fuel transition for the selected fuels from this design. In Section 5.2, the design spiral is derived for HVO. In Section 5.3, the design spiral is run through for ammonia, and in Section 6.1, the design spiral is described for methanol.

5.1. The Reference Ship as a Starting Point

The reference ship that was introduced in Section 4.2 is used as the starting point for every design concept. During the years before the ship is converted to sail on the alternative fuel, the ship will have to sail on LSFO and MGO.

For the first requirement, the ship has a deadweight cargo capacity (DWCC) of 10,200 [tonnes] and a grain capacity of 13,644 [m³]. The holds of the reference vessel are fully box-shaped except on the box structures in the fore and aft parts of the cargo hold. This is due to the vessel's outer shape [8].

For the second requirement, the LHV of LSFO and MGO, discussed in Chapter 3 and shown in Table 3.4, are used as references. Therefore, the ship has a total energy capacity of 36,300 [GJ]. An overview of these values is shown in Table 5.1.

Table 5.1: Energy capacity of the reference ship.

Fuel	Capacity [m ³]	LHV [GJ/m ³]	Energy [GJ]
LSFO	881	38.2	33654
MGO	72.3	36.6	2646
Total	953.3	<i>n/a</i>	36300

For the third requirement, the ship is assumed to be built at the same shipyard as the reference ship and therefore should have a design with a maximum beam of 15.97 [m]. The last requirement is that the ship should be designed so that the tanks and fuel supply, where relevant, can easily switch to the alternative fuel. With the current fuel, the ship does not have to comply with the IGF code.

5.1.1. Current Fuel Tanks

The total energy capacity is divided over 11 tanks for LSFO and three tanks for MGO. A list of these tanks is shown in Table 5.2. A simplified arrangement of these tanks is shown in Figures 5.1 and 5.2.

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Figure 5.1: Sideview of the fuel tank arrangement of the reference ship. The tanks are in different layers of the ship.

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Figure 5.2: Top view of the fuel tank arrangement of the reference ship. The tanks are in different layers of the ship.

Table 5.2: Fuel tanks of the reference vessel.

Number	Tank	Tank Capacity [m ³]
	Description	
201	LSFO Cross Bunker PS	143.9
202	LSFO Cross Bunker centre	262.8
203	LSFO SB	144.2
204	LSFO Hold Bunker PS	39
205	LSFO Hold Bunker SB	39
206	LSFO Bunker PS ER	94.2
207	LSFO Bunker SB ER	119
208	Settling Tank 1	11.1
209	Settling Tank 2	10.1
210	LSFO Daytank 1	9
211	LSFO Daytank 2	8.8
214	MGO Bunker PS	39.6
215	MGO Bunker SB	28.2
216	MGO Daytank	4.57

Low-sulphur fuel oil (LSFO), port side (PS), starboard (SB), engine room (ER), marine gasoil (MGO).

For the tanks with the current fuel, a number of general rules apply. To sail on LSFO and MGO, the tanks need to be located:

1. In front of the aft peak bulkhead.
2. Behind the collision bulkhead.

The bulkheads are illustrated in Figure 5.5.

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Figure 5.3: Location of aft peak bulkhead and collision bulkhead.

5.1.2. Refit Possibilities

Finally, when the refit takes place, there is a choice between reducing cargo capacity, making the ship longer or by reducing sailing range.

To see what the minimum range of the ship should be, the ship's operational profile is considered. The longest trip the ship will make and a very frequent trip are analysed.

Operational profile



Figure 5.4: Estimate of the route, obtained through Dataloy

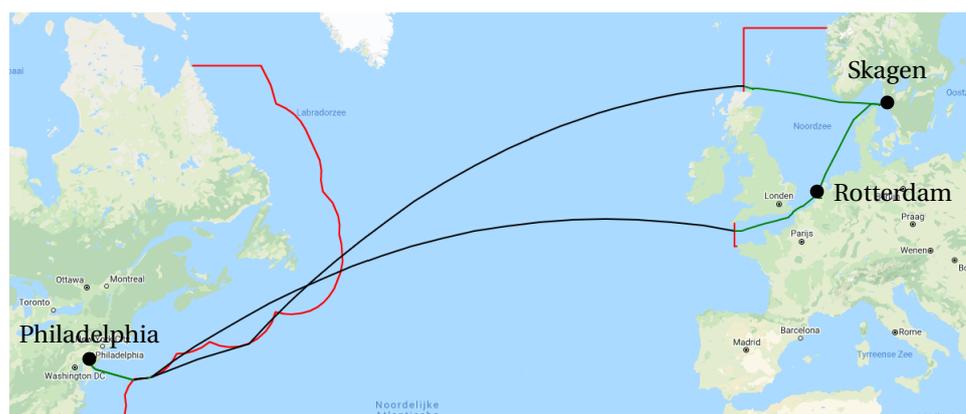


Figure 5.5: Estimate of the route, obtained through Dataloy

The longest voyage the reference vessel makes is from Panama to Shanghai. This is approximately 8579 [nm]. A more regular trip the ship is from Rotterdam to Philadelphia, which is 3554 [nm]. Where the choice remains, it is preferable not to be forced to bunker in the United States to not be forced to bunker in America because

only expensive MGO with 0.1% sulphur can be refuelled there. There is also often bunkered on Skagen from Rotterdam when sailing to the United States. The voyages are summarized and shown in Table 5.3.

Although it may be possible to refuel somewhere else, it is preferable to avoid this, because of fuel prices. Furthermore, the probability that alternatives are likely to be available in big ports may also make it preferable to refuel there and maintain this range.

Table 5.3: Voyage distances for the ship design.

Voyage	Distance [nm]
Rotterdam - Philadelphia - Rotterdam	7108
Skagen - Philadelphia - Rotterdam - Skagen	7678
Panama - Shanghai	8579

Therefore, the longest trip is from Panama to Shanghai. This means that it must be possible to sail a minimum distance of 8579 [nm]; otherwise, the longest trip cannot be made.

In assuming this situation, no account is taken of the fact that a shipowner may have the vision to carry excess fuel to speculate with fuel.

A fuel consumption of 17.5 [mt] per day is assumed at 12 [knots]. The sailing time to travel 8579 [nm] is then about 30 days, and a total energy capacity of 22,281 [GJ] is required.

To achieve the reduction in cargo capacity suggested in the previous chapter, 2% is taken from both the grain capacity and the volumetric capacity. Therefore, the minimum DWCC is 9996 [tonnes] and the minimum grain capacity is 13,371 [m³]. The size of the ship must also be considered, since the ship cannot be infinitely long. If the ship became too long, the cargo capacity would again have to be increased. However, this will only be considered, if necessary; as yet, no boundary is set for this.

In summary, the energy capacity is first reduced to 22,281 [GJ]. When this limit is reached, the cargo capacity is reduced second to the minimum of 9996 [tonnes] DWCC and 13,371 [m³] grain capacity. When this limit is reached, the last factor to be considered is whether the ship can be enlarged. An overview of the options when considering limits is shown in Table 5.4.

Table 5.4: Possible options for the refit with the limits that are used.

Option	Cargo Capacity: DWCC [tonnes] Grain Capacity [m ³]	Energy Capacity [GJ]	Ship Length [m]
1	x1 = 10,200 x2 = 13,644	22,281 < x3 < 36,329	x4 = 137.9
2	9,996 < x1 < 10,200 13,371 < x2 < 13,644	x3 = 22,281	x4 = 137.9
3	x1 = 9996 x2 = 13,371	x3 = 22,281	x4 > 137.9

5.2. Low-Sulphur Fuel Oil and Marine Gasoil to Hydrotreated Vegetable Oil

In this section, the design spiral is followed for a transition to HVO. HVO is very similar to LSFO and MGO in its use on board of a ship. Therefore, only one iteration is required for HVO. After the iteration, the final new vessel design is presented and the requirements when the refit is performed are discussed.

5.2.1. Iteration 1

1. Requirements

(a) Cargo capacity

- DWCC: 10,200 [tonnes]
- Grain capacity: 13,644 [m³]

(b) Energy capacity: 36,329 [GJ]

(c) Beam: 15.97 [m]

(d) Tanks and supply adapted as far as possible for a transition to HVO.

2. Ship Size

- (a) Using the reference ship as a starting point, the length of the ship is 137.9 [m].

3. IGF Code

- (a) The current ship design sailing on LSFO and MGO and so does not have to conform to the IGF code, for HVO, it also does not have to comply with the IGF code, so no adjustments need to be made.

4. Tanks

- (a) HVO can be stored in the same tanks as MGO and LSFO.

5. Fuel Supply

- (a) The fuel supply also remains the same for HVO as for LSFO and MGO.

5.2.2. New Design

No adjustments were made in the new design, so the new ship design remains the same.

5.2.3. The Refit

When switching to HVO, energy capacity is lost. The only option discussed is to reduce the ship's range.

1. Reduce energy capacity

- For the refit, the vessel does not yet have the same energy capacity as with LSFO and MGO. If the fuel tanks are filled with HVO, the energy capacity that remains is 33,174 [GJ], which is well above the minimum fuel capacity. The overall sailing range of the vessel is therefore reduced by 8.6 %. Since this option is offered, expansion of the vessel or reduction of the loading capacity is not important for HVO.

2. Reduce cargo capacity

- Not applicable for HVO.

3. Extend vessel

- Not applicable for HVO.

5.3. Low-Sulphur Fuel Oil and Marine Gasoil to Ammonia

In this section, the design spiral is followed for a transition to ammonia. This is achieved in one iteration. After that the new design for ammonia is discussed and the remaining requirement when the refit is performed are discussed.

5.3.1. Iteration 1

1. Requirements

- (a) Cargo capacity
- DWCC: 10,200 [tonnes]
 - Grain capacity: 13,644 [m³]
- (b) Energy capacity: 36,329 [GJ]
- (c) Beam: 15.97 [m].

- (d) Tanks and supply adapted as far as possible for a transition to ammonia.

2. Ship Size

- (a) Using the reference ship as a starting point, the length of the ship is 137 [m].

3. IGF Code

- (a) The current ship design, sailing on LSFO and MGO, does not have to conform to the IGF code. However ammonia has not yet been included in the IGF code because there is no demand in the market, and capacity within IMO is limited. If ammonia is used as fuel, then it will be covered in the IGF code. As discussed, the IGF code comprises several parts; the parts related to the fuel tanks are discussed in point 4, and the parts related to the fuel supply are discussed in item 5.

4. Tanks

- (a) Ammonia is stored in a differently from LSFO and MGO. Ammonia is stored in pressurized, semi-refrigerated cylindrical type C tanks. These tanks have a minimum and maximum size.

i. Size

- A Type C tank minimum size of 30 [m³].
B Type C tank maximum size of 1000 [m³].

This tank size limits the use of ammonia. In addition to the limits on the size of the ammonia tanks, the location is also more limited than for LSFO and MGO. Type C tanks are independent and self-supporting which means that they do not form part of the ship's hull and therefore are not essential to the hull's strength. This offers the advantages that they do not require a secondary barrier and have fewer requirements. Another advantage is that a type C tank can relatively easily be installed when building new ships and upgrading existing ships [97]. The selection of rules that apply for the location of a type C tank are as follows:

ii Location

- A In front of the collision bulkhead aft.
B Behind the collision bulkhead for.
C At a minimum distance of $B/5$. For the reference vessel this means 3.17 [m].
D The lowermost boundary of the fuel tank(s) must be above a distance of $B/15 = 1.06$ [m].
E Exceptionally, the fuel tank boundary may be closer to the shell plating and to the stern than items D and E. For tanks no larger than or equal to 1000 [m³] this is not closer than 0.8 [m].

Items A and B also apply to LSFO and MGO. Items C, D and E are visualized in Figure 5.6.

- F A fuel containment system located below deck must be gas-tight towards adjacent spaces. All tank connections, fittings, flanges and tank valves must be enclosed in a gas-tight connection space.

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Figure 5.6: Location requirements for a type C tank.

The protective distance for a type C tank is measured to the tank shell that forms the primary barrier for the tank containment system.

The current tanks have been used as a starting point because it is assumed that there will be a complete switch to another fuel; if this space is not used it will be lost space. Therefore, this research investigates whether the LSFO and MGO tanks can possibly be replaced by type C tanks at their current locations.

To study this, the available space was looked at first. The minimum size is determined by the tank capacity. However, the ammonia tank itself also requires more space, as determined in Chapter 4. Therefore a space, of about 45 [m³] is needed. This is only possible at the locations of tanks 201, 202, 203, 206 and 207, which as shown in Table 5.6.

Table 5.5: Tanks and space requirements.

Tank		Size	
		Capacity [m ³]	1
201	HFO Cross Bunker PS	143.9	✓
202	HFO Cross Bunker Centre	262.8	✓
203	HFO SB	144.2	✓
204	HFO Hold Bunker PS	39	✗
205	HFO Hold Bunker SB	39	✗
206	HFO Bunker PS ER	94.2	✓
207	HFO Bunker SB ER	119	✓
208	Settling Tank 1	11.1	✗
209	Settling Tank 2	10.1	✗
210	HFO Daytank 1	9	✗
211	HFO Daytank 2	8.8	✗
214	Gas Oil Bunker PS	39.6	✗
215	Gas Oil Bunker SB	28.2	✗
216	Gas Oil Daytank	4.57	✗

Next, the shape of the tank is considered. Since a type C tank is a cylindrical tank, there must be a cuboid-shaped space where it can be placed. As a result, there is no room for an ammonia tank at the positions of tanks 206 and 207.

Table 5.6: Tanks and shape.

Tank		Shape
		Cuboid Shaped
201	HFO Cross Bunker PS	✓
202	HFO Cross Bunker Centre	✓
203	HFO SB	✓
206	HFO Bunker PS ER	✗
207	HFO Bunker SB ER	✗

To be able to place ammonia tanks, space must be made. The cross-section includes a lashing store, a staircase and an overflow tank that are in the way of the middle ammonia tank. This is why this ammonia tank is not as tall as the adjacent tanks. The ammonia tanks are placed vertically because this is most space-efficient. Due to the width of the cross-section, the diameter is limited.

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Figure 5.7: Fuel tanks for an ammonia system.

A simplified overview of the fuel tanks in the cross section is shown in Figure 5.8.

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Figure 5.8: Simplified ammonia fuel tanks in the cross-section of the ship.

5. Fuel Supply System

- (a) For the ammonia fuel supply system, additional requirements apply. Requirements for the fuel piping for ammonia as follows:
 - i. Fuel Piping
 - A. Fuel pipes must not be located less than 800 [mm] from the ship's side.
 - B. Fuel piping must not be led directly through accommodation spaces, service spaces, electrical equipment rooms or control stations as defined in the SOLAS convention.
 - C. Double-walled piping is required below deck.

As described in point 4, 'Tanks', three fuel tanks are placed in the cross-section. The fuel supply to these tanks needs to be installed. This can be achieved via the pipe duct that is already in the ship, as shown in the double bottom in Figure 5.7. For the bunkering station, there are also a number of rules selected rules, as shown below.

- i. Bunkering station
 - A. The bunkering station must be located on the open deck so that sufficient natural ventilation is provided. It is possible to place a bunkering station below deck, but closed or semi-enclosed bunkering stations are subject to special considerations within a risk assessment.
 - B. The surrounding hull or deck structures must not be exposed to unacceptable cooling, if there is a leakage of fuel. Drip trays can be placed for this purpose.
 - C. The bunker station should be placed as close as possible to the tank to prevent excessive during bunkering.
 - D. The outlet from the pressure relief valves shall normally be located at least 10 [m] from the nearest air intake, air outlet, exhaust outlet from machinery installations or opening to accommodation, service space, control space or other non-hazardous areas.
 - E. The vent mast discharge height must not be less than $B/3$ or 6 [m], whichever is the greater, above the weather deck and 6 [m] above working decks and walkways. For the reference vessel, this is $15.87/3 = 5.29$, so 6 [m] must be maintained.

According to regulations, it is not permitted to place the vent mast within a range of 10 [m] from an outlet, as shown in Figure 5.17. The requirement of 6 [m] of space above working decks and walkways creates problems at the location of the tanks because there is a gantry crane here. The vent mast does not fit under this gantry crane, and this would also be impractical when moving hatchcovers. A logical choice is to place this vent pipe at a height of 6 [m] on the forepeak.

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Figure 5.9: Vent pipe restrictions.

The cross-section can be arranged in such a way that ammonia tanks can easily be placed. In addition, the necessary fuel supply can be placed. These adjustments do not change the requirements, so a second iteration is not necessary.

5.3.2. New Design

For the new design, few changes are made, as discussed in Iteration 1.

5.3.3. The Refit

When switching to ammonia, an extensive refit must be performed.

1. Reduce energy capacity

- For the refit, the vessel does not yet have the same energy capacity as with LSFO and MGO. If the fuel tanks are placed as described in the first iteration, there will be an available capacity for 387 [m³] of pure ammonia fuel. This equals an energy capacity of 4257 [GJ], which is 20% of the required minimum capacity; there is still 18,023 [GJ] to be realized. The energy capacity is therefore reduced to the minimum energy capacity.

2. Reduce cargo capacity

- The energy capacity to be realized can be removed from the cargo capacity first. A space of 1638 [m³] of pure fuel needs to be realized and approximately 2176 m³ of ammonia including system. If this is gained from the cargo capacity, there remains a grain capacity of 11,468 [m³]. This is a reduction of 16%, while the limit is 2%.

3. Extend vessel

- Therefore with ammonia, it is very questionable whether it makes sense to take 2% of the cargo space, if there are still 2175 m³ when there is still so much cubic capacity to be realized.
- It does not make sense to build this formation for ammonia; it is unsuitable because much more capacity is needed. To realize a capacity of 2176 m³, the ship must be extended by 14.7 [m], which is an increase of 10.7%.

5.3.4. The Comparison With Another Ship Design

To determine whether a different design would do better in this situation, consideration is given to a design with the deckhouse on the forepeak. However, the amount of extra fuel space now available at the aft is only a small fraction of the required space (13%). There would only be space for about 300 [m³].

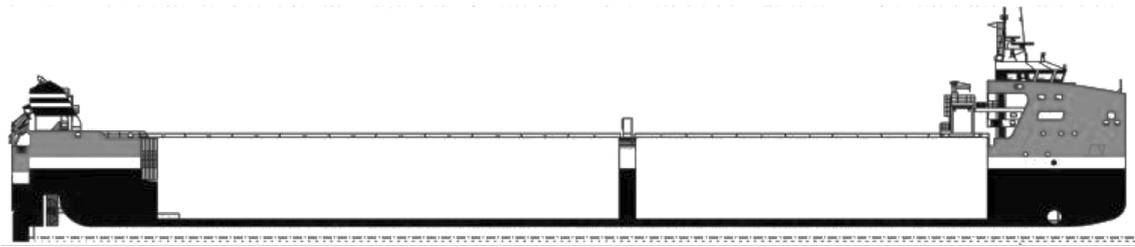


Figure 5.10: Shipdesign with deckhouse on the forepeak.

5.4. Low-Sulphur Fuel Oil and Marine Gasoil to Methanol

In this section, the design spiral is followed for a transition to methanol. This is achieved in three iterations. After the last iteration, the new vessel design is presented and the remaining requirements when the refit is performed are discussed.

5.4.1. Iteration 1

1. Requirements

- (a) Cargo capacity
 - DWCC: 10,200 [tonnes]
 - Grain capacity: 13,644 [m³]
- (b) Water ballast capacity: minimum 30% of DWCC [95].
- (c) Energy capacity: 36,329 [GJ]
- (d) Beam: 15.97 [m]
- (e) Fuel tanks and fuel supply adapted as far as possible for a transition to methanol.

2. Ship Size

- (a) Using the reference ship as a starting point, the length of the ship is 137.9 [m].

3. IGF Code

- (a) The current ship design, sailing on LSFO and MGO does not have to conform the IGF code, but methanol must comply with the IGF code. As discussed, the IGF code comprises several parts. The parts related to the tanks are discussed in point 4 and the parts related to the fuel supply are discussed in point 5.

4. Tanks

- (a) Methanol can be stored in the same way as LSFO and MGO but, due to the nature of the fuel, there are additional requirements in the IGF code.

Methanol can be stored in double bottom ballast tanks. This is possible because methanol disappears quickly in water, and it is not rated as toxic to aquatic organisms. Furthermore, a ballast water tank was converted into a fuel tank during the refit of the Stena Germanica [35]. Although this was not a general cargo ship but a RoPax ferry (RoPax ferries experience less load conditions and stability issues), with the given water-ballast requirement it is assumed that this would also be possible with a general cargo ship.

A schematic overview of the double bottom ballast water tanks is shown in Figure 5.14.

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Figure 5.11: Side view of selected ballast water tanks.

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Figure 5.12: Top view of selected ballast water tanks.

Table 5.7: Ballast water tanks.

Tank		Tank Capacity [m ³]
Number	Description	
103	Ballast water tank 1 PS	128.7
104	Ballast water tank 1 SB	128.7
105	Ballast water tank 2 PS	143.3
106	Ballast water tank 2 SB	143.3
107	Ballast water tank 3 PS	103.0
108	Ballast water tank 3 SB	103.0
113a	Ballast water tank 4 PS	155.0
114a	Ballast water tank 4 SB	155.0
117a	Ballast water tank 5 PS	155.0
118a	Ballast water tank 5 SB	155.0
121a	Ballast water tank 7 PS	60.0
122a	Ballast water tank 7 SB	60.0

In total, the ship has a capacity of 4053 [m³] of ballast water. The double bottom ballast tanks have a capacity of 2305 [m³]. It must be noted that the ballast water tanks are used to maintain stability and keep the ship at the optimal waterline when sailing empty.

To meet the ballast water capacity requirements, 993.4 [m³] of ballast water could be sacrificed for methanol.

The location of the water ballast tanks is of importance to keep the ship stable. To keep an even distribution of ballast tank available at the bottom of the ship, tanks 103, 104, 105, 106, 107, 108, 121 and 122 are used. These tanks are identified as possible tanks to be refitted methanol tanks. Therefore, a cofferdam at the top and sides of these tanks is mandatory and may be installed in advance.

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Figure 5.13: Ballast water tanks with cofferdams (top view).

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Figure 5.14: Ballast water tanks with cofferdams (side view).

The location of the tanks is essential because a tank for LSFO and MGO may be at a location that does not meet the requirements for methanol. The following selection of rules from the IGF code is used for the location of a storage tank:

i. Location

- A. Fuel tanks should be placed abaft of the collision bulkhead.
- B. Fuel tanks should be placed forward of the aft peak bulkhead.
- C. Fuel tanks must not be situated in accommodation spaces or machinery spaces of category A.
 - Accommodation spaces are defined by SOLAS as spaces used for public spaces, corridors, lavatories, cabins, offices, hospitals, cinemas, game and hobby rooms, barber shops, pantries containing no cooking appliances and similar spaces.
 - Machinery spaces of category A are the spaces and trunks that contain internal combustion engines used for propulsion, other internal combustion engines that combined have a total power of >375 [kW] and any oil fired boiler or other oil-burning equipment.
- D. Fuel tanks should be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methanol or fuel preparation space.
 - Cofferdam is a structural space of at least 600 [mm] surrounding a fuel tank that provides an added layer of gas- and liquid tight protection against external fires, toxic or flammable vapours between the fuel tank and other areas of the ship.

The following investigates whether the current tanks are sufficient for the storage of methanol and therefore comply with the above IGF code rules.

The locations of all fuel tanks meet the above-mentioned requirements (A, B and C). To be able to use these fuel tanks for methanol, cofferdams need to be installed. This can already be done to make the transition to this alternative fuel easier in the future. Below a schematic overview of the tanks is shown. The sides that need a double layer to meet the cofferdam requirements are illustrated in red.

It is assumed that no separate settling tanks and daytanks are needed because methanol does not require a separator [99]. Therefore, these small settling tanks (208 and 209) lose

their function when the ship is converted to sail on methanol, so they are not considered for installing a cofferdam. The tank neighbouring these settling tanks (210 and 211) are also relatively small so the impact of installing cofferdams is relatively large. Therefore, it is assumed that these four tanks can best be refitted together during the refit to sail on methanol at that moment. The prior installation of cofferdams for tanks 210 and 211 is also therefore not considered at this stage of design. The remaining fuel capacity with cofferdams installed is calculated for the rest of the tanks and shown in Table 5.8. Tanks that will retain more than 50% of their capacity after cofferdam installation are identified as the tanks that will already receive a cofferdam during this design phase.

Table 5.8: Tank capacities with and without cofferdams.

Tank Number	Tank Capacity [m ³]		Tanks identified for installing cofferdams at the design phase
	without cofferdams	with cofferdams	
201	143.9	92	✓
202	262.8	133	✓
203	144.2	91	✓
204	39	21	✓
205	39	21	✓
206	94.2	40	✗
207	119	61	✓
208	11.1	n/a	✗
209	10.1	n/a	✗
210	9	n/a	✗
211	8.8	n/a	✗
214	39.6	10	✗
215	28.2	6	✗
216	4.57	0.6	✗
103	128.7	80	✗
104	128.7	80	✓
105	143.3	86	✓
106	143.3	86	✓
107	103.0	64	✓
108	103.0	64	✓
121a	60.0	34	✓
122a	60.0	34	✓

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Figure 5.15: Ship with tanks. The tanks are located in different layers of the ship

Due to the cofferdams, the tank capacity for LSFO and MGO is reduced. The remaining capacity is shown in Table 5.10.

Table 5.9: Remaining capacity for MGO and LSFO in the new design and for methanol when the ship is refitted.

Tank Number	Tank Capacity [m ³]	
	MGO/LSFO	Methanol
201	92	92
202	133	133
203	91	91
204	21	21
205	21	21
206	94.2	n/a
207	61	61
208	11.1	n/a
209	10.1	n/a
210	9	n/a
211	8.8	n/a
214	39.6	n/a
215	28.2	n/a
216	4.57	n/a
103	n/a	80
104	n/a	80
105	n/a	86
106	n/a	86
107	n/a	64
108	n/a	64
121a	n/a	34
122a	n/a	34
Total	624.57	947

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Figure 5.16: Design with cofferdams installed.

5. Fuel Supply

- (a) As shown in the previous point, all tanks are able to meet the requirements for methanol after the installation of cofferdams. A methanol fuel supply system has extra requirements, when compared to an LSFO or MGO system.

i. General

- A Fuel pipes must not be located less than 800 [mm] from the ship's side.
- B Fuel piping must not be led directly through accommodation spaces, service spaces, electrical equipment rooms or control stations, as defined in the SOLAS convention.
- C Double walled piping below deck is required if the fuel pipe does not run through a cofferdam.

This results in the need to install double walled piping to each tank.

- A. The outlet from the pressure relief valves must normally be located at least 10 [m] from the nearest air intake, air outlet, exhaust outlet form machinery installations or opening to accommodation, service spaces, control spaces, or other non-hazardous area.
- B. The vent mast discharge height must be less than: B/3 or 6 m, whichever is the greater, above the weather deck and 6 [m] above working decks and walkways.

According to the regulations, it is not permitted to place the vent mast within a range of 10 [m] from an outlet, as shown in Figure 5.17. The requirement of 6 [m] of space above working decks and walkways creates difficulties at the location of the tanks because there is a gantry crane here. The vent mast does not fit under this gantry crane, and this will also be

impractical when moving hatchcovers. A logical choice is to put this vent pipe at a height of 6 [m] on the forepeak.

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Figure 5.17: Vent pipe restrictions.

ii. Bunkering

- The bunkering station should be located on an open deck so that sufficient natural ventilation is provided. Closed or semi-enclosed bunkering stations are subject to special considerations with respect to provisions for mechanical ventilation. Their administration may require special risk assessments.

The adjustments needed to make the transition to methanol result in the requirements no longer being met. This requires the next iteration.

5.4.2. Iteration 2

1. Requirements

- (a) The cargo capacity remains the same, so nothing changes. The weight of the extra cofferdams is assumed to be negligible.
- (b) The ballast water capacity has been reduced to a minimum for the current design, but it still meets the requirements. Even if the transition is made to methanol, the ballast water tanks still meet the requirements.
- (c) With the cofferdams installed, the fuel capacity is reduced to 23,771 [GJ]. The required energy capacity for the reference design is 36,329 [GJ]. Therefore, to achieve the same capacity, an additional energy capacity of 12,557 [GJ] be realized.

2. Ship Size

- (a) The ship needs to be extended to maintain the same capacity.

3. Tanks

- (a) The ship must be extended at the largest tanks, as this is the most efficient. This is because the larger the tank, the less relative effect the cofferdam has on the volume.

4. Fuel Supply

- (a) The fuel supply does not change after Iteration 1. There is no effect on the fuel supply because the current fuel supply is connected to the existing tanks.

5.4.3. Iteration 3

2 Ship Size

- (a) As mentioned in Iteration 2, the ship is extended. To regain a fuel capacity of 36,329 [GJ] the ship must be extended with 2.3 [m], which is an increase of 1.6 %.

5.4.4. New Design

The new design is shown in Figure 5.18. This new design meets all current current requirements.

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Figure 5.18: New design with cofferdams.

Table 5.10: Remaining capacity in the new design for MGO and LSFO and for methanol when the ship is refitted.

Tank Number	Tank Capacity [m ³]	
	MGO/LSFO	Methanol
201	176	176
202	293.7	293.7
203	175	175
204	21	21
205	21	21
206	94.2	n/a
207	61	61
208	11.1	n/a
209	10.1	n/a
210	9	n/a
211	8.8	n/a
214	39.6	n/a
215	28.2	n/a
216	4.57	n/a
103	n/a	80
104	n/a	80
105	n/a	86
106	n/a	86
107	n/a	64
108	n/a	64
121a	n/a	34
122a	n/a	34
Total	953.27	1275.7
Total [MJ]	36329400	20411200

5.4.5. The Refit

To switch to methanol, a fuel capacity of 1275 m³ is already available. For methanol this provides an energy capacity of 1515 [GJ]. This is a decrease of 58%. The options for the refit are discussed below.

1. Reduce energy capacity

- For the refit, the vessel does not yet have the same energy capacity as with LSFO and MGO. The first option, as described in Chapter 4 is to surrender energy capacity. However for the requirements of sufficient fuel capacity described in Section 5.1, the minimum fuel capacity must be 22,810 [GJ]. Since there is only space for 20,411 [GJ], this option does not fulfil the minimum energy requirements. To realize the minimum energy requirement, an extra fuel capacity of 2399 [GJ] still needs to be realized; this represents 151 [m³] of pure fuel.

2. Reduce cargo capacity

- In different places, 151 [m³] can be realized. This roughly boils down to 190 [m³]. As a result, the grain capacity becomes 13,454 [m³], which is a reduction of 1.4%.

3. Extend vessel

- The most efficient way to extend the ship is in the middle of tanks 201, 202 and 203. This way, the ship needs to be extended as little as possible to create enough fuel capacity. To create 190 [m³] of space, the ship needs to be extended by 1.3 [m], which is an increase of 1%.

6

Evaluation of Concepts

The evaluation of concepts consists of two parts. In the first part, an economic evaluation is performed for the preparation of a new-build vessel for a fuel change. Since methanol is the only fuel of interest for which noteworthy preparations can be made for a new-build vessel, which will start to sail on LSFO/MGO, this is the only concept that is economically evaluated. In the second part, all the fuels that were discussed in Chapters 2, 3 and 4 but did not seem the most interesting for the design concept generation, are compared with the fuels that were used for these design concepts.

6.1. Methanol

To further investigate this option, a cost estimation has been made. Therefore, the cost of the reference ship was calculated using Aalbers [46]. The total costs of the reference ship is estimated at €14,435,822.-. The cost of a methanol tank versus a fuel oil tank, according to Brynolf et al., is about \$15 per [GJ] more expensive.

In the new ship design, 20,411 [GJ] is available for methanol. Therefore, the extra costs of the new ship design are estimated to be €260,240. The cost of the extra capacity that still needs to be realized at the refit is approximately €152,936. The ship has been enlarged by 2.3 [m] for the new design, and the costs for this have been estimated at €226,457 euro more than the original ship.

The costs are shown in Table 6.1.

Table 6.1: Costs of reference ship, based on Aalbers [46].

Item	Initial New Build Vessel			
	Reference ship		New Design	
	Material (dollar)	Man-hours	Material (dollar)	Man-hours
1 General and engineering	884,759	41444	896,356	42124
2 Hull and conservation	2,160,473	73137	2,226,925	75246
3 Ship's equipment	1,437,251	9568	1,437,251	9718
4 Accommodation	423,750	8157	423,750	8157
5 Electrical systems	560,634	762	560,634	762
6 Propulsion and power system	1,708,188	2432	1,708,188	2432
7 Systems for Propulsion and power	407,451	9507	407,451	9507
8 Bilge, ballast and sanitation systems	299,165	9716	304,239	9894
Methanol tanks			316,165	n/a
Man-hour costs (Euro/hour)		50,-		
Conversion (Euro/dollar)	0.85			
Total materials costs (Euro)	6,699,422		6,770,078	
Total labour costs (Euro)		7,736,399		7,892,202
Total cost (Euro)	14,435,822		14,922,520	
Difference (Euro)				-486,698
Refit				
Lengthening ship (Euro)	433,978			
Methanol tanks (Euro)	1,420,413		152,936	
Total	1,843,391		152,936	
Difference (Euro)				+1,690,455
Total difference (Euro)				+1,203,757

The investment costs for the new design is about 3% more than the original investment. The cost of the refit is 12% cheaper than the refit for the reference vessel.

6.2. Fuel Comparison

Three different fuels have been discussed. These were HVO, ammonia and methanol. These fuels were selected from a group of eight fuels. Based on their physical properties and the systems that the fuels require, a projection can be made about the other five fuels.

With regard to tank capacity, LPG and DME correspond to ammonia. These fuels are stored in cylindrical, pressurized tanks. Furthermore LPG and DME are heavier than air. Although ammonia is lighter than air, it reacts with air, so it is also considered heavier than air. Due to this, safety systems are also comparable. Ammonia distinguishes itself as the only toxic fuel, which means it requires additional measures to protect people and the environment. Finally, DME and LPG have a higher energy density, so less space is required on board a ship.

LNG and hydrogen could also be compared to ammonia, as they are also stored in cylindrical tanks. However, they must be stored refrigerated. The temperature to which LNG and hydrogen have to be cooled varies widely. Finally, the LNG system requires less space and weight than ammonia. Hydrogen, on the other hand represents much more weight and volume.

Therefore, from this discussion it can be concluded that if it makes no sense to prepare for ammonia, it also makes no sense to prepare for hydrogen. Hydrogen takes up even more space and weight than ammonia and needs to be stored in a similar cylindrical tank but then refrigerated. LPG, LNG and DME need to be examined further because no direct conclusion can be drawn from the examined fuels.

Ethanol, however, can be stored in exactly the same way as methanol. Ethanol even has a number of advantages over methanol; it is not toxic and is more energy dense. As a result, the refit to methanol may require reducing cargo capacity, which may not be necessary for ethanol.

The main issues for switching to the most sustainable fuels is that these fuels are mainly very different from the current fuels (LSFO and MGO). The exception is HVO. It may therefore be interesting to consider starting to design a ship to sail on a different fuel and preparing for a switch to an even more sustainable fuel. It would probably be very interesting to investigate how to prepare a ship for a fuel change to hydrogen or ammonia, starting on LNG or LPG. That scenario could also become more interesting in the next 30 years.

By taking into account methanol for a refit, it would be easy to switch to methanol or ethanol. It would also be possible to switch to HVO. Thus the shipowner has the flexibility to three different fuels with only an investment of an extra 3% of the ship's costs.

7

Conclusions and Recommendations

7.1. Conclusions

The earth's temperature is rising as a result of anthropogenic emissions. The shipping industry is a major contributor to these emissions. To meet the IMO GHG targets, ships must switch to alternative fuels.

However, it is not clear how these IMO goals may be expressed in regulations. As a result, shipowners are in a state of uncertainty about the purchase of newbuild ships that will last 25 to 30 years. Currently, sailing on low-sulphur fuel oil (LSFO) outside sulphur emission control areas (SECAs) and sailing on marine gasoil (MGO) inside SECAs is the easiest and cheapest option because these fuels are widely available and relatively easy to handle on board. Therefore, the main question of this thesis was formulated as follows:

How can a shipowner prepare a new general cargo ship for uncertain future emission regulations with respect to its design for on-board fuel storage and fuel supply that starts sailing on the currently used low-sulphur fuel oil and marine gas oil?

To answer this question, first the possible fuel changes that could take place were investigated. These scenarios were formulated on the basis of literature, regulations, fuel emissions and background information on emissions. The first scenario that was formulated is that a fuel should, if possible, be CO₂ neutral. The second scenario was that a fuel must be carbon-free. For the first scenario, this meant that (with the exception of the currently used fuels) all eight fuels that were included were compliant. These were hydrotreated vegetable oil (HVO), LNG, LPG, ethanol, methanol, dimethyl ether (DME), hydrogen and ammonia. It must be noted, however, that this concerns bio-LNG, bio-LPG, bio-ethanol, bio-methanol, green-H₂ and green-. For the second scenario, only ammonia and H₂ were still eligible.

It is assumed that the ship will still sail on low-sulphur fuel oil (LSFO) and marine gasoil (MGO) in its first years. Therefore, these fuels are compared with eight promising alternative fuels. This thesis focused on the preparations for the design of fuel storage and fuel supply, so the fuels were compared with each other on these points. The fuels that were most similar to the conventional fuels are assumed to be the easiest to prepare for a fuel change. Therefore these have the most potential. For the first scenario this was HVO and for the second scenario ammonia. As an extra fuel, methanol was considered because it was also relative similar to LSFO and MGO after HVO when considering fuel storage and fuel supply, taking into account that the IMO carbon factor has a much lower carbon factor than HVO.

For these fuels, research was conducted to discover what would be needed to sail on these fuels. Then it was investigated if a new ship could be built, how best to prepare for the fuels change and what would be needed during the refit.

It was concluded that the analysed fuels consume more space and weight. Therefore, three possible options have been chosen for a refit. First, the sailing may be reduced. Second, cargo capacity may be reduced. Third, the ship may be enlarged.

The recommended order of these options is to first see if the sailing range can be reduced. The energy capacity of the reference ship discussed in this thesis can be reduced by roughly 40%. Second, the cargo capacity can be reduced. This must be done carefully, as reducing cargo capacity results in potential income loss. According to Kana et al., a 2% reduction in cargo capacity does not affect revenue. It is therefore assumed that 2% of cargo capacity may be surrendered to make way for an alternative fuel. The last option is to make the

ship larger at a refit. As the ship has a limited beam, the decision was made to lengthen the ship; an additional reason was that widening a ship has much more impact than extending it.

It was concluded that no preparations are necessary for HVO. HVO does not require a refit if option 1, to reduce the sailing range, is chosen. The sailing range should then be reduced by 8.6%; this is far above the minimum sailing range, which was defined as 40% lower.

For methanol, it can be useful to prepare for a change. For this purpose, fuel piping and cofferdams may be laid or prepared for. Since methanol can simply be stored as a liquid, it can be placed in many more places than gaseous fuels. Methanol has the advantage that it can be stored in ballast water tanks where no cofferdams are required if the tank is placed against the shell plating below the lowest possible waterline. If the ship is being prepared for methanol, the ship must be lengthened by 1.6%, to meet the initial requirements. During the refit, approximately 1.4% of the grain capacity must be reduced. Preparing the ship for methanol would cost approximately 3% more at the newbuild costs and saves 12% at the refit costs.

Ammonia has such an impact and requires so much space that it has been concluded that preparations for ammonia do not provide an advantage.

When a ship is being prepared for methanol, the ship acquires the flexibility to use five fuels because HVO does not need any modifications and ethanol requires exactly the same systems as methanol.

If a shipowner wants to prepare a ship, the placement of the fuel tanks for the alternative fuels is especially important. This is the starting point because from that point the fuel supply can be examined.

7.2. Recommendations

- This research only focuses on a complete switch to an alternative fuel. A partial, change to another fuel is not included and would be interesting to investigate, as preparations for gaseous fuels then become more convenient.
- No operational costs are included in this thesis. These may have a major impact on the choice of fuel.
- In order to get a better picture, the qualitative transition matrix can be made quantitative.
- The efficiencies of different fuels considered equally for all fuels in this thesis. If these change in the future, they may have an effect on the amount of space and weight required.

A

Fuel Properties

Table A.1: Fuel Properties

Property	Unit	Fuel									
		LSFO*	MGO*	HVO*	LNG*	LPG*	Ethanol	Methanol	DME	Hydrogen	Ammonia
	[MJ/kg]	39.42.44 [10, 60]	42.8 [10]	37.8 [10]	48.6 [10]	45.5 [10]	28.8 [9]	28.9 [10]	120 [10]	18.6 [18]	
LHV	[GJ/m ³]	38.2 ^a [10]	36.6 ^a [10]	34.8 ^a [10]	20.8 ^d [10]	24.4 ^a [10]	22.7 ^b [9]	15.8 ^b [9]	0.012 ^{b,d} [9] 0.16 ^{e,e} [9] 2.5 ^{b,f} [9] 1.43 ^{b,g} [9]	11.2 ^{b,c} [117] 6.8 ^j [18]	
Density	[kg/m ³]	885 ^k [60]	736 ^d [117]	^o 920	0.6 ⁱ [52]	580 [9]	789 ^m [9]	796 ^m [60]	0.1 ^d [9] 1.34 ^e [9] 20.79 ^f [9] 11.98 ^g [9]	603 ^c [117] 0.73 ^m [3]	
Boiling Point	°C	160 - 366 [47]	260-371 [52]	313 [30]	-163 ^h [49]	-43 [9]	78 [52]	64 [52]	-252 [49]	-33.34 [3]	
Auto-Ignition Temperature	°C	257 [47]	338 [52]	204 [49]	537 [49]	410 - 580 ⁿ [49]	363 [52]	470 [49]	577 [9]	630 [49]	
Flashpoint	°C	>70 [60]	66 [52]	>61 [49]	-188 [49]	-104 [49]	13 [52]	11-12 [49]	132 [49]	132 [49]	
Flammability Limit	% in air	0.6 - 7.5 [47]	0.5 - 5 [52]	0.6 - 7.5 [49]	4 - 15 [49]	1.8 - 10.1 [49]	3.3 - 19 [52]	6.7 - 36 [49]	4 - 74.2 [49]	15 - 28 [49]	
Toxicity		No [49]	No [49]	Low[49]	No [49]	High [49]					

* Can vary and is highly dependent on composition

^a At 0 °C and 1 bar^b Based on the density and LHV in MJ/kg^c At 10 bar^d At 25 °C and atm ($\approx 1\text{bar}$)^e At -252 °C and atm ($\approx 1\text{bar}$)^f At -252 °C and 350 atm ($\approx 355\text{bar}$)^g At 25 °C and 350 atm ($\approx 355\text{bar}$)^h At 1 barⁱ At vapour density air = 1^j At ambient pressure and -33 °C^k At ambient pressure and 15 °C^l At -160 °C and 1 bar^m At 15 °C and 1 barⁿ At 20 °C

B

Fuel Properties 1

Table B.1: For convenience, LNG and LPG are written down accordingly. This is actually wrong because at SATP gases are not liquid.

Category	Design Element	Fuel									
		LSFO	MGO	HVO	LNG	LPG	Ethanol	Methanol	DME	Hydrogen	Ammonia
Technical	Boiling Point [°C]	160-366 [47]	260-371 [52]	313 [30]	-162 [49]	-43 [9]	78 [52]	64 [52]	-23.6 [14]	-252 [49]	-33.34 [3]
	Energy density (GJ/m ³) (SATP)	38.2 [10]	36.6 [10]	34.8	0.035 [107]	0.088** [10]	22.7 [9]	15.8 [9]	12.5 [62]	0.012 [9]	0.013* [3]
	Technique	L	L	L	C(-162 [°C])	P(10 [bar])	L	L	P(5 [bar])	C(-252 [°C])	P(10 [bar])
	Energy density (GJ/m ³) at preferred storage	38.2 [10]	36.6 [10]	34.8 [10]	20.8 [10]	24.4 [10]	22.7	15.8	19.2 [10]	8	11
	Energy density (GJ/m ³) incl. system	30	29	25	12	18	16.5	12.6	13.32	5	8.28
Energy density (GJ/kg)	42.44	43	37.8	50.4 [10]	45.5 [10]	25	20	28.8	120	18.36	
Energy density (GJ/kg) incl. system	30	30	27	12	26	32	15	19.8	9	12.96	

SATP Standard ambient temperature and pressure (SATP) (25 °C and atm pressure ($\approx 1\text{ bar}$))

n/a Not applicable

* at 15 °C and atm pressure (1.013 bar)

** Based on Propane

L Liquid

P Pressurized

C Cryogenic

C

Fuel Properties 3

Fuel	Pure Fuel		Including System		System Only	
	Volumetric [GJ/m3]	Gravimetric [GJ/kg]	Volumetric [GJ/m3]	Gravimetric [GJ/kg]	Volumetric [GJ/m3]	Gravimetric [GJ/kg]
LSFO	38.2	42.44	30	30	8.2	12.44
MGO	37	43	29	30	8	13
HVO	32	37.8	25	27	7	10.8
LNG	18	50.4	12	26	6	24.4
LPG	24.4	45.5	18	32	6.4	13.5
Ethanol	21	25	16.5	18.8	4.5	6.2
Methanol	16	20	12.6	15	3.4	5
DME	19.08	28.8	13.32	19.8	5.76	9
LH2	8	120	5	9	3	111
Ammonia	11	18.36	8.28	12.96	2.72	5.4

D

Transition Matrices

D.1. Engine

Fuel A	B ENGINE	LSFO/MGO		HVO		LNG		LPG		MeOH		EtOH		DME		H2		NH3		
		DF	CI	DF	CI	DF	SI	DF	SI	DF	SI	DF	SI	DF	SI	DF	SI	DF	SI	
LSFO/MGO	DF																			
	CI																			
HVO	DF																			
	CI																			
LNG	DF																			
	SI																			
LPG	DF																			
	SI																			
MeOH	DF																			
	SI																			
EtOH	DF																			
	SI																			
DME	DF																			
	SI																			
H2	DF																			
	SI																			
NH3	DF																			
	SI																			

Figure D.1: Transition matrix engine

D.2. Fuel Storage

D.2.1. Storage Method

Fuel	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A	STORAGE	l	l	cr	p	l	l	p	cr	p
LSFO/ MGO	l									
HVO	l									
LNG	cr									
LPG	p									
MeOH	l									
EtOH	l									
DME	p									
H2	cr									
NH3	p									

Figure D.2: Transition matrix storage method

D.2.2. Volumetric Energy Density Including System

Fuel	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A	STORAGE	l	l	cr	p	l	l	p	cr	p
LSFO/ MGO	l									
HVO	l									
LNG	cr									
LPG	p									
MeOH	l									
EtOH	l									
DME	p									
H2	cr									
NH3	p									

Figure D.3: Transition matrix Volumetric Energy Density Including System

D.2.3. Gravimetric Energy Density Including System

Fuel	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A	STORAGE	l	l	cr	p	l	l	p	cr	p
LSFO/ MGO	l									
HVO	l									
LNG	cr									
LPG	p									
MeOH	l									
EtOH	l									
DME	p									
H2	cr									
NH3	p									

Figure D.4: Transition matrix Gravimetric Energy Density Including System

D.2.4. Sum of the Separate Aspects

Fuel	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A	STORAGE	l	l	cr	p	l	l	p	cr	p
LSFO/ MGO	l									
HVO	l									
LNG	cr									
LPG	p									
MeOH	l									
EtOH	l									
DME	p									
H2	cr									
NH3	p									

Figure D.5: Transition matrix sum of the separate aspects

D.3. Other Systems

D.3.1. IGF Code

Fuel	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A										
LSFO/ MGO										
HVO										
LNG										
LPG										
MeOH										
EtOH										
DME										
H2										
NH3										

Figure D.6: Transition matrix IGF Code

D.3.2. Air Density

Fuel	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A										
LSFO/ MGO										
HVO										
LNG										
LPG										
MeOH										
EtOH										
DME										
H2										
NH3										

Figure D.7: Transition matrix air density

D.3.3. Sum of the separate aspects

Fuel	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A										
LSFO/ MGO			Green	Red						
HVO		Green		Red						
LNG		Red	Red		Yellow	Yellow	Yellow	Yellow	Green	Yellow
LPG		Red	Red	Yellow		Yellow	Green	Yellow	Green	Green
MeOH		Red	Red	Yellow	Yellow		Green	Yellow	Yellow	Yellow
EtOH		Red	Red	Yellow	Yellow	Green		Yellow	Yellow	Yellow
DME		Red	Red	Yellow	Green	Yellow	Yellow		Yellow	Green
H2		Red	Red	Green	Yellow	Yellow	Yellow	Yellow		Yellow
NH3		Red	Red	Yellow	Green	Yellow	Yellow	Green	Yellow	

Figure D.8: Transition matrix sum of the separate aspects

D.4. Sum of all separate elements

c	B	LSFO/ MGO	HVO	LNG	LPG	MeOH	EtOH	DME	H2	NH3
A	ENGINE	DF CI	DF CI	DF SI						
LSFO/ MGO	DF CI		Green	Yellow	Red	Yellow	Orange	Yellow	Red	Red
HVO	DF CI	Green		Orange						
LNG	DF SI	Orange	Orange		Yellow	Green	Green	Green	Green	Green
LPG	DF SI	Orange	Orange	Yellow		Green	Green	Green	Green	Green
MeOH	DF SI	Orange	Orange	Yellow	Yellow		Green	Green	Green	Green
EtOH	DF SI	Orange	Orange	Yellow	Yellow	Green		Green	Green	Green
DME	DF SI	Orange	Orange	Yellow	Yellow	Green	Green		Green	Green
H2	DF SI	Orange	Orange	Yellow	Yellow	Green	Green	Green		Green
NH3	DF SI	Orange	Orange	Yellow	Yellow	Green	Green	Green	Green	

Figure D.9: Total transition matrix

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